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WORKING PAPER

RENEWABLE NATURAL GAS AS A CLIMATE STRATEGY: GUIDANCE FOR STATE POLICYMAKERS

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EXECUTIVE SUMMARY

Highlights

- Renewable natural gas (RNG), also known as biomethane or upgraded biogas, is growing in prominence as a strategy to help achieve state climate, waste management, and other sustainability goals.
- This working paper provides guidance for state policymakers on evaluating RNG resource potential, greenhouse gas emissions impacts, market opportunities, and policy options.
- To evaluate how RNG can contribute to state climate and other policy objectives, we highlight a variety of methods and tools available to identify feedstock supply, resource potential, and emissions benefits.
- Depending on how it is deployed, RNG has the potential to reduce methane emissions from organic wastes and provide fuel for applications that lack other low-carbon alternatives, such as heavy-duty freight or existing building and industrial heat sources. We highlight pathways for bringing RNG to market, current opportunities, and implications for decarbonization.
- States have considerable ability to drive RNG markets. We highlight a suite of mandates, incentives, and other complementary policies that are available, each of which comes with unique considerations that we discuss in detail. These range from climate and energy mandates that place greater value on RNG's environmental attributes to regulations that promote sustainable waste management and feedstock availability.

CONTENTS

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Overview

Across the country, states are strengthening their decarbonization goals and targeting emissions from short-lived climate pollutants including methane, a gas that has a global warming potential (GWP) 25–34 times that of carbon dioxide (CO_2) on a 100-year timescale (or far higher when evaluated on a shorter time horizon).[1] Nearly 30 percent of human-caused methane emissions in the United States stem from organic wastes that are typically managed at farms, landfills, and water resource recovery facilities (U.S. EPA 2020a), and which may be converted to biogas for RNG production. In addition, some sectors of the U.S. economy currently lack cost-effective low-carbon technology options suitable for all applications. Thus, deployment of RNG may contribute to climate goals, particularly to the extent that it

a. results in additional capture of methane from organic wastes; and

b. displaces fossil fuels in emissions-intensive sectors that currently lack cost-effective alternatives, such as heavy-duty freight or existing building and industrial heat sources.

In addition to potential climate benefits, the production and use of RNG may contribute to additional environmental or sustainability goals, including in the following areas:

- **Waste management** – Each year, the United States generates millions of tons of food scraps, sewage, oils and greases, manure, and other organic wastes. Currently, only a small fraction of these wastes is sustainably managed. Food waste and other organics can contaminate otherwise recyclable materials in municipal waste streams, while animal manure can infiltrate local ecosystems, negatively impacting air, water, and soil quality. While sustainably managing and reducing these waste streams requires a multifaceted approach, biogas and RNG projects can contribute to alleviating their adverse impacts.

- **Energy sustainability and resilience** – Many states and regions remain net importers of energy in the form of electricity and pipeline natural gas. Reducing this dependence through locally sourced alternatives can create new, local revenue streams and offer clean alternatives to consumers. For states with high energy import bills and significant untapped feedstock supply in the form of animal manure, municipal organic waste, or other residuals, organic waste-to-energy investment may contribute to sustainable energy goals.

While the potential benefits of RNG are significant, decision-makers are faced with uncertainty on whether projects can be easily deployed, the extent to which they can contribute to ambitious climate and environmental goals, and the trade-offs of supporting RNG versus alternative decarbonization strategies. Whether RNG production and use is an appropriate strategy depends on a number of local and regional factors, each of which requires careful consideration.

Purpose of this guidance and summary of topics covered

To facilitate informed and balanced decision-making, this guidance aims to aid policymakers in evaluating RNG resource potential and the role RNG resources may play in broader decarbonization goals, and understanding the toolkit of policies available for resource development and various forms of deployment. This guidance is structured to help policymakers answer the questions below.

Section I: Assessing RNG Resource Potential and Climate Impacts by Feedstock

What is the potential supply available from various waste streams?

National-level assessments find that existing organic waste streams in the United States could yield energy equivalent to approximately 7 percent of present-day natural gas consumption if converted to RNG (or more depending on assumptions regarding feedstock availability). The amount of RNG that may be feasibly brought online, however, will vary considerably by state and region.

Recent state-level assessments conducted in California, Colorado, Iowa, Oregon, and Washington all find substantial resource potential for RNG produced from local wastes that can meaningfully contribute to local climate and energy goals. Drawing on examples from these assessments as well as recent literature, this paper presents key methods and tools to evaluate technical potential and economic viability.

What are the emissions impacts of producing RNG?

Climate impacts differ substantially from feedstock-to-feedstock and project-to-project. Larger, more concentrated resources such as landfills generally yield the greatest amount of fuel potential at the lowest cost.

Distributed resources such as dairy farms may have much lower overall yield but—pound-for-pound—deliver more significant emissions reductions or other environmental benefits. The emissions impact of a particular RNG project also depends on the ultimate end use of the fuel. We summarize common approaches to determine whether a particular project may yield considerable climate benefits or more modest emissions reductions relative to fossil fuels on a life cycle basis.

Section II: RNG Market Opportunities and Role in Decarbonization

What are the options for bringing RNG to market?
The market for RNG is shaped by a variety of still-evolving factors. On the supply side, there is no one-size-fits-all approach to bringing resources online, and viable deployment pathways will depend on feedstock type, project location, offtake infrastructure, and other factors. On the demand side, RNG may be used in a wide array of applications given its flexibility as a drop-in fuel that is interchangeable with natural gas, leading to questions of market optimization and efficiency.

Driven largely by recent state and federal mandates, RNG has risen to nearly 40 percent of fuel consumed by natural gas vehicles in the United States, making vehicle fuel the fastest-growing form of RNG use today. In addition, RNG is increasingly being considered as a low-carbon fuel option for stationary end uses, particularly as a replacement for natural gas in heating, cooking, or other applications in residential and commercial buildings or as a low-carbon fuel to meet industrial heating needs.

Focusing on the transportation and stationary sectors in particular, we explore fundamental considerations regarding deployment strategies, market potential, and the role of policy in driving demand.

How does RNG deployment factor into decarbonization?
For many states and regions, the challenge of achieving ambitious emissions reduction goals will require a diversity of strategies across major emissions sectors. On its own, RNG derived from organic wastes cannot displace sufficient amounts of fossil fuel consumption to achieve long-term climate goals. However, RNG may still play a significant complementary role, particularly in cases where its production and use result in the following:

a. Net reduction in methane emissions

a. Displacement of fossil fuel use in sectors that lack economically viable alternatives

To help identify these opportunities, we highlight key factors and considerations that may be used in determining cost-effectiveness, emissions impacts, and complementarity with other vital decarbonization strategies.

Section III: Barriers to RNG Deployment and Policy Solutions

What are the key barriers and policy options affecting RNG deployment?
Despite significant market opportunities for RNG and its potential to contribute to climate, energy, and other policy goals, the majority of available resource potential in the United States remains untapped. Persistent barriers include feedstock availability; project economics; and market, regulatory, and operational risk factors.

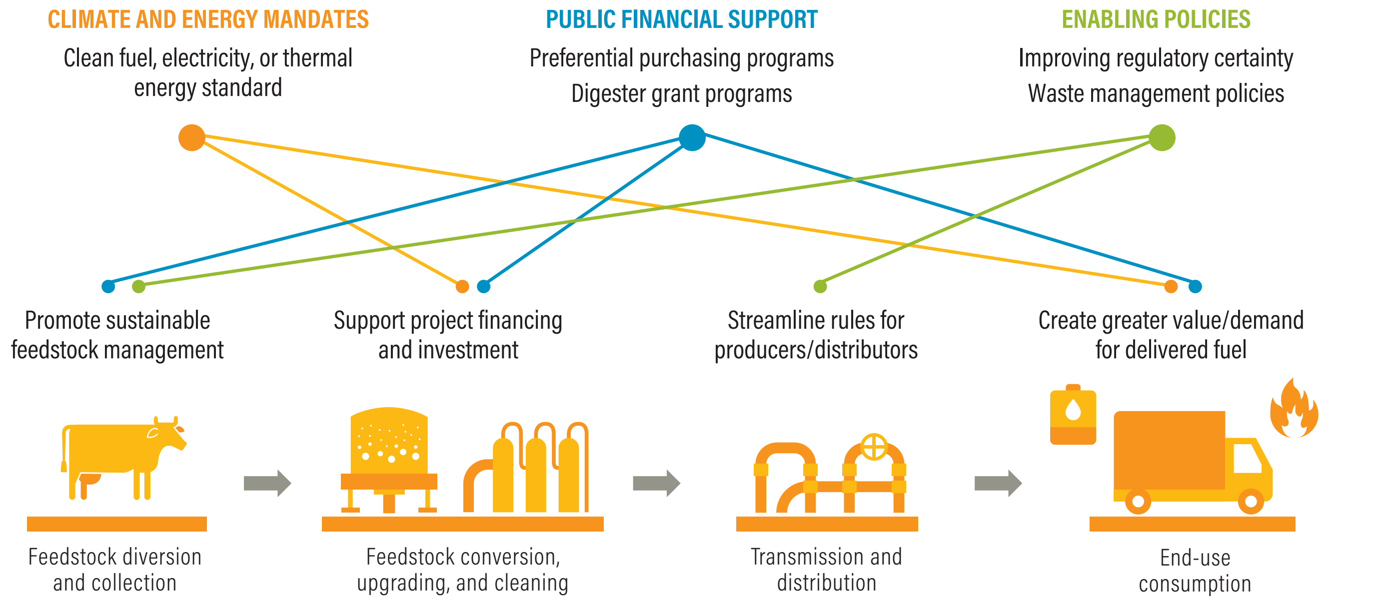
States seeking to develop RNG resources have a number of policy options to address these barriers, including mandates, public financing programs, and other enabling policies that can improve feedstock availability or streamline regulations. However, the impacts of various policy options and how they link to the different market barriers is not often well understood. Addressing this knowledge gap, we examine a comprehensive set of policy options, laying out fundamental considerations and providing concrete examples of how they can impact RNG. Rather than emphasizing any single approach, we highlight a wide array of options, with the understanding that projects will typically benefit from a mix of policies and incentives as depicted in Figure ES-1. Moreover, the appropriate mix will likely vary depending on the political and regional context.

How to use this document

This paper is designed to guide readers through key questions around renewable natural gas as a state-level climate strategy. In each section we draw on existing literature and experience to provide insights for informed decision-making. Rather than providing specific prescriptions or boilerplate solutions, the aim is to facilitate decision-making by highlighting current trends, exploring current data and estimates, and discussing key considerations.

Ultimately, decisions around how to assess resource potential, which market opportunities to pursue, or which barriers to address through policy will be guided by a variety of factors, ranging from local economics and infrastructure to state regulatory and political priorities. The sections of this guidance may be used as a general framework for understanding key decision points or as a starting point from which to develop a more comprehensive strategy. Throughout, the intention is to help inform decisions that can be adapted to different regional and political contexts. Table ES-1 below shows the three main sections of this paper along with examples of guiding questions discussed within each:

Figure ES-1 | **RNG Policy and Deployment Nexus**



Notes: A number of policy options are available for RNG resource deployment, each of which may impact feedstock availability, end use, and other factors differently. A suite of complementary solutions may be required to address barriers across the RNG supply chain and ensure that incentives promote efficiency while maximizing environmental benefits.
Source: WRI authors.

Table ES-1 | **Organization of This Working Paper**

SECTION	GUIDING QUESTIONS	KEY CONSIDERATIONS AND TOPICS COVERED IN THIS PAPER
Section I: Assessing RNG Resource Potential and Climate Impacts by Feedstock	■ How much RNG supply is technically available from different feedstocks? ■ What are the steps to evaluating resource potential at the state level? ■ What are the climate benefits of RNG produced from different feedstock types?	■ Review of available feedstocks and findings from existing national- and state-level assessments (Section 1.1) ■ Synthesis of common approaches, available tools, and other important factors to consider in evaluating resource potential and climate impacts, by feedstock (Section 1.2)
Section II: RNG Market Opportunities	■ What are common options for bringing RNG resources online? ■ What are the primary market opportunities for RNG and the market drivers? ■ How to evaluate RNG's role and impact on decarbonization?	■ Discussion of common supply-side considerations and deployment strategies (Section 2.1) ■ Discussion of market potential, drivers, and pathways in transportation and stationary sectors (Section 2.2) ■ Synthesis of approaches and studies on RNG carbon intensity, GHG cost-effectiveness, and role in decarbonization (Section 2.3)
Section III: Barriers to RNG Deployment and Policy Solutions	■ What are common barriers to RNG deployment? ■ What are the various state-level policy levers for RNG deployment and the fundamental considerations they entail? ■ What is the existing impact or experience of various policy options to date?	■ Discussion of primary barriers to resource and project development (Section 3.1) ■ Exploration of available state policy options, important decision points and their inherent trade-offs, and concrete examples of how various options have been used in different regional and political contexts (Section 3.2)

Note: GHG = Greenhouse gas.
Source: WRI authors.

SECTION 1: ASSESSING RNG RESOURCE POTENTIAL AND CLIMATE IMPACTS BY FEEDSTOCK

A key first step in evaluating renewable natural gas (RNG) as a climate strategy is to assess resource potential. In this section, we highlight both "technical" resource potential (i.e., the amount of raw feedstock supply that can be made available in a particular state or region) and approaches for determining "economic" resource potential (i.e., the amount of supply that may be viably converted and upgraded to produce biomethane). We also include a discussion of the emissions impacts associated with RNG production from various resources.

Each of these factors—resource availability, economic viability of conversion to RNG, and climate impact—varies considerably from one feedstock type to the next. Moreover, a variety of approaches to assessing them exists. Below, we include preliminary questions that can guide the overall direction of an assessment.

GUIDING QUESTIONS: DETERMINING RESOURCE ASSESSMENT SCOPE

- What potential feedstocks are most relevant, given the local economy?
- What are their respective greenhouse gas (GHG) emissions benefits?
- What level of data resolution (e.g., state-level, county-level, point-source) will be required to inform resource development and policy priorities?
- What factors should be considered to determine economic viability?
- What other factors should be considered, including other energy and environmental cobenefits?
- What studies or estimates have already been conducted by federal agencies, state universities, agricultural agencies, waste management agencies, trade groups, or other relevant organizations that can be used to inform the assessment?

The sections that follow include a high-level overview of RNG feedstocks and findings from current state and national assessments. We then present a variety of methods and considerations intended to help guide decision-making, organizing the discussion by primary RNG feedstocks.

1.1 – Summary of RNG Feedstocks, Climate Impacts, and Existing Resource Assessments

We use the term "feedstock" broadly to mean any raw input that may be used to produce RNG through anaerobic digestion (AD) or other more nascent, near-commercial technologies. In addition, we use the term "biogas" to refer to the mix of carbon dioxide, methane, and other trace elements that may be generated from organic wastes through decomposition. To be classified as RNG, this biogas undergoes upgrading to remove constituent gases such that it is nearly pure methane.

We discuss two primary types of RNG feedstocks commonly included in resource assessments:

1. **Wet-waste feedstocks**, such as diverted food waste, livestock manure, wastewater sludge, or the organic fraction of waste managed at landfills. Wet-waste feedstocks are converted to biogas through AD, which may then be upgraded and processed into RNG. The vast majority of RNG projects in the United States to date are derived from wet-waste sources processed through anaerobic digestion.
2. **Dry feedstocks**, which include agricultural crop residues and forestry or forest product residues. Examples of agriculture crop residues include plant portions of crops that aren't removed during harvesting (e.g., corn stover, wheat straw), while examples of forestry or forest product residues include woody material not removed in forest harvesting operations, unused mill processing materials, or urban wood waste. In small amounts, these feedstocks may be codigested with wet wastes to improve biogas yield in processes using AD. However, conversion of larger amounts of woody biomass as a stand-alone feedstock requires thermal gasification and methanation technology that is not yet economically mature in the United States.

The sections that follow provide details on resource potential and climate impacts for the majority of feedstocks and technologies that may be used for RNG production in many parts of the country. Certain categories are not included but may still merit consideration from policymakers (Box 1-1).

Box 1-1 | Feedstocks and Technologies Not Discussed in This Paper

Fats, oils, and greases (FOG) may come from commercial and industrial food processing operations. These resources on their own do not merit stand-alone RNG projects, given the relatively small quantities available. In addition, much of current FOG waste streams are converted to biodiesel rather than diverted to generate biogas. However, certain types of FOG may be unsuitable for conversion to biodiesel and are energy-dense wastes that can substantially increase biogas yield when codigested with other feedstocks (U.S. DOE 2017). Therefore, while not covered in detail in this guidance, they should be considered as a valuable supplement to the feedstocks discussed in more detail in this section.

Power-to-gas technology—while currently in nascent stages of development—could prove to be a significant source of synthetic gas production in the future. In power-to-gas applications, electricity is used to split water into its constituent elements of hydrogen and oxygen. At this stage, the hydrogen can be used as a fuel, or it can be further processed with carbon to produce methane. When powered by zero-carbon sources such as excess renewable electricity, the technology could effectively serve as an important energy storage and transmission strategy since the resulting gas could be used as a low-carbon fuel to more flexibly meet demand and/or help decarbonize pipeline gas.

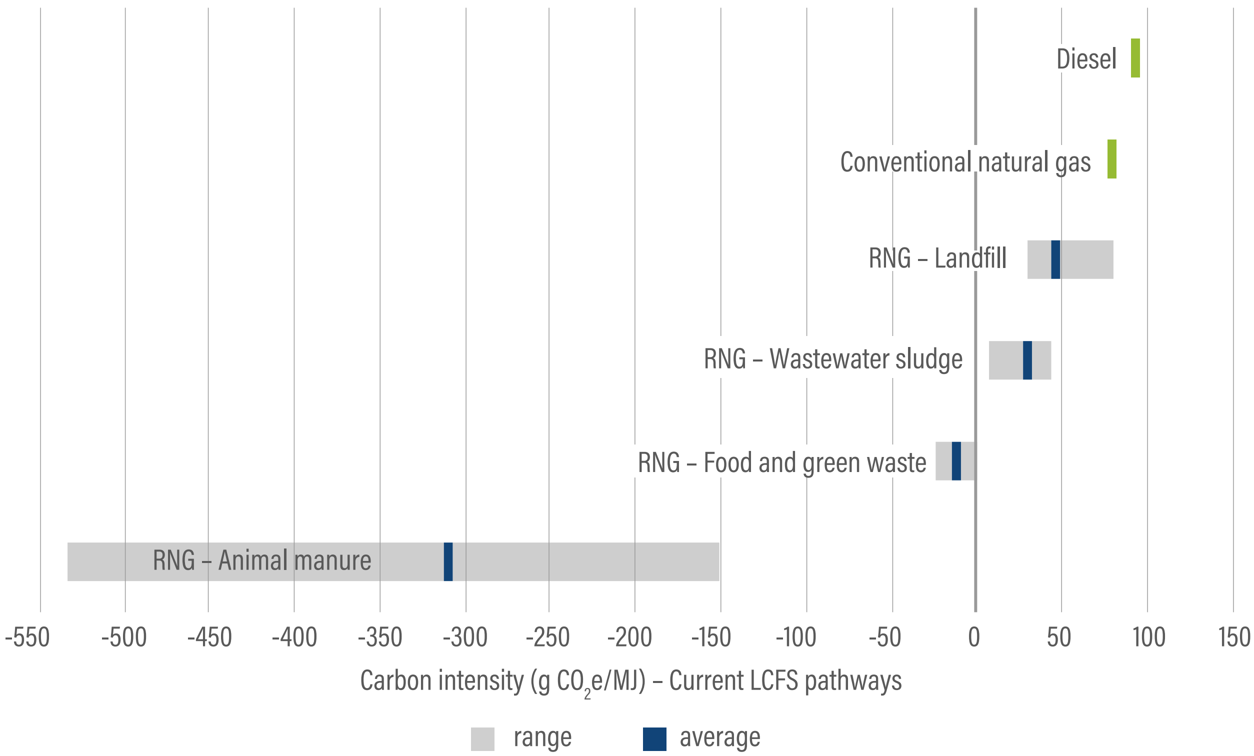
Source: WRI authors, based on study cited above.

When evaluating the relative climate benefits of various feedstocks, an important consideration is that RNG is most likely to achieve net greenhouse gas (GHG) benefits when it meets two conditions: it is made from waste rather than dedicated uses of land, and its production and use results in real reductions in methane emissions (Gasper and Searchinger 2018). Wet-waste sources whose current management methods result in substantial methane emissions, such as livestock manure treated in uncovered lagoons, are therefore the most likely candidates to meet these criteria. Other potential sources of RNG—such as landfills with preexisting methane capture or dry agricultural wastes that are not otherwise significant sources of methane emissions—may also yield emissions benefits, but their benefits may be more muted and risk being undermined if there is any methane leakage during fuel production, distribution, or use (Grubert 2020).

Given the wide range of emissions benefits across feedstocks and projects, a life cycle emissions accounting approach is recommended to evaluate net impacts. This means accounting for both positive and negative emissions impacts over a specific RNG production and use pathway, including avoided methane emissions at the feedstock source, emissions from energy consumption for fuel upgrading, methane leakage, and end-use emissions. These impacts are then compared to a counterfactual "reference case" in which the RNG is not produced and the feedstocks are managed according to existing practices. Depending on the accounting framework, this reference case may also include end-use emissions that would otherwise occur from conventional fossil fuel use. Widely accepted tools for the calculation of life cycle emissions by feedstock include Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model and its California-specific version, CA-GREET, used in the implementation of the state's Low Carbon Fuel Standard (LCFS).

Figure 1-1 below shows the average carbon intensity of RNG from various feedstocks according to a life cycle accounting approach, based on project-level data from California's LCFS. While a life cycle accounting approach is well-suited to determine project-level impacts, it is inherently complex and subject to uncertainty (Box 1-2).

Figure 1-1 | **Carbon Intensity of RNG Feedstocks**



Notes: "Green waste" in the above pathway refers to yard clippings, grass, leaves, and brush (e.g., from residential curbside pickup programs that is codigested with food waste).
g CO_2e/MJ = Grams of carbon dioxide equivalent per megajoule.
Source: Based on raw data from CARB (2020a), modified by WRI.

Box 1-2 | **Approaches to Accounting for RNG Climate Impacts**

Throughout this document, we highlight the use of a life cycle accounting (LCA) approach to evaluate climate impacts of RNG. An LCA approach is commonly used in conjunction with current state-level resource assessments to estimate the climate impacts of potential RNG development. It is also used as the basis for state-level regulatory programs such as the California Low Carbon Fuel Standard and Oregon Clean Fuels Program. Advantages of the approach are that it allows for the accounting of avoided methane emissions on a project-by-project basis, and for "well-to-wheels" comparisons of net impacts relative to alternative fuel options.

However, an LCA framework is not without challenges and limitations. Specifically, the approach requires rigorous data collection in order to quantify full impacts. It is also typically premised on a counterfactual that may be uncertain or change over time (e.g., that methane emissions would otherwise occur at a farm or landfill). Given the significant impact these assumptions can have, care should be taken to ensure accuracy and avoid exaggeration of perceived benefits (Grubert 2020). In addition, project-level LCA data may not necessarily be representative since they incorporate assumptions and factors that can vary substantially from one project to the next.

Alternative approaches to accounting for RNG's climate impacts exist; however, they come with their own limitations. For example, a "combustion approach" may be applied, whereby avoided methane emissions from the feedstock source are ignored, and emissions from combustion are assumed to be zero or "carbon-neutral", because they are ultimately derived from biogenic sources (AGF 2019). This approach essentially treats feedstocks equally and avoids dealing with complex counterfactuals, but does not allow for the same project- and feedstock-specific nuance.

Source: WRI authors, based on studies cited above.

Summary of national-level resource assessments

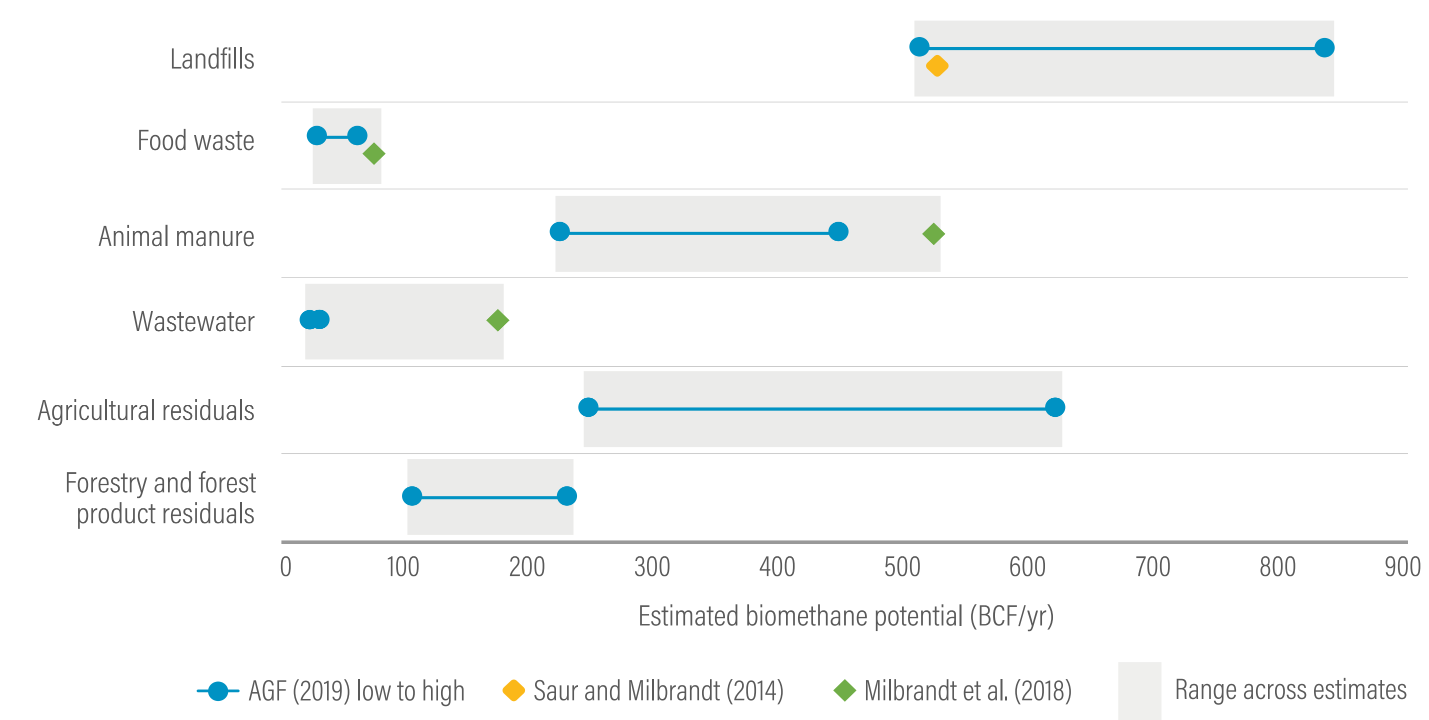
Several national-level studies have been conducted on biogas or RNG resource potential. Considering the technical potential of only wet-waste feedstocks (landfills, food waste, animal manure, and wastewater), United States Department of Energy (U.S. DOE) studies find approximately 1,300 billion cubic feet (BCF) per year in potential biomethane resources (Saur and Milbrandt 2014; Milbrandt et al. 2018). This is equivalent to nearly 7 percent of total natural gas demand in the United States in 2018. Meanwhile, an estimate of economic resource potential from the American Gas Foundation (AGF) estimates 780–1,400 BCF per year could be made available by the year 2040 from wet-waste feedstocks (or 4–7 percent of natural gas demand in 2018) (AGF 2019).

