COLORADO
Energy Office

RENEWABLE NATURAL GAS (RNG) IN TRANSPORTATION: COLORADO MARKET STUDY

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Prepared for the Colorado Energy Office by Energy Vision

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EXECUTIVE SUMMARY

The purpose of this document is to provide a preliminary, objective evaluation of the potential to produce renewable natural gas (“RNG,” also “biomethane”) from the major sources of organic waste in Colorado, and use it in the state’s on-road transportation market.

As a large state with significant agricultural activity and a growing population, Colorado has a significant potential resource for producing RNG, at wastewater facilities; landfills; from the anaerobic digestion of animal manure generated by the beef, dairy, hog and poultry industries; and from the anaerobic digestion of residential, commercial and manufacturing food waste.

Based on known organic feedstocks and existing technologies—to capture and refine the methane-rich biogases produced as these materials decompose—the total technical potential for the RNG resource in Colorado is nearly 19.5 million MMBTUs of production, or the equivalent of nearly 142 million gallons of diesel fuel. This production capacity—based on empirical industry data and preliminary estimates—equates to approximately 24% of the state’s annual on-road diesel consumption in the medium- and heavy-duty transportation sector.

To date, however, Colorado’s RNG potential remains largely untapped. Research for this report indicates that the only operational or soon-to-be completed projects in the state are at wastewater facilities. One project is planned for the state’s largest landfill, a single agricultural project is in advanced planning and there are no food waste projects (since the closing of the ill-fated Heartland facility).

The findings of this assessment indicate that Colorado has a significant opportunity to produce and use RNG in vehicles, or for other energy end-uses currently dependent on conventional natural gas. The combined displacement of conventional natural gas or diesel fuel; the mitigation of fugitive methane emissions from oil and gas production; and the similar mitigation of fugitive methane emissions from agricultural, municipal and commercial waste management practices in the state could provide measurable climate and clean air benefits, primarily in the form of reduced greenhouse gas and nitrogen oxide emissions.

Overall, there is significant opportunity for RNG development in Colorado, but also a range of economic, regulatory, geographic and policy barriers, many of which are detailed in this assessment.

GLOSSARY/ACRONYMS/USEFUL TERMS (Alphabetical)

“2014 Inventory”: The Colorado Department of Public Health and the Environment’s “Colorado Greenhouse Gas Inventory, 2014.”

AD: Anaerobic digestion.

Anaerobic digestion: the decomposition of organic materials in the absence of oxygen, a process that releases methane. Anaerobic digestion takes place in airless environment of landfills, and can be recreated in purpose built **anaerobic digesters** processing sewage at wastewater plants, manure on farms or food waste at solid waste processing facilities.

AR4: Assessment Report 4, the fourth report of the **Intergovernmental Panel on Climate Change (IPCC)**. AR4 assigned a short term (20 year) global warming potential (GWP) of 72 to methane, and a long term (100 year) GWP of 21. *See “Global warming potential below.*

AR5: Assessment Report 5, the fifth assessment report of the **Intergovernmental Panel on Climate Change (IPCC)**. AR5 assigned a short term (20 year) GWP of 86 to methane, and a long term (100 year) GWP of 28. *See “Global warming potential/GWP” below.*

Biogas: the methane rich gas released from landfills, or by decomposing organic materials such as sewage, food waste and animal manures under anaerobic conditions. Biogas is the precursor to, but not the same as, renewable natural gas; it has not yet been upgraded, contains significant impurities and has an energy content 40% - 50% lower than RNG.

Biomethane: another term for renewable natural gas/refined and purified biogas. Used more commonly in Europe than in North America.

BTU: British thermal unit, measure of energy.

BTU/CF: BTUs per cubic foot—a measure of the energy content of a volume of gas. Biogas that has not yet been upgraded generally has an energy content of 500-600 BTU/CF. Renewable natural gas is assumed to have a BTU content of 970 – 1000 BTU/CF. According to US EIA, conventional natural gas dispensed by utilities generally has a BTU content of 1037 BTU/CF.

CAFO: concentrated animal feeding operation. An animal feeding operation in which more than 1000 “animal units” are confined on site for more than 45 days during the year. One “animal unit” is based on 1000 pounds live weight of animals, but appears to be flexible. According to the USDA, 1000 animal units equates to 1000 beef cattle, 700 dairy cows (generally heavier than beef cattle), 2500 swine weighing more than 55 pounds or 82,000 laying hens. (USDA Natural Resources Conservation Service.)

California Air Resources Board (CARB): “The California Air Resources Board (CARB) is charged with protecting the public from the harmful effects of air pollution and developing programs and actions to fight climate change.” CARB research on emissions and fuels is extensive, and broadly considered authoritative. CARB is widely viewed as a peer of the EPA, which uses its research.

Carbon Intensity (CI): a rating for the carbon content of a fuel, usually done in calculated grams of CO2e (see below) per megajoule of energy (gCO2e/MJ), per the California Air Resources Board.

CDPHE: Colorado Department of Public Health and the Environment.

CH_4: methane

CNG: compressed natural gas

CO_2: carbon dioxide

CO_2e: carbon dioxide equivalent. CO_2 is the benchmark greenhouse gas with a “global warming potential” (GWP) of 1. The GWP of other greenhouse gases is measured in relation to CO_2; e.g. methane has a GWP 28 times greater than CO_2 (100 year timeline), so that a ton of methane has a “CO_2e” value of 28.

CO-DIGESTION: the processing of multiple feedstocks together. For instance, the addition of food waste to the sewage at a wastewater treatment plant, or to the manure at an agricultural digester.

DGE: diesel gallon equivalent. A measure of energy used to equate the energy content of e.g. (renewable) natural gas to that of diesel fuel. According to US EIA, equivalent to 137,381 BTUs.

DIGESTATE: the solids remaining at the end of the anaerobic digestion process. Digestate is rich in nutrients, is valuable as a fertilizer or soil amendment, and is virtually odor free.

(US) DOE: (United States) Department of Energy

(US) DOE RNG Database: a database compiled and curated by Energy Vision for Argonne National Laboratory, listing biogas projects producing around the country that are producing renewable natural gas, or where such projects are under construction or in planning.

(US) EIA: (United States) Energy Information Administration

(US) EPA: (United States) Environmental Protection Agency

(US) EPA Inventory: EPA's 2019 "Inventory of Greenhouse Gas Emissions and Sinks, 1990-2017."

FEEDSTOCK: The biogas emitting material on which a project is based—e.g., manure, food waste, wastewater, landfill gas.

GGE: gasoline gallon equivalent. A measure of energy used to equate the energy content of e.g. (renewable) natural gas to that of gasoline. According to US EIA, equivalent to 120,429 BTUs.

GHG(s): greenhouse gas(es). Gases like carbon dioxide, methane and nitrous dioxide, emissions of which contribute to the "greenhouse effect" of trapping heat in the earth's atmosphere.

Global warming potential/GWP: The relative atmospheric warming impact of a given GHG, usually measured in tons of CO_2e. The understanding of GWP has evolved over time, and GWP values have changed with different editions of the IPCC's Assessment Reports.

- **Long-term GWP:** the GWP of a GHG over a 100-year time frame.
- **Short term GWP:** the GWP of a GHG over a 20-year time frame. Given the short time frame thought to be available to avoid the worst effects of climate change, the short term GWP of methane is considered more important than the lower, long term GWP.

IPCC: Intergovernmental Panel on Climate Change. An intergovernmental body of the United Nations, dedicated to providing the world with an objective, scientific view of climate change, its natural, political and economic impacts and risks, and possible response options.

Lifecycle emissions: the GHG emissions of a fuel from all stages of the fuel's life—extraction/production, transport to point of use and combustion. For vehicle fuel, also called "well-to-wheels" emissions.

LMOP: Landfill Methane Outreach Program. A program of the EPA that tracks biogas projects at landfills; regularly publishes a database of projects.

LNG: Liquefied natural gas. (Renewable) natural gas that has been pressurized and cooled until it takes a liquid form. RNG can be used in either compressed form (CNG) or liquid form (LNG). This document generally discusses CNG, which appears to be the widely preferred form. In curating the RNG Database for the US DOE, Energy Vision has come across very few projects producing LNG, and those tend to be legacy projects.

MMCF: Million cubic feet

MGY/MGD million gallons per year/million gallons per day (measure of waste water flow)

MMBTU: million British thermal units

NAICS (Code): North American Industrial Classification System. A numbered index for industrial sectors.

Near-zero engine ("NZ" engine): a new generation of natural gas engines designed to minimize NOx emissions.

RNG: renewable natural gas. Biogas that has been "upgraded" using any of several available technologies, by removing CO2, moisture and other impurities. This leaves a high-methane content gas that is interchangeable with conventional natural gas across all platforms/applications, but has a much lower lifecycle emissions profile.

(S)CF: (standard) cubic foot, a measure of volume for (renewable) natural gas

(S)CFD: (standard) cubic feet per day, a measure of the flow rate of biogas or (renewable) natural gas over 24 hours

(S)CFM: (standard) cubic feet per minute, a measure of the flow rate of biogas or (renewable) natural gas in one minute

(S)CFY: (standard) cubic feet per year, a measure of the flow of biogas or (renewable) natural gas in one year.

TPY/TPD: Ton(s) per year/Ton(s) per day

VIRTUAL PIPELINE: a system whereby, in the absence of a nearby pipeline, gas is loaded onto special container trucks and driven to an injection point along a more distant pipeline. Gas can also be delivered by this method directly to fueling stations.

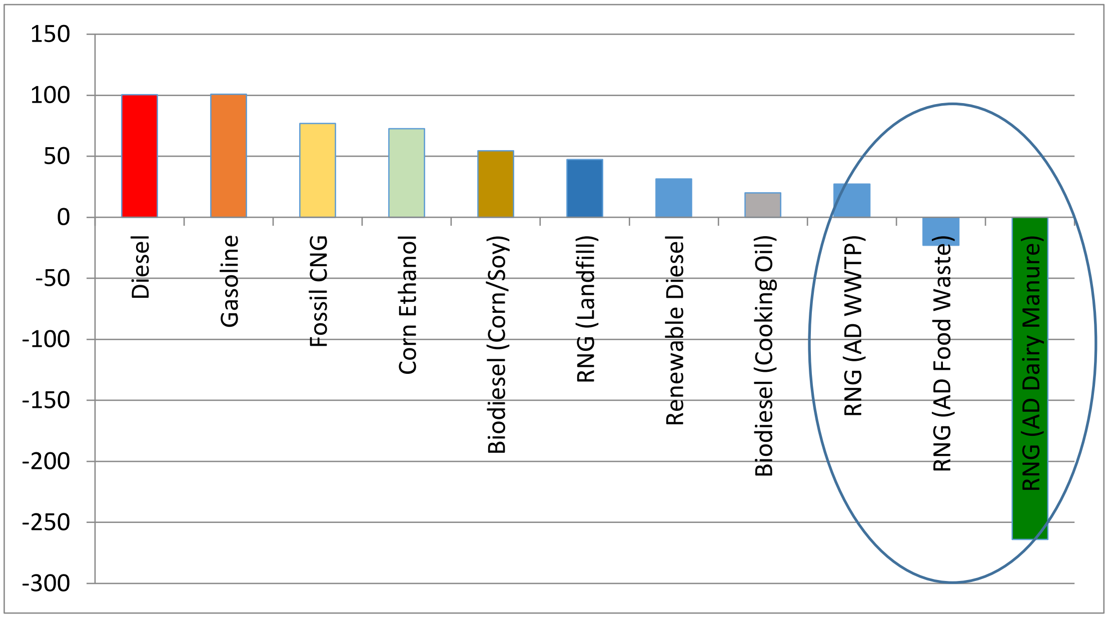
WWRF: Wastewater recycling facility; wastewater recovery facility

WWTP: Wastewater treatment plant

BACKGROUND

Renewable natural gas, or "RNG" (also called "biomethane") is made by capturing and refining the biogases emitted from decomposing organic materials like food scraps, animal manure and sewage. Once refined (see below), RNG is interchangeable with conventional natural gas, and can be transported and utilized via the same pipelines and infrastructure; however, it is not a fossil fuel, and requires no drilling or fracking. As an energy source, RNG can "decarbonize" the gas grid. As a transportation fuel, RNG can readily replace high-carbon diesel in trucks and buses. According to the **California Air Resources Board ("CARB")**, on a lifecycle basis vehicular RNG use represents a 70%-300% reduction in **greenhouse gas (GHG) emissions** compared to diesel, as it both captures methane emissions from organic waste *and* displaces emissions from fossil fuels. When derived from separated food waste or dairy manure processed in "anaerobic digesters," it is actually *net carbon negative*—meaning that its production prevents more GHG emissions than are produced by combusting it.[1]

FIGURE 1: Lifecycle Carbon Intensity (g CO2e/MJ); Petroleum & Alternative Fuels



(Source: CARB 2017, 2019[2])

Renewable natural gas is a real and proven option, available right now, and in ever-growing use. New York's Metropolitan Transportation Authority issued an RFP in May 2019 seeking RNG suppliers for its nearly 800 CNG fueled buses. Also in May, UPS announced the largest RNG deal ever to fuel its fleets, committing to purchase 170 million gallons over the next 7 years. Private hauler Waste Management uses RNG produced at its landfills to fuel its trucks, and competitor Republic Services does the same. SoCal Gas in California and CenterPoint Energy (serving Arkansas, Louisiana, Minnesota, Mississippi, Oklahoma, and Texas) have announced plans to offer renewable natural gas as an option to their customers, following the lead of Vermont Gas. LA Metro now runs half of its 2,200 CNG bus fleet on RNG. Cosmetics giant L'Oreal is using RNG from a nearby landfill to provide energy for a plant in Kentucky.