The inclusion of dry feedstocks in resource assessment significantly increases total potential supply. For example, when including agriculture and forestry residues, AGF's 2019 study finds total biomethane potential of 1,100–2,200 BCF, or 6–11 percent of natural gas demand in 2018 (AGF 2019). However, there are important caveats regarding dry feedstocks:

- **Technological and economic feasibility** – Conversion of large amounts of agricultural and forestry residuals to RNG requires thermal gasification and methanation technologies that are not yet commercially mature in the United States. By contrast, wet-waste feedstocks may be readily converted to RNG through anaerobic digestion, a technology that is quite mature domestically and globally.
- **Climate benefits** – Best management practices regarding agricultural and forestry residues have the potential to reduce emissions by optimizing fertilizer use and suppressing wildfires, though these and other effects have not been well quantified to date and may prove to be significant only in certain regions.

Figure 1-2 below summarizes resource potential findings from national-level assessments by feedstock.

Figure 1-2 | **National Resource Potential by Feedstock**



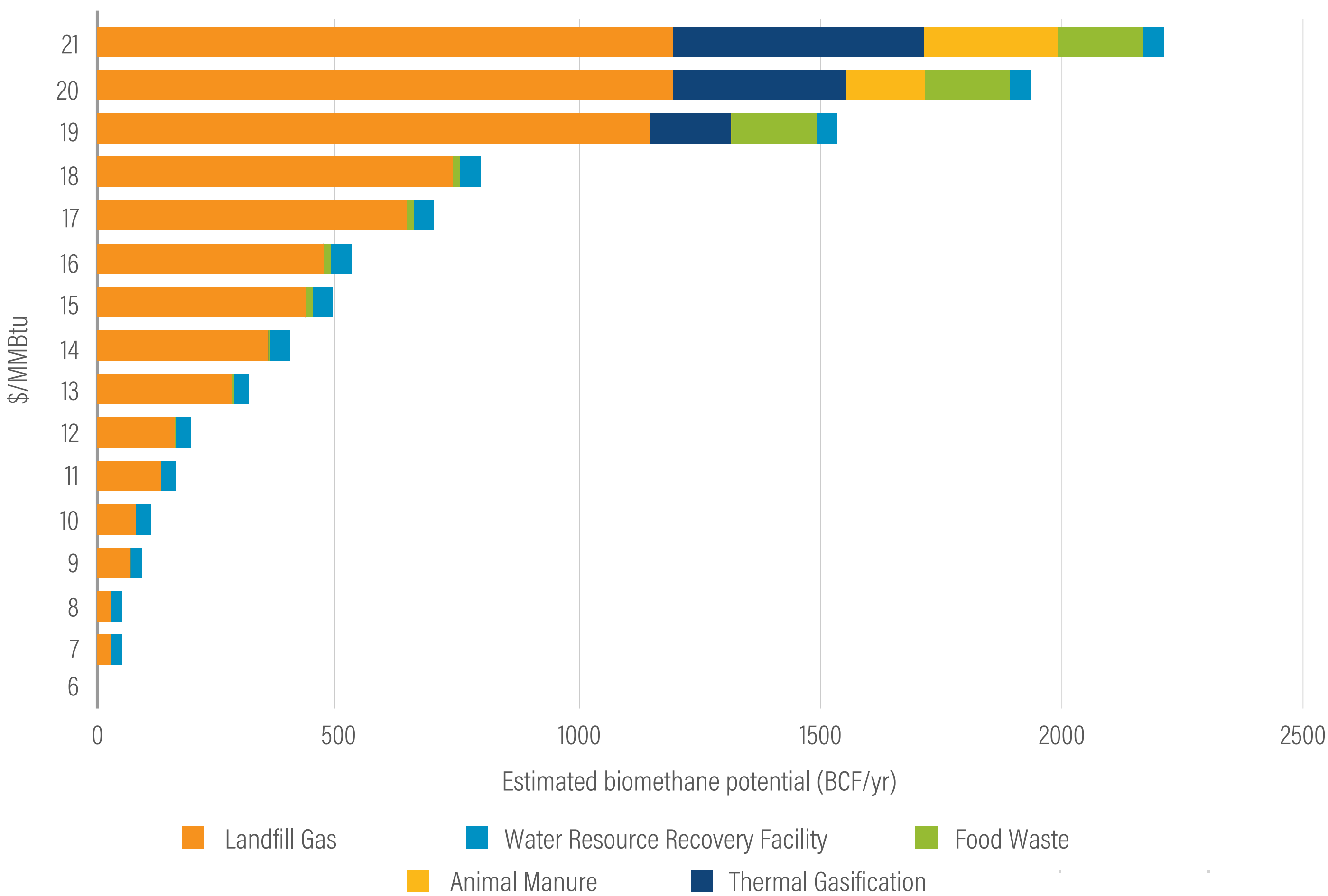
Note: Studies vary in terms of assumed yield, amount of supply that may be made available, and other factors.
BCF/yr = Billion cubic feet/year.
Sources: Based on raw data from AGF (2019); Saur and Milbrandt (2014); and Milbrandt et al. (2018); aggregated and modified by WRI.

In addition to the wide range of emissions benefits, RNG feedstocks vary substantially in terms of the amount of resource supply that may be produced at a given price point. Generally, studies find that more concentrated, high-yield resources that serve multiple purposes and use existing infrastructure (such as wastewater plants and landfills) tend to be economically viable at a lower price point, while more distributed sources of RNG and/or sources requiring the scaling up of nascent technologies (such as food waste, animal manure, and thermal gasification) involve higher costs. Figure 1-3 illustrates this point, showing national-level supply based on modeling and analysis conducted by ICF International (AGF 2019).

Summary of state-specific resource assessments

While national-level assessments can provide important benchmarks and give local decision-makers an understanding of overall resource potential, state-specific assessments are advantageous in that they can provide more nuanced, targeted insights into local sources of RNG and the potential for projects within a particular geographic, economic, and political context. For example, national-level data may point to significant biomethane potential from a subset of feedstocks in a given region. Building on this, a more localized assessment can then identify feedstock availability on a more granular scale and determine economic feasibility and climate impacts by examining proximity to pipeline infrastructure, existing waste management practices, etc. For certain regions, it

Figure 1-3 | **Supply Curve for Renewable Natural Gas by Feedstock in 2040: High Resource Potential Scenario**



Notes: Btu = British thermal units; BCF = Billion cubic feet.
Source: AGF 2019.

may make sense to prioritize a particularly predominant source of biomethane, whereas for others it may be useful to assess all potential feedstocks equally. In all cases, a local-level inventory can lead to more informed decision-making and answer questions around project viability, biomethane sources to prioritize, and local benefits.

To date, few states have conducted independent assessments of RNG resource potential. However, those that have conducted such studies find moderate-to-significant resource potential as a share of current fossil fuel demand (see Table 1-1). These studies also find potential for emissions benefits through use of RNG. For example, a recent study in Colorado found local resource potential amounting to 19 BCF from waste-derived feedstocks. Assuming these resources are deployed to displace fossil natural gas consumption, the study found there would be an estimated net emissions reduction of 2.17 million metric tons (MMT) of carbon dioxide equivalent (CO_2e) annually on a life cycle basis. This value equates to approximately 1.5 percent of projected in-state emissions in 2020 (Arnold et al. 2014). The same study found that deployment in the medium- and heavy-duty transportation sector could displace approximately 24 percent of in-state diesel fuel consumption and yield an emissions reduction of 2.54 MMT CO_2e on a life cycle basis (Colorado Energy Office 2019).

1.2 – Resource Assessment and Climate Considerations by Feedstock

Landfills

FEEDSTOCK OVERVIEW

A significant share of national landfill resource potential is already used to produce energy in the form of electricity, heat, or vehicle fuel. While only 20 percent of landfills reporting to the United States Environmental Protection Agency (U.S. EPA) have active energy recovery projects, these landfills account for the majority of landfill gas collected by volume since projects tend to be installed at the highest-yield sites (U.S. EPA LMOP 2019). At present, a majority of the gas collected at sites and routed to energy recovery goes to electricity generation, although the share dedicated to RNG has increased in recent years.[2] In addition, not all gas collected at sites with energy recovery projects is necessarily utilized, and a significant portion may still be flared due to maintenance, gas quality issues, or simply because landfill gas yield exceeds the capacity of installed project equipment.

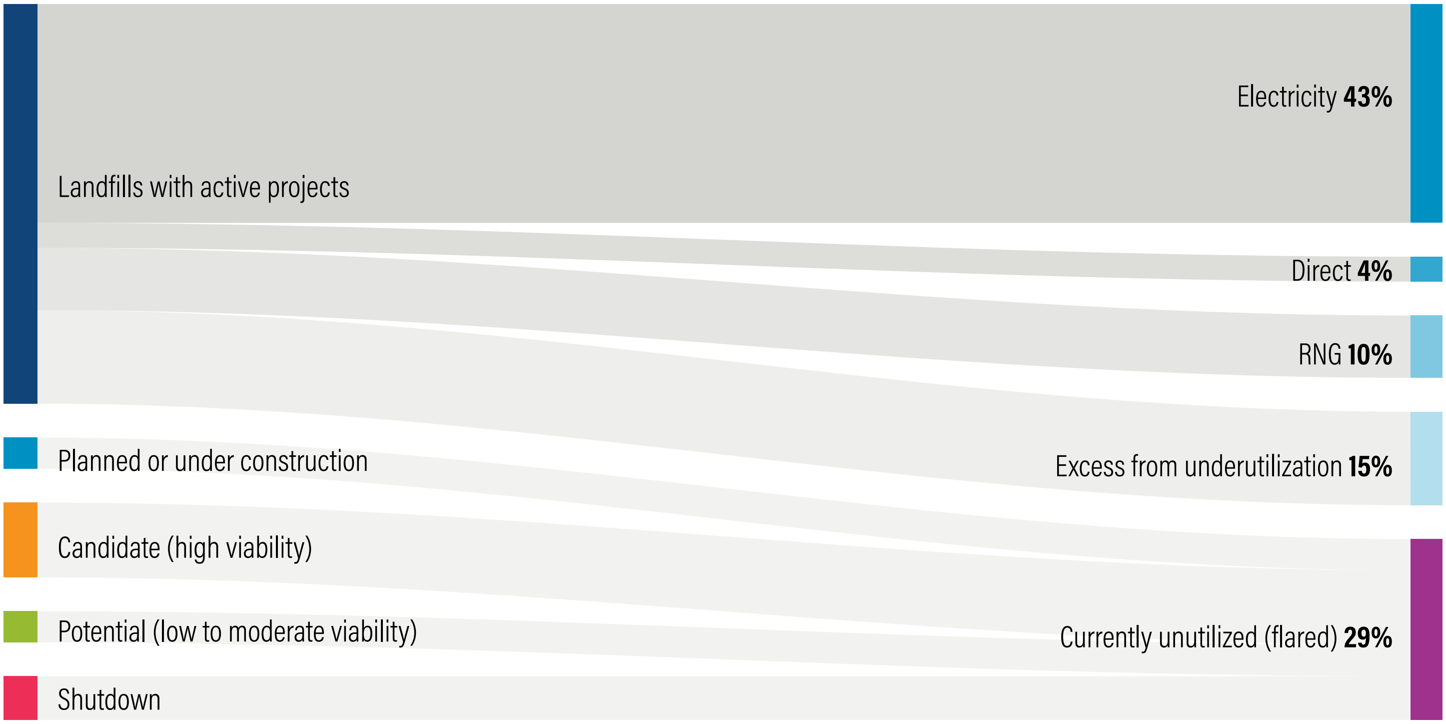
Landfills without active gas-to-energy projects already in place generally have smaller overall waste intake capacity or waste in place than those that do have energy recovery projects. However, the EPA still identifies a significant share of currently unused landfills that have projects planned or under construction or are defined

Table 1-1 | **Summary of State-Specific RNG Resource Assessments**

STATE	ASSESSED RNG SUPPLY FROM WET-WASTE SOURCES (BCF/YR)	2019 RESIDENTIAL AND COMMERCIAL NATURAL GAS CONSUMPTION (BCF/YR) (RNG SUPPLY AS A % OF CONSUMPTION)	2019 INDUSTRIAL NATURAL GAS CONSUMPTION (BCF/YR) (RNG SUPPLY AS A % OF CONSUMPTION)	VEHICLE DIESEL CONSUMPTION (BCF EQUIVALENTF/YR) (RNG SUPPLY AS A % OF CONSUMPTION)
California[a]	90.6	721 (12.6%)	768 (11.8%)	507 (17.9%)
Colorado[b]	19.0	205 (9.3%)	92 (20.7%)	93 (20.4%)
Iowa[c]	65.3	129 (50.6%)	250 (26.1%)	190 (34.4%)
Oregon[d]	10.4	80 (13%)	57 (18.2%)	90 (11.6%)
Washington[e]	14.7	151 (9.7%)	78 (18.8%)	137 (10.7%)

Notes: Existing state-level studies differ in terms of feedstocks assessed and assumptions regarding resource availability. Generally, these studies account for local constraints on potential supply and often focus on more economic, near-to-medium-term opportunities for project development. Therefore, totals may be of a lower magnitude (in terms of share of natural gas demand) than findings in national-level studies.
BCF/yr = Billion cubic feet/year.
Assuming 144 cubic feet of natural gas is equivalent to 1 gallon of diesel
[a] Jaffe et al. 2016.
[b] Colorado Energy Office 2019
[c] Li and Mba-Wright 2014
[d] Oregon Department of Energy 2018
[e] WSU Energy Program 2018
Sources: Based on studies cited above and raw data from U.S. EIA (2020b) and U.S. DOE (2020a), aggregated and modified by WRI.

Figure 1-4 | **Estimated Landfill Gas Utilization in the United States (Percentage of Landfill Gas Collected by Volume)**



Note: Based on sites included in EPA LMOP database. Values may not add up to 100 percent due to rounding.
Source: Based on raw data from U.S. EPA LMOP (2019), aggregated and modified by WRI.

as "candidate" sites that are ripe for waste-to-energy projects. All collected landfill gas that is not routed to energy recovery will typically be flared off as directed under federal regulations, as shown in Figure 1-4.

Importantly, these estimates only account for biogas that is reported to be collected or estimated to be collected by the EPA, and do not account for gas that may be released into the atmosphere due to inefficiencies in the collection process, venting, or incomplete combustion from flaring. These uncertainties are discussed in more detail in the section on GHG impacts below.

ASSESSING RESOURCE POTENTIAL

An initial step in assessing resource potential is conducting an inventory of in-state landfills. While compiling this data, there are important factors to consider:

- **Operating status** — What is the current operating status of in-state landfills and expected closure dates?
- **Waste characteristics** — What are the size characteristics of in-state landfills in terms of waste in place, and what is the organic fraction of currently landfilled waste?
- **Current use** — Which in-state landfills already have waste recovery projects in place and currently produce electricity, RNG, or other forms of energy; what is their use rate? Are current energy projects reliant on power purchase agreements that may soon expire?

This information may be used to identify both currently unused sites that are viable candidates for projects and underused sites with existing projects that may be candidates for expanded or upgraded feedstock conversion. Data may be derived from existing studies conducted by state agencies or local universities. Alternatively, states may conduct an updated survey of in-state landfills.

To determine overall technical potential, data on in-state landfills can be combined with estimated yield (i.e., methane generation per waste ton). Yield will vary from site to site depending on landfill age, degradable organic carbon (DOC) within the waste stream, regional climate, and other variables. In addition, yield over time will be impacted if the site is expected to close or if local organic waste diversion mandates reduce future waste intake. To improve accuracy when dealing with these uncertainties, an assessment of resource potential can employ measured or reported data, where available, such as from surveys or studies conducted for local landfills (see Box 1-3). Well-vetted tools and existing datasets can also be used to produce modeled estimates of yield based on local factors and are highlighted in this report's accompanying appendix.

States may also establish criteria to determine which resources represent the most significant near-term opportunities in terms of economic potential (see Box 1-4). Specific criteria used will depend on assessment scope and state objectives; however, the following are some common considerations in this area:

- **Size** — Landfills that have at least 1 million tons of waste in place are typically considered viable candidates for project development at least for local use of energy, while even larger landfills may be candidates for more capital-intensive projects that include pipeline injection.
- **Infrastructure in place** — In compliance with federal regulations, landfills over a certain size threshold will already have gas capture and flaring equipment installed and therefore have a significant cost advantage. Landfills that do not yet meet this threshold may still be viable candidates if planned expansion will trigger these requirements at a later date.
- **Current and expected waste intake** — Landfills that are currently accepting waste or have been closed for fewer than five years are typically considered to be viable candidates.
- **Location** — Proximity to offtake infrastructure, such as natural gas pipelines, may improve prospects for RNG development. However, non-pipeline solutions may exist for more remote resources.

Box 1-3 | Landfill Resource Assessment in Oregon

At the direction of the state legislature, in 2018 the Oregon Department of Energy published a "Biogas and Renewable Natural Gas Inventory" to assess in-state resource potential. To assess landfill resource potential, the Oregon Department of Energy relied on both estimated and reported data to gain a more complete perspective. The inventory authors first narrowed the list of potential in-state sources to 13 landfills currently or formerly receiving municipal solid waste (MSW) with an amount of waste in place above a threshold of 1 million tons, a sufficient share of which comprised degradable organic material. Data on these landfills were derived from both the Oregon Department of Environmental Quality (ODEQ) and survey responses collected from individual landfill operators during the assessment. Data from these two sources provided separate estimates of landfill methane potential; the ODEQ data provided modeled estimates of methane generation and the survey data provided supplementary measurements of actual resource yield for useful comparison.

Source: WRI authors, based on Oregon Department of Energy (2018).

Notably, the relatively large size of landfill-gas-to-energy projects gives them a significant cost advantage over other sources of biomethane due to economies of scale. According to data published by Argonne National Laboratory, the average landfill RNG project generates 670,000 million British thermal units (Btu) of biomethane per year, whereas the average large dairy or swine project generates 94,000 million Btu per year (ANL 2019). Up-front feedstock conversion costs are also typically much lower relative to other feedstocks, since already-in-place waste intake and biogas collection systems negate the need for investment in anaerobic digesters. Due to this, gas collection typically represents a small share of total cost for RNG projects from landfills, while gas clean-up, balance of plant, and interconnection make up significant shares (37 percent, 37 percent, and 21 percent, respectively), according to recent analysis (MJB&A 2019).

Box 1-4 | Assessment of Viable Landfill Projects in Colorado

For the Colorado Energy Office's 2019 report, "Renewable Natural Gas (RNG) in Transportation: Colorado Market Study," researchers combined a number of publicly available data sources and methods to conduct an assessment of potentially economic landfill sources. As an initial step, data were synthesized from the Environmental Protection Agency's (EPA's) Landfill Methane Outreach Program (LMOP) database, and potential output from each source was modeled using EPA's LFG (Landfill Gas) Cost-Web tool. Data on landfill location were then layered onto pipeline location data from the United States Energy Information Administration (U.S. EIA). The assessment identified at least a dozen facilities within three miles of local pipelines, making them potential candidates for interconnection. The assessment also acknowledged that additional landfills outside of the three-mile range could be candidates for virtual pipeline or trucking solutions.

Source: WRI authors, based on Colorado Energy Office (2019).

In addition to using the above factors to identify economic sites, depending on assessment scope and objectives, it may also be useful to develop supply curves of total resources that may be brought online at a given price. To date, several such analyses have been conducted at the national and state levels, finding that the majority of landfill RNG resource potential in the United States may be deployed at a break-even cost of \$4–\$15/million Btu (Gasper and Searchinger 2018). A table of estimated break-even costs for landfill RNG projects from multiple studies is included in this report's accompanying appendix.

ASSESSING LIFE CYCLE GHG IMPACTS AND BENEFITS

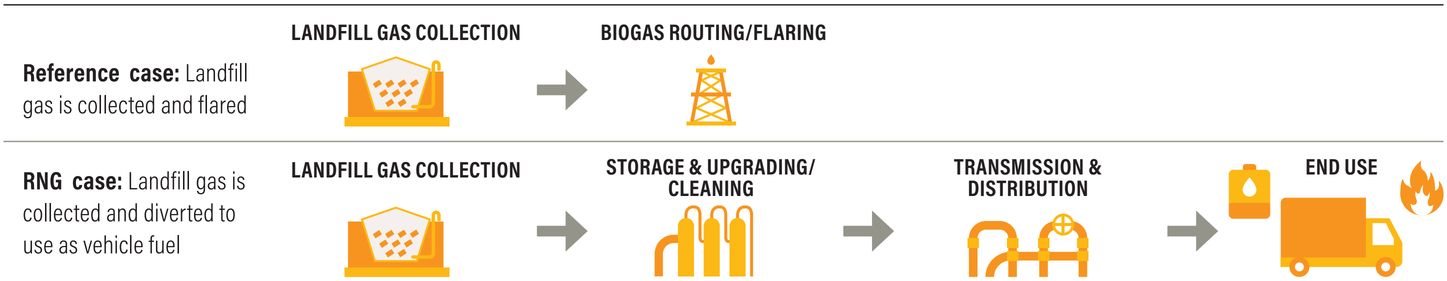
Federal regulations under the Clean Air Act require that all landfills designed to collect at least 2.5 million cubic meters of waste and emitting over 50 metric tons of non-methane organic compounds annually must install systems to capture and route gas to energy recovery or flares (U.S. EPA 1996). While this covers the majority of currently operating landfills in the United States, leakage and venting may still occur, depending on the efficiency of biogas capture, routing, and energy recovery practices. Previous EPA accounting has estimated that roughly one-third of methane generated at landfills in the country (regulated and unregulated) is either uncollected or collected and vented (U.S. EPA 2014b).

Policymakers seeking to promote the most climate-beneficial projects may wish to target sites where new projects would result in improved gas capture and reduced venting beyond existing practices, as well as minimal methane leakage from fuel production and distribution. A life cycle approach may be used to determine the net benefits of project development at various sites. Common factors to be included in such an assessment include the following:

- Emissions from electricity and other fuels used on-site for gas collection, treatment, and processing
- Methane leakage from on-site gas collection, treatment, and processing
- Emissions occurring during fuel delivery to processing plants and distribution centers from vehicle combustion (if transported via truck)
- Methane leakage from gathering and/or transmission lines (if transported via pipeline)
- Emissions from combustion at end-use applications (i.e., engines or boilers the fuel is ultimately delivered to)

Figure 1-5 below illustrates where these emissions occur along a landfill RNG project's life cycle relative to a reference case in which gas is not used for energy.

Figure 1-5 | **RNG Production Pathway and Life Cycle Analysis Components for Landfill Gas Feedstocks**



LIFE CYCLE PHASE	EXAMPLE LIFE CYCLE ANALYSIS COMPONENTS	NOTES
Landfill gas collection	■ Emissions or leakage due to biogas collection inefficiencies ■ Energy use for biogas collection and processing	Biogas losses may be 5–40%, depending on type of cover and other equipment used
Biogas routing/ flaring	■ Emissions from flaring combustion ■ Fugitive emissions from incomplete flaring combustion	Flare combustion efficiency of >99% is typically assumed
Storage & upgrading/cleaning	■ Leaks or venting from gas upgrading and storage ■ Energy use for gas upgrading equipment and storage	Fugitive losses during processing at upgrading facility may result in additional leakage of 1%
Transmission & distribution	■ Leaks or venting from compressors, storage facilities, gas metering, regulating stations, and pipelines ■ Leaks or venting from compressors, fuel line components, storage, transfer, and refueling	Transmission and distribution leakage may be 0.4–0.9% depending on equipment and efficiency
Vehicle end use	■ Fuel combustion emissions from tailpipe ■ Leaks or venting from crankcase, storage, fueling system, and incomplete combustion	Tailpipe and crankcase leakage may be 0.5–1.7% depending on efficiency

Sources: Sources referenced for methane leakage rates and other emission factors by category: landfill gas collection (CFR 2016; Lee, Han, and Wang 2016); storage and upgrading/cleaning (CARB 2019); transmission and distribution (Delgado and Muncrief 2015); vehicle end use (Delgado and Muncrief 2015).

Figure 1-5 assumes that gas collection and flaring occur in the reference case emission pathway. This is typical of methodologies published by EPA, California Air Resources Board (CARB), and other sources to determine the life cycle emissions of landfill projects relative to other fuel sources. The actual efficiency of biogas capture, flaring, and energy recovery will vary from project to project.

Food waste

FEEDSTOCK OVERVIEW

Overall, food waste represents the largest share, by weight, of the municipal solid waste stream in the United States. Pound-for-pound, food waste is also one of most energy-rich feedstocks that can be processed in an anaerobic digester (WSU 2018).

While food waste-to-RNG projects can offer significant climate benefits, it is important to consider biogas and RNG development as part of a broader suite of potential waste management options. Optimal strategies that maximize societal and environmental benefits will depend on a variety of factors, and the EPA suggests a food waste recovery hierarchy to facilitate decision-making. Under this framework, source reduction (i.e., reducing waste to begin with) is generally the preferred option, followed by donation to food banks and diversion of scraps for animal feed. After consideration of these measures, waste-to-energy conversion via anaerobic digesters can be an efficient and beneficial means of using remaining waste (U.S. EPA 2019a).

The diversion of food waste to dedicated digesters poses several advantages over business-as-usual landfilling practices, including

- more efficient waste-to-energy conversion;
- reduced need for new landfill capacity and acreage;
- production of nutrient-rich digestate as a valuable coproduct; and
- avoidance of methane emissions from inefficiencies in the landfill gas capture process.

The Department of Energy (DOE) estimates that annual food waste generation in the United States totals 61 million wet tons, stemming largely from residential (64 percent), commercial (24 percent), and institutional (10 percent) sources. In terms of where this waste ends up, over half of the total (approximately 58 percent) is landfilled, while approximately 8.5 percent goes to composting, food banks, and animal feed. "Other" forms of use including waste-to-energy via anaerobic digestion (AD) make up the remaining 34 percent (U.S. DOE 2017). These estimated trends are shown in Figure 1-6.

Figure 1-6 | **Estimated Food Waste Diversion and Utilization in the United States (Percentage by Volume)**

Note: Percentages may not add up to 100 percent due to rounding.
Source: Based on raw data from U.S. DOE (2017), aggregated by WRI.

While these estimates do not indicate the exact share of food waste currently converted to biogas or RNG, a recent national survey found that at least 10.5 million tons of waste was processed in digester facilities in 2016 (based on data submitted by digester operators participating in the survey) (Pennington 2019). While sizable, the fact that a majority of food waste is still either landfilled or combusted indicates that significant potential remains for additional food waste reduction strategies or more efficient use.

ASSESSING RESOURCE POTENTIAL

A resource assessment of in-state food waste sources may include both the following:

- Food waste from downstream or postconsumer sources such as supermarkets, restaurants, or private residences
- Food waste from upstream sources such as processing and manufacturing plants

Importantly, these categories of waste may come with significantly different considerations regarding project economics or environmental benefits, which are discussed in more detail below.

Key considerations and datapoints to evaluate in an inventory of in-state resources are as follows:

- **Opportunities for redistribution and waste prevention** – Could the waste be prevented or diverted through improved redistribution to food banks or animal feed?
- **Size and location of waste streams** – What are the primary sources of food waste in-state (e.g., residential and commercial sources, food manufacturing plants); where are they located, and what is the extent of waste generated? Are sources colocated or in proximity to one another?
- **Distribution and homogeneity of waste streams** – Are identified waste streams relatively concentrated and homogeneous, requiring minimal source separation? Or are resources more distributed and heterogeneous?
- **Size and location of existing facilities** – What is the current operating status, capacity, and location of in-state digester facilities, if any?
- **Opportunities for codigestion** – What are the use rates of current in-state digester facilities? Are there existing mixed-waste facilities or wastewater treatment plants with capacity for additional codigestion of food waste?

Existing state or local waste management or waste characterization studies may help identify the potential of residential and commercial sources. Such studies often contain estimates of annual waste generation and/or the share of food waste and other organics in the municipal waste stream at the state or substate level. Alternatively, estimates may be produced by applying a per-capita food waste generation factor, which in the United States ranges from 0.03 to 0.24 tons annually depending on region, local waste management practices, and other factors (U.S. DOE 2017).

Several public data sources exist to identify potential of institutional (i.e., nonresidential or commercial) sources, including EPA's "Excess Food Opportunities" map, which provides estimates of excess food waste from facilities and institutions at the state, county, and municipal levels. Additional resources and tools are included in this report's appendix.

When identifying potential sources, a fundamental, cross-cutting factor to consider pertains to the distribution and relative homogeneity of various waste streams. Generally, more concentrated food waste streams will be the most feasible for recovery. For example, food/beverage processors, restaurants/food service, and supermarkets are among the most common sources currently supplying operating stand-alone digesters in the United States (Pennington 2019). By contrast, more distributed, heterogeneous waste streams such as residential sources are less likely to be economical without significant policy support. However, as discussed in the following section on climate impacts, these more distributed sources are also most commonly landfilled and therefore may yield more significant emissions benefits if recovered.

In terms of near-term economic potential, the most viable RNG projects will likely involve the codigestion of food waste at existing facilities such as wastewater treatment plants or on-farm digesters. Food waste can be a valuable, energy-rich supplementary feedstock at these facilities, improving efficiency and yield of RNG. In addition, many stand-alone food waste digesters process less waste than their design capacity. In an EPA survey of stand-alone food waste digesters, participating facilities reported a combined capacity use rate of under 50 percent (Pennington 2019). States can identify opportunities and existing capacity within their borders or region using data published by EPA on known stand-alone food waste digestion facilities (operational and planned) and wastewater or on-farm facilities that are candidates for codigestion.

More mid- to long-term RNG opportunities involve the construction of additional digester capacity, particularly in areas with access to consistent, high-volume sources of food waste, to ensure project viability. However, in determining the practicality and impacts of new-build projects, careful consideration should also be given to whether these projects would complement or potentially undermine other food waste reduction strategies such as source reduction and redistribution.

The most significant costs for stand-alone food waste digester projects stem from the construction and operation of the facility itself. The capital expenditure for a facility with a design capacity of 50,000–100,000 tons may cost $15–$23 million (Jaffe et al. 2016). National and regional analyses of economic potential find that food waste digester projects may be deployed at a cost ranging from $19 to $35/MM Btu on a levelized basis, with design capacity being a critical factor in helping to drive down costs due to economies of scale (Jaffe et al. 2016; AGF 2019). A table of estimated break-even costs for food waste RNG projects from multiple studies is included in this report's appendix.

Finally, current or future food waste diversion policies can impact the amount of supply potentially available for waste-to-energy conversion and can therefore be incorporated into an assessment of resource potential (see Box 1-5).

Box 1-5 | Assessment of Potential Food Waste Diversion in Colorado

The growing prominence of food waste recycling mandates and food waste bans means that, in many states and municipalities, additional food waste may be diverted away from landfills and become available for projects over the next decade. An assessment of resource potential can therefore be aligned with existing mandates or goals.

As an example of this, the Colorado Energy Office's 2019 report, "Renewable Natural Gas (RNG) in Transportation: Colorado Market Study" provides a comprehensive assessment of in-state potential for RNG and considers the impact of food waste diversion goals. To assess total resource potential for food waste-to-RNG projects in the state of Colorado, the authors compiled data on food waste generation from a combination of sources including a state-level integrated waste management plan and EPA's Excess Food Opportunities database. Total waste generated in tons was then multiplied by the state's current food waste diversion goal (35 percent) to produce an estimate of roughly 350,000 tons of food waste (approximately 900,000 MMBtu on an energy equivalent basis) that could be available for RNG production.

Source: WRI authors, based on Colorado Energy Office (2019).

ASSESSING LIFE CYCLE GHG IMPACTS AND BENEFITS

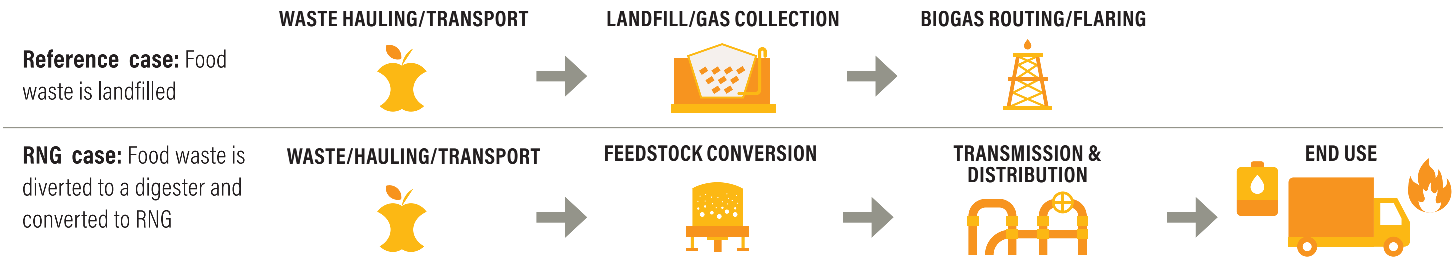
As described above, after consideration of source reduction and redistribution strategies, the diversion of food waste to dedicated digesters can have significant emissions benefits over business-as-usual waste management practices. Quantifying these benefits involves consideration of the "fate" of food waste if not diverted to a digester. For example, after factoring out any share of residential and commercial waste that is sent to beneficial uses such as food banks, the remainder in most parts of the United States is sent to landfills, where it generates methane and other gases. Much of these gases will likely be routed and flared, but a significant remainder may escape into the atmosphere as fugitive emissions. The avoidance of these fugitive emissions makes food waste one of the more climate-beneficial feedstocks for RNG discussed in this guidance.

As with other feedstocks, a full life cycle assessment can be used to determine the net emissions impacts of food waste to RNG deployment. Specific sources of emissions to include in an assessment of RNG project impacts are as follows:

- Emissions from electricity and other fuels used in the operation of an anaerobic digester and additional gas cleaning and upgrading equipment
- Emissions from waste transportation (if diversion requires additional long-distance hauling that would not otherwise occur in the reference case)
- Methane leakage from on-site digester, as well as from treatment and processing equipment
- Emissions during fuel delivery to processing plants and distribution centers from vehicle combustion (if transported via truck)
- Methane leakage from gathering and/or transmission lines (if transported via pipeline)
- Emissions from combustion at end-use applications (i.e., the engines or boilers where fuel is ultimately delivered)

Figure 1-7 illustrates where these emissions occur over both a reference case and food waste-to-RNG pathway.

Figure 1-7 | **RNG Production Pathway and Life Cycle Analysis Components for Food Waste Feedstocks**



LIFE CYCLE PHASE	EXAMPLE LIFE CYCLE ANALYSIS COMPONENTS	NOTES
Landfill gas collection	■ Emissions or leakage due to biogas collection inefficiencies ■ Energy use for biogas collection and processing	Biogas losses may be 5–40%, depending on type of cover and other equipment used
Waste Hauling/Transport	■ Emissions due to collecting and transporting biomass with medium- and heavy-duty trucks	650 g CO_2e/mile
Biogas routing/flaring	■ Emissions from flaring combustion ■ Fugitive emissions from incomplete flaring combustion	Flare combustion efficiency of >99% is typically assumed
Feedstock conversion	■ Leaks or venting from feedstock storage, anaerobic digester, gas upgrading, and storage ■ Energy use for anaerobic digester facility, gas upgrading, and storage	Leakage may be 1–10%, depending on equipment and efficiency
Transmission & distribution	■ Leaks or venting from compressors, storage facilities, gas metering, regulating stations, and pipelines ■ Leaks or venting from compressors, fuel line components, storage, transfer, and refueling	Transmission and distribution leakage may be 0.4–0.9% depending on equipment and efficiency
Vehicle end use	■ Fuel combustion emissions from tailpipe ■ Leaks or venting from crankcase, storage, fueling system, and incomplete combustion	Tailpipe and crankcase leakage may be 0.5–1.7% depending on efficiency

Sources: For methane leakage rates and other emission factors by category: Landfill gas collection (CFR 2016); feedstock conversion (CARB 2019; Börjesson and Berglund 2006; UNFCCC 2012); transmission and distribution (Delgado and Muncrief 2015); vehicle end use (Delgado and Muncrief 2015).

While landfilling is shown as the presumed reference case in the above figure, the actual fate of various food waste streams—and thus their potential climate benefits—may need to be evaluated on a case-by-case basis. An important general distinction is that more distributed downstream sources (which are also more costly to recover) can offer significant environmental benefits as they are typically otherwise landfilled. By contrast, byproducts from manufacturing plants (which are concentrated and more economical to recover) may be more likely to have existing sustainable uses such as animal feed or composting as opposed to being landfilled.

Finally, food waste diversion may also have significant cobenefits that are not accounted for in the example life cycle analysis shown in Figure 1-7, but which may play an important role in policy considerations. These include more efficient capture of the energy content within the organic waste stream, production of valuable digestate as a byproduct of feedstock conversion, and separation of organics from potentially recyclable nonorganic wastes such as plastics, metals, and glass.

Animal manure

FEEDSTOCK OVERVIEW

Animal manure can be processed in an anaerobic digester to produce biogas, which can then be cleaned and upgraded to produce RNG. At present, animal manure RNG feedstocks in the United States are limited to dairy cow, swine, and beef cattle manure. Dry manure, such as poultry manure, currently requires codigestion with other manures for economic reasons, though pilot projects have demonstrated proof of concept.

While 289 farms in the United States produce biogas using anaerobic digesters, 19 currently upgrade the biogas to renewable natural gas. This includes 14 dairy operations, 4 swine operations, and 1 beef and swine operation (The Coalition for Renewable Natural Gas 2020; U.S. EPA AgSTAR 2019). The remaining digesters are used primarily for waste/nutrient management purposes and for fertilizer benefits of the digestate; the biogas they produce is used for maintaining an optimal digester temperature and for on-site heat and power needs. Currently, approximately 96 percent of animal manure produced on RNG candidate farms is not utilized for biogas or RNG production (see Figure 1-8).

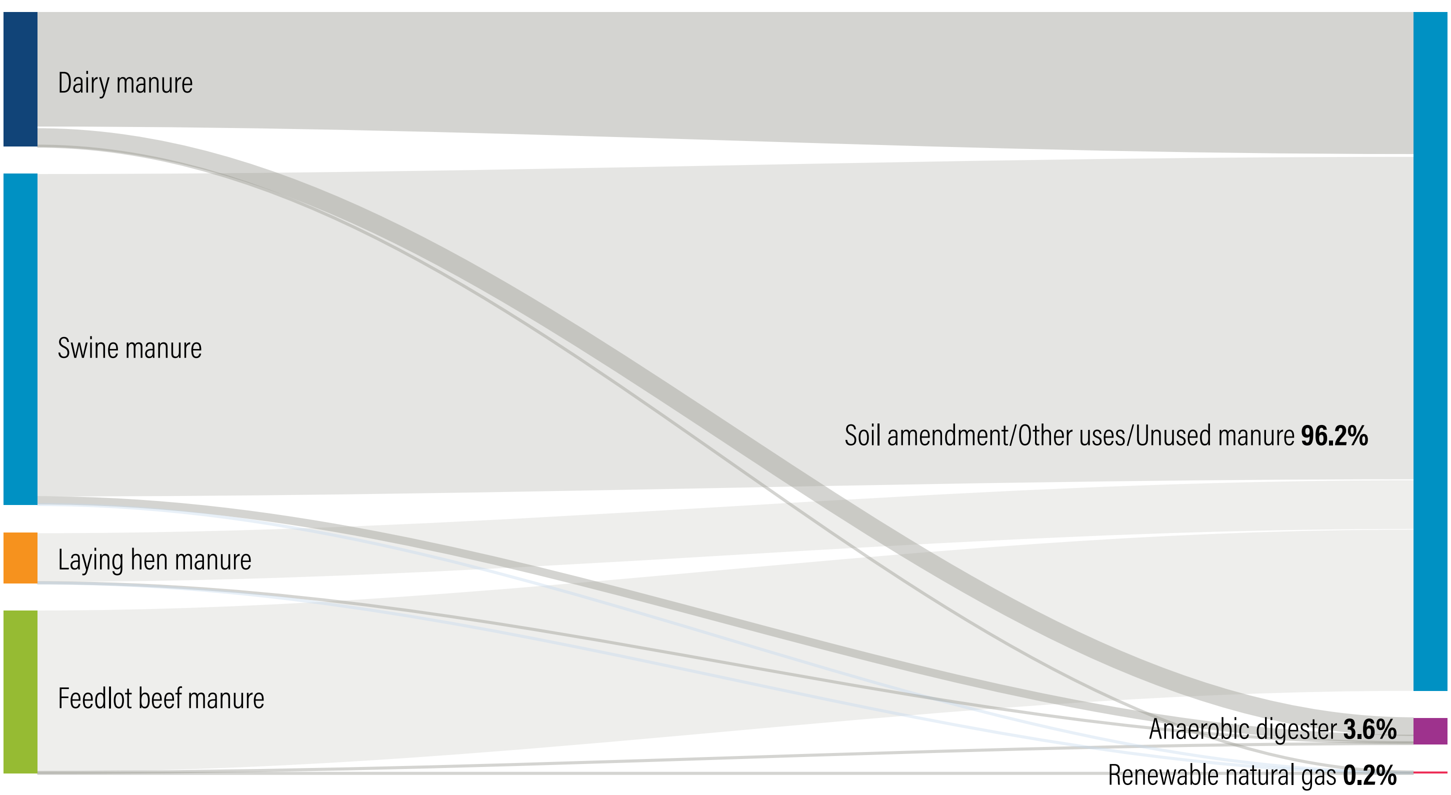
Animal manure RNG has seen recent growth in production, though it is still not economical when compared to fossil natural gas unless the projects receive additional compensation for their environmental benefits. Since 2012, animal manure's share of total generation in the cellulosic biofuel category (D3) under the federal Renewable Fuel Standard program has grown 63 percent. While this growth is significant, animal manure RNG supplies less than 2 percent of total D3 generation, and economic feasibility is dependent upon funding from this and similar programs (U.S. EPA 2020b).

ASSESSING RESOURCE POTENTIAL

An initial step in assessing animal manure resource potential is conducting an inventory of confined livestock operations in the state. Important factors to consider in the assessment are as follows:

- **Number and size of existing animal livestock operation**s – How many animal livestock operations exist in the state and what is their size distribution?
- **Current manure management practices** – What are the prevailing manure management practices in the state, and how might they be upgraded or retrofitted to align with RNG production practices such as digestion and methane capture?
- **Location and distribution** – Are some livestock production facilities in the state located relatively close together to increase gas offtake efficiency?

Figure 1-8 | **Animal Manure Use and Diversion in the United States (Percentage by Volume)**



Notes: End uses of animal manure waste from candidate dairy, swine, laying hen, and feedlot beef farms, which are above a minimum operation size. An estimated 370 million wet tons of manure are produced per year on farms that are candidates for anaerobic digestion, which generates approximately 0.1 billion cubic feet (BCF) of methane—assuming 10 tons of animal manure per year (60 pounds per day) per animal unit (1,000 pounds), 10 percent dry solids content, 8 percent volatile solids, and 3.25 cubic feet of methane per pound of volatile solid (for a more precise estimate, see Saur and Milbrandt 2014). Only manure from confined animals is included. Laying hen manure is currently only codigested with other animal manure feedstocks.
Sources: Based on raw data from U.S. EPA AgSTAR (2019) and USDA (2019), aggregated by WRI.

- **Offtake options** – Are livestock operations located near natural gas pipeline injection points, or are they accessible for trucking offtake?

States can use national-level studies to estimate resource potential, but state-level and regional-level studies offer the ability to provide greater granularity and accuracy. Basic guidelines exist to determine whether a farm is a viable candidate for RNG production, and these can assist states in assessing their share of the resource. A livestock operation must have efficient manure collection and process approximately 2,000 kilograms (kg) of volatile solids per day with appropriate management practices in place that allow for cost-effective RNG production (U.S. EPA 2018b).

In determining resource potential, states may also wish to consider economic, environmental, and animal welfare trade-offs to determine the optimal end use for potential RNG feedstocks. For instance, manure is often stored in a lagoon and then sold or used on-site as a soil amendment in place of artificial fertilizer, and this can be profitable or result in cost savings for a farm operation. Fortunately, manure digestate—the solids that are left over after biogas is produced in an anaerobic digester—also has considerable value as animal bedding or as a soil amendment, and therefore this source of revenue, or reduction in fertilizer costs, can be preserved with RNG production. In the case of an operation using biogas for combustion in a boiler or a combined heat and power generator, however, the costs and benefits of on-site heat and electricity production must be weighed with those of RNG production to determine which offers greater economic and environmental value.

Development and use of dry manure technologies for RNG production would greatly increase the resource potential of animal manure RNG projects in states with large hen laying operations. A study performed in 2006 in South Carolina found that 82 percent of manure produced by poultry in the state took the form of dry manure from broiler chicken and turkey operations (Flora and Riahi-Nezhad 2006). Dry manure offers another example of economic trade-offs, however, as RNG projects must compete with the common practice of using dry manure as an agricultural soil amendment due to its relative ease of transport and high nitrogen content.

Production costs are also a major determinant of resource potential from animal manure RNG. The main costs associated with RNG production from animal manure are in manure handling, building and maintaining the anaerobic digester, biogas upgrading, and delivering the RNG to market (offtake). The variance in these factors leads to dairy manure RNG production costs ranging from \$25–\$65 per million Btu (Jaffe et al. 2016).

Box 1-6 | Iowa Biogas Assessment Model

In 2014 Iowa State University and EcoEngineers collaborated on the Iowa Biogas Assessment Model to inform Iowa policymakers and the public about the availability of biogas and RNG as an energy resource and to provide guidance on incentives that are currently in place to aid in the development of biogas production projects. The model provides two main functions: geographic visualization of biogas resource potential and economic analysis of net revenue for a biogas facility (Li and Mba-Wright 2014).

The model is available online and free to the public and provides a mapping function that shows the location and amount of biogas resource available. The geographic visualization includes many useful layers that can be overlaid on top of the biogas data, including gas pipeline locations. The economic model allows the user to tune a comprehensive list of parameters, including production technology options and state and federal policy incentives. The accompanying report provides a life cycle cost assessment of a sample dairy cow RNG project.

Source: WRI authors, based on studies cited above.

Given the number of variables impacting the economics of animal manure projects, it will typically be helpful to integrate assessment data spatially to identify opportunities. Data on farm size and location, local pipeline infrastructure, projected project economics, and expected policy incentives, among other factors, may be mapped to assess economic viability through these multiple lenses (see Box 1-6).

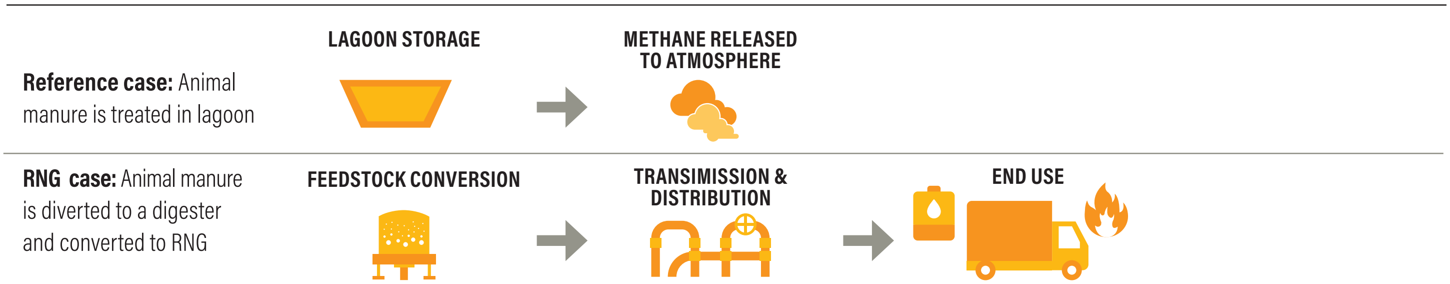
States may also wish to consider the many possible cobenefits of animal manure RNG projects, such as odor reduction associated with manure management and improved air and water quality through reduction of air pollutants such as nitrogen oxides, volatile organic compounds, and carbon monoxide (Williams, et al. 2016). While these cobenefits are not monetized, they can result in increased economic and social welfare in surrounding communities, and in the increased viability of a livestock operation.

Nationally, livestock are estimated to produce 13.0 percent of U.S. agricultural emissions and 8.4 percent of U.S. GHG emissions, with cattle alone responsible for 3.4 percent (U.S. EPA 2020a). Most confined animal livestock operations use lagoons for manure management—a practice that results in methane release as the waste decomposes. If an anaerobic digester is used for waste management, this methane can be captured and flared, or it can be used in a number of ways, such as in a boiler, combined heat and power generator, fuel cell, or microturbine. While these options eliminate nearly all methane emissions during waste management, RNG production can further reduce emissions by utilizing the methane to displace fossil fuel use in the transportation sector, so long as additional leakage from transmission and distribution of the RNG does not outweigh the additional emissions reduction benefit (see Figure 1-9).

Furthermore, the solid digestate that is left over after the biogas has been produced is a valuable soil amendment for agricultural crops, as is also the case when manure is treated in a lagoon. This reduces the need for synthetic fertilizer, avoiding substantial GHG emissions from its production and use.

To assess GHG impacts of animal manure RNG production, a state should determine the current practices of livestock operations. If current infrastructure in facilities is geared toward biogas production and on-site heat and power generation, then it must be determined whether it would be economical to upgrade these facilities to RNG production or to transport the biogas to a facility where it can be upgraded to RNG. In both cases life cycle impacts must be taken into account to determine actual GHG impacts. Methane leakage is also a major factor in determining the life cycle benefits of RNG production; therefore, the assessment should consider emissions during the transmission and fueling stages. Figure 1-9 provides a simplified illustration of key sources of emissions within a specific reference case—one where a lagoon is used for manure management, as in dairy and swine operations—and an RNG project case that should be accounted for to determine life cycle impacts.

Figure 1-9 | **RNG Production Pathway and Life Cycle Analysis Components for Animal Manure Feedstocks**



LIFE CYCLE PHASE	EXAMPLE LIFE CYCLE ANALYSIS COMPONENTS	NOTES
Lagoon storage	■ Release of biogas to the atmosphere	6 kg CH_4 per cow per month
Feedstock conversion	■ Leaks or venting from feedstock storage, anaerobic digester, gas upgrading, and storage ■ Energy use for anaerobic digester facility, gas upgrading, and storage	Leakage may be 2–10%, depending on equipment and efficiency
Transmission & distribution	■ Leaks or venting from compressors, storage facilities, gas metering, regulating stations, and pipelines ■ Leaks or venting from compressors, fuel line components, storage, transfer, and refueling	Transmission and distribution leakage may be 0.4–0.9% depending on equipment and efficiency
Vehicle end use	■ Fuel combustion emissions from tailpipe ■ Venting or leaks from crankcase, storage, fueling system, or incomplete combustion	Tailpipe and crankcase leakage may be 0.5–1.7% depending on efficiency

Sources: Methane leakage rates and other emission factors by category: Lagoon storage (CARB 2014); feedstock conversion (Börjesson and Berglund 2006; UNFCCC 2012); transmission and distribution (Delgado and Muncrief 2015); vehicle end use (Delgado and Muncrief 2015).

Wastewater

FEEDSTOCK OVERVIEW

Water resource recovery facilities (WRRFs) manage municipal wastewater in the form of sewage, storm runoff, and other residential, commercial, and industrial liquid wastes. These facilities often use anaerobic digesters to manage waste because of the benefits these provide for odor control and because of their low energy requirements. Approximately 15,000 WRRFs currently serve 75 percent of the U.S. population, processing 12.6 trillion gallons of wastewater annually (Seiple et al. 2017). Of these centralized facilities, 1,269 currently utilize anaerobic digestion (AD) (WEF 2019), processing approximately 50% of the total volume of wastewater produced in the U.S. (see Figure 1-10). While many of these facilities use this biogas directly for on-site energy needs, 15 WRRF facilities currently upgrade their biogas to RNG, and 20 more are in the construction or late development stage for RNG production (The Coalition for Renewable Natural Gas 2020). The recent increase in RNG project development can be attributed in part to favorable economics due to policy incentives at the state and local levels.