Organic wastes decomposing in an oxygen free environment like a landfill release methane-rich "biogas". This process of "anaerobic digestion" (AD) is replicated in the purpose-built anaerobic digesters that are standard equipment at many wastewater treatment plants (WWTPs), capturing methane from sewage. Anaerobic digesters are increasingly being used around the country to process animal manures and other agricultural wastes on farms, as well as food waste collected with or diverted from municipal solid waste (MSW). According to the American Biogas Council, there are currently over 2,200 biogas projects in the United States, with the potential for over 14,000 (see Table 1, below). This projected potential may actually be conservative; there are estimated to be over 14,000 publicly-owned wastewater treatment works throughout the United States,[3] and nearly 19,000 concentrated animal feeding operations (CAFOs).[4]

TABLE 1. CURRENT AND POTENTIAL U.S. BIOGAS PROJECTS[5]

	Current	Potential
Farm-based digesters	250	8,241
Food waste	66	931
Landfill	652	1,067
Wastewater	1,269	3,888
TOTALS	**2,237**	**14,127**

(Based on American Biogas Council estimates.)

Biogas produced via AD is typically between 50-60% methane, and 40-50% carbon dioxide (CO_2), moisture and other impurities. This "raw," unrefined biogas is often used to fuel on-site boilers, to generate electricity on-site or to fuel combined heat and power (CHP) systems which generate both electricity and thermal energy.

When biogas is "upgraded," using one of several available technologies to remove the CO_2 and other contaminants, the gas that remains is as high as 99% pure methane.[6] This is renewable natural gas (RNG)—interchangeable with conventional natural gas across all applications, and usable in all of the same infrastructure for transport, dispensing and combustion, with no modifications required. But RNG's lifecycle GHG emissions are at least 50% lower than conventional natural gas, and 80% lower than diesel fuel. When it is made from food waste or dairy manure, it can actually be net carbon-negative, as noted in Figure 1, above.

Based on comprehensive research performed by Energy Vision in collaboration with Argonne National Lab, as of the end of Q1 2019 there are 89 confirmed operational RNG projects in the U.S., with another 38 under construction and 93 in planning.

TABLE 2. U.S. RENEWABLE NATURAL GAS (RNG) PROJECTS AS OF SPRING 2019[7]

	Operational	Construction	Planned	Total Operational, Construction, Planned	*2017 Total Operational, Construction, Planned*	**Increase, 2018/2017**
Landfills	58	8	14	80	*55*	**45%**
Farms	11	21	63	95	*28*	**239%**
Food Waste	7	2	5	14	*12*	**17%**
Wastewater	13	7	11	31	*15*	**107%**
Totals	**89**	**38**	**93**	**220**	***110***	**100%**

Energy Vision's assessment of the potential role of organic waste-derived renewable natural gas (RNG) in advancing Colorado's ambitious environmental, climate and economic goals is divided up in to five "Tasks," each of which is described at the beginning of its own section.

Task 1: ***Literature review evaluating the Colorado market and the economic, environmental and energy security benefits the use of RNG in the transportation sector may provide.***

RNG IN THE CONTEXT OF COLORADO'S GREENHOUSE GAS EMISSIONS

Production and use of RNG plays a dual role in reducing GHG emissions. First, **its production prevents the escape of methane into the atmosphere**; second, **it reduces the emissions from and reliance on fossil fuels.**

This first role is crucial. According to the fifth assessment report ("AR 5") of the Intergovernmental Panel on Climate Change (IPCC), methane is a short-lived climate pollutant that has 86 times the global warming potential (GWP) of CO2 in the near term (10-20 years)[8] – the window climate scientists believe we have to prevent the worst impacts of climate change. As part of the effort to forestall those impacts, emissions of "fugitive" methane—from landfills, wastewater, agriculture—must be captured. Once captured, this methane can be used to reduce demand for fossil fuels, while generating revenue for producers including farmers and surrounding rural communities, municipalities with wastewater treatment facilities and landfill operators.

Table 3 below shows the contribution of major potential RNG sources to Colorado's total methane emissions (2010 actual and 2020 projected) based on the "Colorado Greenhouse Gas Inventory" of 2014. To reflect the urgency of looking at methane's climate impact in the *short term*, the table shows both the long-term GWP of 21 used by the Inventory, as well as the AR5 short-term value of 86. The differences are striking.

TABLE 3. COLORADO METHANE EMISSIONS BASED ON 2014 "GREENHOUSE GAS INVENTORY"[9]

(Million Metric Tons CO_2e)

	2010 MMT CO_2e		**2020 MMT CO_2e**	
	Based on "Inventory" GWP of 21	**Based on AR 5 short term GWP of 86**	**Based on "Inventory" GWP of 21**	**Based on AR 5 short term GWP of 86**
Natural Gas and Oil Systems	10.05	41.16	13.01	53.28
Manure Management	0.87	3.56	0.75	3.07
Landfills	2.19	8.97	2.83	11.59
Wastewater	0.39	1.60	0.46	1.88
Other	12.632	51.73	11.364	46.54
Subtotal (methane)	26.13	107.02	28.41	116.36
Total CO_2e (MMT)	*130**	*210.88***	*134**	*221.95***
These methane sources as % Total CO_2e	**20.10%**	**50.75%**	**21.20%**	**52.43%**

**Inventory CO_2e total; **Inventory CO_2e total adjusted for revised methane value.*
Note: No GWPs other than methane's have been adjusted

Table 4 below shows Colorado's methane emissions as a portion of the state's total GHG emissions, again based on the 2014 Inventory. As above, both the Inventory's GWP and the AR5 GWP—21 and 86 respectively—are included.

TABLE 4. METHANE FROM MAJOR RNG SOURCES AS COMPONENT TOTAL EMISSIONS[10]

(Million Metric Tons CO_2e)

	2010	2020
Total CO2e emissions, based on 2014 "Inventory"	130	134
Methane from manure mgmt., wastewater and landfill as MMT CO2e, GWP 21	3.45	4.04
As percent total CO_2e	2.65%	3.01%
Total CO2e emissions, adjusted for AR5*	210.88	221.95
Methane from manure mgmt., wastewater and landfill as MMT CO2e, GWP 86	14.13	16.54
As percent total CO_2e*	6.70%	7.45%

**Inventory CO2e total adjusted for revised methane value.*

Note: No GWPs other than methane's have been adjusted

CURRENT STATUS OF RNG IN COLORADO

So far, RNG project development in Colorado is limited. The state has one operational project, at the Persigo WWTP in Grand Junction, and projects are under construction at the Longmont WWTP and in Englewood (South Platte Water Renewal Partners). A dairy manure project is in planning near Yuma. A food waste and manure "co-digestion" project in La Salle (Heartland) closed in January 2017, and the facility's ultimate fate remains uncertain. Colorado currently has three operational landfill-gas-to-electricity projects,[11] but no landfill-based RNG projects.

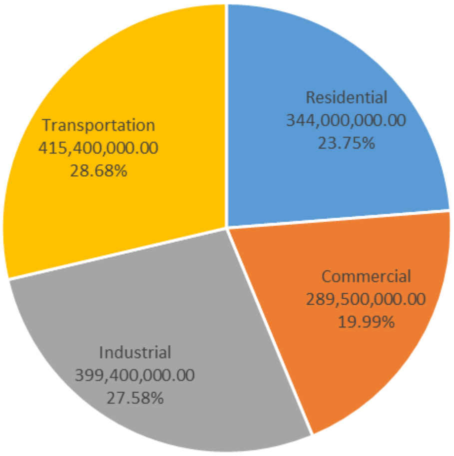
COLORADO GHG REDUCTION GOALS

On May 1st 2019, the Colorado Legislature passed new state goals for reducing GHG emissions: 26% by 2026, 50% by 2030 and 90% by 2050, all against a 2005 baseline.[12]

COLORADO'S OVERALL ENERGY MIX

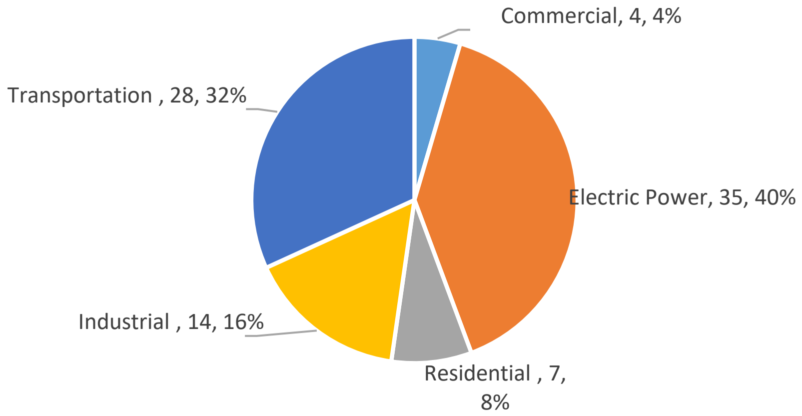
According to data from the US Energy Information Agency, out of total state-wide energy consumption of nearly 1.45 billion MMBTUs (million British thermal units), the transportation sector was the largest single energy consumer, accounting for 28.68% of consumption, or over 415 million MMBTUs.

Figure 2. Colorado Energy Consumption by Sector, MMBTU's and percent total, 2016[13]



Transportation also plays a major role in statewide GHG emissions, coming in second only to electricity generation (half of which was still produced with high-emissions coal as of January 2019[14]).

Figure 3. Colorado Emissions by Sector, MMT CO_2e and percent total, 2016[15]



COLORADO TRANSPORTATION ENERGY CONSUMPTION

Within transportation, on-road fuel use (excluding rail and aviation applications) in 2016[16] included:

TABLE 5. ESTIMATED TRANSPORTATION FUEL CONSUMPTION, 2016[17]

(Based on US EIA)

Fuel	2016 MMTBUs	Diesel Gallon Equivalents (DGEs)[18]	Percent consumption
Distillate fuel oil (diesel)	81,000,000	589,601,182.11	22.96%
Electricity[19]	249,625	1,817,028.63	0.07%
Motor gasoline	270,600,000	1,969,704,689.88	76.72%
Conventional natural gas[20]	470,798	3,426,951.33	0.13%
Propane	400,000	2,911,610.78	0.11%
TOTALS	**352,720,423**	2,567,461,462.72	100.00%

Diesel fuel and motor gasoline clearly dominate highway fuel consumption in Colorado, accounting for over 99% of on-road fuels consumed.

COLORADO ENERGY CONSUMPTION COSTS

In 2016, highway fuel consumers in Colorado spent over $6 billion dollars.

TABLE 6. ESTIMATED TRANSPORTATION FUEL COSTS (RETAIL), 2016[21]

Fuel	2016 Average $/MMBTU	2016 MMTBUs	Total
Distillate fuel oil (diesel)	$16.12	81,000,000.00	$1,305,720,000
Electricity[22]	$28.63	249,625.21	$7,174,228
Motor gasoline	$17.37	270,600,000.00	$4,701,800,000
Conventional natural gas[23]	$9.21	470,798.00	$4,336,049
Propane	$12.40	400,000.00	$4,960,000
TOTALS	**N/A**	**352,720,423.21**	**$6,023,990,278**

CURRENT TRENDS IN NATURAL GAS USE AS A TRANSPORTATION FUEL IN COLORADO

RNG is most readily substituted for conventional natural gas (compressed or liquefied), and requires natural gas pipeline infrastructure for transport, as well as fueling infrastructure. Though still a small portion of the vehicle fuel mix, natural gas has risen relatively consistently since 2008.

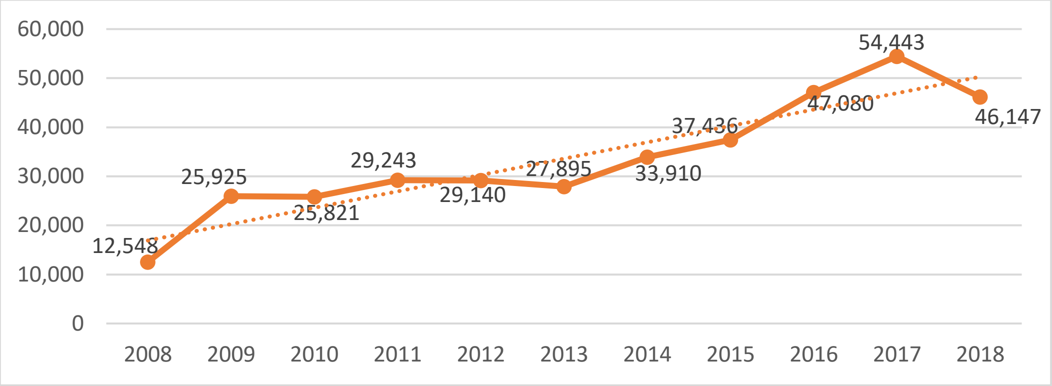
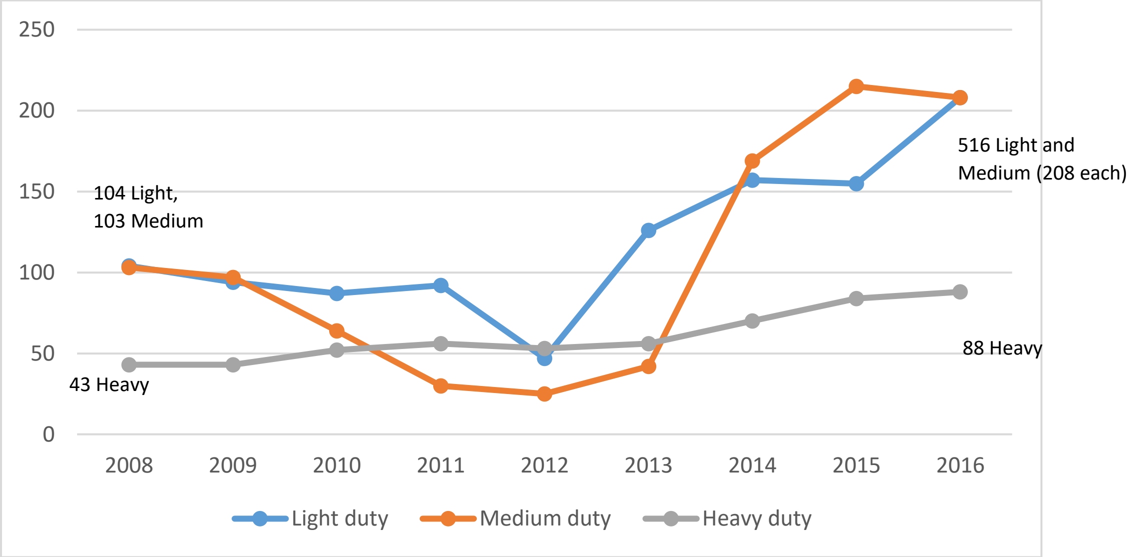


Figure 4: Natural gas vehicle fuel consumption in Colorado, 2008-2018 (MMBTU)[24]

Based on data voluntarily provided by Federal and State agencies, natural gas providers and electricity providers, natural gas vehicle use among fleets has also increased, more than doubling across light-, medium- and heavy-duty classes between 2008 (250 vehicles total) and 2016 (604 vehicles total). The only vehicle class to see relatively consistent growth in natural gas usage with no major dips over that period has been the heavy-duty sector (primarily buses and larger trucks). (As noted, this data is provided voluntarily by a limited subset of potential users, and may not reflect complete uptake of natural gas vehicles.)

Figure 5. Natural gas vehicles in Colorado, 2008-2016[25]



The Colorado Clean Cities Coalitions credit natural gas with significant reductions in petroleum transportation fuel use in the state, and with substantial emissions reductions in the Northern and Denver regions. (Ethanol accounts for 65% of alternative fuels and 74.5% of related emissions reductions in the Southern Colorado Coalition area.)[26] It is also worth noting that US EIA's estimates of CNG consumption and those of the Clean Cities Coalitions do not match.

Table 7. Conventional CNG in Colorado Clean Cities Petroleum Displacement and Emissions Data[27]

Clean Cities Coalition	Petroleum fuel displaced by alternative fuels (GGE)	Fuel displaced through CNG use (GGE)	Portion fuel displaced by CNG	Emissions reduction through CNG use (tons CO2e)
Northern Colorado	2,753,051	1,844,544	67%	1,708
Denver Metro Region	7,482,736	6,248,085	83.50%	5,382
Southern Colorado	2,010,833	347,874	17.30%	387
Total:	***12,246,620***	***8,440,503***		***7,477***

STATE SUPPORT FOR NATURAL GAS VEHICLES AND INFRASTRUCTURE

Vehicles

Colorado has a history of promoting clean energy, in 2004 becoming the first state to adopt a voter-approved Renewable Portfolio Standard (RPS), which currently requires investor-owned utilities to generate 30% of electricity from renewable sources by 2030.[28]

The state has taken similar action on transportation. In November 2011, Colorado and Oklahoma drove adoption of a Memorandum of Understanding (MOU) to stimulate natural gas vehicle (NGV) production in the US by aggregating state procurement under a joint RFP. Ultimately, 22 states signed on to the MOU. In response, Chrysler, Ford, GM and Honda dealers in all 22 states agreed to offer dedicated compressed natural gas (CNG) or bi-fuel options for vans, pickup trucks or compact cars,[29] and Colorado's 2014 State Energy Report cited an increase in the state NGV fleet from 3 vehicles to 225.[30]

Colorado introduced credits for the purchase or lease of alternative fuel vehicles, or conversion of vehicles to alternative fuels, including natural gas. As shown in the table below, these credits are ramping down from a high in 2014-2016, and the tax credit for natural gas vehicles will be phased out altogether after tax year 2021.

Table 8: Colorado Tax Credits for Purchase of/Conversion to CNG Vehicles[31,32,33]

Vehicle Type	Tax year(s)				
	2014-2016	**2017**	**2020**	**2021**	**2022**
Light duty passenger	$6,000	$5,000	$4,000	$2,500	$0
Light duty truck (14,000 lbs. or less)	$7,500	$7,000	$5,500	$3,500	$0
Medium duty (14,000 to 26,000 lbs.)	$15,000	$10,000	$8,000	$5,000	$0
Heavy duty (more than 26,000 lbs.)	$20,000	$20,000	$16,000	$10,000	$0

Between 2014 and 2019, the vehicle portion of the ALT Fuels Colorado program (AFC), administered by the Regional Air Quality Council (RAQC), has provided over $10.5 million of Congestion, Mitigation and Air Quality (CMAQ) funds for CNG and CNG bi-fuel vehicles, funding 604 CNG vehicles and 87 CNG bi-fuel vehicles. Between 2018 and 2019 the AFC program has provided $1.65 million of VW settlement funds for 30 CNG vehicles. Going forward, VW settlement funds for CNG vehicles will only be available for vehicles with long term commitments to the use of RNG.

Infrastructure

There are currently 37 public and private natural gas fueling stations in Colorado, with the largest concentration in the Denver metropolitan area.[34] Twenty-five of the existing stations have been built since 2012,[35] 8 of them with funding from the station portion of the AFC program, administered by the Colorado

Energy Office.[36] At a per-station average capital cost of approximately $1.65 million, that's over $40 million in public and private dollars over the past seven years alone.[37]

RENEWABLE NATURAL GAS (RNG) RESOURCES IN COLORADO

In order to provide an estimate of cost savings from displacing fuels with RNG, it is first necessary to calculate the potential RNG resource in Colorado, based on known feedstocks and existing, proven conversion technologies. To develop this assessment, Energy Vision looked at four key resources: animal manure, specifically from dairy and beef cattle; food waste; landfills; and wastewater. The potential resource is summarized in Table 6 below.

TABLE 9. ESTIMATED POTENTIAL ANNUAL RNG PRODUCTION FROM MAJOR SOURCES*

	MMBTU	Diesel Gallon Equivalents (DGE)[38]
Agriculture [39,40]	7,880,593	57,363,049
Food waste[41,42]	901,966	6,565,433
Landfills[43,44]	9,667,407	70,369,316
Wastewater[45]	1,032,601	7,516,333
Totals	19,482,567	141,814,130

(Assumes a 35% food waste diversion rate, per state's 2026 goal of 35% MSW diversion; and varying recovery rates for manures. It does not account for limitations on swine manure created by Amendment 14, discussed below.)

Based on these estimates, Colorado's RNG resource could replace nearly 142 million gallons of diesel, or 24% of the state's total diesel consumption for transportation, eliminating approximately 1.44 million metric tons of CO2e from fuel combustion annually.[46]

Energy Vision's research has indicated that the best use for RNG in transportation is as a substitute for diesel fuel in the heavy-duty vehicle sector, for multiple reasons:

- Medium and heavy-duty diesel vehicles account for 25% of all transportation emissions according to the EPA,[47] but are less than 4.5% of registered vehicles in the US.[48]
- The power and torque requirements of these vehicles have made them very challenging to decarbonize/move off of diesel using technologies other than RNG.
- Emerging options such as electrification are still in the very early stages of development for heavy-duty vehicles like Class 6-8 trucks designed for refuse or regional/long haul applications, particularly those operating in mountainous terrain and extreme weather like Colorado's.

INVESTMENT AND EMPLOYMENT POTENTIAL OF DEVELOPING BIOGAS AND RNG PROJECTS

The direct and indirect investment and job creation impacts associated with RNG production and use vary widely based on the size of a given facility and the volume of organic waste feedstock(s) processed. Depending on project size and type, capital investments may be required for many of the following:

- installation of biogas collection system at landfills, or collection system upgrades;
- construction of anaerobic digesters for livestock or wastewater facilities;
- installation of conditioning equipment for cleaning/upgrading raw biogas to RNG;
- installation of compressors and pipeline infrastructure for interconnecting to the natural gas pipeline system;
- storage facilities and transport trucks for delivering RNG in the absence of an economic pipeline interconnection.

Empirical project-level data has been compiled by Energy Vision, the Coalition for Renewable Natural Gas and others, including global consulting firm ICF, which has analyzed the California RNG market extensively. Total capital costs for smaller projects are often in the range of $5 million to $25 million, and upwards of $100 million for large, state-of-the-art merchant food waste and co-digestion projects. Based on the publicly available data that exists, the RNG Coalition estimates that the average RNG project requires approximately $17 million of capital investment.[49]

A study by ICF of economic impacts from expanded production of RNG and deployment of low NOx natural gas trucks in California applied a cost analysis reflecting average capital expenditures by RNG project. The study found that regardless of project size and feedstock(s), the development of a new RNG facility can create significant local employment, in the form of design and engineering services, 20-40 local trade positions during construction, and typically 3 to 5 permanent employees for on-site operations.[50]

The same ICF study estimated an output multiplier for RNG production investment of 1.83, meaning that each million dollars invested translates to a total increase in value to the economy of $1.83 million. The study estimated aggregate employment effects, including additional associated investments in low NOx trucks and fueling infrastructure.[51]

Perhaps most relevant to the Colorado assessment, the ICF California study developed a calculator for jobs created per volume of fuel produced, finding that RNG production facilities generate 4.7 to 6.2 jobs per million ethanol gallon equivalents (EGE, equal to 77,000 BTUs).[52] Using the average of the range—5.5 jobs per million EGE—each additional 100 million EGE of RNG production would drive the creation of 550 additional jobs.

In the California study, these jobs were estimated to provide income per worker of $68,960, or more than twice the median income per capita in the state. Although not addressed explicitly in the ICF study, job impacts from RNG projects are generally concentrated in rural areas, where the effects are more likely to be significant relative to the size of the local economy and the availability of well-paying jobs.

Applying some of these metrics to the production estimates highlighted in Table 5, fully developing Colorado's RNG resource could generate in excess of 850 jobs; if the salary ratio seen in California held, each of those jobs would pay a salary of roughly $72,000.[53]

ENVIRONMENTAL AND CLEAN AIR BENEFITS (REDUCTIONS IN GHGS AND CRITERIA POLLUTANTS)

Colorado has a significant opportunity to expand its production and use of RNG for use in heavy-duty vehicles. The most immediate opportunity is to transition existing natural gas refueling infrastructure and vehicles from geologic natural gas to RNG, which can be done with no modifications to vehicles, gas transport or fueling infrastructure required. Doing so, the state would displace more than 3.4 million DGEs and reduce greenhouse gas emissions by 40% or more.[54]

Expanding in-state RNG production offers an even greater clean transportation opportunity: use the supply of RNG made from captured methane as a basis for transitioning heavy-duty vehicles away from diesel to natural gas engines, specifically newer "near-zero" models. As indicated in Table 5, Energy Vision estimates that known technology and organic waste resources could potentially yield an estimated 140 million DGEs of annual RNG production in Colorado. Assuming that all new RNG supply went toward displacing current in-state on-road diesel demand (~589 million gallons of diesel), displacing approximately 140 million gallons of diesel would reduce the climate impacts of the transportation sector by over 1.4 million metric tons of CO2e per year.[55]

In addition to the GHG reduction benefits of using RNG, the wider use of the latest natural gas engines has ground-level air quality benefits with regard to tailpipe emissions. The difference in criteria pollutant emissions between a near zero ("NZ") engine and a diesel model is dramatic. (Levels for conventional natural gas and RNG used in a near zero engine are essentially the same). NZ natural gas engines are certified by both the US EPA and CARB to achieve nitrogen oxide (NOx) emissions at or below .02 grams/brake horsepower hour[56], which is 90% below the most stringent federal (2010) standard of 0.2 grams/bhp of NOx for the most advanced diesel engines. Reductions in particulate matter (PM) have also been as much as 90% below the EPA standard.[57]

Also worth noting about NZ engines:

- testing by the Center for Environmental Research and Training at the University of California-Riverside (UCR CERT) has confirmed reductions in NOx emissions for NZ engines that are significantly below even the optional low-NOx standard of .02 grams/bhp referenced above;[58]
- NZ engines do not require the after-treatment systems that diesel engines do—the inadequate performance of which has meant that diesel engines often didn't meet the 0.2g/bhp standard under actual in-use conditions;[59]
- NZ engines are available in 6.7 liters, 9 liters and 12 liters, covering most medium- and heavy-duty uses.

The opportunity to reduce NOx and PM emissions across a range of vehicle sizes is important for many reasons, particularly in the Front Range urban corridor, home to many of Colorado's air-quality non-attainment areas.[60] NOx adversely impacts human health in its own right, but is also a key contributor to formation of ground level ozone ("smog"), and is considered by the EPA a "precursor emission" in the formation of lung-damaging particulate matter (PM);[61] both ground level ozone smog and PM contribute to air quality non-attainment status.[62] Reducing NOx levels thus has a ripple effect, benefitting human health directly as well as reducing smog and particulate matter formation.