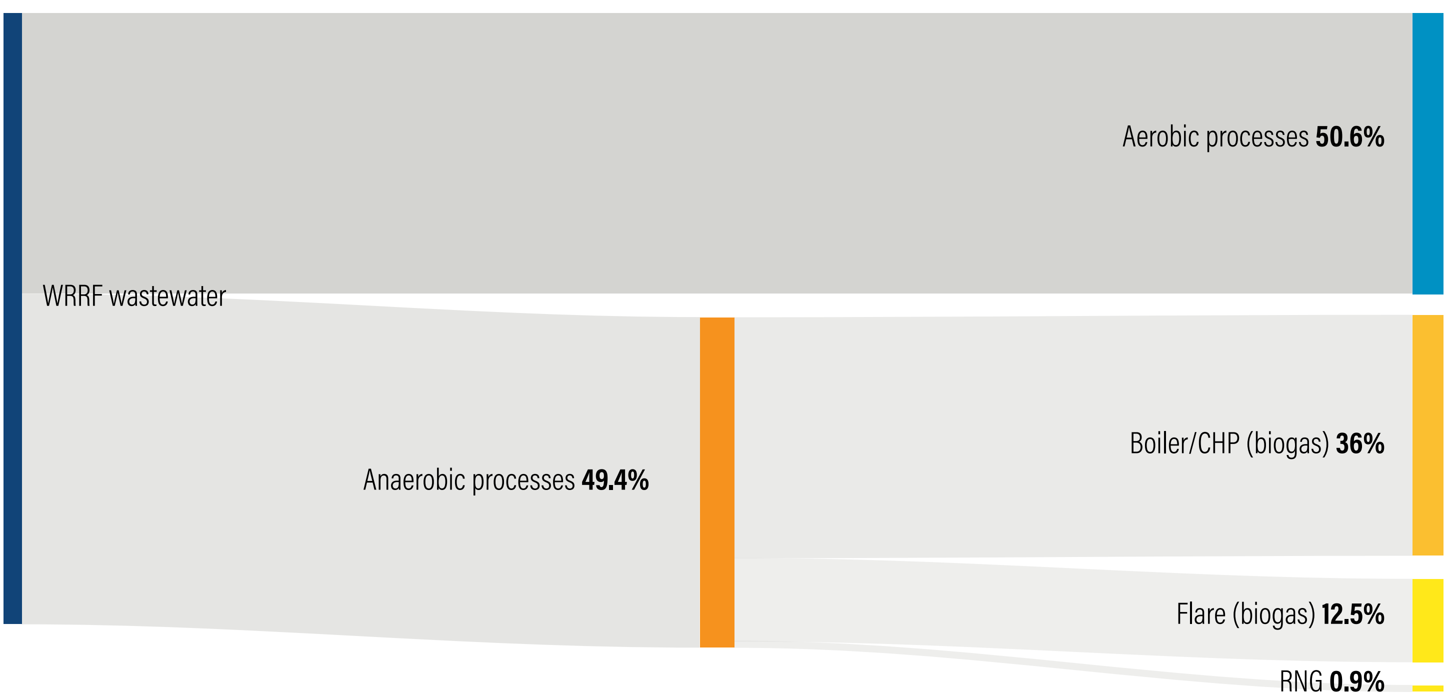
ASSESSING RESOURCE POTENTIAL

WRRF RNG resource potential is mainly calculated using the size of the population served in a wastewater collection area. At the facility level, RNG production potential is determined by facility size and existing infrastructure, with feedstock characteristics and quality also playing an important role.

Three criteria are commonly used to determine candidate WRRFs for cost-effective RNG production when conducting a resource assessment:

- Facility treats more than 1 million gallons of wastewater per day.
- Facility already uses anaerobic digestion for secondary treatment.
- Facility does not currently use a boiler or combined heat and power (CHP) generator for on-site energy production.

Figure 1-10 | **Municipal Wastewater Use and Diversion in the United States (Percentage by Volume)**



Notes: Facilities utilizing anaerobic processes are candidates for RNG production.
CHP = Combined heat and power.
Sources: Based on raw data from Seiple et al. (2017); WEF (2019); U.S. DOE (2019); and ANL (2019); aggregated by WRI.

Economies of scale are such that 80 percent of WRRFs that use anaerobic digesters treat over 1 million gallons per day (U.S. EPA 2012, 2019b; WEF 2019). If a facility is already using an anaerobic digester, and the biogas is being flared, the conversion to RNG production is much more economical than if the facility does not have an anaerobic digester. Facilities due for infrastructure improvements provide an opportunity for digester and RNG upgrades, as well. Data regarding WRRFs that currently use anaerobic digestion are available in the Clean Watershed Needs Survey (U.S. EPA 2012).

The development of WRRF RNG projects is limited in part by the competing use of biogas for on-site heating and electricity. Due to high energy requirements for wastewater treatment, it can be advantageous for a facility to use its biogas on-site. Electricity can be produced for on-site use for as little as 1.1 cents per kilowatt-hour (kWh), and using this electricity can cut facility energy costs by 20 percent (U.S. DOE 2019; U.S. EPA CHP 2011). Depending on which policy and market incentives, and environmental and climate goals are in place, however, it may be advantageous for WRRFs to produce RNG rather than using biogas for on-site heating and electricity. Working together, states, localities, and facilities can determine which end use is more profitable or valuable to the stakeholders involved (see Box 1-7).

Box 1-7 | **New York State WRRF Methane Potential**

In 2014, researchers at Cornell University estimated the net available resource potential for methane capture from water resource recovery facilities in New York State (Wightman and Woodbury 2014). While their study focused on methane recovery for on-site electricity and heat generation, the results can be used to determine RNG resource potential as well (NYSERDA 2008).

The study found that New York State WRRFs currently use approximately 50 percent of the state's methane production potential. The report also identified 72 WRRFs that treat more than 1 million gallons per day and have not been retrofitted for over 30 years. These facilities are high-priority candidates for retrofits for methane capture.

Source: WRI authors, based on studies cited above.

ASSESSING LIFE CYCLE GHG IMPACTS AND BENEFITS

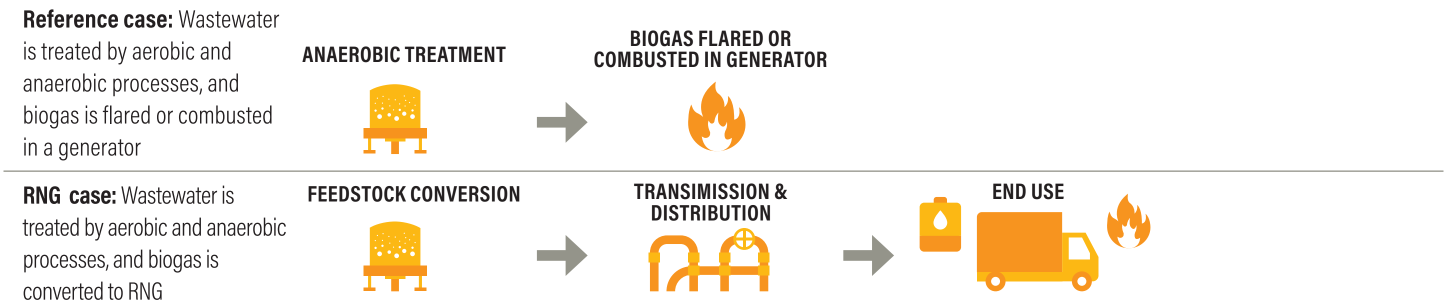
GHG emissions from WRRFs contribute 14.0 percent of U.S. emissions from waste, 2.3 percent of U.S. methane emissions, and 1.5 percent of U.S. nitrous oxide emissions (U.S. EPA 2020a). Energy-intensive aerobic treatment processes are widely used because they remove impurities more effectively than anaerobic processes. However, anaerobic digesters are also popular in wastewater treatment because they offer a low-cost, odor-reducing purification method.

For a state to assess the GHG impacts of RNG production, data must be collected and analyzed regarding WRRF practices in the region. Many WRRFs flare biogas produced from anaerobic digestion; and even with boilers or CHP systems installed, some biogas must be flared occasionally to moderate the flow of biogas to these systems. Venting biogas to the atmosphere is a common practice for smaller WRRFs.

Wastewater treatment requires energy-intensive processes for the timely breakdown of volatile organic material. Aeration, movement of waste, and thermal requirements for anaerobic digestion result in typical energy intensities of 1,500 kWh to 2,000 kWh per 1 million gallons of influent for WRRFs (EPRI and WRF 2013). If a facility were to produce RNG for transportation rather than burning its biogas in a CHP generator, it would have to source more of its electricity from the grid, and the emissions impact would depend on the relative emissions of on-site generation versus grid generation.

As is the case with animal manure RNG, the digestate from WRRF anaerobic digesters is often used as an agricultural soil amendment, depending on reuse options for the specific class of biosolid (U.S. EPA 2020c) (see Figure 1-11). This displaces synthetic fertilizer use, which avoids GHG emissions from its production and use, but raises concerns about perfluoroalkyl and polyfluoroalkyl substances (PFASs) levels in the soil (Blaine et al. 2013).

Figure 1-11 | **RNG Production Pathway and Life Cycle Analysis Components for Water Resource Recovery Facilities**



LIFE CYCLE PHASE	EXAMPLE LIFE CYCLE ANALYSIS COMPONENTS	NOTES
Biogas flaring and combustion	■ Emissions from flaring combustion ■ Fugitive emissions from incomplete flaring combustion and incomplete generator combustion	0.1 kg CO_2/M^3 of wastewater
Feedstock conversion	■ Leaks or venting from feedstock storage, anaerobic digester, gas upgrading, and storage ■ Energy use for anaerobic digester facility, gas upgrading, and storage	Leakage may be 2–10%, depending on equipment and efficiency
Transmission & distribution	■ Leaks or venting from compressors, storage facilities, gas metering, regulating stations, and pipelines ■ Leaks or venting from compressors, fuel line components, storage, transfer, and refueling	Transmission and distribution leakage may be 0.4–0.9% depending on equipment and efficiency
Vehicle end use	■ Fuel combustion emissions from tailpipe ■ Venting or leaks from crankcase, storage, fueling system, or incomplete combustion	Tailpipe and crankcase leakage may be 0.5–1.7% depending on efficiency

Sources: Methane leakage rates and other emission factors by category: Biogas flaring and combustion (Campos et al. 2016; Lee, Han, Demirtas et al. 2016); feedstock conversion (Börjesson and Berglund 2006; UNFCCC 2012; Lee, Han, Demirtas et al. 2016); transmission and distribution (Delgado and Muncrief 2015; Lee, Han, and Wang 2016); vehicle end use (Delgado and Muncrief 2015).

Forestry and agriculture (Lignocellulosic)

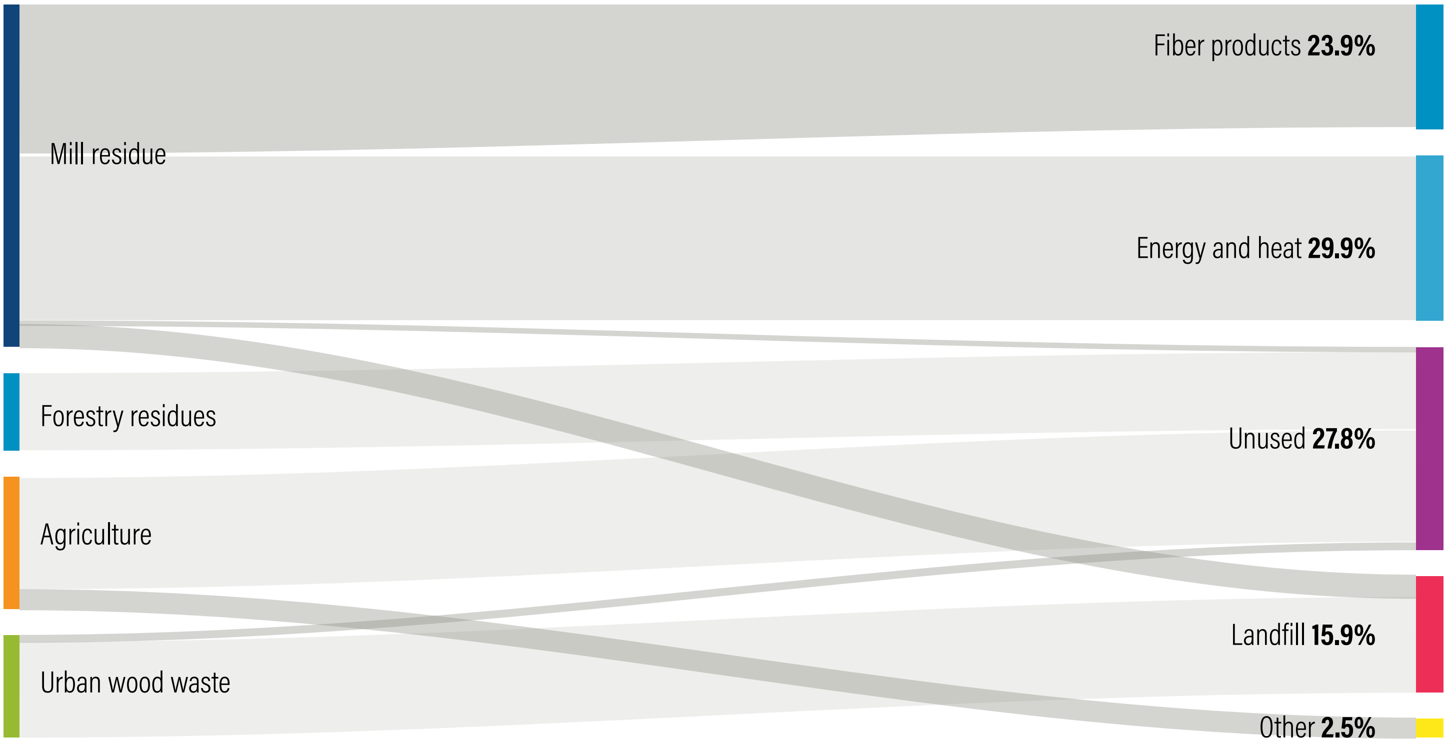
FEEDSTOCK OVERVIEW

Lignocellulosic waste from forestry, agriculture, and other waste sources can be used as a dry biomass feedstock for RNG production using gasification methods. Nonedible crop residues such as corn stover, wheat stalks, rice hulls, nut shells, and fruit tree trimmings are examples of crop residue lignocellulosic feedstocks. Forest management residues, paper mill waste, and construction wood waste are examples of forestry lignocellulosic feedstocks.

Whereas anaerobic digestion is the dominant waste-to-energy conversion technology in the United States for wet RNG feedstocks, thermal gasification is a leading conversion technology for lignocellulosic RNG feedstocks. However, only a few thermal gasification projects are currently in operation globally. Given the abundance of forest and agricultural waste, thermal gasification has the potential to be a dominant waste-to-energy process, assuming that economic and technical hurdles regarding residual tar production and methane leakage can be overcome (AGF 2019).

Lignocellulosic waste can also be codigested at low percentages with wet feedstocks to increase waste-to-energy efficiency (U.S. EPA AgSTAR 2012). Codigestion can help to optimize biogas production by providing the right carbon to nitrogen ratio for methanogenic bacteria. Currently in the U.S., lignocellulosic waste is used for making fiber products and for generating energy and heat (see Figure 1-12).

Figure 1-12 | **Current Uses of Lignocellulosic Waste (Percentage by Mass)**



Note: An estimated 60 million dry tons of unused lignocellulosic residue is available annually in the United States for conversion to RNG, which could be converted to approximately 540 billion cubic feet (BCF) annually, assuming a yield of 9,000 BCF per dry ton.
Source: Based on raw data from U.S. DOE (2016); aggregated by WRI authors.

ASSESSING RESOURCE POTENTIAL

The four main lignocellulosic feedstock categories are crop, mill, urban wood, and forest residues. Below we outline major questions to consider when assessing each.

- **Crop residues** – What are the main agricultural crops in the state? Does the production and harvesting of these crops result in unused residues, such as corn stover or tree and vineyard trimmings?
- **Mill residues –** Does the state possess a robust timber or paper mill industry? What is the current use rate of primary and secondary mill residue at the facility level?
- **Urban wood** – How are construction and demolition debris currently used or discarded in the state? Are waste disposal facilities currently equipped to separate construction and demolition debris? How are state and local governments currently disposing of tree trimming debris from public lands?
- **Forest residues** – What is the available acreage of forest resources and their current management practices? Do these practices result in the removal and disposal of secondary timber products, and how are these timber products used?

These factors will vary considerably from one region to the next depending on local agricultural and forestry industries, land-use practices, and other factors (see Box 1-8). Two prominent national-level studies concerning the country's lignocellulosic biomass resource potential provide useful starting points for resource assessment: the Billion Ton Study and a study by the National Renewable Energy Lab of the spatial distribution of the four main lignocellulosic feedstock subcategories (U.S. DOE 2016; U.S. DOE NREL 2014).

Box 1-8 | Woody Biomass in Oregon and Crop Residue in Nebraska

Oregon State University researchers estimated biomass supply and assessed barriers and opportunities for woody biomass use in the state. In addition to summarizing Oregon's forestry products industry and the literature surrounding biomass fuel use in the state, the study interviewed private landowners and stakeholders from the forestry industry. The study, conducted as part of a biofuels readiness survey commissioned by the Oregon Economic and Community Development Department, reported resource assessments and recommendations for the four major regions of the state and recommended using the results of the report as a guide for finer-detailed, community-level assessments to inform project development decisions (Oregon State University 2008).

In Nebraska, university researchers built on a prior National Renewable Energy Lab (NREL) study of corn residue potential in the region, adding feasibility and cost considerations of residue collection and processing. The study was part of a bigger effort undertaken by the Western Regional Biomass Energy Program. The study found that it was economically feasible for the region to supply 240,000 dry tons of corn residue annually, which correlates to approximately 0.005 BCF of RNG capacity (Sayler et al. 1993).

Source: WRI authors, based on studies cited above.

A rough estimate of crop residue generation can be obtained by assuming that around 3 to 4 tons is generated per acre, but this varies considerably based on the type of crop. For urban wood waste, around 0.1 tons of waste is generated per person per year. Forest residue—or nonmerchantable timber, branches and tops—from forest management is generated at an approximate rate of 10–30 tons per acre (U.S. DOE 2016). Mill residue is technically available in substantial quantities, but this waste stream currently has other end uses, and therefore potential for RNG production from this feedstock is considered very limited.

Forestry and agricultural waste have many competing end uses, such as primary paper products, construction materials, and soil nutrient management. Different allotments for these end uses in a resource assessment can lead to a wide range of estimates for lignocellulosic waste resource potential. RNG resource assessments typically include only waste feedstocks, since these have the greatest GHG benefits. If a state's assessment of resource potential also includes dedicated feedstocks (intentionally produced for biofuel generation), then it is important to consider the full life cycle impacts of those fuels (Searchinger and Heimlich 2015; U.S. DOE 2016).

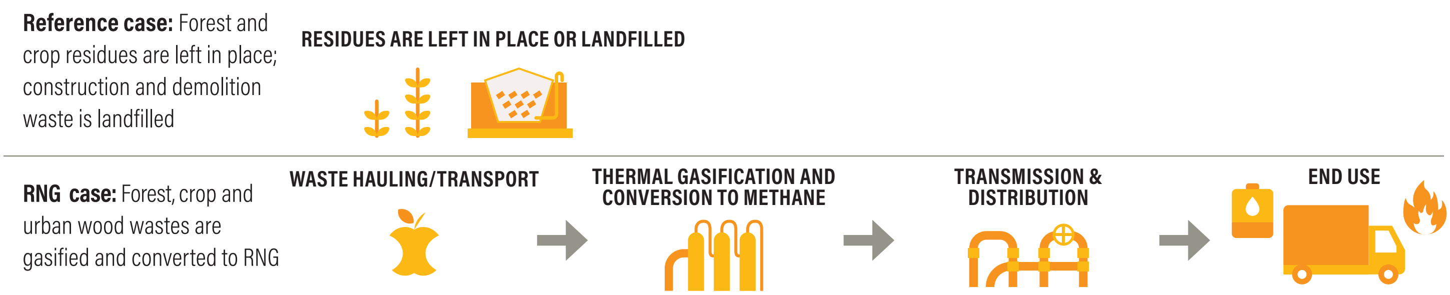
While lignocellulosic RNG can be produced by anaerobic digestion or thermal gasification, the latter is predicted to be the preferred technology, since it is a faster and more efficient process in terms of RNG production per dry ton of waste (NPC 2012). Whereas anaerobic digestion produces about 6,000 cubic feet of RNG per dry ton of animal manure and 8,000 cubic feet per dry ton of WRRF feedstock, thermal gasification produces about 9,000 cubic feet per dry ton for forest, agricultural, municipal, and other waste feedstocks (NPC 2012). Typical costs of producing RNG from thermal gasification of woody biomass range from \$8 to \$25/million Btu (\$1.9 to \$3.1/gasoline gallon equivalent), with collection and transportation distance being major drivers of cost (NPC 2012).

ASSESSING LIFE CYCLE GHG IMPACTS AND BENEFITS

Factors to consider when assessing the life cycle benefits of RNG production from lignocellulosic feedstocks include soil and nutrient retention, emissions from decaying biomass, collection and transport of feedstocks, and emissions due to the thermal gasification process itself (see Figure 1-13). Leaving crop residue on the field can increase soil and nutrient retention, decreasing the need for synthetic fertilizer. As discussed in the animal manure feedstock section, diversion of agricultural residues for RNG production can result in increased synthetic fertilizer requirements, which would impact GHG emissions relative to the business-as-usual case. However, this impact can be reduced in the RNG case, if the digestate is recovered and used as a soil amendment (Mitchell et al. 2015).

Collecting and transporting lignocellulosic biomass over large distances increases costs and GHG emissions of RNG production. Innovation in the processing of crops and forestry products could result in the simultaneous collection of primary products and waste, therefore reducing the GHG impacts of collection and transport.

Figure 1-13 | **RNG Production Pathway and Life Cycle Analysis Components for Lignocellulosic Feedstocks**



LIFE CYCLE PHASE	EXAMPLE LIFE CYCLE ANALYSIS COMPONENTS	NOTES
Landfill/gas collection	■ Leakage from biogas collection ■ Energy use for biogas collection and processing	Biogas losses may be 5–40%, depending on type of cover and other equipment used
Waste hauling/ transport	■ Emissions due to collecting and transporting biomass with medium- and heavy-duty trucks	650 g CO_2e/mile
Thermal gasification and conversion	■ Leakage and venting from thermal gasification, gas upgrading, and gas storage ■ Energy use for thermal gasification and gas conversion equipment	8.43 g CO_2e/MJ of methane produced; 60% conversion efficiency
Transmission & distribution	■ Leaks or venting from compressors, storage facilities, gas metering, regulating stations, and pipelines ■ Leaks or venting from compressors, fuel line components, storage, transfer, and refueling	Transmission and distribution leakage may be 0.4–0.9% depending on equipment and efficiency
Vehicle end use	■ Fuel combustion emissions from tailpipe ■ Venting or leaks from crankcase, storage, fueling system, or incomplete combustion	Tailpipe and crankcase leakage may be 0.5–1.7% depending on efficiency

Sources: Methane leakage rates and other emission factors by category: Thermal gasification and conversion (Gas Technology Institute 2019); transmission and distribution (Delgado and Muncrief 2015); vehicle end use (Delgado and Muncrief 2015); waste hauling/transport (U.S. EPA 2018a).

SECTION 2: RNG MARKET OPPORTUNITIES AND ROLE IN DECARBONIZATION

In this section, we explore various forms of RNG deployment and use, drawing on findings and approaches from recent literature. The aim is to explain how RNG resources may be developed in different contexts, the current drivers of demand, and the implications of use in terms of market potential and decarbonization. We cover the following specific topics and underlying considerations:

- **Bringing resources online:** There is no one-size-fits-all approach to bringing biogas and RNG resources online. Rather, a number of deployment options exist that may be driven by feedstock type, project location, and other factors. We begin this section by unpacking these considerations to highlight how resources can be deployed efficiently in different contexts.
- **Assessing current and emerging markets:** Biogas and RNG may be used in a wide variety of downstream applications in the transportation, power, and buildings sectors. We lay out key sources of demand and fundamental considerations for evaluating various opportunities, including market potential, policy drivers, and emerging pathways.
- **Evaluating decarbonization potential:** After surveying key supply- and demand-side considerations, the remainder of this section focuses on the key policy question of how RNG development can contribute to broader decarbonization goals. We present recent findings, evaluation metrics, and long-term technical and economic considerations regarding the complementary role biogas and RNG can play alongside other vital decarbonization strategies.

Importantly, each of these topics and their underlying considerations are linked. For example, how RNG is brought to market is defined in part by existing policy and market drivers, which may in turn be influenced by how various RNG resources complement decarbonization priorities.

Thus, while presented sequentially, the considerations below will likely need to be assessed holistically to identify key opportunities for RNG deployment.

2.1 Bringing Resources Online

A wide array of deployment pathways are available for bringing biogas and RNG resources online, each of which comes with important trade-offs in terms of cost, efficiency, and overall project footprint. While multiple factors influence how resources are deployed, fundamental considerations include fuel specification, pipeline versus non-pipeline delivery options, and clustered versus stand-alone project development.

Fuel specification

Fuel specification refers to the purity of cleaned or upgraded biogas needed for any particular use. Requirements vary substantially from one project to the next, with significant implications for the overall cost of bringing fuel to market.

Biogas is only considered RNG once it has been treated and upgraded to a high-Btu fuel that is interchangeable with pipeline gas. While the upgrading and pipeline interconnection process is costly (upgrading alone may amount to 30–40 percent of total project capital and operating costs), the advantage lies in the potential to reach a wide array of end-use markets in the transportation and buildings sectors (Ahlm et al. 2018).

However, biogas may also have useful applications in pre-upgraded stages. Prior to upgrading, raw biogas undergoes initial cleaning and conditioning to remove moisture, siloxanes, and other impurities. This "cleaned biogas" may be deployed in more tolerant equipment that does not require high-Btu gas, such as industrial boilers or internal combustion engines to generate electricity (WSU 2018; EPA LMOP 2017). The trade-off is that such projects may have lower overall costs but more constrained market opportunities.

Figure 2-1 below highlights the general distinction between cleaned, medium-Btu biogas and upgraded, high-Btu RNG (also referred to as biomethane). While presented as two categories, in reality different types of equipment and end uses run on a spectrum of fuel purity requirements that adds further nuance to these considerations. For example, pipeline injection will generally require higher levels of methane content and purity, while natural gas vehicle engines may technically be able to operate on fuel with a slightly lower methane content. In either case, however, the fuel is referred to as RNG since it has undergone substantial upgrading.

For projects that feature pipeline injection, fuel specification requirements are also highly dependent on gas quality standards. In many jurisdictions in the United States, standards are implemented independently by pipeline operators and will vary depending upon type of pipeline (e.g., transmission or distribution), relative volumes, seasonality, and other factors. As discussed later, wide variance in standards can cause significant uncertainty and increased costs for producers.

Figure 2-1 | **Characteristics and Common End Uses for Biogas and RNG**

CLEANED/CONDITIONED BIOGAS	UPGRADED BIOMETHANE/RNG
Treatment Required	**Treatment Required**
Initial cleaning and conditioning (moisture, siloxane, and H_2S removal). Medium-Btu gas (>50% CH_4)	Additional upgrading to increase purity (removal of nearly all non-methane trace gases such as CO_2, O_2, and N_2). High-Btu gas (>95% CH_4)
Common end uses & markets	**Common end uses & markets**
Boiler or process heat; On-site electricity generation	Compressed RNG to vehicle fuel; Gas pipeline and delivery to multiple end-use markets

Notes: Btu = British thermal unit; H_2S = Hydrogen sulfide; CH_4 = Methane; CO_2 = Carbon dioxide; O_2 = Oxygen; N_2 = Nitrogen.
Source: WRI authors.

Pipeline versus non-pipeline options

A related, vital consideration regarding how RNG is deployed is whether pipeline interconnection and injection is feasible, or whether the project will need to rely on non-pipeline options for fuel delivery and use. In 2020, 98 out of 119 operational RNG projects in the United States used pipeline injection for fuel delivery (The Coalition for Renewable Natural Gas 2020). This allows developers a high level of flexibility in meeting off-site demand and—by extension—tapping into credit markets for environmental benefits that may be earned under federal and state incentives such as California's Low-Carbon Fuel Standard. In general, the closer a potential RNG project is to local pipeline infrastructure, the more viable interconnection and injection will be.

However, while pipeline interconnection and injection are a feature of a majority of RNG projects, distributed biogas sources such as dairies or food manufacturing plants in rural areas may be too remote for interconnection to be feasible. In such cases, virtual pipelining, whereby compressed RNG is transported via truck to local injection hubs, may be a viable alternative way to bring resources to market.

In addition, RNG may have on-site or local sources of energy demand. A "closed loop" model in which biogas or RNG is used on-site rather than being delivered to off-site markets via trucking or pipeline interconnection may make economic sense, particularly for more distributed resources. On-site use to power local vehicle fleets, for example, can be a feature of successful RNG projects (Tomich and Mintz 2017). In general, these models avoid high distribution costs, potentially improving efficiency and cost-effectiveness.

Clustered versus stand-alone project development

Given the high cost of upgrading and cleaning equipment, pipeline interconnection, and other capital expenses, bringing resources online cost-effectively may require projects to share infrastructure. Project "clustering," whereby several sources of nearby RNG feedstocks use shared digester, upgrading, and/or pipeline interconnection and injection facilities, is often a vital strategy to reduce infrastructure costs on a levelized basis and bring resources online. For example, a study conducted for California found that project clustering could lower project costs by as much as 60 percent (Jaffe et al. 2016), and this strategy is being pursued to bring multiple dairy digester projects online in the state's agricultural hub.

Generally, the extent to which these strategies can lower costs depends largely on the type of project. For large landfills and wastewater plants, infrastructure sharing may have minimal impacts on a project's overall bottom line. However, for resources such as food waste and animal manure, shared digester, upgrading, or injection facilities may be critical to project viability. It may therefore be useful to identify resources that are colocated or in close proximity to one another when evaluating project viability and conducting assessments of resource potential as discussed in Section 1 of this guidance.

Implications for deployment

The above factors highlight the significant variability in how biogas and RNG projects may be pursued to bring resources to market. From a policymaking perspective, a key takeaway is that there is no one-size-fits-all approach to development, and the economic viability of various options will depend on factors related to location, existing infrastructure, and local sources of demand. While deployment strategies are ultimately at the discretion of project developers, decision-makers can nonetheless aim to create investment signals and regulations that facilitate flexible and efficient strategies for a wide array of contexts. Given the inherent complexity, it may also be useful to evaluate multiple deployment pathways and their expected costs (see Box 2-1) to inform such decisions. Taken together, these factors can help ensure RNG feedstocks and financial resources are deployed as efficiently as possible.

2.2 – Assessing Current and Emerging Markets

Just as there is significant variance in deployment options for RNG, resources may also be used to meet a wide array of downstream end uses. Recent years have seen significant shifts in terms of key sources of demand and market drivers. In this section, we highlight both current and emerging trends, framing the discussion around the following considerations and guiding questions:

- **Market potential**: What is the current market potential for RNG in various end-use sectors, and what are the implications of future growth?
- **Market drivers**: How do current policies, incentives, and voluntary programs impact the value of RNG resources and drive deployment toward specific end uses?
- **Alternative and emerging pathways**: Besides use as a direct fuel, what are alternative pathways for use of biogas and RNG resources that may be important to consider when moving forward?

Box 2-1 | Evaluating Project Costs Based on Differing Deployment Pathways

Biogas and RNG projects can vary substantially in terms of production costs, from $5 per million Btu on the low end to upward of $35 per million Btu. This variance in cost is determined in large part by how resources are deployed; for example, the extent to which projects use existing infrastructure or require new investment, level of treatment required for gas upgrading, and whether fuel is used on-site or is delivered to more distant downstream consumers. Evaluating each of these factors to determine the most economic and efficient opportunities is an inherently complex exercise; however, recent studies can provide useful points of reference and serve as examples of effective approaches.

A particularly illustrative example is a recent study by Great Plains Institute that models cost components of anaerobic digester projects under six distinct end-use and production volume scenarios, based on independent research and industry interviews. Demonstrating economies of scale, the study found that projects with higher production volumes are generally more cost-effective. For example, projects processing 100,000 tons of waste had approximately 20 percent lower capital and operating costs per unit of fuel produced relative to projects processing 50,000 tons of waste. The study also found that biogas upgrading increased total project costs by approximately 40–65 percent, with these costs being somewhat lower for projects deploying RNG in local compressed natural gas (CNG) vehicle fleets versus projects injecting into gas pipelines. Projects upgrading to RNG also had significantly higher assumed revenues, given their ability to capture Renewable Fuel Standard (RFS) and/or Low Carbon Fuel Standard (LCFS) credits.

Source: WRI authors, based on Ahlm et al. (2018).

In covering each of these considerations, we focus the discussion on two broad sources of demand:

1. **Transportation sector** – which encompasses RNG use as a vehicle fuel, particularly for long-haul and heavy-duty vehicle applications.
2. **Stationary end uses** – which encompass use of RNG as a replacement for natural gas in heating, cooking, or other applications in residential and commercial buildings or as a low-carbon fuel to meet industrial heating needs.

The primary rationale for focusing on these two sectors is that they include hard-to-abate end uses—such as heavy-duty freight and industrial heating—which currently lack cost-effective zero-emission or low-carbon technology options. Given this, these sectors represent practical sources of demand where RNG can add significant value, particularly if the policy and market signals discussed later in this section continue to gain momentum. For these same reasons, the below discussion omits the potential for application of RNG in the power sector. RNG may offer value in the power sector as a dispatchable energy source; however, current evidence suggests that such applications will be limited due to the distributed and finite nature of organic-waste feedstocks, falling costs of renewables and battery storage solutions for grid decarbonization, and stronger incentives for RNG in other sectors.

Market potential

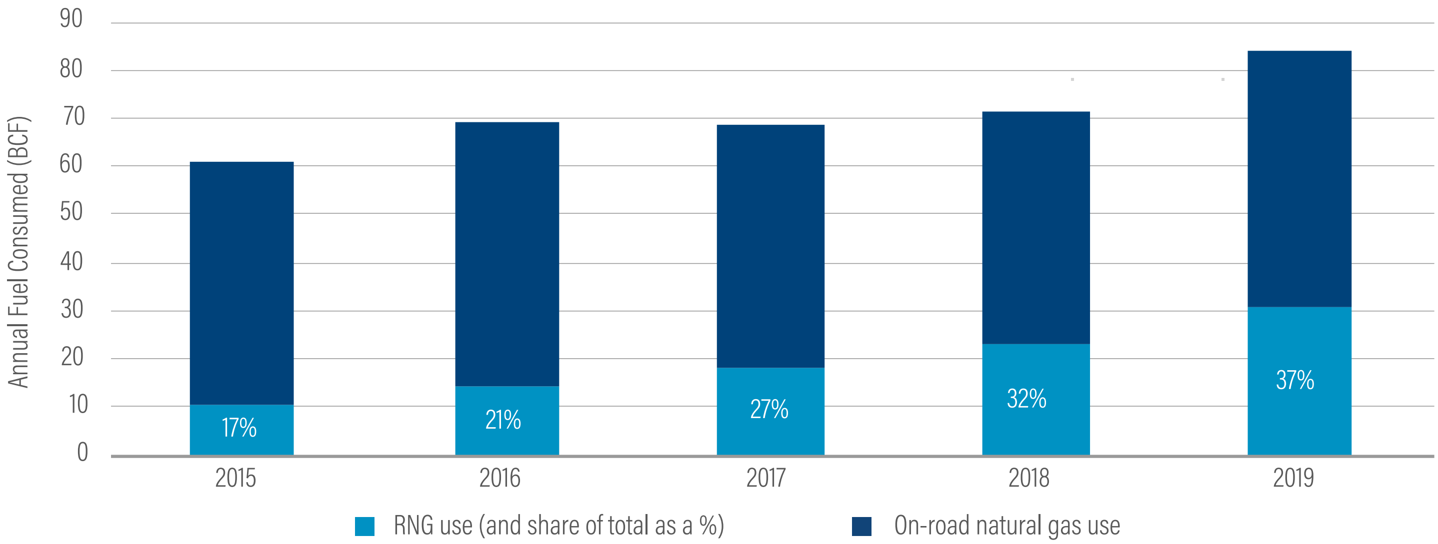
Current energy demand in the transportation and stationary end-use sectors far exceeds potential supply of RNG from organic waste–derived resources. However, RNG resources have the potential to displace significant amounts of fossil fuel within specific categories of energy demand. According to recent modeling, the amount of RNG from organic wastes that could be economically produced at $20/million Btu or less by 2040 would amount to roughly 25 percent of current fossil fuel demand for either residential and commercial natural gas, industrial natural gas, or on-road diesel (AGF 2019; U.S. EIA 2020a).

This naturally leads to questions of optimization; that is, which markets and end uses are best suited for RNG and can yield the greatest net economic and environmental benefits. This is a complex question with many factors at play; however, an important starting point is the consideration of current market capacity for RNG deployment based on existing infrastructure as well as the implications of continued growth, discussed below by sector.

TRANSPORTATION SECTOR POTENTIAL

The vast majority of present-day RNG projects supply fuel for the transportation sector, particularly for natural gas vehicles designed for long-haul and heavy-duty applications. In 2019, approximately 31 BFC of RNG was used as vehicle fuel in the United States, or approximately 37 percent of all natural gas vehicle fuel consumption in the same year (U.S. EPA 2020b; U.S. EIA 2020a). Market penetration is more pronounced in California. By 2018, the amount of RNG supplying the state's Low Carbon Fuel Standard (through book and claim) reached 17 BCF, equivalent to 70 percent of total fuel consumption for natural gas vehicles in the state for that year (CARB 2020c; U.S. EIA 2020b). Figure 2-2 below shows recent national trends in natural gas consumption by on-road vehicles, along with the increasing penetration of RNG in this sector.

Figure 2-2 | **RNG Market Penetration in the Transportation Sector**



Note: BCF = Billion cubic feet.
Sources: Based on raw data from U.S. EPA (2020b) and U.S. EIA (2020a), aggregated and modified by WRI authors.

Increased capacity for RNG use in the transportation sector will necessarily require further buildout of natural gas vehicle fleets and fueling stations, and recent forecasts in this area are illustrative. The Energy Information Administration (EIA) currently estimates that demand for natural gas as a transportation fuel will continue to increase in the United States, rising to 148 BCF in 2025. The Fuel Institute estimates that demand for natural gas in transportation will increase to 198 BCF in 2025 (Bates White 2019), or more than double today's levels. Thus, market demand and capacity may continue to increase even as use of RNG as a vehicle fuel grows. However, current natural gas use in vehicles still amounts to approximately just 1 percent of total fuel consumption in the heavy-duty freight sector (U.S. EIA 2020a).

STATIONARY END-USE POTENTIAL

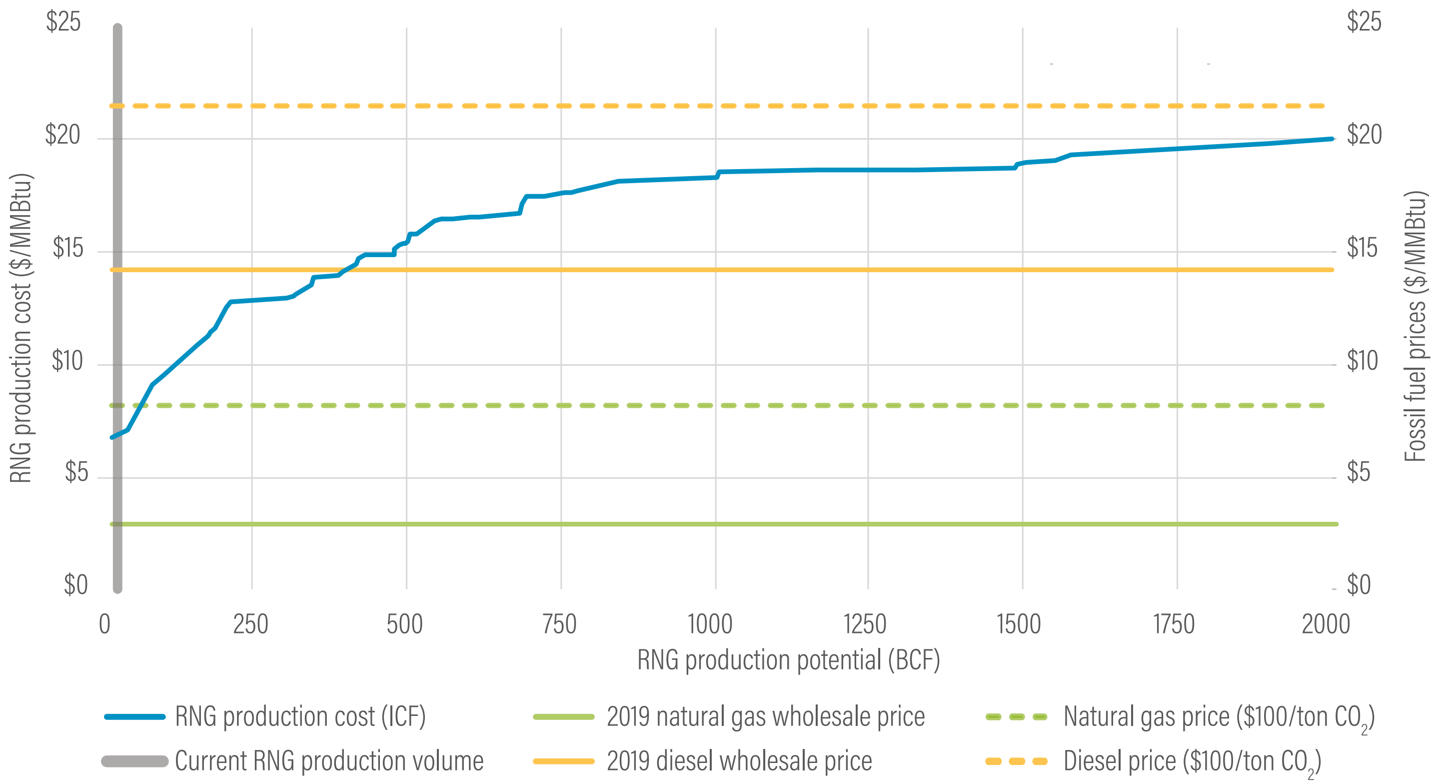
While the transportation sector is currently driving the majority of RNG projects in the United States, stationary end uses represent a much larger source of potential demand that may increase as markets develop. Whereas fuel consumption by natural gas vehicles accounts for less than 1 percent of current natural gas consumption in the United States, industrial, residential, and commercial end uses make up 30 percent, 18 percent, and 13 percent, respectively (U.S. EIA 2020b). Together these sectors accounted for 17 trillion cubic feet of natural gas consumption in 2018. By comparison, as discussed in Section I of this guidance, national estimates of potential RNG production from organic wastes range from approximately 1,300 to 2,200 BCF (Saur and Milbrandt 2014; Milbrandt et al. 2018; AGF 2019).

Unlike the transportation sector, use of RNG as a direct fuel in stationary end uses relies largely on existing infrastructure, thanks to the substantial reliance on natural gas to meet heating and other building energy needs in many regions of the United States. In the long term, this infrastructure is likely to be gradually phased out as electrification and efficiency efforts move forward. However, full electrification of energy services currently supplied by natural gas faces inherent challenges including scale, uncertain pace of infrastructure turnover, and potential electric grid impacts, among other factors. As we discuss in more detail in the section on decarbonization, demand for RNG as a complementary strategy that leverages existing infrastructure—even as broader electrification and efficiency efforts progress—will likely continue in the near- to mid-term (and potentially longer depending on technology advancement).

Market drivers

In addition to overall market potential, policies such as incentives from climate and energy mandates have a strong impact on RNG markets and will likely continue to be a key driver in the future. This is particularly true since RNG production costs are generally higher than those of fossil fuels, and thus incremental incentives are required to reach price parity.

Figure 2-3 | **Estimated RNG Production Cost Curve Relative to Fossil Fuel Prices**



Notes: In a market where the emissions impacts of carbon are priced at $100/ton CO_2, the gap in production costs between RNG and natural gas narrows, and the majority of potential RNG supply becomes cheaper than diesel. This figure shows long-term RNG production costs (through 2040) for waste-derived feedstocks together with current and projected fossil natural gas and diesel wholesale prices. It does not consider taxes; distribution and marketing costs; or the incremental investment in infrastructure, such as fueling stations, that may be required for delivery. In addition, it does not consider the variance in life cycle GHG emissions performance for different RNG feedstocks, which may further improve RNG's cost-competitiveness, depending on incentive structure. MMBtu = Million British thermal units; BCF = Billion cubic feet.
Sources: Based on raw data from AGF (2019); U.S. EIA (2020c, 2020d), aggregated and modified by WRI authors.

When considering all organic waste feedstocks in aggregate, research suggests that a significant share of RNG can be produced at a cost ranging from $15 to $20 per million Btu (AGF 2019). By contrast, in 2019 wholesale natural gas prices hovered at around $3/million Btu, and wholesale diesel prices were at around $14/million Btu (on an energy equivalent basis). Figure 2-3 highlights this gap, while also showing how the gap narrows in a market in which carbon is directly or indirectly priced through policy. While an illustrative $100/ton carbon price is shown, it is important to note that other types of incentives can have similar or greater impacts. In addition, policies and incentives that place value on the emissions benefits associated with RNG production can further improve its competitiveness, effectively shifting its production costs below the curve shown in Figure 2-3.

The main takeaway is that a given policy or set of policies can have substantial impacts on RNG's overall competitiveness. Typically, investors will weigh the cost of bringing biogas or RNG resources to market against the price that the delivered fuel can bring, including the value of environmental and/or clean energy "tags," such as carbon credits, Renewable Identification Numbers (RINs), renewable energy credits (RECs), or other market-based incentives. In addition, programs such as utility offerings and public or private procurement efforts may provide significant incentives for RNG by placing a premium on its environmental attributes. As ambitious state-level climate goals proliferate in the United States, these market signals may continue to shift, with important implications for RNG deployment. These factors are discussed in more detail by sector below.

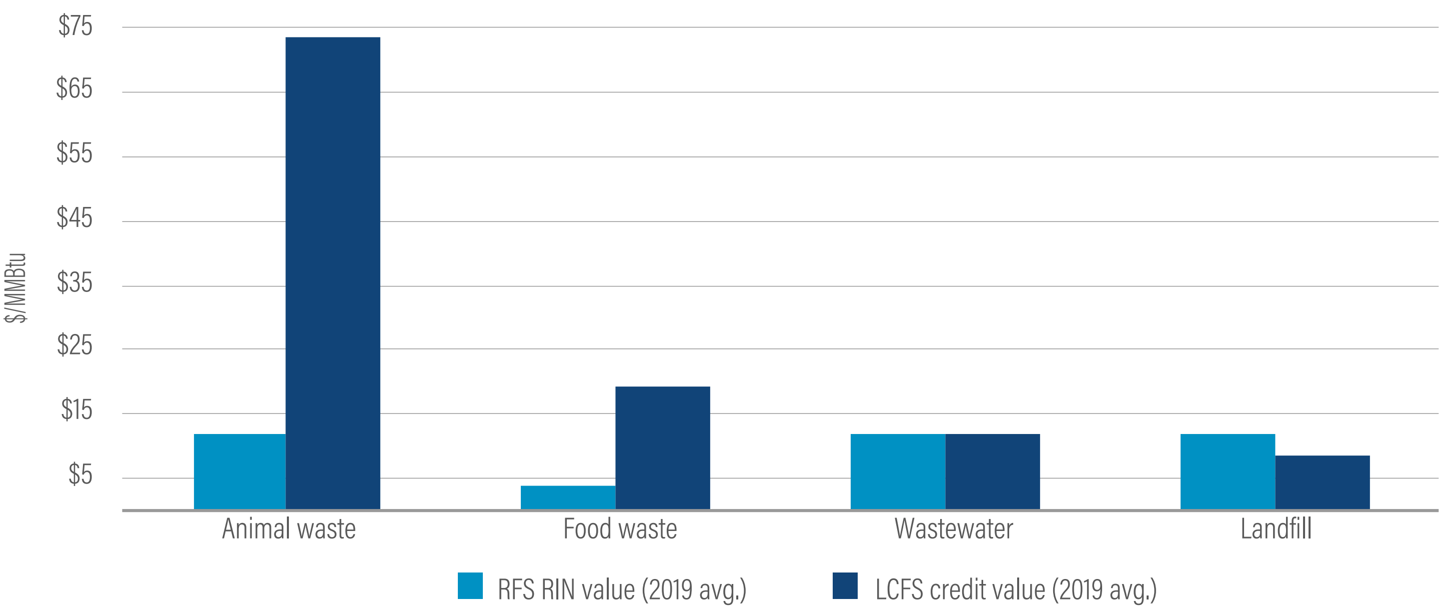
TRANSPORTATION SECTOR DRIVERS

Clean fuel policies at the state and federal levels have been the primary driver of recent growth in RNG use in the transportation sector. These policies, most notably the federal Renewable Fuel Standard (RFS) and California's Low Carbon Fuel Standard (LCFS), create strong incentive value for environmental attributes of RNG. The impact of these mandates on the value of RNG is shown in Figure 2-4. Incentive values illustrated in the figure are based on average RFS Renewable Identification Number (RIN) trading prices and LCFS credit prices for the year 2019.

Assuming a project can earn incentives at these levels, revenues may well be sufficient to offset the gap between RNG production costs and fossil fuel production costs and earn a return on investment. For example, if a food waste derived RNG project costs $20/million Btu to produce and deliver biomethane, an incremental incentive of roughly $17/million Btu would be required to "break even" after factoring out an assumed $3/million Btu commodity value of natural gas. If the project is able to earn more than this break even value after accounting for fuel credits from the RFS and any state programs such as the LCFS, then there may well be sufficient revenue to achieve market parity and gain a modest return on investment.

However, credit value from these incentives is variable and can shift dramatically over time, leading investors to discount their value due to perceived risk. Soft costs for project developers and debt financing can further erode potential profit margins. Thus, while the above example is illustrative of current RNG market opportunities in the transportation sector, project viability is often more complex than a simple comparison of incentive values and production costs may suggest. These issues are discussed in more detail in Section 3 of this paper on market barriers.

Figure 2-4 | **Value of RNG by Feedstock under Current Transportation Sector Incentives**



Notes: California's Low Carbon Fuel Standard (LCFS) credits RNG feedstocks according to the avoided methane emissions associated with production, leading to greater value for RNG derived from animal or food waste. Under the federal Renewable Fuel Standard (RFS), RNG from animal waste, landfills, and wastewater may qualify for D3, "cellulosic" biofuel credits. By contrast, RNG from food waste does not fall under this category and may instead qualify for D5, "advanced" biofuel credits, which are currently less valuable.

LCFS credit value by feedstock was calculated using average carbon-intensity scores for currently approved projects and an assumed program credit price of approximately $191 per metric ton, based on the 2019 average. RFS value by feedstock was calculated based on average D3 and D5 RIN (Renewable Identification Number) prices for 2019. These values may fluctuate and therefore are not necessarily representative of the value of current or future RNG projects.

MMBtu = Million British thermal units

Sources: Based on raw data from CARB (2020c) and U.S. EPA (2020b), aggregated and modified by WRI authors.

STATIONARY END-USE DRIVERS

RNG deployment in the stationary end-uses sector is currently driven largely by growing demand from downstream users and an increasing number of utilities seeking to offer a low-carbon alternative to natural gas. To date, these programs are limited; however, they have potential to bring significant shares of RNG online as markets further develop. While incentive values are unlikely to reach levels seen in the transportation sector, utilities and large consumers may nonetheless be able to provide long-term contracts for fuel delivery that are attractive to RNG producers.

In recent years, an increasing number of natural gas utilities have launched initiatives to accept and deliver RNG to commercial and residential customers. In 2017, Vermont Gas became the first utility in the country to offer a voluntary, opt-in program for its customers to procure RNG. Since then, additional utilities in Maine, Michigan, and Utah have begun offering similar programs, while several more—including utilities in California, Minnesota, New Hampshire, and New York—have applied to state public utility commissions to offer similar programs. As of September 2020, a total of 15 natural gas utilities had either active or under-development voluntary RNG procurement programs for residential, commercial, and/or industrial customers.[3]

These programs may become more commonplace as policy develops. As an example, in 2019 the Washington state legislature passed HB 1257, which requires Washington's four regulated natural gas utilities to offer RNG procurement options. The bill directs them to offer "voluntary renewable natural gas service available to all customers to replace any portion of the natural gas that would otherwise be provided" (WA State Legislature 2019a).

In addition, momentum toward RNG use in stationary applications may be further driven by demand from large industrial customers in manufacturing and other sectors. The industrial sector consumes more natural gas than any other sector in the United States, typically using the fuel for heating, on-site power generation, or as an intermediate feedstock for the production of fertilizers and other chemical products (U.S. EIA 2020a). As a result, some may procure RNG through long-term offtake agreements to decarbonize fuel supply.

In some regards, the status of these nascent markets parallels early development of renewable electricity tariffs, which have since grown into robust, mutually reinforcing sources of compliance-based and voluntary demand. Drawing on experience in the power sector, third-party verifiers of renewable energy credits, including the Midwest Renewable Energy Tracking System (M-RETS) and the Center for Resource Solutions (CRS) have begun tracking RNG sales and are developing standards to ensure integrity.

Alternative and emerging pathways

At present, the vast majority of RNG use in the transportation and stationary end-use sectors are in the form of direct fuel use, whereby the fuel is used as a substitute in natural gas infrastructure. This form of use leverages RNG's value as a drop-in fuel. However, biogas and RNG resources may also be deployed as intermediate feedstocks rather than final sources of fuel. Such applications may provide unique benefits and/or unlock new market segments and key sources of demand in the future.

Biogas and RNG resources may be used to produce hydrogen, which may in turn be used for a variety of end uses including hydrogen fuel cell vehicles, fuel for combustion-based heat in stationary applications, or as a feedstock in industrial processes such as petroleum refining and ammonia production. Each of these cases provides a low- or net-negative emissions alternative to existing fuel sources or feedstocks. The extent to which these markets gain traction will depend largely on policy and infrastructure investments made in the coming years.