ENVIRONMENTAL BENEFITS OF REDUCED NATURAL GAS AND OIL EXPLORATION

The primary GHG emissions associated with oil and gas exploration are methane—which, as noted above, has 34 times the global warming potential (GWP) of CO2 over a 100-year time horizon, and 86 times the GWP of CO2 over a 20-year time horizon, according to the IPCC.[63]

Figure 6 below shows estimates for Colorado methane emissions from natural gas production from 2013 to 2018, based on emissions numbers for American natural gas production from the US EPA "Inventory of Greenhouse Gas Emissions and Sinks" and US EIA production numbers.[64] EPA's Inventory uses a GWP for methane of 25 (per IPCC AR 4), which is shown on the left; the middle and right-hand columns have been adjusted to the values used in AR 5, 34 for 100 years and 86 for 20 years.

Figure 6. Estimated Methane Emissions from Colorado Natural Gas Production, MMT CO_2e, 2013-2018

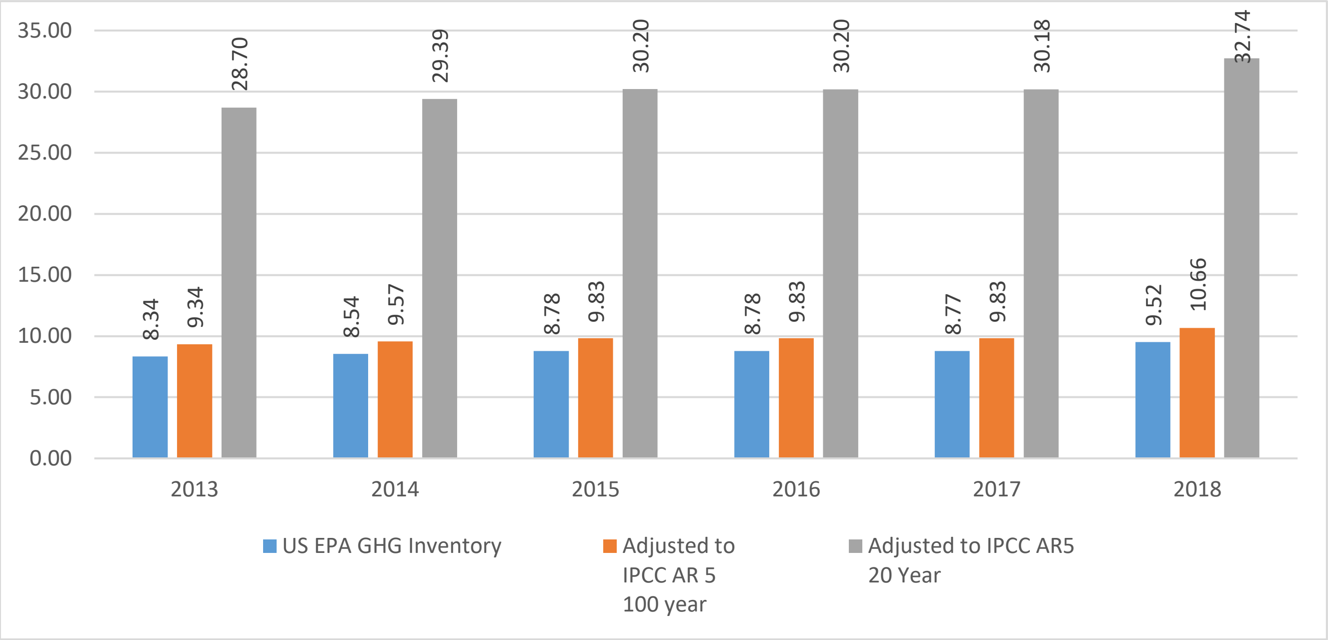
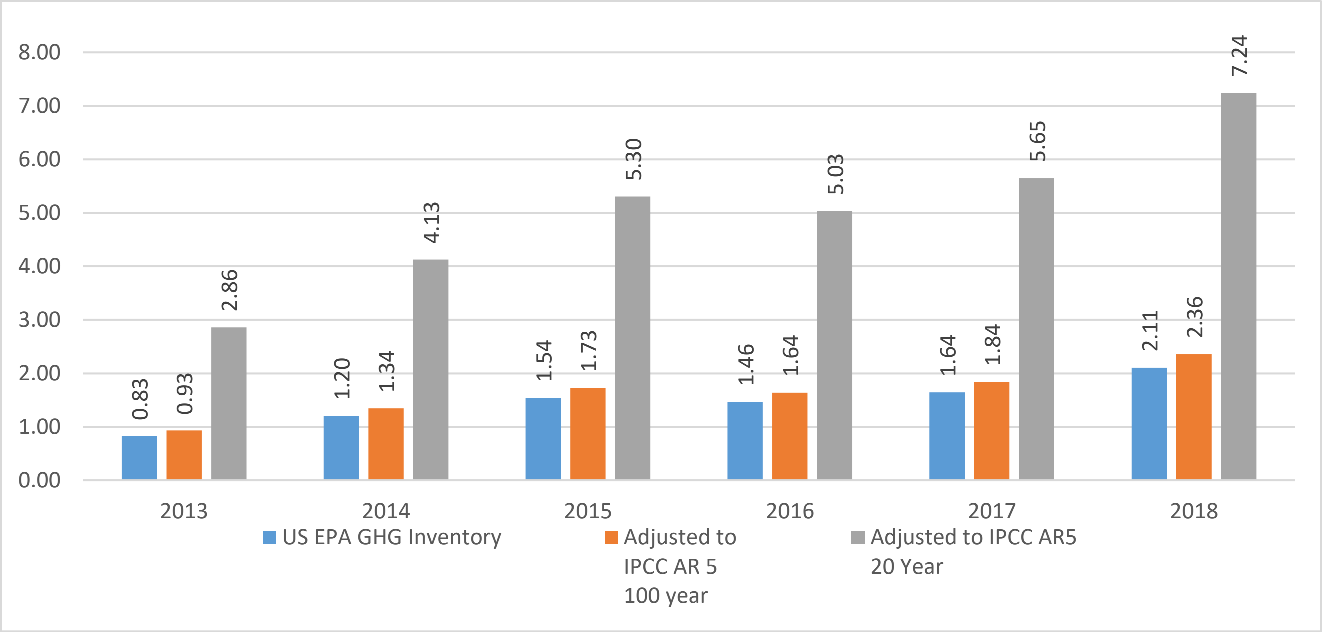


Figure 7. Estimated Methane Emissions from Colorado Oil Production, MMT CO_2e, 2013-2018



As indicated by the figures above, emissions from natural gas production in Colorado outpace emissions from oil production by an average of nearly 6.5 to 1.

The table below indicates the amount of methane emissions related to fossil fuel production that could be prevented annually by replacing fossil energy with RNG. The quantities of oil or gas shown equate to the 19,482,567 MMBTU of potential renewable natural gas resource in Table 5. Emissions are based on IPCC AR 5 and a GWP for methane 86 times that of CO2 over a 20-year time frame, or the period between now and 2040 when aggressive action on climate is most pressing if we are to achieve the international goals set forth in Paris in 2015 – an 80% reduction in global GHG emissions from a 2005 baseline by 2050.

TABLE 10. POTENTIAL REDUCTION OF METHANE EMISSIONS FROM REDUCED FOSSIL ENERGY EXTRACTION[66]

	Equivalent barrels crude displaced by RNG	Equivalent MMCF gas displaced by RNG
	3,404,853	19,483
Associated methane emissions (MT CO_2e)	146,994	348,504

COLORADO'S CURRENT LEVEL OF "ENERGY INDEPENDENCE"

While Colorado actively engages in inter-state import and export of both petroleum and natural gas, given the state's rich supply of each, it is effectively "energy independent," producing more energy than it consumes. Maximizing the production and use of its RNG resources would not meaningfully affect this. For example, Colorado currently produces nearly 40% more petroleum than it consumes, which is reflected in Colorado's production of refined petroleum products.

Figure 8. Petroleum production and consumption, barrels, 2017[67]

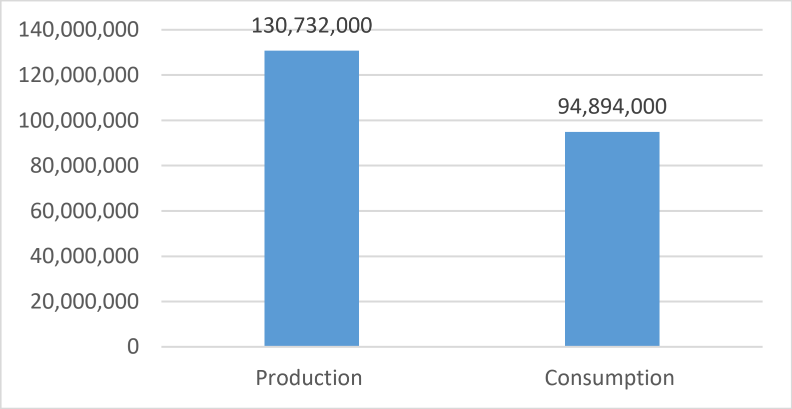
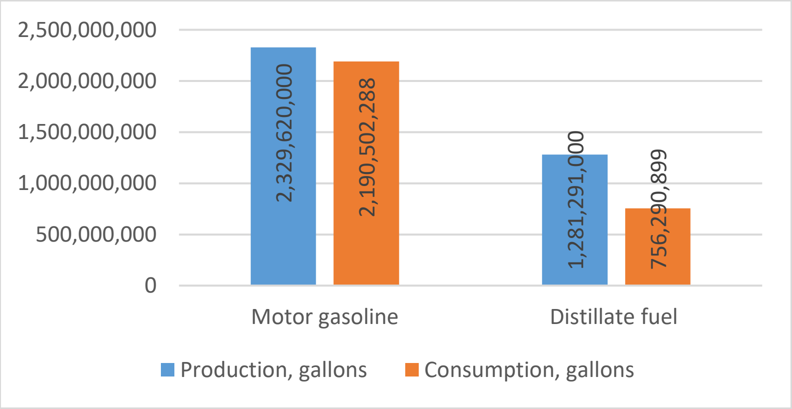
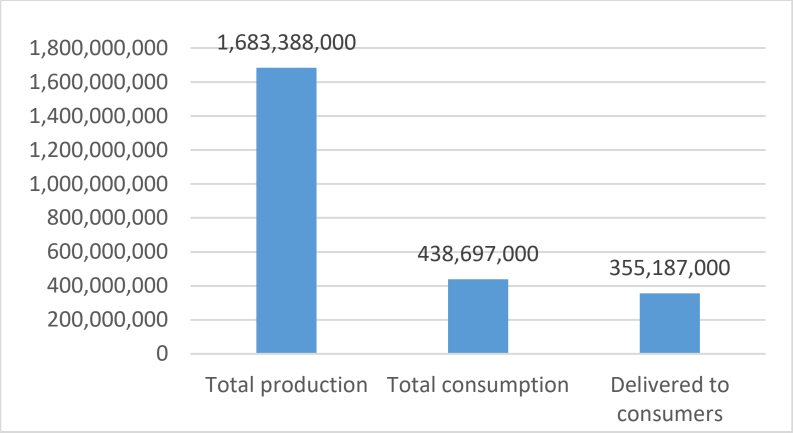


Figure 9. Estimated diesel and gasoline production and consumption, 2016 (gallons)[68,69]



Colorado also produces roughly 3.8 times as much natural gas as it uses. Such an abundant supply of inexpensive geologic natural gas potentially hampers RNG development.

Figure 10. Natural gas production and consumption, 2017, in MMBTUs [70,71,72]



RENEWABLE ENERGY INDEPENDENCE

As noted above, Colorado's Renewable Portfolio Standard requires that 30% of electricity come from renewables by 2030. The state now ranks 12th in the country for solar energy[73], and 8th in the country for wind energy.[74] Colorado's overall renewables capacity is shown in the table below. (Colorado's renewable portfolio standard considers woody biomass a renewable energy source.)

TABLE 11. RENEWABLE ENERGY CAPACITY (MWs)[75]

Solar	925.8
Wind	3703
Woody biomass	11.5
Landfill gas	7.6
Hydropower	1150
TOTAL	5,797.9

RNG could contribute considerably to Colorado's renewable electricity profile, as shown in Table 12, below. It is important to note that this dispatchable capacity would be available 24/7, making RNG a considerable resource for providing continuity of supply when solar and wind are not available.

Table 12. POTENTIAL CONTRIBUTION OF RNG TO RENEWABLE ELECTRICITY[76]
(based on using all RNG for power generation)

Estimated Hourly Capacity (MW)	652
% of Renewable Power Supply	11.25%

(For more on emissions reductions associated with using RNG to displace conventional natural gas or to generate electricity, please see "Climate and Clean Air Benefits of Displacing Conventional Natural Gas with RNG" in Task 3.)

Alternatively, the potential RNG resource could be used to establish a beachhead to "renewables independence" in transportation, an area that currently has few options. The potential RNG resource represents 48 times the amount of natural gas currently used as vehicle fuel, and potentially 24% of diesel fuel now used—in both cases with significantly lower emissions. The coordinated expansion of CNG capable vehicles and fueling infrastructure would provide a beneficial outlet for methane from decomposing organics that will need to be captured in order to prevent the worst impacts of climate change

Task 2: Preliminary Evaluation of Colorado's Current & Potential RNG Resource

RNG PROJECTS OPERATING/UNDER CONSTRUCTION/IN DEVELOPMENT IN COLORADO, BY FEEDSTOCK

WASTEWATER PROJECTS

At this time, wastewater is the only waste resource in Colorado that has seen any real RNG development.

- A project is already in operation at **Grand Junction's Persigo facility**, where the output is being used to fuel municipal vehicles.
- RNG projects are also under construction at the wastewater facility in **Longmont**, and at the **South Platte Water Renewal Partners facility in Englewood**.[77]
  Another project is in the planning stages in **Boulder**, and is anticipated to go online spring 2020.[78]
  (Longmont plans to use RNG for local fleets, and anticipates using only a portion of the estimated output shown below.[79])

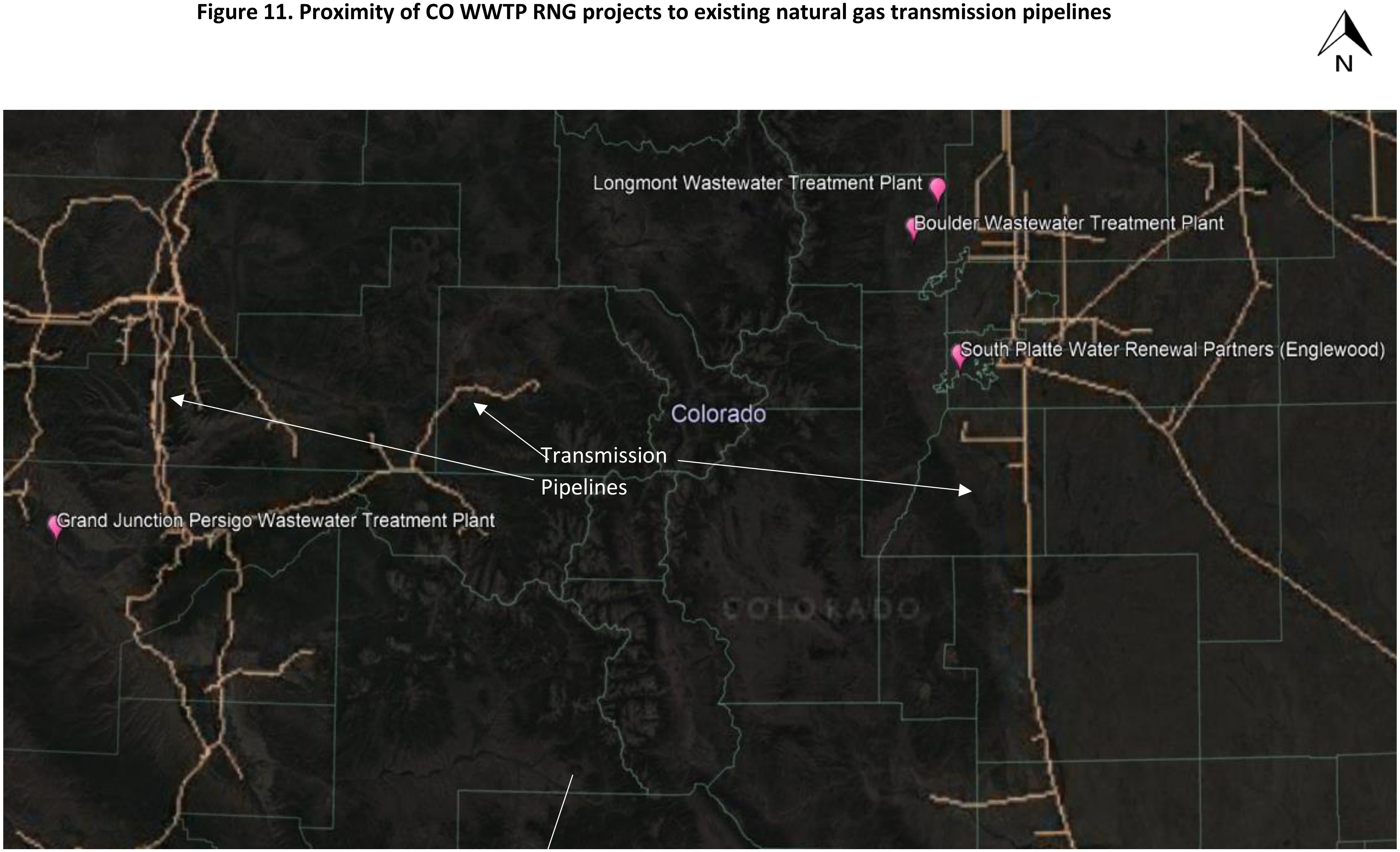
Information about these projects is summarized below, sorted by project status.

TABLE 13. WASTEWATER PROJECTS IN OPERATION OR UNDER DEVELOPMENT

City/Utility	Status	End use	Average flow, MGD	SCFD biogas	SCFY biogas	BTUs/CF	SCFY RNG (assumes 970 BTU/CF)	MMBTU/ year	DGE/year
Grand Junction	Operational	Municipal fleets	8.5	93,000	33,945,000	587	20,541,974	19,925	145,040
Longmont	Under Construction	Municipal fleets	7	100,000	36,500,000	570	21,448,454	20,805	151,440
Englewood (SPWRP)	Under Construction	Pipeline injection	20	365,300	133,334,500	600	82,474,948	80,000	582,327
Boulder	Planning	Pipeline injection for fleet use in Colorado	15	197,260	72,000,000	550	40,824,742	39,600	288,249
TOTALS			**50.5**	**755,560**	**275,779,500**		**165,290,119**	**160,331**	**1,167,057**

A map showing the location of these facilities in relation to natural gas transmission pipelines in Colorado is below,[80] followed by a table showing estimated distances to the pipelines. These and similar maps and tables below are based on inter-and intrastate transmission pipelines only, and do not include local distribution lines that may provide more local access to the larger natural gas transmission network.)

Figure 11. Proximity of CO WWTP RNG projects to existing natural gas transmission pipelines



(Based on US EIA pipeline maps and Google Earth.)

Estimated distance between facilities and nearby transmission pipelines is summarized in the table below. It is worth noting that due to the combination of relatively small scale and large distance from pipelines, the Grand Junction project's RNG production is used locally by municipal fleets; the same is planned for Longmont's production.

TABLE 14. Estimated distances of operational/under construction/in planning Wastewater RNG projects from natural gas transmission pipelines

Facility	Estimated RNG potential (DGE)	Estimated distance from Pipeline (miles)
Grand Junction	145,040	25
Longmont	151,440	18
Englewood	582,327	10
Boulder	288,249	14

(Distances are estimates based on Google Earth scale.)

LANDFILL PROJECTS

There are currently no RNG projects operating at Colorado landfills. One is in the planning stages at the **Denver Arapahoe Disposal Site (DADS)**, roughly 15 miles southeast of central Denver and owned by the City and County of Denver. A landfill gas to energy project has been in place at DADS since 2008, using approximately 1000 CFM of landfill gas (LFG) to generate electricity that is sold to utility Xcel Energy under a power purchase agreement (PPA).

With the site still flaring ~2000 CFM of LFG, and the challenging economics of LFG to electricity, the City plans to terminate the PPA with Xcel early and switch to producing RNG. Approval from the Mayor's office is expected summer 2019; the Colorado Department of Public Health and the Environment (CDPHE) anticipates issuing a request for proposals (RFP) by the end of the year, with an intended timeline that includes construction beginning summer 2020 and the facility becoming operational by the end of that year. A major gas pipeline runs within 200 feet of the existing gas-to-electricity project.[81]

The anticipated output of the project is shown below, based on 3,000SCFM flow of gas and 500 BTU per cubic foot of gas.[82]

TABLE 15. Estimated output of planned DADS RNG project

Estimated flow of landfill gas to project (SCFD)	Total annual flow in (SCFY)	Est. annual upgraded gas (SCFY)	Total BTUs @ 970/CF	Estimated annual MMBTU	Estimated annual DGE
4,320,000	1,576,800,000	812,783,505	788,400,000,000	788,400	5,738,785

AGRICULTURAL PROJECTS

Based on Energy Vision's work curating a national database of RNG projects for the US DOE, there is a single agricultural RNG project in development in Colorado.[83] This project, approximately 1 mile east of Yuma in Yuma County, is in the advanced planning stages, and will agglomerate manure from 7,000 cows on multiple dairy farms at a single digester facility. Gas will be injected into the interstate pipeline network; based on US EIA maps, pipelines pass approximately 2 miles to the west, approximately 8 miles to the east, and less than 3 miles to the south.

The developer hopes to move into construction in the fall of 2019, and be operational by summer 2020. Estimated output for the project is shown in Table 16.

TABLE 16. Estimated output of Yuma County dairy RNG project[84]

Estimated flow of untreated biogas (CFD)	Total annual flow (CF)	Estimated annual upgraded gas (CF)	Total BTUs @ 970/CF	Estimated annual MMBTU	Estimated annual DGE
800,000	292,000,000	181,000,000	177,570,000,000	177,570	1,278,000

FOOD WASTE PROJECTS

Other than the Heartland Biogas digester project in LaSalle, Weld County, which was shut down in late 2016 due to odor complaints and other regulatory challenges, Energy Vision found no references to dedicated food waste RNG projects in Colorado in either the construction or planning phases. While there appears to be interest in reviving the Heartland project, at this point there are no guarantees that any effort(s) to do so will be successful.

POTENTIAL COLORADO RNG PROJECTS, BY FEEDSTOCK

The gap between existing production and in-state RNG potential is extremely large in Colorado, which is also the case at the national level. Abundant feedstocks for RNG production exist in the state, as indicated in the following section.

WASTEWATER

In addition to the existing RNG projects described above, Energy Vision identified other facilities with sufficient flow of wastewater to potentially support a project. These include the Metro Wastewater Reclamation District (MWRD), which serves 60 municipalities and sanitation districts, including some of the state's largest (e.g. Denver, Aurora); and other independent facilities serving populations over 50,000.

TABLE 17. POTENTIAL ENERGY PRODUCTION FROM WASTEWATER FACILITIES

POTENTIAL ENERGY PRODUCTION FROM WASTEWATER								
City/Utility	**Total Capacity, MGD**	**Average flow, MGD**	**SCFD biogas**	**SCFY biogas**	**BTUs/CF**	**SCFY RNG (assumes 970 BTU/CF)**	**MMBTU/ year**	**DGE/year**
MWRD	244	134.5	2,745,000	1,001,925,000	570	588,760,052	571,097	4,157,032
Colorado Springs	95	39	576,000	210,240,000	600	130,045,361	126,144	918,206
Fort Collins	29	20.7	169,717	61,946,705	600	38,317,549	37,168	270,547
Pueblo	19	10	144,000	52,560,000	580	31,427,629	30,485	221,900
Greeley	14.7	7.7	211,194	77,085,896	560	44,503,198	43,168	314,222
Broomfield	5.4	3.6	55,000	20,075,000	550	11,382,732	11,041	80,370
Loveland	10	5.5	62,195	22,700,000	550	12,871,134	12,485	90,879
Centennial	8.48	6.5	172,800	63,072,000	645	41,939,629	40,681	296,121
TOTALS	**425.58**	**227.5**	**4,135,903**	1,509,604,601		899,247,283	872,270	7,129,333

The location of these facilities relative to natural gas transmission pipelines in Colorado is shown on the map on the following page—bearing in mind that the presence of a pipeline does not mean that it has capacity to accept RNG.

While only a few of these facilities are close enough to a pipeline to do a direct physical connection, all are theoretically close enough to transfer RNG via “virtual pipeline”—i.e., by loading gas onto special transport trucks for direct delivery to an end user, or to a central injection point along a natural gas distribution or transmission pipeline.

FIGURE 12. Colorado Wastewater Treatment Facilities in relation to natural gas transmission pipelines

(Based on US EIA pipeline maps and Google Earth.)

The table below shows the estimated distance between various wastewater treatment facilities and the nearest natural gas pipeline.

TABLE 18. Estimated distances of wastewater facilities from natural gas transmission pipelines

(Distances are estimates based on Google Earth scale.)

Facility	Estimated Annual RNG potential (DGE)	Estimated distance from Pipeline (miles)
MWRD, Brighton	116,696	3
Colorado Springs	918,206	3
Pueblo	221,900	3
MWRD, Denver	4,157,032	10
Fort Collins	270,547	10
Greeley	314,222	10
Englewood	582,327	10
Loveland	90,884	12
Boulder	288,249	14
Broomfield	80,370	15
Centennial	296,121	16
Longmont	151,440	18
Grand Junction	145,040	25

LANDFILLS

A note on landfills and local climate: Three developers of landfill biogas projects, one specifically referencing projects in Colorado, have noted that biogas output from landfills in more arid climates is generally lower than for landfills in wetter locations.[85] While one developer saw the impact as relatively dramatic, another described it as “recognizable,” emphasizing that each landfill site is unique in the factors that might reduce its ouptut—for example, its proximity to a major metropolitan center, the existence of area food waste diversion mandates, and whether the landfill is recirculating leachate.[86] The third noted that the depth of the landfill can also impact the presence/availability of moisture and thus of biogas production.

Data from the US EPA’s Landfill Methane Outreach Program (LMOP) also indicates that climate makes a difference: LFG projects in Colorado show lower production than simlar-sized projects elsewhere. While this should not be considered conclusive in terms of the degree of impact—the data doesn’t address additional factors that might be at play—it should be taken into account.

Table 19 below compares LMOP data for each of three Colorado landfills with two similarly sized projects in other states. (For all projects the “waste in place year” is 2017.)