Biogas and RNG used to generate clean electricity can also support decarbonization of electric vehicles by allowing them to run on cleaner electricity. California's Low Carbon Fuel Standard (LCFS) has begun to allow RNG projects supplying electricity within the regional grid to qualify under the program, and such projects are expected to grow in the coming years as additional clean fuel policies allow for similar pathways and as electric vehicles become more prevalent. These projects can use engine-generators or fuel cells to generate electricity from RNG or cleaned biogas, and this electricity, when used to charge electric vehicles, can generate credits under the LCFS program (CARB 2020b) (see Box 2-2). Driven by these opportunities, LCFS-qualifying biogas-to-electricity projects using dairy manure have recently been developed and are generating credits under the program (Srivatsan 2019; CARB 2020a).

Box 2-2 | **Bloom Energy and California Bioenergy Convert Biogas to Electricity Using Fuel Cells**

Bloom Energy has partnered with California Bioenergy LLC (CalBio) to develop dairy projects that convert biogas to electricity directly, using fuel cell technology. Fuel cells combine hydrogen with oxygen to produce electricity, water, and heat. Bloom Energy claims that its technology can produce twice as much energy per cubic foot of biogas compared to conventional combustion generators, and it only requires the removal of impurities, such as hydrogen sulfide, from the biogas itself—avoiding the need for upgrading the biogas to RNG (Little et al. 2019).

The electricity generated using Bloom's and CalBio's fuel cell process will generate credits for California's Low Carbon Fuel Standard (LCFS) (Bloom Energy 2019). Bloom estimates that the LCFS carbon intensity value for this technology will be approximately -550 g CO_2e/MJ. The economics of a fuel cell system is aided by the fact that fuel cells can run constantly, without the need for cycling on and off—as is required in the case of combustion engines. This also reduces or eliminates the need for flaring biogas. Furthermore, the pathway is exempt from California air permits, since the fuel cell process doesn't produce excess pollution. Using this fuel cell technology, California would have an estimated 320 MW worth of dairy biogas, which could be used for on-site power generation or for electric vehicle charging stations (Bloom Energy 2019; Little et al. 2019).

Notes: g CO_2e/MJ = Grams of carbon dioxide equivalent per megajoule; MW = Megawatts.
Source: WRI authors, based on studies cited above.

2.3 – Evaluating Decarbonization Potential

There is no single factor to consider when evaluating how RNG deployment may contribute to decarbonization. Rather, a number of factors should be evaluated to determine overall potential. These include project-specific variables that serve as benchmarks for comparison as well as broader, system-wide impacts and complementarity with other vital decarbonization strategies, such as electrification.

In this section, we cover approaches for evaluating RNG life cycle carbon intensity and cost-effectiveness, both of which are useful metrics in determining the emissions impacts of bringing RNG resources online. We also discuss RNG's effectiveness as a complementary climate strategy in the long term. Taken together, these factors can help policymakers form a complete picture, and identify deployment options that maximize emissions abatement opportunities and offer a low-carbon fuel in emissions-intensive sectors that lack viable alternatives.

Carbon intensity

Carbon intensity refers to a fuel's average rate of emissions and is typically expressed in terms of grams of carbon dioxide equivalent (CO_2e) per relevant unit of energy expended. This can be a useful means of comparing the emissions impacts of various fuels alongside one another on a comparable basis.

When accounting for complete "well-to-wheels" emissions for a given pathway, RNG may often have a net negative carbon intensity. This happens primarily in cases where emissions reductions associated with methane capture outweigh emissions from production, distribution, and combustion. Particularly in the case of RNG, carbon intensity varies substantially from feedstock to feedstock. For example, carbon intensity scores for RNG projects under California's LCFS program in 2020 ranged from approximately 81 to -533 grams CO_2e per megajoule (MJ) (CARB 2020a).

Given this variance, an ideal approach would be to evaluate potential of in-state sources on a feedstock-by-feedstock or even project-by-project basis to determine how RNG can contribute to decarbonization. Prominent, well-vetted tools may be used to evaluate emissions by fuel pathway, including Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model and California's state-specific version, CA-GREET. In addition, California has developed simplified calculators for fuel produced specifically from RNG feedstocks (CARB 2019). These tools include default factors that may be used to calculate key sources of emissions along the fuel cycle, including energy consumption required for feedstock conversion, leakage from pipelines and equipment, and combustion. States may choose to conduct independent analyses using these models or use the results of previous life cycle analyses to get a preliminary sense of the emissions impacts of RNG deployment (see Box 2-3).

Box 2-3 | **Assessment of Average RNG Carbon Intensity in Colorado**

The Colorado Energy Office's 2019 report, "Renewable Natural Gas (RNG) in Transportation: Colorado Market Study," leveraged existing data and life cycle assessment tools to evaluate the emissions impact of multiple RNG deployment options. To do this, the report's authors used data on average carbon intensity factors from existing RNG projects that had been generated using California's CA-GREET 3.0 model. While these data stemmed from out-of-state projects, they were a viable proxy for the emissions impacts of deploying the same types of feedstocks in Colorado.

The data on average carbon intensities were then combined with data on assessed resource potential by feedstock to determine a weighted average carbon intensity for all sources of RNG in Colorado, estimated to be –83 g CO_2e per MJ. The report found that full deployment of in-state RNG resources would reduce emissions by 2.17 MMT CO_2e when displacing natural gas, or 2.54 MMT CO_2e when displacing diesel fuel, on a life cycle basis.

Notes: g CO_2e = Grams of carbon dioxide; MJ = Megajoule; MMT = Million metric tons.
Source: WRI Authors, based on Colorado Energy Office (2019).

GHG cost-effectiveness

A related point of reference regarding RNG's potential as a decarbonization strategy is its "GHG cost-effectiveness" on a dollar-per-ton abated basis.[4] Such metrics are useful when determining which types of projects can yield the most benefit at the lowest cost. They may also be useful when comparing RNG to alternative emissions reduction strategies such as electrification in the transportation or buildings sectors. An important caveat with these comparisons, however, is that they often imperfectly account for dynamics such as shifts in costs over time or full system costs associated with high levels of fuel switching.

For RNG projects, GHG cost-effectiveness varies significantly depending on a number of factors including feedstock production costs, deployment pathway, and the carbon intensity of displaced fuel. A starting point for evaluating GHG cost-effectiveness may entail using existing data on the costs of in-state projects and their estimated emissions benefits, to the extent such data are available. For example, using data on investments made with cap-and-trade revenues, a report in California found that dairy and food waste digester projects were relatively cost-effective at just \$8–\$9 per ton of abatement (CA LAO 2016). While illustrative of RNG's abatement potential, the estimates only quantified emissions reductions per dollar of cap-and-trade revenue spent rather than the full cost of a given GHG strategy.

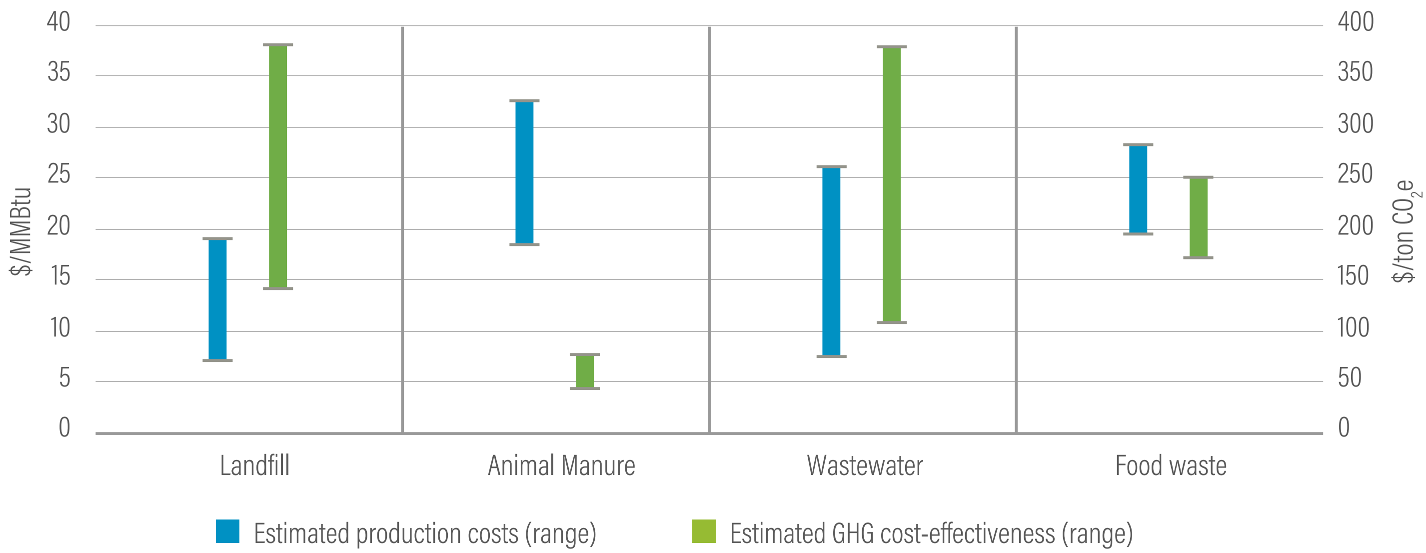
Feedstocks with lower production costs generally represent the most cost-effective opportunities. However, feedstocks with higher production costs may still be relatively cost-effective on a dollar-per-ton basis if they have a net negative life cycle carbon intensity. This point is illustrated in Figure 2-5, which shows the range in production costs for RNG projects by feedstock on a dollar-per-million-Btu basis compared to their GHG cost-effectiveness on a dollar-per-ton basis, using a life cycle emissions accounting approach. As shown, lower production costs do not necessarily translate into low abatement costs (i.e., high cost-effectiveness).

Importantly, while these estimates are illustrative, they do not capture the full nuance of cost-effectiveness considerations. For example, food waste could be codigested as a feedstock in an existing digester facility, or other opportunities for use of shared or existing infrastructure could be leveraged, potentially driving down production costs (and cost-effectiveness) below the values shown in Figure 2-5. In addition, the above underlying life cycle carbon intensity estimates are based solely on average values for approved projects under California's LCFS, and therefore are not necessarily representative for all regions and contexts. Finally, the estimates illustrate ranges of potential cost-effectiveness for different feedstocks. However, another vital consideration for policymakers is the total abatement potential that can be achieved under a certain dollar-per-ton threshold (see Box 2-4).

Complementarity

Achieving deep decarbonization means considering not only a given strategy's cost-competitiveness or carbon intensity relative to others, but also how it fits within a broader portfolio of GHG mitigation measures in the near and long term and under shifting market dynamics. A primary consideration in this area is how system-wide cost reductions may be achieved through strategic, complementary deployment that leverages the comparative advantages of different technology options. Viewed through this lens, RNG is likely to add the most value as a decarbonization solution when displacing fossil fuel use in sectors that lack economically viable alternatives, filling in important gaps alongside other vital strategies such as electrification.

Figure 2-5 | **Estimated Project Costs and Greenhouse Gas Cost-Effectiveness for Major Feedstocks**



Notes: Production costs by feedstock are derived from AGF (2019). Greenhouse gas (GHG) cost-effectiveness was then calculated using the average life cycle carbon intensity of current projects for each of the above feedstocks, based on data published by CARB. Diesel fuel carbon intensity was used as the reference case for these calculations.

MMBtu = Million British thermal units; CO_2e = Carbon dioxide equivalent abated

Sources: Based on raw data from AGF (2019) and CARB (2020a), aggregated and modified by WRI authors.

These considerations may shift over time, and the relative costs and performance of various technology options may increase or decrease as they are scaled up. In addition, future technology breakthroughs may create additional synergistic opportunities. For example, advances in carbon capture and storage (CCS) technology and its deployment in tandem with RNG projects may allow for net removal of carbon from the atmosphere in addition to mitigation benefits (Baker et al. 2020). While these dynamics are complex and can only be imperfectly simulated, most deep decarbonization studies (and the strategies they are intended to inform) find that an optimized suite of technology solutions is more economically feasible than an approach that calls for going “all in” on any single option.

Table 2-1 summarizes recent state and regional deep decarbonization studies and findings regarding the potential role of RNG. One takeaway from these studies is that, assuming a finite supply of sustainable, waste-derived feedstocks, RNG alone cannot displace sufficient amounts of fossil fuel consumption for states to achieve long-term climate goals (Mahone

Box 2-4 | **Evaluating Total Abatement Potential**

The amount of emissions reduced per dollar will tend to show diminishing returns once the most cost-effective resources have been brought online. Therefore, it is important to consider total abatement that can be achieved before reaching a certain cost threshold. Recent data and analysis published by the United States Environmental Protection Agency (U.S. EPA) compiles estimates of emissions and abatement costs from sources of non-CO_2 gases, including methane from organic wastes. The analysis finds that livestock manure in particular has significant cost-effective abatement potential relative to other sources of methane emissions. Approximately 50 percent of emissions from manure management can be abated at a cost of less than \$50 per ton, while 60 percent can be abated at a cost of less than \$100 per ton (U.S. EPA 2019c).

These datapoints are based on aggregate trends and assumptions, and actual GHG cost-effectiveness will vary by state and region depending on available feedstocks, project capital costs, and other factors. Given this, local assessments of potential abatement under specific cost thresholds are recommended to determine the most cost-effective resources and the level of incremental financing that may be required to achieve emissions reductions via RNG projects.

Source: WRI authors, based on studies cited above.

Table 2-1 | **The Role of RNG in Deep Decarbonization Studies**

REGION	STUDY	FINDINGS AND ASSUMPTIONS RELATED TO ROLE OF RNG IN DEEP DECARBONIZATION BY MIDCENTURY OR EARLIER
California	Deep Decarbonization in a High Renewables Future (Mahone et al. 2018)	**Transport**: Light-duty vehicles move toward 100% electrification. Medium- and heavy-duty vehicles use biomethane alongside mix of CNG, hydrogen, and other biofuel options. **Stationary end uses:** Alongside large-scale building electrification, RNG displaces additional building gas demand.
California	Getting to Neutral: Options for Negative Emissions in California (Baker et al. 2020)	**Cross-cutting**: Reaching net-zero emissions will require scaling of net-negative decarbonization strategies. RNG and hydrogen from organic wastes can play a role if coupled with emerging CCS technologies to achieve added carbon removal.
Oregon/ Washington	Pacific Northwest Pathways to 2050 (Aas et al. 2018)	**Stationary end uses**: Alongside electrification efforts, RNG and hydrogen may be used in existing gas distribution networks to help decarbonize hard-to-abate end uses and meet peak heating demand.
Northeast	Northeastern Regional Assessment of Strategic Electrification (Hopkins et al. 2017)	**Cross-cutting**: Alongside rapid electrification, RNG and other low-carbon fuel supply can be deployed to further lower emissions.
Northeast	Northeast 80x50 Pathway (National Grid 2018)	**Stationary end uses**: Region can reduce emissions through rapid transition away from liquid fuels in building heating and conversion to electric heat pumps, natural gas, and renewable natural gas from local feedstocks.
Northeast	The Role of Renewable Biofuels in a Low Carbon Economy (Lowell and Saha 2020)	**Cross-cutting**: Complementary deployment of biofuels may be viable for decarbonization. **Transport**: Alongside significant electrification of heavy-duty vehicles (with the exception of combination trucks), RNG fuels 80–100% of NG vehicles in 2030. **Stationary end uses**: Alongside electrification, RNG may be used to meet 5–10% of residential and commercial heating demand in 2030.

Notes: CNG = Compressed natural gas; CCS = Carbon capture and storage; NG = Natural gas.
Source: WRI authors, based on studies cited above.

et al. 2018). At the same time, even in a moderately aggressive electrification scenario with significant infrastructure and equipment turnover, the gradual nature of the transition means there will be a need to decarbonize remaining fossil fuel infrastructure to the extent possible (Lowell and Saha 2020). RNG can therefore play a significant complementary role by displacing fossil fuel use in sectors that are otherwise difficult to decarbonize or electrify, whether due to high energy density requirements, the cost of retrofits, or other technological and economic hurdles.

The viability of RNG as a decarbonization strategy will vary depending on regional context, and ultimately the role that it plays in decarbonization and how it complements other key strategies may shift over time. However, through careful consideration of the factors included in the preceding discussion, policymakers can explore and identify opportunities for targeted RNG production and use that can meaningfully contribute to GHG reduction goals. Overall, the flexibility of RNG, along with the methane emissions reductions associated with its production, mean that it can play a dynamic and complementary role in decarbonization in the long term.

SECTION 3: BARRIERS TO RNG DEPLOYMENT AND POLICY SOLUTIONS

The previous two sections of this guidance paper detail approaches that may be used to assess RNG resource potential by feedstock and identify climate and other implications of deployment in various end-use markets. Applying these frameworks and principles, decision-makers may identify opportunities for development of in-state sources of RNG that can meaningfully contribute to climate goals. However, significant barriers may still need to be addressed to realize this potential.

Common barriers to RNG deployment include uncertainty around resource potential that can be made available, investment risk, and project economics. To address these challenges, a wide array of policy options may be employed. In this section, we first provide an overview of key barriers. We then explore a suite of policies that may be employed and lay out key considerations that may influence the selection of any particular option.

These discussions are linked in important ways. Table 3-1 provides an overview of some of these linkages as well as some of the trade-offs around different policy frameworks. Overall, it highlights how different policies can complement one another by addressing different barriers to deployment; how different policies produce different outcomes around financing; how RNG is valued; and the role of competition. Each of these is discussed in more detail in the subsections that follow. However, a general takeaway is that development will typically be the product of a number of overlapping policy support mechanisms that address different barriers and other climate and environmental priorities simultaneously. Viewing these together can therefore help guide resource development that is efficient, effective, and best-suited to local economic and political priorities.

Table 3-1 | **Illustrative RNG Policies and Key Evaluation Criteria**

● Policy directly impacts or relates to criteria

○ Policy indirectly impacts or relates to criteria

		CLIMATE AND ENERGY MANDATES					DIRECT PUBLIC FINANCE			ENABLING POLICIES			
GUIDING QUESTIONS	EVALUATION CRITERIA	CLEAN FUELS STD. (VOLUMETRIC)	CLEAN FUELS STD. (CARBON-WEIGHTED)	RENEWABLE GAS STD. (VOLUMETRIC)	RPS CARVE-OUT (VOLUMETRIC)	THERMAL RPS CARVE-OUT (VOLUMETRIC)	GENERAL GRANT FUNDING	TAX INCENTIVES	PUBLIC PROCUREMENT	FOOD WASTE REGULATION	WATERSHED REGULATION	PERMITTING AND SITING RULES	INTERCONNECTION AND GAS QUALITY RULES
WHICH BARRIERS TO ADDRESS?	Improve project economics (cost)	●	●	●	●	●	●	●	●			●	○
	Reduce regulatory uncertainty (risk)											●	●
	Reduce price uncertainty (risk)											○	○
	Improve feedstock availability (scale)									●	○		
WHICH SECTOR TO DECARBONIZE?	Electricity				●		○	○				○	○
	Vehicle fuels	●	●				○	○	●			○	○
	Stationary fuels (thermal)			●		●	○	○	●			○	○
WHO PAYS?	Government funding						●	●	●				
	Producer/Consumer funding	●	●	●	●	●							
HOW IS RNG VALUED?	By quantity (volumetric)	●		●	●	●							
	Relative GHG impacts by feedstock		●										
TARGET SUPPLY OR DEMAND?	In-state supply/infrastructure						●	●		●	○	●	○
	In-state fuel demand	●	●	●	●	●			●				
IS COMPETITION ALLOWED?	Technology-neutral	●	●			●	●	●	●				
	Explicit mandate for RNG			●	●								

Source: WRI authors.

3.1 - Understanding Barriers to RNG Resource Deployment

The major barriers to RNG production fall into three main categories: feedstock availability, risk, and project economics. Risk can be divided into regulatory risk, market risk, and operational risk. Once feedstock availability and risk have been assessed, a project developer must be able to verify a positive net present value for the project for it to be economically viable.

Uncertainty around feedstock availability

A major barrier to RNG production in the United States is the uncertainty around feedstock availability and scalability of production. Ever-increasing granularity of feedstock resource potential is necessary to pave the way for project development. National, state, and regional assessments can provide a valuable boost to RNG deployment by providing a helpful starting point for project developers to assess project siting and economics.

RNG project development is facilitated by the availability of data regarding existing facilities and their operations, as well. For example, the size of a facility or an operation, its current waste management practices, age of infrastructure, waste composition, and proximity to pipeline infrastructure are essential data for determining RNG potential at the facility level.

Another barrier to RNG project development and production is that feedstock availability can vary throughout the year due to differing waste production cycles across waste feedstocks. These variations in feedstock availability require flexibility in RNG production, or reliable storage options. Furthermore, effects of feedstock storage on RNG potential and life cycle methane emissions for a given feedstock are not well understood and are a topic of ongoing research (U.S. DOE 2020b). For example, the energy content of corn stover is known to decrease over time, but storage conditions could affect the rate of decline significantly. Timely animal manure management is also important to maximize energy content and RNG production efficiency, as these both decline with time when exposed to ambient conditions.

Demand from competing uses for feedstocks is another major barrier to RNG production, as many RNG waste feedstocks are increasingly finding market value. Examples include crop residues for fertilizer and soil nutrient retainment, mill residues for wood pellets and energy production, and biogas itself as a heating and electricity feedstock.

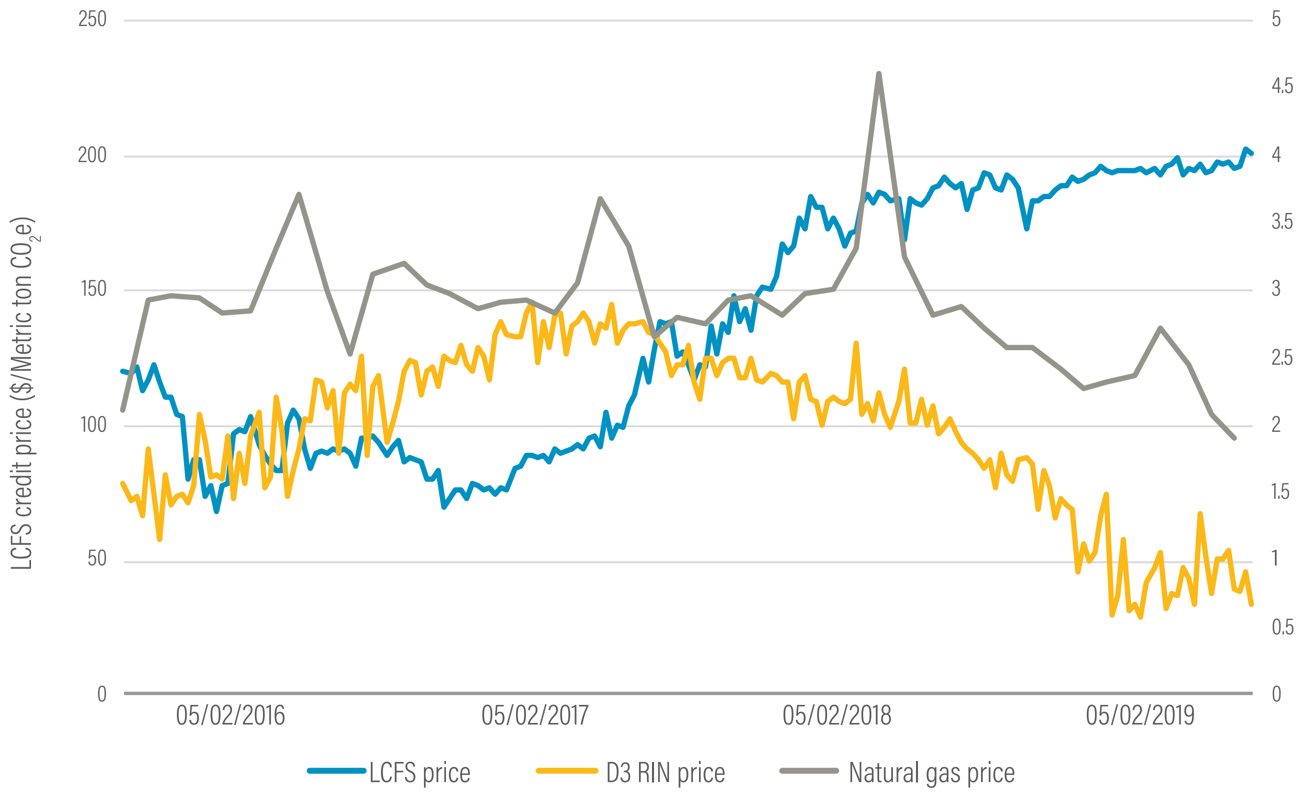
Regulatory, market, and operational risk

Regulatory risks can arise from legislative and regulatory changes that are the result of shifting political forces, market forces, or stakeholder needs. Regulatory and legislative time horizons are a source of risk when a policy incentive is structured to rely on a series of extensions as opposed to a long-term solution. Many policy incentives associated with renewable energy production, such as RNG, contain contingencies that allow for automatic sunsetting of the policy if certain conditions are not met. While these out clauses play a crucial role in policy effectiveness and efficiency, they can be a source of financial risk for RNG project development and infrastructure development.

RNG market risks arise from uncertainty and volatility in natural gas prices and regulatory credit prices. The market price of RNG that is injected into the pipeline is assumed to be equal to the price of fossil natural gas, which fell 30 percent from 2018 to 2020. Renewable Fuel Standard credit prices fell 80 percent from September 2017 to January 2020, as fuel mandates were not increased substantially, while the number of exempt producers increased. Finally, while California's Low Carbon Fuel Standard credit price has doubled in the same time period, developers can't assume that prices will remain at this level, given that prices fell 40 percent over a one-year period from May 2016 to May 2017.

Two prominent and often related **operational risks** associated with RNG are equipment failure and feedstock inconsistency. Many projects report difficulty in keeping the anaerobic digester running smoothly and consistently, which affects production capacity. In addition, it is often necessary to shut down the digesting equipment for regular cleaning and maintenance, but longer shutdown periods are sometimes necessary—sometimes for weeks or months—in cases where feedstock inconsistency has led to machinery failure. The composition of feedstock can also vary greatly on short and long timescales, and this poses challenges for adjusting machinery loads and settings for optimal production.

Figure 3-1 | **Volatility of RNG Credit and Commodity Prices Is a Deterrent to Project Financing**



Notes: California's Low Carbon Fuel Standard (LCFS) credit prices, federal Renewable Fuel Standard (RFS) Renewable Identification Number (RIN) D3 cellulosic credit prices, and U.S. natural gas prices (not adjusted for inflation) for May 2016 to January 2020.

MMBtu = Million British thermal units; CO_2e = Carbon dioxide equivalent

Sources: Based on raw data from CARB (2020d); U.S. EPA (2020b); and U.S. EIA (2020c); aggregated and modified by WRI authors.

Project economics

RNG projects can face steep up-front costs for infrastructure related to waste harvesting and processing, anaerobic digester, gas treatment and upgrading, and offtake. Operational and maintenance costs are also a significant share of total RNG production costs. These costs lead to RNG prices that range from slightly above parity with fossil natural gas, in the case of some feedstocks and projects, to much higher prices. Projects that are cost-competitive can take seven years or more before they provide a return on investment. As a result, policy incentives are typically essential for project feasibility and viability.

The distances that feedstocks and RNG must be transported are key factors of project economics. Important transport considerations include the distance from the feedstock harvest site to the RNG production site, and the distance from RNG production to pipeline injection point because pipeline extensions to RNG production sites can be prohibitively expensive. While trucking gas to nearby pipeline injection points can be more cost-effective for some projects, environmental benefits of RNG over natural gas are reduced as trucking distances increase. Projects that are close to the feedstock source, pipeline injection points or an end-use market have a considerable economic advantage over those that are not.

State utility regulations can also inhibit RNG deployment because they often require natural gas utilities to secure least-cost and reliable energy sources for their customers. This requirement often precludes the purchase of RNG by utilities and its availability for customers, as prices for RNG are often much higher than those for fossil natural gas (MJB&A 2019).

3.2 – Policy Options for RNG Deployment

Overview

Renewable natural gas development can be supported by a wide range of policies spanning climate, energy, and waste management. Broadly speaking, policies impacting RNG can be grouped into one of the following categories: climate and energy mandates, direct financial support, and additional enabling policy options (see Table 3-2). The following sections walk through each of these categories in more detail, highlighting key considerations and concrete examples.

Rather than viewing these categories in isolation, it is important to note that typically a suite of policies and approaches is necessary to address barriers at various stages of resource development. For example, enabling policies may play a role in creating incentives for more sustainable feedstock management, public funding can help offset capital costs to get projects off the ground, and fuel mandates play a role in creating more demand for low-carbon fuel. Illustrating this point, Figure 3-2 shows how policies in each of the categories discussed in this section may interact and relate to RNG deployment at various stages of development.

Climate and energy mandates

Implemented at both the state and federal level, climate and energy mandates are a primary driver of RNG production in the United States. Often, these mandates provide compliance flexibility to project developers through the use of market-based mechanisms. These mandates can be categorized as follows:

1. **Volumetric renewable fuel standards** – Set production targets for various categories of fuels in the transportation sector. As an example, the federal Renewable Fuel Standard (RFS) sets targets for predefined categories including renewable, cellulosic, and advanced biofuels. The production of RNG from qualifying sources may generate Renewable Identification Number (RIN) credits under one or more of these categories, which may be traded between producers and regulated entities to achieve compliance.

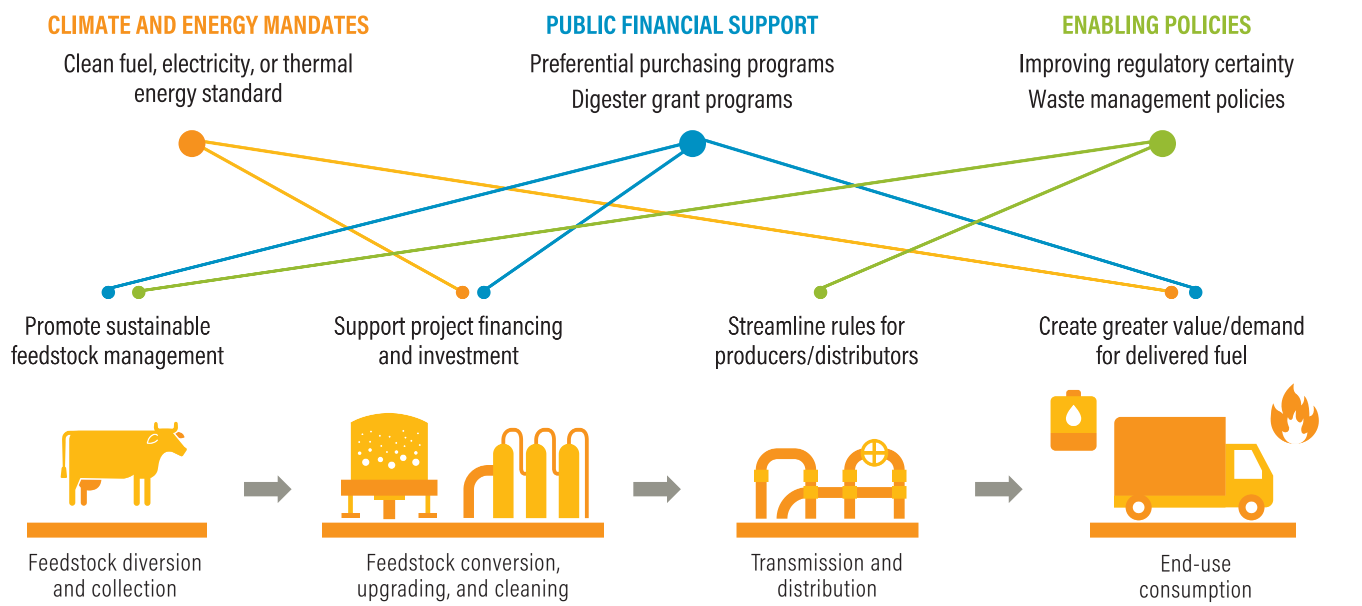
2. **Low-carbon fuel standards** – Set carbon intensity standard for fuels in the transportation sector. Regulated entities can meet those targets by reducing the emissions intensity of their production processes or by obtaining credits generated from qualified

Table 3-2 | **Supporting Policy Categories and Key Considerations**

POLICY CATEGORY	ILLUSTRATIVE CONSIDERATIONS
Climate and energy mandates – Policies that set explicit requirements for emissions reductions and/or the share of energy derived from clean and renewable sources. These are typically enacted through binding regulatory authority and achieved through tradeable performance standards.	■ Do performance-based mechanisms (e.g., credit or allowance trading) allow for flexibility and innovation over time? ■ How are the environmental attributes of RNG credited under such programs? ■ Who pays? Are incremental costs passed on to consumers?
Public financial support – Policies that promote project development through public financing. This may include grant programs or tax incentives to offset capital expenditures or establishing preferential purchasing standards for publicly funded institutions.	■ How do financial support mechanisms reinforce achievement of broader mandates and regulations? ■ Where is funding sourced from? ■ What level of incremental public support is required to bolster project viability and attract additional private investment?
Additional enabling policy options – Other regulatory policies that may have important effects, either directly or indirectly, on RNG deployment. For example, an organic waste recycling mandate may have the effect of improving local feedstock availability and more efficient conversion to RNG. Or updates to local siting and permitting rules may provide greater regulatory certainty for producers.	■ How can RNG contribute to existing or in-development waste management regulations and policy priorities? ■ Are there areas of regulatory uncertainty that can be clarified through updated rulemaking? ■ Can soft-cost barriers to deployment be lifted while still meeting sufficient public health and safety criteria?

Source: WRI authors.

Figure 3-2 | RNG Policy Nexus



Notes: A number of policy options are available for RNG resource deployment, each of which may impact feedstock availability, end use, and other factors differently. A suite of complementary solutions may be required to address barriers across the RNG supply chain and ensure that incentives promote efficiency while maximizing environmental benefits.
Source: WRI authors.

activities that lead to emissions reductions. RNG from particularly low- or negative-emissions sources will earn greater incentive under these programs.

3. **Renewable portfolio standards** – Set targets for utilities, typically expressed in terms of percentage of total energy demand to be met from renewable sources. Some state programs allow biogas or RNG to qualify for credit. Renewable portfolio standards (RPS) have traditionally been set for electricity generation. However, newly evolving alternatives such as renewable thermal standards or renewable gas standards have the potential to drive RNG demand.

4. **Emissions standards/Cap-and-trade** – Enforce a limit on GHG emissions through tradeable permits. Permits may be freely allocated to emitters or auctioned. Any revenue raised at auction can be used for a range of purposes, including investment in clean and low-carbon technologies. Such programs may promote RNG or other clean fuel deployment through two mutually reinforcing mechanisms: they increase the cost of emitting pollution, thus raising the cost of fossil fuel usage vis-à-vis cleaner alternatives; and they can provide a source of revenue with which to finance clean energy projects.

Table 3-3 highlights jurisdictions where these types of mandates are in effect. Importantly, even within a given category, no two mandates are the same. In terms of impact on RNG, currently active programs range from those that drive a majority of present-day demand (such as the federal RFS and state clean fuel policies) to those that promote the deployment of more limited amounts of fuel in state and local markets. Table 3-3 highlights existing programs, but future innovations in policy and markets may lead to additional types of mandates. An example of this is a carbon-based RNG procurement standard for nontransportation uses, which, while not yet enacted, is under consideration in multiple jurisdictions.

Drawing on examples from existing mandates at the state and federal levels, we highlight below several program design elements that can affect RNG—eligibility, credit value, stringency, technology neutrality versus carve-outs, and additionality. For each of these elements, we lay out important high-level considerations along with concrete examples of how these considerations play out in various contexts.

Table 3-3 | **Current Climate and Energy Mandates in the United States**

MANDATE/PROGRAM TYPE	SECTOR/FUEL	CURRENT IMPLEMENTING JURISDICTIONS
Volumetric renewable fuel standard	Transportation	Federal (Renewable Fuel Standard)
Low Carbon Fuel Standard (LCFS); Clean Fuels Program	Transportation	California (Low Carbon Fuel Standard); Oregon (Clean Fuels Program)
Renewable portfolio standard	Electricity	Active, mandatory targets are currently implemented in nearly 30 states, with biogas/RNG eligibility varying on a case-by-case basis
	Thermal energy	Currently, 13 states allow for limited amounts of thermal energy to contribute to broader power sector mandates, with biogas/RNG eligibility varying on a case-by-case basis
	Gas distribution	Mandate for voluntary programs established in Washington State. Aspirational targets have been adopted in Oregon, Nevada, and California
Emissions limits/cap-and-trade	Economy-wide	California
	Electricity	Northeast and Mid-Atlantic states (Regional Greenhouse Gas Initiative)
	Transportation	No active programs currently implemented. Under consideration in Northeast/Mid-Atlantic states through Transportation Climate Initiative

Source: WRI authors.

ELIGIBILITY

Mandates will have varying impact on RNG development, depending on a number of program design factors. However, an initial, more fundamental consideration is whether or not RNG or various RNG feedstocks are eligible under a given mandate. For policymakers, the decision to broaden or restrict eligibility will depend on a number of factors, and important guiding questions include the following:

- **Whether RNG production satisfies the overall objectives of the program.** Mandates will typically have overarching goals to increase renewable energy deployment, lower emissions, and/or reduce dependency on imported fuel. Assessing how RNG and specific RNG feedstocks align with these goals is an important first step in making eligibility determinations.
- **Whether RNG production can help fill important gaps in compliance.** Mandates may be designed with quotas or carve-outs for specific categories of renewable or low-carbon fuel, and RNG may help meet specific targets that lack other cost-effective options.
- **How RNG can complement other qualifying technology options.** As a flexible, drop-in fuel source, RNG may contribute to a more balanced mix of overall compliance options, for example as a nonelectric option in meeting thermal energy targets or as a dispatchable fuel alongside more intermittent renewable options.

These considerations are not static and may at times need to be revisited due to changing technology costs and renewable energy markets or shifting priorities. Accordingly, the role that biogas and RNG resources play in a given mandate may shift over time, as illustrated in the following cases.

At the state level, changes to energy or climate program objectives can potentially create new opportunities for RNG to complement other technology options. While state renewable portfolio standards (RPS) have traditionally focused on the power sector, several jurisdictions including the District of Columbia, Massachusetts, Nevada, and New Hampshire have expanded their mandates to include thermal technologies. These programs may be designed to include RNG, given its flexibility and potential to meet thermal demand. For example, in 2017 the state of Massachusetts approved a requirement that the equivalent of 5 percent of the state's electricity load be met with "alternative" resources, and allows credits to be earned based on the heat value of RNG injected into the natural gas distribution system (Donalds 2018).

In other cases, states may seek to curtail eligibility for RNG and biogas resources to prioritize other renewable technology options that better align with objectives. For example, in Connecticut, biomass and landfill gas effectively met 76 percent of the state's Class I RPS requirements as of 2014, due in part to the relative value of these sources under Connecticut's program within the broader New England compliance market. Seeking to reduce this saturation and prioritize new, additional sources of zero-carbon electricity, the state's Department of Energy and Environmental Protection has recommended a phasedown schedule in which eligible generation for biomass and landfill gas would be reduced while still allowing facilities reasonable time to recoup investments (CT DEEP 2018).

Federal-level policy can also have implications for state policymaking. The reclassification of various feedstocks under the RFS in 2014 drove significant new demand for RNG resources. Prior to this, biogas and RNG resources only qualified under the program's "advanced biofuel" category. However, the level of market-based incentives within this fuel category was insufficient to drive significant volumes of RNG production. In the mandate's update in 2014, eligibility for RNG from landfills and other feedstocks was expanded to qualify under the program's "cellulosic biofuel" category. This effectively allowed RNG resources to fill an important compliance gap in the program, since less technologically mature cellulosic biofuel options had previously been insufficient to meet ambitious program targets. The shift had a dramatic impact on RNG production nationwide, with RNG now supplying the vast majority of RINs for the cellulosic biofuel category[5] and potentially serving as a bridge fuel while more nascent cellulosic biofuel technologies develop.

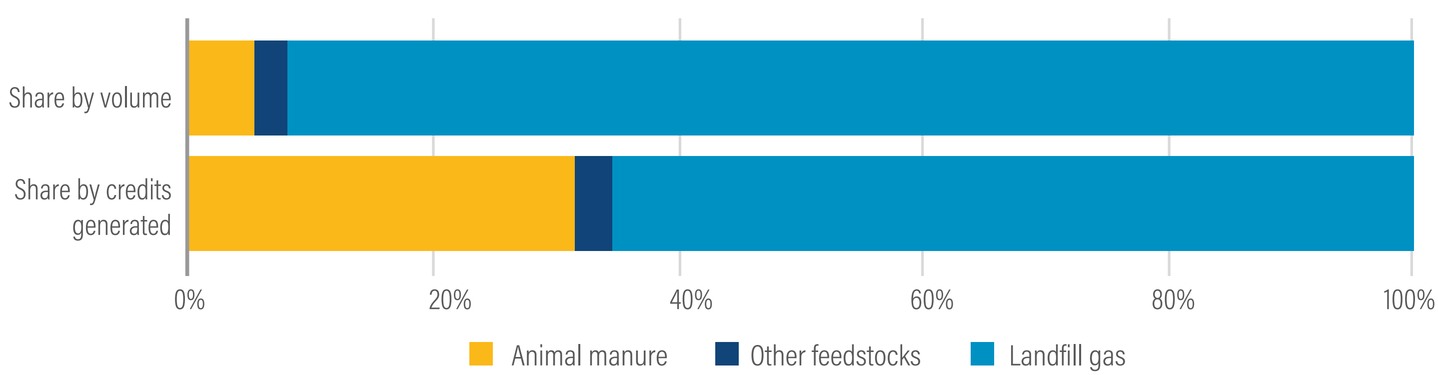
CREDIT VALUE

Beyond eligibility, mandate performance criteria more directly specify how qualifying technology options contribute to compliance and how their relative benefits are valued. While decisions around performance criteria are complex, key considerations impacting RNG are as follows:

- **How are different RNG feedstocks treated?** Differing compliance achievement mechanisms, such as volumetric targets or emissions-based standards, will impact and incentivize RNG feedstocks differently. Mandates that account for full life cycle emissions and credit emissions benefits proportionally will have the effect of creating greater value for projects with the greatest net benefit on emissions.
- **What level of administrative complexity is feasible for regulators and producers?** Full life cycle crediting of emissions benefits may increase value for projects that yield the greatest net climate benefits, but may also add to administrative costs for producers and complexity for regulators.

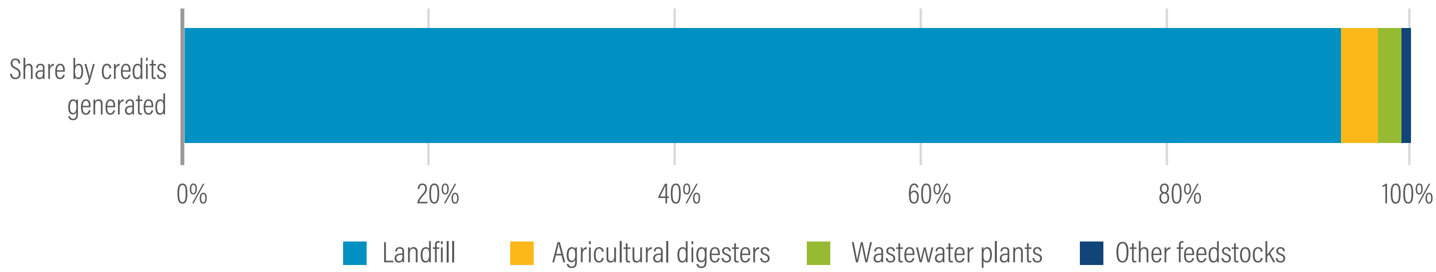
Key examples of mandates that credit fuels proportionally based on emissions impacts include California's Low Carbon Fuel Standard (LCFS) and Oregon's Clean Fuels Program, which benchmark performance against a target carbon intensity for all transportation fuels in the state. The lower a qualifying fuel or technology's life cycle carbon intensity relative to the target, the more credit it generates. This has the effect of allowing RNG feedstocks that contribute to greater material reductions in emissions—such as animal manure—to earn significantly higher value than other sources. In 2019 animal manure made up just 5 percent of total RNG in California's LCFS market, but it represented 32 percent of credits generated due to its highly negative carbon intensity score (see Figure 3-3).

Figure 3-3 | **RNG Feedstocks by Volume and by Credits Generated in California's Low Carbon Fuel Standard (2019)**



Source: Based on raw data from CARB (2020c), aggregated and modified by WRI.

Figure 3-4 | **RNG Feedstocks by Credits Generated for Federal Renewable Fuel Standard (2019)**



Source: Based on raw data from U.S. EPA (2020b), aggregated and modified by WRI.

By contrast, under the federal Renewable Fuel Standard (RFS), performance is based on the achievement of volumetric targets set for program-specific fuel categories, such as "advanced biofuel," "cellulosic biofuel," and "biomass-based diesel." A majority of RNG projects qualify for the cellulosic biofuel category, which requires a minimum GHG reduction of 60 percent below a fixed petroleum baseline. RNG from landfills, wastewater plants, and animal manure all meet this threshold; however, only the most economic resources will tend to generate credits. For the cellulosic biofuel category, landfill gas projects represented 94 percent of RIN credits generated for RNG projects in 2019 (Figure 3-4).

STRINGENCY

The more stringent a program, the higher the price incentive it provides to eligible activities, such as RNG. There are numerous program design decisions that may impact the overall price signal:

- **How much of a change do the targets require compared to today?** Generally, policies that mandate a significant near-term shift in markets will create stronger signals.
- **Does the program contain mechanisms designed to limit prices, such as ceilings, alternative compliance payments, cost-containment reserves, etc.?** These mechanisms are important in limiting the level of price increases that can be passed on to consumers but may also limit achievement of policy outcomes if prices are suppressed too far.
- **Does the program contain mechanisms that prevent prices from falling below a desired floor?** Some programs include price floors to ensure that they provide an adequate investment signal or include provisions to increase stringency in response to lower-than-anticipated compliance costs.
- **Are there exemption criteria for certain categories of regulated entities?** Many mandates will either exempt or place into a separate category certain types of entities such as municipal utilities or small fuel producers. These mechanisms are designed to prevent undue regulatory burden or costs on certain groups, but can also limit achievement.

California's LCFS provides an example of the important interplay between policy ambition and program costs. The program requires transportation fuels to become less carbon-intense over time, ensuring that transportation fuels continue to become cleaner as low-carbon technologies scale up. In 2018, the program was extended with an updated target reduction of 20 percent by 2030 relative to a 2010 baseline, up from its initial requirement of 10 percent by 2020. Post-2030, the annual target will remain at 20 percent reduction unless CARB decides to further strengthen the targets. Since the most recent update, LCFS credit prices have steadily risen to values approaching or occasionally exceeding $200/MT (through the first quarter of 2020), creating strong incentives for RNG projects that yield negative emissions on a life cycle basis (CARB 2020c). Notably, the program has an overall credit price ceiling of $200/MT (in 2016 dollars, adjusted annually for inflation), meaning credit prices will not increase beyond these levels without further updates to the policy.

As an example of how program exemptions can depress incentive value, the federal RFS defines small fuel refiners as a special class of regulated entity that may apply for waivers. This allows for some regulatory discretion to limit economic burden on small producers. Recently, a significant increase in the number of allowed exemptions has effectively contributed to a decrease in overall volumetric requirements and thus the demand for renewable fuels including RNG. In 2019, RIN prices for the cellulosic biofuel category in the program fell by 57 percent, from $2.04/RIN in January to $0.87/RIN in October, a decline that has been attributed to the increased exemptions (BNEF 2020).

Mandates may also be established that do not set explicit targets for emissions reductions or fuel volumes, but which may nonetheless drive RNG market opportunities. For example, in 2019 Washington State passed legislation requiring its four regulated natural gas utilities to offer RNG procurement options. The mandate requires utilities to offer voluntary renewable natural gas service to customers "to replace any portion of the natural gas that would otherwise be provided by the gas company." The mandate further states that there will be "reasonable limits on participation based on the availability of renewable natural gas" (WA State Legislature 2019a). Such policies may play an important role in driving innovation and may be increased in stringency over time depending on results.

TECHNOLOGY-NEUTRALITY VERSUS CARVE-OUTS

As discussed above, factors related to credit value and stringency play a significant role in increasing or decreasing overall incentives for RNG and other technologies under a given mandate. However, policymakers also have the option of effectively insulating RNG or other technology options from these effects by establishing fuel-specific carve-outs to ensure a minimum level of deployment. There is no single right answer on whether to allow for carve-outs; however, important considerations include the following:

- **Which technology option(s) will likely "win out" in the near to medium term?** Under a technology-neutral approach, the most cost-effective options among qualifying fuels will generally be used to meet a mandate's goals. However, the most cost-effective options are not always those that yield the greatest benefits and contributions to decarbonization in the long term.
- **Are there technology options that merit more direct support?** Certain types of renewable and low-carbon fuels may be a particular priority and therefore merit their own explicit carve-outs. This may be due to their economic and environmental cobenefits and/or their status as more nascent technologies requiring additional subsidies before they can achieve economies of scale.
- **How will program costs be impacted?** Depending on scale and the relative costs of fuels that are targeted, carve-outs can potentially increase overall program costs that are passed on to consumers.

The majority of mandates impacting RNG development, including the LCFS and RFS in the transportation sector and most RPS policies, are effectively technology neutral. As a result, the production and use of RNG is one of many potential ways to achieve compliance and is on a level playing field with other options (although, as demonstrated above, program design can have important impacts on how different RNG feedstocks are valued). The advantage of a technology-neutral mandate is that it essentially allows for the most cost-effective technologies and fuels to be utilized when achieving compliance, thus protecting consumers. Should alternative approaches with greater environmental benefits become cheaper, RNG's competitiveness in such markets would naturally decrease and vice versa if RNG economics improve.

However, some jurisdictions have taken the step of establishing explicit carve-outs for RNG to more directly promote its environmental benefits. An example is North Carolina's Renewable Energy and Efficiency Portfolio Standard (REPS), which requires that electric utilities meet 0.2 percent of demand with swine waste–derived RNG (DSIRE 2018). This effectively ensures that the state's renewable mandate for the electricity sector will be met with a minimum share of RNG from a specific feedstock. In this case, an explicit carve-out promotes environmental benefits unique to a state where hog production is a key sector of the economy and manure management is a top environmental priority.

ADDITIONALITY

Given limited financial resources for decarbonization efforts, it is important that incentives result in environmental benefits that would not otherwise have occurred and are therefore "additional" to existing programs. The question of additionality does not always have a clear-cut answer, however; important considerations pertaining to RNG are as follows:

- **Where do overlaps occur?** In the case of biogas and RNG resources, projects may earn credits under a variety of mandates, such as state RPS programs for thermal energy, electricity generation, or transportation fuel programs. Overlap on its own does not necessarily raise additionality concerns; however, understanding where it can occur is important to evaluate total policy support and ensure resources are being deployed efficiently.

- **When to allow for credit stacking?** In some cases, a project may require credits from multiple programs to be economically viable, and policies are reinforcing rather than redundant. In others, stacking may be economically inefficient and undermine the environmental objectives of the overlapping mandates.
- **Should preexisting projects be able to earn credit?** Credits from market-based programs will typically have the underlying aim of incentivizing the development of new resources rather than existing projects. However, in cases where existing projects would otherwise be terminated, there may be a case for their continued or renewed participation in environmental credit markets.

Overlaps can occur in RNG project development. Prominent examples include many resources being deployed in the transportation sector that are eligible for credit under both California or Oregon's clean fuel standards and RIN credits under the federal RFS. Rather than being redundant, the two mandates may actually reinforce one another in important ways. Given the volatility of tradeable standards, the ability to earn credits in multiple markets may serve as additional insurance for investors that otherwise would not pursue development. In addition, the state-level standards currently implemented in Oregon and California value feedstocks proportionally based on their life cycle emissions benefits. Given that projects yielding the greatest net-negative reductions also often have higher costs, they would likely be unable to attract investment based on the RFS RIN value alone.

There is also potential for overlap to occur between mandatory compliance-based programs and voluntary programs. Voluntary markets for renewable fuels, whereby corporations or other downstream consumers pay a premium for renewable or low-carbon fuels, typically operate separately and in parallel with compliance-driven markets. For example, state-level RPS mandates and voluntary corporate-level procurement have both driven deployment of renewable electricity in the United States over the last decade and been designed to avoid double claiming across programs. As voluntary markets for RNG develop further, tracking, verification, and data sharing across jurisdictions will be required to ensure similar levels of integrity (Box 3-1).

Box 3-1 | Ensuring Market Integrity and Traceability

As both voluntary and compliance-based markets for RNG further expand and develop, the potential risk of double counting of environmental attributes or other forms of fraud may also increase. However, policymakers and regulators may face challenges in dedicating sufficient resources to review contracts and accounting records, cross-check information with daily pipeline injection statements, or conduct audits.