TABLE 19. Differences in landfill gas production by region/climate[87]

Colorado Landfill	Waste In Place (tons)	Gas Output, MMSCFD	Comparison landfill	Waste In Place (tons)	Gas output, MMSCFD	Ratio W-I-P	Ratio Gas Ouput
Denver Arapahoe Disposal Site	66,291,826	3.816	Altamont, CA	60,362,396	8.33	1.098	2.182
Denver Arapahoe Disposal Site	66,291,826	3.816	DFW, Lewisville TX	68,232,232	8.13	0.972	2.131
Denver Regional Landfill (South)	14,430,062	1.273	Jefferson Parish, LA	14,576,327	1.809	0.990	1.421
Denver Regional Landfill (South)	14,430,062	1.273	C&C LF, Marshall MI	14,536,878	3.8	0.993	2.985
Front Range Landfill	14,253,008	0.814	Sonoma County, CA	14,211,211	2.872	1.003	3.528
Front Range Landfill	14,253,008	0.814	Ada County, ID	14,257,317	4.226	1.000	5.192

However, when one of the Colorado sites is compared to a landfill in another arid climate—Nevada—the gas ouput is much more similar, supporting the idea that area climate effects gas production.

TABLE 20. Similarities in landfill gas production by region/climate[88]

Colorado Landfill	Waste In Place (tons)	Gas ouput, MMSCFD	Comparison landfill	W-I-P (tons)	Gas output, MSCFD	Ratio W-I-P	Ratio Gas Ouput
Denver Arapahoe Disposal Site	66,291,826	3.816	Apex,Las Vegas NV	67,436,645	3.652	0.983	0.957

POTENTIAL BIOGAS PRODUCTION FROM COLORADO LANDFILLS

According to the US EPA's Landfill Methane Outreach Program (LMOP) database, there are 38 landfills in Colorado. 13 have biogas collections systems in place; 7 of these are flaring all the gas they collect. Twenty-seven landfills are discussed here. Landfills that have been excluded include:

- one for which LMOP had no location information;
- one that is actually a "dry" landfill that does not accept putrescible (i.e. organic) waste;
- five classified in LMOP as having "low [biogas] potential";
- four others that have been closed for 25 years or more, weakening them as candidates.

The remaining landfills are still open, or have been closed within the last few years. It is worth noting that of these 27, only 9 are confirmed to have landfill gas collection systems in place, according to LMOP. Of these, 5 are reportedly flaring all their gas.

The potential output for these sites is summarized in the table below, using the EPA's **"LFGCost"** landfill gas production modeling tool. Because of incomplete data on waste in place, open and close dates and the amount of waste added annually—all important variables for using LFGCost—various assumptions have been applied, flagged by ***bolded italic text***.[89]

Per the climate discussion above, these are gross numbers. The LFGCost tool does not all allow input of geographical information, and the impact of area climate on gas production is ***not*** accounted for.

TABLE 21. Colorado Landfills and Potential Biogas Production Estimates

(Based on EPA LMOP database and EPA "LFGCost" tool)

County	Landfill name	Type	Waste in Place (tons)	Estimated Annual Intake	LFG Collection?	Acres	Open Date	Close date	Est. LFG collection (SCFM)	Est. MMBTUs	Est. DGEs
Adams	East Regional	Private	1,773,299	197,033	No	142	2010	2053	1,073	160,819	1,170,608
Adams	Tower	Private	41,348,299	1,088,113	Yes	40	1981	2050	9,598	1,522,962	11,085,682
Arapahoe	Denver Arapahoe	Public	66,291,826	1,250,789	Yes	677	1966	2139	10,997	1,900,998	13,837,417
Archuleta	Archuleta Cty.	Public	***9,550,340***	***280,892***	No	***148***	1985	***2042***	2,403	380,162	2,767,210
Eagle	Eagle Cty.	Public	2,723,818	52,381	No	81.1	1967	2026	427	64,587	470,133
El Paso	Colorado Springs	Private	9,947,285	195,045	No	156	1968	2089	1,842	294,062	2,140,484
El Paso	Fountain	Private	5,456,668	102,956	Yes	104	1966	2079	980	156,477	1,138,997
El Paso	Midway	Private	6,570,008	234,643	No	74.6	1991	2091	1,890	297,441	2,165,083
Fremont	Phantom	Private	180,000	9,000	No	38	1999	***2068***	65	10,068	73,289
Garfield	South Canyon	Public	1,798,154	27,245	No	***148***	1953	***2022***	203	30,183	219,706
Garfield	W. Garfield Cty.	Public	***9,550,340***	***251,325***	Unknown	***148***	*1981*	2041	2,217	351,764	2,560,496
Jefferson	Foothills	Private	21,717,730	658,113	Yes	229	1986	2043	5,580	882,300	6,422,284
La Plata	Bondad	Private	***9,550,340***	***434,106***	No	47.2	1997	2019	1,791	266,487	1,939,765
Larimer	Larimer Cty.	Public	7,684,794	137,228	Yes	180.8	1963	2024	1,067	159,611	1,161,815
Mesa	Mesa Cty.	Public	8,688,255	241,340	Yes	127	1983	2045	2,098	332,433	2,419,789
Montrose	Montrose Cty.	Public	3,258,243	75,773	No	37.2	1976	2085	690	109,714	798,611
Montrose	Broad Canyon	Private	454,401	19,757	No	***148***	1996	2020	89	13,311	96,893
Morgan	Morgan Cty.	Public	915,183	19,895	No	***148***	1973	***2042***	184	29,297	213,256
Pitkin	Pitkin Cty.	Public	2,465,911	44,835	No	150	1964	2042	430	68,646	499,676
Pueblo	Broadacres	Private	393,114	14,560	No	283	1992	***2061***	3,133	492,331	3,583,688
Pueblo	Southside	Private	3,529,430	61,920	Yes	84	1962	2043	597	95,447	694,762
Routt	Milner	Private	2,469,485	45,731	No	51.7	1965	2058	437	69,766	507,829
Summit	Summit Cty.	Public	2,268,783	41,251	No	63.3	1964	2055	395	63,159	459,733
Weld	North Weld	Private	9,416,904	348,774	No	91.1	1992	2021	1,829	272,082	1,980,492
Weld	Denver Regional S.	Private	14,430,062	370,002	Yes	290	1980	2020	2,167	322,402	2,346,774
Weld	Front Range	Private	14,253,008	619,696	Yes	78.3	1996	2048	4,681	731,620	5,325,483
Weld	Buffalo Ridge	Private	***9,550,340***	***561,785***	No	230	2002	2061	3,815	589,277	4,289,361
TOTALS									**60,678**	**9,667,407**	**70,369,316**

The map below shows the location of the 27 landfills in question in relation to existing gas transmission pipelines.

Figure 13. Colorado landfills in relation to natural gas transmission pipelines.

(Based on US EIA pipeline maps and Google Earth.)

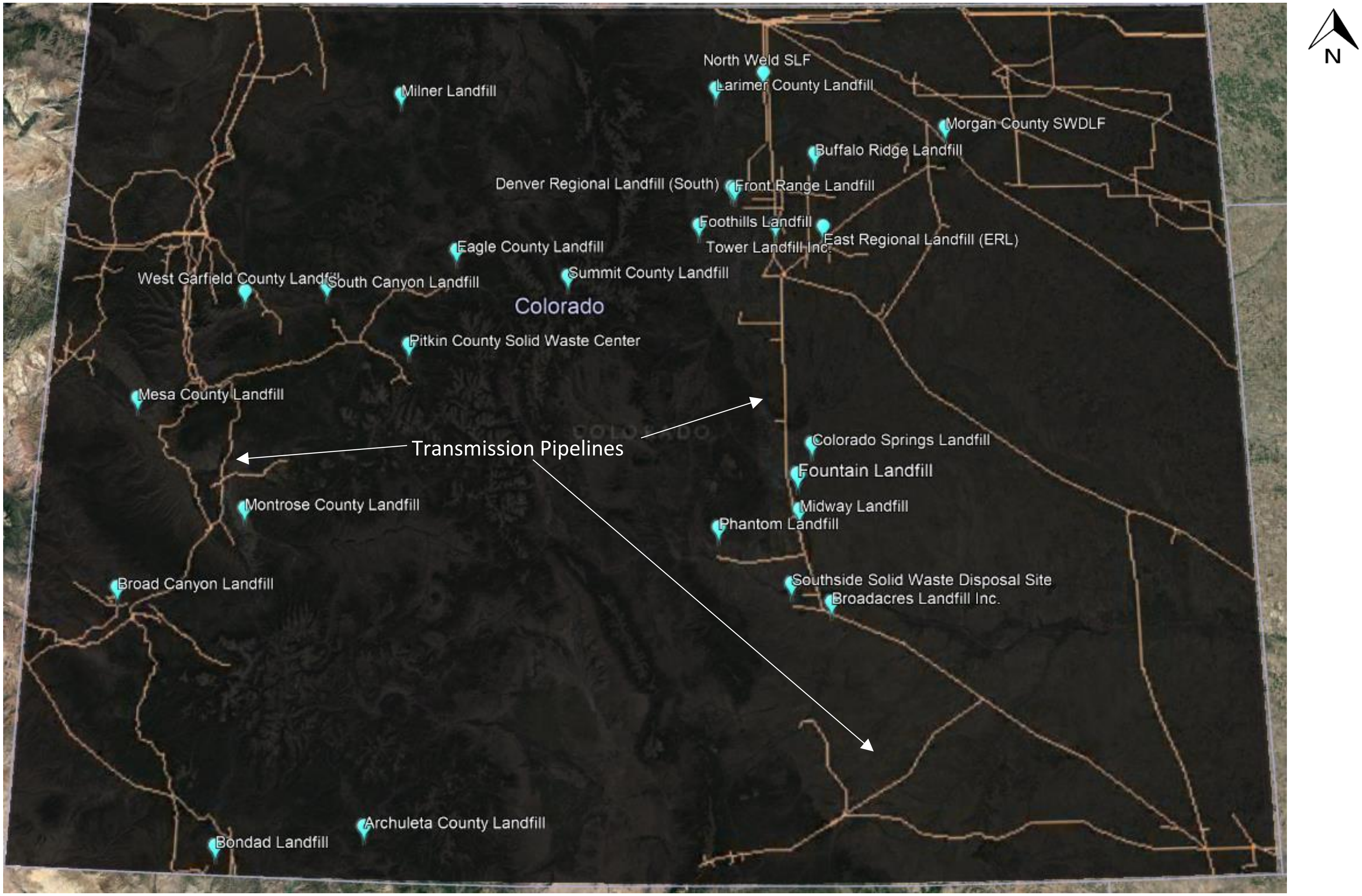


TABLE 22. Estimated distances of landfills from natural gas transmission pipelines (near to far)

(Distances are estimates based on Google Earth scale)

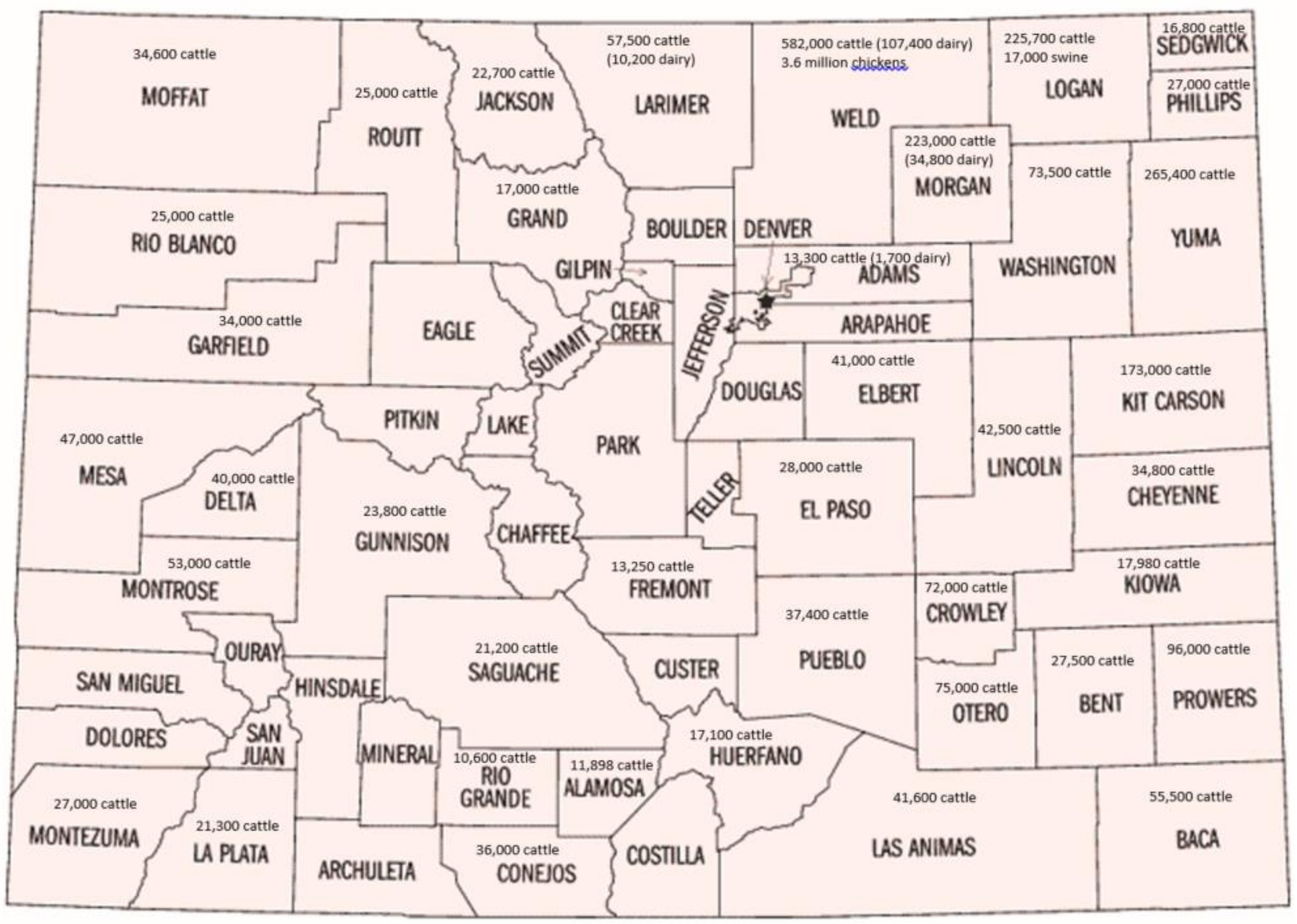
County	City	Landfill name	Estimated LFG collection (SCFM)	Estimated Average Annual RNG production (DGE)	Estimated distance from pipeline (miles)
Adams	Bennett	East Regional LF	1,073	1,170,608	1
Adams	Commerce City	Tower LF	9,598	11,085,682	1
El Paso	Fountain Valley	Midway LF	1,890	1,138,997	1
Weld	Ault	North Weld SLF	1,829	1,980,492	1
Arapahoe	Aurora	Denver Arapahoe Disposal Site	10,997	13,837,417	2
Montrose	Naturita	Broad Canyon LF	89	96,892	2
Pueblo	Pueblo	Broadacres LF	3,133	3,583,688	2
El Paso	Fountain	Fountain LF	980	1,138,987	3
Morgan	Fort Morgan	Morgan Cty. SWDLF	184	213,256	3
Pueblo	Pueblo	Southside Solid Waste Disposal Site	597	684,762	3
Weld	Erie	Front Range LF	4,681	5,325,483	3
Weld	Keensburg	Buffalo Ridge LF	3,815	4,289,361	3
Weld	Erie	Denver Regional LF (South)	2,167	2,346,774	4
La Plata	Durango	Bondad LF	1,791	1,939,765	5
Pitkin	Snowmass Village	Pitkin Cty. Solid Waste Ctr.	430	499,676	5
Fremont	Penrose	Phantom LF	65	73,289	6
Garfield	Glenwood Springs	South Canyon LF	203	219,706	6
Garfield	Rifle	West Garfield Country LF	2,217	2,560,496	6
El Paso	Colorado Springs	Colorado Springs LF	1,842	2,140,484	7
Montrose	Montrose	Montrose Country LF	690	798,611	7
Eagle	Wolcott	Eagle Cty. LF	427	470,133	9
Mesa	Grand Junction	Mesa Cty. LF	2,098	2,419,789	15
Larimer	Fort Collins	Larimer Cty. LF	1,067	1,161,815	18
Jefferson	Golden	Foothills LF	5,580	6,422,284	25
Routt	Milner	Milner LF	437	507,829	30
Archuleta	Pagosa Springs	Archuleta Cty. LF	2,403	2,767,210	40
Summit	Dillon	Summit Cty. LF	395	45,9733	40