To ensure market integrity and transparency, third-party standards and tools can play a role in establishing more consistent protocols and data sharing between producers, consumers, and regulators. At the time of the writing of this report, the Center for Resource Solutions, currently the leading certifier of voluntary renewable electricity procurement in North America, is in the process of developing environmental criteria and verification standards for biomethane sold to residential and commercial customers. In addition, the Midwest Renewable Energy Tracking System (M-RETS) has developed a tracking platform for renewable thermal certificates that may be used by regulators or other users in the fulfillment of state mandates or voluntary commitments. For example, the Oregon Public Utility Commission plans to use the M-RETS system in the implementation of a recent state mandate for a renewable natural gas program (OR PUC 2020). These verification resources will likely be critical to the development markets moving forward and to reducing burden on state agencies.

Source: WRI authors, based on studies cited above.

A final consideration is whether preexisting resources should be eligible under new mandates and incentive programs. For example, there may be cases where RNG projects convert and upgrade existing biogas-to-electricity generation projects to qualify for transportation fuel mandates, particularly once prior power purchase agreements expire. Such projects may have faced a declining market for biogas-derived electricity and therefore would have otherwise ceased operation. While original capital expenditures for the project may be effectively paid off, the addition of biogas upgrading equipment required for RNG conversion would require significant additional investment, and therefore the project would not be economically viable without added incentives. For policymakers, such projects may merit new incentives so long as environmental benefits associated with the project are no longer counted under other existing mandates and if these benefits would cease without new incremental incentives or investment.

Public financial support

Public funds are often a vital means of supporting RNG. They offset capital costs and improve project financing. Such policies can be used in place of mandates or used alongside them to complement those programs. Financial support mechanisms vary considerably across and within states, and we highlight several illustrative examples of key approaches and considerations. We discuss three broad categories of public financial support in this section:

- **Grant and loan programs** – Public financing in the form of grant and loan programs often significantly reduces capital costs of digesters or for upgrading and cleaning equipment, allowing producers to meet remaining costs through private investment. Grant and loan programs may be funded from a variety of sources, including cap-and-trade revenues, ratepayer-funded initiatives, or other dedicated funds.
- **Tax incentives** – Effective tax policy can lower the overall financial burden of qualifying projects, in some cases allowing for the recovery of a significant share of total project investment through credits.
- **Preferential purchasing programs** – In some cases, preferential procurement and green buildings standards implemented by public entities may be designed to include RNG procurement, leveraging government purchasing power to shore up demand.

Public financing mechanisms are extremely diverse in terms of scope, funding sources, and overall impact. We organize the discussion that follows around two broad considerations pertaining specifically to RNG resource development and deployment options: supply-side considerations and demand-side considerations.

SUPPLY-SIDE CONSIDERATIONS

State financing in the form of grant and loan programs or tax incentives can play an important role in driving supply of in-state sources of RNG. Such programs are typically quite targeted, and careful consideration is required in terms of how to best align financial incentives with priorities. Important questions to consider will include the following:

- **Is the development of local RNG resources a priority?** In some cases, demand-side drivers such as national or regional fuel mandates may create sufficient incentives for projects. However, particularly for states seeking to capitalize on emissions reduction, job creation, or other cobenefits associated with projects, providing funding can help ensure local projects get off the ground.
- **Are there specific feedstocks that merit investment?** In some cases, sources of RNG that yield the most climate-related and other cobenefits—such as animal manure—will also be the most costly to bring online.
- **Are there specific regions that merit investment?** The negative impacts of certain types of waste streams will often be geographically concentrated (e.g., nutrient runoff and air quality impacts in agricultural hubs). In such cases, targeted investment for digester projects that can mitigate these issues may make sense.
- **What will be the role of private capital and other nonstate funding sources?** Nonstate funding sources such as private investment and federal grant and loan programs also play an important role in project financing. Often, successful RNG projects are viable as a result of a combination of state and nonstate funding sources.

As an example of many of these considerations at play, in 2019 Washington State allocated roughly $1 million in funding for a Dairy Digester Enhancement program implemented through the state Department of Commerce. The program aims to promote a number of cobenefits, including energy efficiency, nutrient recovery, the creation of value-added biofertilizers, reduced trucking of lagoon water, and improved soil health and air and water quality. The program focuses on supporting the enhancement of existing or in-development projects and requires that awards include projects located in both the eastern and western portions of the state, and that a minimum of 1:1 matching funds be committed from private or federal sources (WA SDC 2020).

In Wisconsin, state officials have allocated funding for new digester projects to reduce nutrient loading and other adverse impacts of livestock operations while creating jobs in the state's rural northeastern agricultural hub. In 2017, $15 million in funding was allocated from the state's Focus on Energy program, levied through in-state electric and natural gas utility ratepayers (Wis. Stat. n.d.; WI PSC 2017a, 2017b). The grant program is administered jointly by the state's Department of Natural Resources, Department of Agriculture, and Trade and Consumer Protection.

DEMAND-SIDE CONSIDERATIONS

In addition to driving supply and production from specific feedstocks or regions, incentives may also help ensure RNG resources are directed to specific sources of energy demand and end-use sectors to better meet state priorities. Important considerations in this area include the following:

- **How do financial incentives complement sector-specific decarbonization goals and energy mandates?** Public financing may be deployed in parallel with energy mandates or other state-level targets to drive RNG deployment toward specific end uses in addition to providing financing to reduce capital costs. Ensuring that incentives and programs are well-aligned may therefore be a priority.
- **Should incentives be sector-specific or allow for flexibility over time?** State priorities may shift over time, as can the relative benefits and feasibility of biogas and RNG utilization in various end-use sectors. To account for these shifts, decision-makers may consider updating existing incentives to allow for flexibility.

Public financing in the form of grants and loan guarantees is often required to offset capital costs for anaerobic digesters, upgrading and cleaning equipment, and pipeline interconnection, and these incentives may often be designed to complement broader, sector-specific goals for the decarbonization of specific end uses and applications. In California, grant programs awarded specifically to anaerobic digester projects that produce transportation fuel have played a key role in promoting the development of in-state resources that can contribute to reducing the state's targeted transportation sector fuel carbon intensity under the LCFS. In North Carolina, a combination of state and federal financing has helped spur development of new swine manure digester projects that will contribute to a mandated power sector carve-out (Live Oak Banking Company 2018).

Over time, incentives may also need to be updated or realigned to promote the use of biogas and RNG resources in the most optimal end-use sectors. Historically, tax credits have been an effective means of incentivizing biogas project development but have focused largely on projects that produce electricity. In 2019, 19 states had rules on the books allowing property tax abatement for qualifying anaerobic digestion facilities, 9 had rules allowing facilities to claim production or investment-based tax credits (depending on project size, location, and other factors), and 13 states allowed for sales tax exemptions for renewable energy facilities and equipment including anaerobic digesters (DSIRE 2019). Since the majority of these incentives are geared toward electricity generation, states seeking to direct biogas and RNG resources toward alternative end uses and create more flexibility may need to incorporate updated provisions that include transportation, thermal, or other applications of RNG.

Preferential purchasing policies may also be an effective means of establishing demand for RNG in specific sectors with public dollars. Such policies typically operate by requiring public entities such as government offices, schools, or other public institutions to consider efficiency, GHG emissions, and other environmental factors in the procurement of goods and services or the construction of new facilities. Procurement criteria may be updated to more directly encourage RNG uptake in specific areas; for example, by allowing public fleet owners to meet these criteria through investment in RNG-fueled vehicles.

Additional enabling policies: Establishing regulatory certainty

While climate and energy mandates and public financing play a key role in driving RNG, a number of other enabling policies may improve project economics or help create greater market and/or regulatory certainty. First, we discuss state-level policies that may provide greater regulatory certainty for potential developers, producers, distributors, and/or investors:

- **Permitting and siting procedures** – Zoning and permitting procedures ensure that the construction and development of new projects comply with local environmental and public health and safety concerns. In some cases, these rules may be streamlined for certain types of renewable energy development, such as anaerobic digester construction, to reduce soft costs and required lead time between proposal and construction phases of development.
- **Gas quality standards for pipeline distribution** – Gas quality standards for pipeline operators ensure the safety and reliability of the gas grid and end uses and set criteria that determine how RNG project developers must evaluate and deploy gas upgrading technologies. In many jurisdictions, these standards are applied inconsistently and can be better defined and streamlined to alleviate uncertainty for producers and distributors alike.
- **Guidelines for rate-based RNG investment** – In addition to public financial incentives described above, RNG projects may be able to partially recover investment costs through utility rate–based financing. This form of investment can come in the form of voluntary opt-in programs or be distributed across a utility's customer base. In either case, enabling regulations and clear guidelines from state utility commissions are required.

In many cases, decisions to update or streamline rules and regulations can reduce burden on project developers and remove barriers to market entry. However, these decisions will typically need to be balanced with considerations around public safety and environmental and consumer protection. Key considerations in this area are, as follows:

- **Are there bottlenecks or barriers to project development?** Existing rules may potentially delay or inhibit project development by increasing soft costs or creating regulatory uncertainty. In some cases, there may be opportunities to streamline these requirements without undermining protective standards.
- **Do existing or proposed rules appropriately account for project-specific nuance?** At times, rules may be patchwork in nature or be designed with overly broad criteria that can inhibit certain types of projects. Ensuring that rules are consistent while also allowing for project-specific nuance may be vital in ensuring that rules are not discriminatory and allow for broad resource development and utilization.
- **Do the benefits of RNG merit increased costs for consumers?** Certain forms of RNG investment on the part of utilities may increase energy prices for consumers. The question for policymakers is whether or not RNG projects that can meet certain climate or other environmental criteria merit exemption from typical "least-cost" resource considerations, particularly if directed toward end uses where other decarbonization options are limited. Some policymakers have also chosen to answer this question differently for voluntary opt-in markets.
- **Do rules impacting RNG development allow for fair competition and distribution of economic benefits?** The biogas and RNG industry is a relatively small segment of the overall energy economy, but it has the potential to create new revenue streams and other economic benefits in many regions of the country, including in rural agricultural hubs. Given this, consideration may need to be given to whether rules promote fair competition for small producers and ensure that project revenues are distributed to the communities where they are located.

As an example of cases where zoning rules have been updated to better facilitate project development and eliminate bottlenecks, states including Massachusetts, New York, and Rhode Island have adopted streamlined permitting systems for waste recycling facilities including anaerobic digesters (Sandson and Leib 2019). In each case, the streamlined rules involve more explicit definitions and procedures tailored specifically to digester projects. As a result, developers are able to better avoid uncertainty that stems from regulatory ambiguity or cases where digester facilities are simply not defined at all. In the case of New York, separate tiers of digester facilities were established based on size, with larger facilities facing stricter requirements than small-or mid-sized facilities. This system not only helps remove ambiguity, but also creates a more level playing field for smaller producers.

Efforts currently underway to harmonize pipeline gas quality standards for RNG also provide an example of how requirements can be more effectively tailored to account for project-specific nuance without compromising safety and reliability concerns. A recent study conducted for New York State provides frameworks for producers and pipeline operators to align on project specifications with greater consistency and transparency. The study provides guidance on constituent gases that can be reasonably expected within the raw biogas stream for different types of RNG projects, and recommends using such information as a starting point for developing a suitable gas quality management plan for any given project (NGA and GTI 2019). The adoption of such protocols can help avoid one-size-fits-all approaches with potentially unnecessary testing and monitoring requirements, given that trace gases will vary significantly from one category of RNG feedstocks to the next.

Efforts currently underway in California, Nevada, Oregon, Utah, and Washington to enable utility investment in RNG projects also demonstrate how a number of the above considerations factor into decision-making. In recent years, each of these states has passed legislation establishing basic criteria for investments or directing state utility commissions to create rules for rate-based cost recovery for RNG, thus enabling procurement of RNG even when it leads to increased costs (CA Assembly 2018; OR Senate 2019; NV Senate 2019; UT House of Representatives 2019; WA State Legislature 2019b). While final rules will be determined at the utility commission level, these bills may open the door for gas utilities to more actively invest in, procure, and sell RNG. At the heart of these proceedings will be the question of whether and when the benefits of certain forms of RNG investment merit the increased costs to consumers.

An added consideration raised by the prospect of rate-based investment pertains to ownership and where utilities may invest along the RNG supply chain. For example, rules may be established such that utilities can engage in investment "up to the point of interconnection," thus offsetting one of the most significant costs for producers but maintaining nonutility ownership of the RNG supply and production facilities. Alternatively, utilities may be able to invest in RNG production facilities and thus own and operate both supply and distribution in a more vertically integrated fashion. In determining what qualifies for utility investment, decision-makers will need to weigh impacts on market competition and how costs and revenues are shared across producers, distributors, farmers or other landowners, and other stakeholders.

Additional enabling policies: Waste management and other environmental regulations

An additional key category of enabling policy in the development of RNG is regulation of organic waste streams and the systems involved in treating that waste. These policies may have more indirect but nonetheless important impacts on opportunities for waste-to-energy project development. We discuss the following policies in this subsection:

- **Food waste regulations** – Rules to reduce food waste may come in the form of organic waste bans that prohibit the disposal of waste in landfills and recycling mandates requiring that waste be composted or diverted to anaerobic digesters. These policies may create new market opportunities by isolating waste streams that would otherwise be disposed of less efficiently. These regulations are also growing in prominence, with existing rules now in place in California, Connecticut, Massachusetts, New Jersey, New York, Rhode Island, and Vermont.
- **Emissions and air quality regulations** – Rules to limit air pollutants may impact RNG economics by requiring that biogas from waste streams be captured, flared, and/or diverted to energy recovery instead of being released into the atmosphere. As an example at the federal level, landfill gas capture rules originally promulgated in 1996 under the Clean Air Act require operators of the nation's largest landfills to install gas capture systems that may include energy recovery in the form of biogas or RNG.
- **Water quality regulations** – Rules designed to prevent watershed pollution may also have important impacts, particularly those aimed at reducing nutrient loading and other forms of contamination from excess animal manure. Biogas and RNG may be one of several viable strategies that can be employed to more effectively control and utilize wastes from dairy, swine, and other livestock operations.

This discussion is not intended to imply that regulatory decisions around whether and how to reduce pollutants from various waste streams are made to promote RNG development. Rather, we highlight examples of how regulations and prospects for project development may interact. Key considerations in this area include the following:

- **Which types of RNG feedstocks are impacted?** Regulations designed to reduce pollutants and other adverse impacts from organic waste streams will have important effects on different types of potential waste-derived feedstocks.
- **How do regulations shift incentives?** Whether through a carrot- or stick-based approach, regulations can disincentivize forms of waste disposal or mismanagement that damage ecosystems, while potentially creating new incentives for more sustainable practices. Understanding how these incentives shift can be key in identifying new opportunities for waste-to-energy strategies.
- **How will economic impacts be felt?** Regulatory approaches may create new opportunities for the waste-to-energy industry but may also increase economic burden on regulated industries. Regulatory expansion will therefore need to be implemented in tandem with incentives and opportunities for revenue sharing that minimize these impacts.

Implemented at the state and local levels, food waste bans are key examples of enabling regulations that have a strong impact on a specific feedstock category and can improve prospects for project development. These policies can create a strong signal to developers in terms of demand for food processing capacity. For example, in Massachusetts, within the first three years of the state's food waste landfill ban taking effect in 2014, the number of operational anaerobic digestion facilities in the state doubled from four to eight, while four more were permitted and went into development. As a result, the state's food waste processing capacity grew from 220,000 tons annually to 617,000 tons (Sandson and Leib 2019). Food waste bans also vary in terms of scope, sources of waste covered, and intended outcomes. For example, the ban in Massachusetts covers only institutional and commercial facilities that produce at least one ton of waste per week (MA CMR 2017). Similar rules were also recently passed in New Jersey requiring facilities generating 1 ton of food waste per week (or 52 tons annually) to divert waste to composting or anaerobic digestion (NJSA 2020).

Food waste bans are typically more politically and economically viable in regions where landfilling is already costly. Tipping fees, which landfill operators generally charge to waste haulers to offset their operating costs, vary across the country but are highest in northeastern, mid-Atlantic, and western states (EREF 2019). Food waste-to-energy projects are therefore more likely to be cost-competitive with other disposal options in these regions. Since tipping fees are driven by supply and demand, regions with relatively low fees may require additional policies to further incentivize waste diversion and/or disincentivize the disposal of food and green waste in landfills.

Rules designed to prevent watershed pollution may similarly have positive impacts on RNG economics by encouraging better manure treatment practices. As an example, watershed nutrient trading programs have been piloted in Maryland, Pennsylvania, Virginia, and West Virginia that may serve as a model for other regions aiming to protect local watersheds via market-based mechanisms (Branosky et al. 2011). These programs function like cap-and-trade schemes, in which a watershed-wide nutrient allowance is set, and individual operations may generate and trade credits to demonstrate compliance (Bilek 2010). In this way, manure management practices that result in contamination are disincentivized, while new opportunities are created for projects that utilize anaerobic digestion or other strategies to earn credits. The proliferation of similar programs could have the effect of creating stable, bankable sources of additional revenue for digester projects that yield cobenefits for local watersheds (Levin 2017).

While the future expansion of waste management regulations may create opportunities for RNG project development, these efforts will typically need to be balanced with concerns regarding the economic feasibility of compliance and how impacts will be felt by different industries. For example, in 2016 California adopted SB 1383. The bill requires the state Air Resources Board to begin implementing a comprehensive short-lived climate pollutant strategy and mandates the adoption of specific regulations to reduce methane emissions from animal manure. However, the legislation also stipulates that these regulations may be adopted no earlier than 2024 and only if certain conditions regarding technical and economic feasibility are met (CA Senate 2016). In the meantime, the state has allocated funding for its Public Utility Commission (PUC) and Department of Food and Agriculture to award and implement dairy manure biomethane projects. Moving forward, the lessons learned in terms of economic viability from these projects will help inform the state's decision to more directly regulate methane from animal manure.

CONCLUSIONS

This report provides guidance for state and local policymakers regarding renewable natural gas resource assessments, market opportunities, the role RNG can play in decarbonization, barriers to deployment, and policy solutions. It is important to remember that these categories overlap and strongly influence each other. In addressing each of these topics, the report provides guiding questions and key considerations that can facilitate decision-making at the state and local levels.

Resource Assessments

To evaluate RNG resource potential, policymakers may begin with a survey of national-level estimates of RNG feedstocks for the state and region. Existing RNG resource assessments performed by other states and regions can also be used as guidance, as these can offer important methodological considerations. For more targeted insights into local sources of RNG and the potential for projects within a particular geographic, economic, and political context, local resource assessments may be appropriate, particularly as feedstock types and resources vary greatly by region.

In this report, we provide a review of national- and state-level RNG resource assessments and summarize common approaches and tools used in these assessments. Considerations regarding feedstock availability, competing uses, suitable technologies, and near- and long-term economic potential vary by feedstock, and are elaborated on to inform the assessment process. For each feedstock, we also highlight important considerations regarding climate impacts. To maximize the decarbonization potential of RNG production, resource assessments should consider the extent to which RNG production from a particular organic waste feedstock will result in the additional abatement or capture of methane emissions and whether the RNG produced will displace fossil fuel use. These considerations are elaborated upon in the discussion around RNG's role in decarbonization.

Market Opportunities

Appropriate RNG market opportunities and deployment pathways can vary greatly from project to project. In this report, we outline current practices for RNG production, while providing insights into technological advances and trends that could lead to changes in the way RNG is produced and how it is used.

RNG's ability to be used as a drop-in fuel in natural gas infrastructure and appliances implies potentially vast market demand and numerous end uses. This report outlines the current trends in RNG deployment and use, noting that transportation and pipeline injection currently dominate RNG use. We acknowledge, however, that this current market landscape is in part the result of the current policy landscape, and that as new policies are enacted, the market distribution of RNG usage could change as well.

RNG's Role in Decarbonization

RNG is most likely to contribute meaningfully to decarbonization when it results in a real reduction in methane emissions and when it is deployed in otherwise hard-to-abate sectors. We walk through how these considerations can be evaluated based on existing approaches and research findings.

The report emphasizes the importance of considering RNG as a complementary fuel in applications where natural gas or other energy sources are currently used. In this way, RNG can be seen as a flexible, low-carbon fuel source that can potentially be deployed in a variety of applications, even as other vital strategies such as electrification are pursued in parallel.

Barriers to Deployment

The report outlines key barriers to RNG deployment, including feedstock availability; project economics; and market, regulatory, and operational risk factors. The prevalence and extent of these barriers will vary in each state or region, and it is important to identify the specific obstacles on the ground to address them appropriately with policy solutions.

Chief among the barriers to RNG deployment is project economics, specifically large up-front equipment and regular maintenance costs. However, as production technologies mature, and as regulatory landscapes become more consistent and streamlined—for example, regarding pipeline injection standards—current barriers could become less prominent.

Policy Solutions

A primary goal of this report is to provide guidance regarding policy design and implementation for RNG production. Many policy options are available to states and localities to address barriers to efficient and climate-friendly RNG production. Among those outlined in this report are fuel mandates, public financing, regulatory updating and streamlining, and waste management policies.

Each of these options links in specific ways to production and deployment barriers and other potential policy priorities, and these considerations are laid out in detail. Examples from a wide array of states and regions are also provided to illustrate these linkages and how they affect biogas and RNG markets in practice. Policy solutions are not presented in a one-size-fits-all manner, nor in a "one policy for one barrier" manner. Instead, we stress that a mix of policies might be the best solution to encourage resource development that is efficient, yields climate benefits, and is best-suited for the local political and economic context.

APPENDIX – RNG RESOURCES, TOOLS, AND DATA

Table A-1. Tools and Resources for Assessing RNG Resource Potential by Feedstock

FEEDSTOCK	KEY RESOURCE	DETAILS
All wet-waste feedstocks	Argonne National Laboratory GREET Model	Excel-based model that provides a comprehensive, life cycle–based approach to compare energy use and emissions of conventional and alternative fuel and vehicle technologies, including RNG.
	CA-GREET 3.0 Model and Tier 1 Simplified CI Calculators	Modified California-specific version of the Argonne model and supporting simplified calculators for common pathways and feedstocks including RNG from landfills, animal waste, wastewater sludge, and food waste.
	NREL Biomethane GIS Data	County-level geographic dataset with estimates of available biomethane resource potential from landfills, animal manure, organic waste, and wastewater. Already dedicated resources are factored out of estimates.
	Argonne National Laboratory Renewable Natural Gas Database	Database providing a comprehensive list of biogas projects that upgrade gas for pipeline injection or use as vehicle fuel in the U.S., and key variables including operational status, location, average yield, designated end use, etc.
Landfills	EPA Landfill Methane Outreach Program (LMOP) Database	Database containing information on more than 2,600 landfills in the U.S., including location, tons of waste in place, and operation status.
	EPA RNG Flow Rate Estimation Tool	Technical resource that allows users to estimate LFG flow rate and Btu content after wellfield is adjusted to meet inlet gas specifications for RNG upgrading equipment.
	EPA LFG Cost-Web Tool	Technical resource allowing users to estimate methane generation potential and project costs based on parameters such as waste intake, landfill closure year, and landfill design.
Food waste	EPA Excess Food Opportunities Map and Database	Database containing high and low estimates of tons of excess food waste generated by institutional sources such as manufacturing and processing facilities, hospitals, and supermarkets.
	EPA Survey of Anaerobic Digestion Facilities Processing Food Waste in the United States	Report and accompanying datasets on anaerobic digestion facilities processing food waste in the U.S., including stand-alone facilities and wastewater or on-farm facilities that codigest food waste.
Lignocellulosic	2016 Billion Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy	A regularly updated study performed by U.S. DOE regarding the potential of biomass resources to contribute to a national energy strategy.
	NREL Solid Biomass Data	Downloadable dataset containing biomass resource potential data (in million tons) by U.S. county and state for 5 categories: crop residue, urban wood, forest residue, and primary and secondary mill residues.
Water Resource Recovery Facility	Clean Water Survey Needs	Contains location and wastewater flow data for facilities across the U.S., assessing capital investment necessary to achieve water quality goals.
Animal manure	EPA AgSTAR Database	Maintains an updated list of farms using anaerobic digesters in the U.S., including data regarding operation type, production data, and emissions avoided.
	CARB Compliance Offset Protocol Livestock Projects	Provides methods to quantify and report greenhouse gas (GHG) emission reductions associated with the installation of a biogas control system for manure management on dairy cattle and swine farms.
	CFFA Dairy Digester Research and Development Program – Quantification Methodology	Includes quantification methodologies, cobenefit assessment methodologies, and benefits calculator tools. Also contains average factors that can be used to estimate resource potential.

Notes: GREET = Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation; CI = Carbon Intensity; NREL = National Renewable Energy Lab; GIS = Geographic Information System; EPA = Environmental Protection Agency; LFG = Landfill gas; Btu = British thermal unit; U.S. DOE = United States Department of Energy.
Source: WRI authors, with tools and resources cited above.

Table A-2. Estimated Break-Even Costs for RNG Projects by Feedstock

FEEDSTOCK	ESTIMATED BREAK-EVEN COST	DETAILS	STUDY/REPORT
Landfills	$8.70/million Btu	Mid-to-large-sized landfill producing ~700,000 million Btu/year of methane	MJB&A 2019
	$6.75/million Btu	Large landfill in California	Jaffe et al. 2016
	$4.00/million Btu	Large landfill producing ~1,130,000 million Btu/year of methane	Murray et. al 2014
	$7.00–$19.00/million Btu	Landfill RNG project	AGF 2019
Food waste	$35.00/million Btu	MSW digester with 50,000 TPY capacity	Jaffe et al. 2016
	$27.00/million Btu	MSW digester with 100,000 TPY capacity	Jaffe et al. 2016
	$19.40–$28.30/million Btu	Food waste RNG project	AGF 2019
Animal manure	$25.00–$65.00/million Btu	RNG production costs in California	Jaffe et al. 2016
	$18.40–$32.60/million Btu	Animal manure RNG project	AGF 2019
Water Resource Recovery Facility	$10.00–$50.00/million Btu	RNG production costs in California	Jaffe et al. 2016
	$7.40–$26.10/million Btu	Wastewater sludge RNG project	AGF 2019
Lignocellulosic waste	$50.00/million Btu	RNG production from thermal gasification of biomass chips	Ruegsegger and Kast 2019

Note: Btu = British thermal units; MSW = Municipal solid waste; TPY = Tons per year.
Sources: WRI authors, with studies cited above.

ENDNOTES

1 On a 20-year timescale, methane has a global warming potential (GWP) 84–86 times that of CO_2 (see Myhre et al. 2013).

2 At present, landfills generate close to 90 percent of cellulosic biofuel credits under the federal RFS (U.S. EPA 2020b).

3 The number of utilities with active or under development programs may change rapidly. Numbers presented in this report were based on correspondence between the authors and 3Degrees, Inc., which regularly tracks such programs, in September 2020.

4 For the purposes of this guidance, GHG cost-effectiveness is meant to indicate an action's cost on a dollar-per-ton basis relative to other actions that may be taken to reduce emissions. Since this is an inherently comparative metric, an action or mitigation strategy can only be considered cost-effective relative to another action.

5 However, despite the sizable impact on RNG production overall, certain feedstocks, including food waste, still do not qualify as cellulosic biofuels under the RFS.

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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.