Based on US EIA pipeline maps, at least a dozen of these facilities are close enough to a pipeline to do a direct connection, again recognizing that pipeline proximity and pipeline capacity are two different things. All are theoretically close enough for a “virtual pipeline” connection.

AGRICULTURAL SOURCES

The main potential agricultural sources of biogas in Colorado are livestock manures, including from chicken, swine and beef/dairy cattle. Select livestock populations around the state are shown on the map below. Projects based on chicken "litter" require hundreds of thousands of birds, and only Weld County had a population meriting inclusion. Swine manure projects require tens of thousands of animals, and only Logan County crossed that threshold. Minimum cattle herd size reflected below is 10,000 head. (*It should be remembered in all cases that these populations are spread out across multiple farms within the county, requiring either centralized projects to which manure is delivered or multiple projects involving several farms each.)*

FIGURE 14. Notable Colorado Livestock Populations[90]



POULTRY

As noted, RNG projects based on chicken manure require very large bird populations. Such a population of layer chickens (as opposed to broilers) exists only in Weld County, as detailed in Table 23.[91]

Table 23. Potential energy production from Weld County poultry

County	Chickens	Estimated tons manure per day	Estimated tons manure annually	Annual energy, MMBTU	Annual energy, DGE
Weld	3,589,000	181.73	66,332	430,424	3,133,045

SWINE

The largest swine population in the state is in Logan County, and estimated energy production for that population is shown in Table 24 below. Spread across 22 farms in the county, it seems unlikely that a project attempting to agglomerate this total amount of manure would make economic sense for a developer.

Further, swine farms in Colorado are regulated by 1998's *Amendment 14*, which imposes strict controls on handling and disposal of swine manure (it applies to no other livestock). Farmers cannot transfer their liability for their manure to another party—e.g., the owner of a merchant digester. While a swine farm can build its own digester, even land application of that digestate is subject to strict regulation, and the digestate can't be transferred, except possibly for use out of state. [92,93]

Table 24. Potential energy production from Logan County swine[94]

County	Swine Population	Estimated tons manure per day	Estimated tons manure annually	Est. Potential MMBTU/year	Est. Potential DGEs per year
Logan	17,000	134	48,910	15,300	111,369

CATTLE

According to the USDA's Census of Agriculture, Colorado had over 2.8 million cattle in 2017.[95] The vast majority of these were beef cattle. Beef and dairy cattle are addressed separately below since, among other factors, dairy cows are generally larger, and produce more manure and therefore more biogas. More is also known about biogas production from dairy manure.

TABLE 25. Estimated Potential Biogas Production from *Dairy* Cattle Manure[96]

County	Dairy cattle	Total CF biogas/day	Total CF clean gas	Daily BTU @ 970 BTU/CF and 70% manure recovery	Annual BTU	Annual MMBTU	Annual DGE
Weld	107,387	8,590,960	4,871,163	3,307,519,600	1,207,244,654,000	1,207,245	8,787,566
Morgan	34,838	2,787,040	1,580,280	1,073,010,400	391,648,796,000	391,649	2,850,822
Larimer	10,199	815,920	462,635	314,129,200	114,657,158,000	114,657	834,593
TOTALS	**152,424**	**12,193,920**	**6,914,078**	**4,694,659,200**	**1,713,550,608,000**	**1,713,551**	**12,472,981**

Producing biogas from beef manure is historically more challenging than for dairy manure, and literature on it is extremely limited. Challenges include the amount of manure produced; how/whether the animals are sheltered; and animal life span. In broad terms, beef cows physically produce less manure; live the early stage of their lives in pasture where manure recovery is impractical; and pass roughly the last five months of their lives in feedlots, where manure is collected from pens only infrequently, and is exposed to the elements, causing it to dry out or wash away. (For a more detailed discussion, see *Appendix 1.)* Despite these challenges, a major regional gas utility is involved the development of AD/RNG projects at beef feedlots in Iowa that “aggressively manage” their manure.[97]

Estimates for potential biogas production from beef manure in Colorado are shown below. Based on USDA literature and communications with industry and academia (see endnotes in Appendix 1), it is assumed that beef cattle produce roughly 45CF of biogas daily compared to 80 for a dairy cow. Though two people interviewed maintained that beef manure has a slightly higher energy content than dairy manure (~9%), in the interests of a conservative estimate it is assumed below to be the same. For the table below, manure recovery is assumed to take place on a more regular basis than is likely the case in Colorado’s feedlots, and is pegged at a probably-optimistic 25%. Even so, this represents a substantial potential resource.

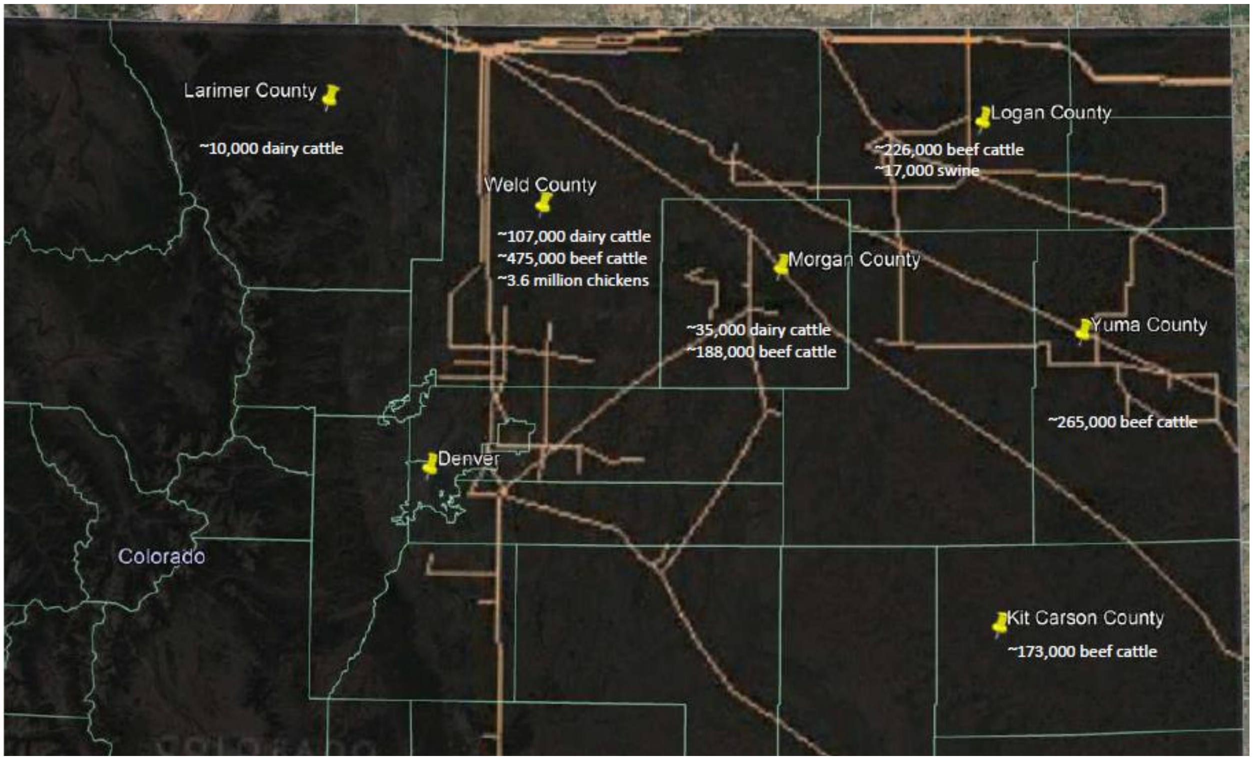
TABLE 26. Estimated Potential Biogas Production from *Beef* Cattle Manure[98]

(by County in descending order)

County	Total cattle	Total CF biogas/day	Total CF clean gas	BTU/day at 970 BTU/CF	Assume 25% manure collection	Annual BTU	MMBTU/Year	DGE/year
Weld	474,880	21,369,600	12,116,784	11,753,280,000	2,938,320,000	1,072,486,800,000	1,072,487	7,806,660
Yuma	265,393	11,942,685	6,771,626	6,568,476,750	1,642,119,188	599,373,503,438	599,374	4,362,856
Logan	225,744	10,158,480	5,759,963	5,587,164,000	1,396,791,000	509,828,715,000	509,829	3,711,057
Morgan	188,200	8,469,000	4,802,010	4,657,950,000	1,164,487,500	425,037,937,500	425,038	3,093,863
Kit Carson	173,384	7,802,280	4,423,973	4,291,254,000	1,072,813,500	391,576,927,500	391,577	2,850,299
Prowers	96,398	4,337,910	2,459,640	2,385,850,500	596,462,625	217,708,858,125	217,709	1,584,709
Otero	75,253	3,386,385	1,920,115	1,862,511,750	465,627,938	169,954,197,188	169,954	1,237,101
Washington	73,532	3,308,940	1,876,203	1,819,917,000	454,979,250	166,067,426,250	166,067	1,208,809
Crowley	72,158	3,247,110	1,841,145	1,785,910,500	446,477,625	162,964,333,125	162,964	1,186,222
Baca	55,493	2,497,185	1,415,930	1,373,451,750	343,362,938	125,327,472,188	125,327	912,262
Montrose	53,051	2,387,295	1,353,621	1,313,012,250	328,253,063	119,812,367,813	119,812	872,117
Larimer	47,300	2,128,500	1,206,881	1,170,675,000	292,668,750	106,824,093,750	106,824	777,575
Mesa	46,952	2,112,840	1,198,002	1,162,062,000	290,515,500	106,038,157,500	106,038	771,855
Lincoln	42,545	1,914,525	1,085,555	1,052,988,750	263,247,188	96,085,223,438	96,085	699,407
Las Animas	41,650	1,874,250	1,062,719	1,030,837,500	257,709,375	94,063,921,875	94,064	684,694
Elbert	40,779	1,835,055	1,040,495	1,009,280,250	252,320,063	92,096,822,813	92,097	670,375
Delta	40,550	1,824,750	1,034,652	1,003,612,500	250,903,125	91,579,640,625	91,580	666,611
Pueblo	37,418	1,683,810	954,738	926,095,500	231,523,875	84,506,214,375	84,506	615,123
Conejos	35,855	1,613,475	914,857	887,411,250	221,852,813	80,976,276,563	80,976	589,428
Cheyenne	34,782	1,565,190	887,479	860,854,500	215,213,625	78,552,973,125	78,553	571,789
Moffat	34,663	1,559,835	884,443	857,909,250	214,477,313	78,284,219,063	78,284	569,833
Garfield	34,267	1,542,015	874,338	848,108,250	212,027,063	77,389,877,813	77,390	563,323
El Paso	28,082	1,263,690	716,525	695,029,500	173,757,375	63,421,441,875	63,421	461,646
Bent	27,518	1,238,310	702,135	681,070,500	170,267,625	62,147,683,125	62,148	452,375
Phillips	27,298	1,228,410	696,521	675,625,500	168,906,375	61,650,826,875	61,651	448,758
Montezuma	26,889	1,210,005	686,085	665,502,750	166,375,688	60,727,125,938	60,727	442,034
Rio Blanco	25,253	1,136,385	644,342	625,011,750	156,252,938	57,032,322,188	57,032	415,140
Routt	24,882	1,119,690	634,876	615,829,500	153,957,375	56,194,441,875	56,194	409,041
Gunnison	23,819	1,071,855	607,753	589,520,250	147,380,063	53,793,722,813	53,794	391,566
Jackson	22,758	1,024,110	580,681	563,260,500	140,815,125	51,397,520,625	51,398	374,124
La Plata	21,301	958,545	543,505	527,199,750	131,799,938	48,106,977,188	48,107	350,172
Saguache	21,264	956,880	542,561	526,284,000	131,571,000	48,023,415,000	48,023	349,564
Kiowa	17,980	809,100	458,768	445,005,000	111,251,250	40,606,706,250	40,607	295,577
Huerfano	17,144	771,480	437,437	424,314,000	106,078,500	38,718,652,500	38,719	281,834
Grand	17,031	766,395	434,554	421,517,250	105,379,313	38,463,449,063	38,463	279,976
Sedgwick	16,849	758,205	429,910	417,012,750	104,253,188	38,052,413,438	38,052	276,985
Adams	13,300	598,500	339,356	329,175,000	82,293,750	30,037,218,750	30,037	218,642
Fremont	13,250	596,250	338,080	327,937,500	81,984,375	29,924,296,875	29,924	217,820
Alamosa	11,898	535,410	303,583	294,475,500	73,618,875	26,870,889,375	26,871	195,594
Rio Grande	10,598	476,910	270,413	262,300,500	65,575,125	23,934,920,625	23,935	174,223
TOTALS	**2,557,361**	**115,081,245**	**65,252,252**	**63,294,684,750**	**15,823,671,188**	**5,775,639,983,438**	**5,775,640**	**42,041,039**

The first 5 counties listed in Table 26 (highlighted) account for over 50% of the beef manure RNG potential. The same counties account for the one swine population with any RNG potential (Logan); the only county with any poultry potential (Weld); and 2 of the 3 with dairy potential. All these counties are in the northeastern part of the state, and their location in relation to Denver and natural gas transmission pipeline infrastructure is indicated on the map below. Larimer County, the third with dairy potential, is also shown.

Figure 15. Counties with the greatest manure potential for RNG production



Based on US EIA's pipeline maps, Logan, Weld and Yuma County have significant natural gas transmission pipeline infrastructure. Kit Carson has only a single line crossing the northeast corner of the state. Larimer County appears to have natural gas transmission pipeline infrastructure only in the furthest northeast corner.

Information on the exact locations of livestock farms/feedlots was unavailable. The Colorado Livestock Association used to maintain and publish maps of facilities, but as sentiment grew against concentrated animal feeding operations (CAFOs), they stopped collecting the data.[99] According to a representative of the CLA, there is some clustering of cattle farms along state highway 34, which runs roughly east-west through Yuma and Morgan counties, paralleling and crossing pipelines in those counties. There is similar clustering around I-76, which runs northeast from Morgan City through Morgan and Logan Counties to join I-80 near the Nebraska border, crossing pipelines as it goes.

Figure 16. Major Manure Producing Counties in Relation to Key Roads

FOOD WASTE

A note on anaerobic digestion vs. composting: *AD and composting are both methods for managing organic wastes. They are often viewed in opposition to each other, as an "either/or" equation. This is not necessarily the case. Some materials are better suited for one than the other—food waste put in a digester produces more energy and digests more easily than yard waste, for instance—and local conditions and needs will also affect which makes more sense. Anaerobic digesters have the advantage of producing energy* ***and*** *compost as a by-product, but that doesn't mean AD is going to be practical in every locale. For a general discussion of AD vs. compost and the opportunities for integrating them, please consult the BioCycle article referenced in this endnote.*[100] As noted above, food waste in Colorado has the potential to contribute 902,000 MMBTU/6.565 million DGE of renewable natural gas (see Table 8). This is based on a diversion rate of 35% for all food waste, per the state's goals for 35% MSW diversion.

This number is a composite of multiple sources, including estimates for commercial and residential food waste in a 2016 "Colorado Integrated Solid Waste & Materials Management Plan" prepared by consultants for CDPHE.[101,102] Communication with an author of that report and review of some of its source documents indicate that its commercial sources include food waste from supermarkets, restaurants and hotels, but not from food and beverage manufacturing or from institutional generators (correctional facilities, educational institutions or hospitals).[103,104]

Table 27 below provides a rough estimate of food waste potentially available from these sources. This is based on the EPA's "Excess Food Opportunities" database, which tracks potential sources of excess food for recycling (whether for human consumption, composting or anaerobic digestion), but is by no means exhaustive.[105] Table 28 shows the data from the "Integrated Solid Waste Management Plan". In both cases, a diversion rate of 35%, in keeping with state diversion targets for municipal solid waste, is assumed.

TABLE 27. Estimated biogas production from discarded food at various types of facilities.

Limited to facilities generating at least one half ton of food waste weekly.

Type of Institution	Tonnage Estimate[106]	Percent Diverted to AD	Tonnage to AD	Estimated MMBTU	Estimated DGE
Food and Beverage manufacturing	59,317.00	35%	29,658.50	81,561	593,684
Educational	13,076.65	35%	4,576.83	12,586	91,616
Correctional	7,435.55	35%	3,717.77	10,224	74,420
Hospitals	2,493.59	35%	1,246.80	3,429	24,957
Totals	82,322.79	35%	41,161.39	107,799.71	784,677

TABLE 28. Estimated biogas production from residential and commercial food waste

(Based on 2016 "Integrated Solid Waste and Materials Management Plan.")

Region	Residential & commercial food scraps	Percent Diverted to AD	Tonnage to AD	Estimated MMBTU	Estimated DGEs
Front range	736,600	35%	257,810	660,475	4,807,615
Mountains	40,600	35%	14,210	36,404	264,986
Eastern/southeastern	31,300	35%	10,955	28,065	204,286
Western Slope	77,200	35%	27,020	69,222	503,869
Totals	885,700	35%	309,995	794,166	5,780,756

TABLE 29. Estimated totals for food waste

	Estimated Tonnage	Percent Diverted to AD	Tonnage to AD	Estimated MMBTU	Estimated DGE
Estimated Grand Total, Food Waste	***968,022.79***	35%	***351,156.39***	***901,965.71***	***6,565,432.73***

According to US Census data from 2012, food and beverage manufacturing in Colorado employs over 21,000 people in over 1,300 firms with a combined payroll of more than $870 million.[107] It seems likely that these business generate a significant amount of food scraps that cannot be redirected for human consumption. For example, a representative of the natural gas vehicle industry who recently visited a major meat-processing facility estimates that the plant's wastewater represented a potential 500,000 DGEs of RNG annually.[108]

Appendix 2 includes a partial count of food and beverage manufacturing businesses in Colorado. (A report run from the US Census database for establishments by county and NAICS industry group only yielded 468 firms.) Appendix 2 also provides maps showing geographical industry concentrations in the state (provided by the Colorado Office of Economic Development and International Trade).

Colorado Food Waste Diversion Policies

Colorado has no state food waste diversion mandate promoting recycling of food waste.[109] General MSW diversion targets proposed in the 2016 "Colorado Integrated Solid Waste and Materials Management Plan"[110] were adopted as goals in 2017 by the CDPHE's Solid and Hazardous Waste Commission,[111] and are now part of legislation taking effect in August 2019.[112] Given the "economic and logistical challenges" of recycling in thinly populated areas, the goals established higher targets for the “Front Range” counties containing the majority of Colorado’s population than for the counties of “Greater Colorado” (see below).[113,114]

TABLE 30. Waste Diversion Goals for Colorado

Diversion Goals	2016	2021	2026	2036
Front Range*	N/A	32%	39%	51%
Greater Colorado*	N/A	10%	13%	15%
Statewide	19%	28%	35%	45%

**“Front Range” includes counties of Adams, Arapahoe, Boulder, Broomfield, Denver, Douglas, El Paso, Jefferson, Larimer, Pueblo and Weld. “Greater Colorado” covers the rest of the state.*

It should be noted that the goals set no targets specifically for diversion of food waste or other organics, and both the Solid and Hazardous Waste Commission’s resolution and the new legislation treat them as aspirational, with no enforcement or penalty provisions. However, the new legislation does provide funding to help achieve them (see below).

State Support for Organics Diversion

Since 2007 CDPHE, through its Pollution Prevention Advisory Board, has administered the *“Recycling Resources Economic Opportunity” (RREO)* grant program. The program seeks to promote economic development through diversion of materials from landfills, by helping to promote development of recycling infrastructure and of “sustainable behavior change” statewide. The program, funded through landfill tipping fees, has made nearly $25 million in grants to non-profits, local governments, business, schools and universities. The program website specifically states support for anaerobic digestion; according to a program representative, it has made a single $400,000 AD-related grant. The program is scheduled to sunset in 2026.[115]

The new legislation mentioned above, in an effort to meet the waste-diversion goals, establishes the *“Front Range Waste Diversion Enterprise Grant Program.”* This program will be very similar to the RREO, and will also be funded through landfill tipping fees, but will focus specifically on the Front Range counties. The Diversion Enterprise Program legislation does not specifically mention anaerobic digestion, but does specify that funding be available for both residential and commercial food waste diversion. The program’s mandate expires in 2029.

Local Food Waste Diversion Policies

There is currently little in the way of local food waste diversion programs, though some localities are working to raise the profile of organics recycling.

Boulder’s “Universal Zero Waste Ordinance” mandates that all multifamily property managers arrange for recycling and compost collection, and provide appropriate containers. Property managers are required to provide information and training on how to use the different containers, but nothing in the ordinance actually requires residents to use them.

Boulder businesses are required to separate recyclables and compostables into appropriate containers, and to train employees on how to use them. Haulers are required to accept compostables, and to deliver them to a facility that complies with state composting regulations and “can certify that the material is processed into a compost or biogas product.”[116]

The City and County of Denver offers voluntary, fee-based curbside organics pick up for single family homes and multifamily buildings with seven units or less.[117] At least one commercial hauler offers organics collection services to its commercial clients, but there are no organics diversion mandates.[118]

Vail's curbside recycling program does not include organics. Other than periodic composting events held by the city, it is up to whether or not a specific hauler provides organics services.[119]

***Task 3:** Environmental, Climate & Other Benefits of Using RNG to Displace Conventional Natural Gas or Diesel*

While Colorado's existing RNG production is limited to a handful of its smaller municipal wastewater facilities, as detailed in Task 2, the state's resource potential—based on known organic waste feedstocks and proven technology(s)—is approximately 19.4 million MMBTU per year.

CURRENT NATURAL GAS DEMAND IN RELATION TO PROJECTED RNG SUPPLY POTENTIAL

In comparison to existing non-transportation natural gas consumption in Colorado across all sectors/end-uses (see Table 31 below), anticipated RNG production potential is rather small, at approximately 4.6% of total current demand.

TABLE 31. Colorado Natural Gas Consumption by Sector and Estimated Associated Emissions (2018)

	Million MMBTU	**Million Metric Tons CO2e[120]**
Total Consumption	***423.4***	***22.42***
Volumes Delivered to Colorado Consumers		
Residential	138.3	7.3
Commercial	59.9	3.2
Industrial	92	4.9*
Vehicle Fuel	.461	.02*
Electric Power	132.7	7

**US EIA Emissions Estimates for Industrial and Transportation sector natural gas usage are inconsistent with the EPA emissions calculator. For purposes of consistency and comparability, we have deferred to the EPA calculations for this assessment.*

However, when compared to individual segments of natural gas demand in Colorado, the potential for in-state RNG production to displace conventional natural gas becomes more promising, as indicated in Table 32 below. The associated carbon emission reduction benefits are also significant.

TABLE 32. In-State RNG Production Potential as a Percentage of Existing Sector-Specific Demand

Natural Gas Demand by Sector (Million MMBTU)	***2018***	**% Displacement via RNG**
Residential	138.3	13.7%
Commercial	59.9	31.7%
Industrial	92	21%
Vehicle Fuel	.461	4,187%
Electric Power	132.7	14.5%

CLIMATE & CLEAN AIR BENEFITS OF DISPLACING CONVENTIONAL NATURAL GAS WITH RNG

RNG—nearly pure methane (CH_4)—burns nearly identically to conventional natural gas, meaning that its combustion generates carbon dioxide (CO_2) and water (H_2O). Because of this similarity—RNG is interchangeable and indistinguishable from conventional gas once it enters a pipeline—the clean air (criteria pollutant) benefits associated with displacement or replacement of fossil gas with RNG are minimal.

TABLE 33. Estimated Potential RNG Production & Associated Average Carbon Intensity Values

	MMBTU	**CARB Average Carbon Intensity (g/MJ CO2e)***
Animal Manure [121, 122]	7,880,593	-264
Food waste[123,124]	901,966	-24
Landfills[125,126]	9,667,407	47
Wastewater[127]	1,032,601	27
North American Average Natural	NA	79.2

**This figure is based on CNG used in a vehicle, as opposed to NG used for other end uses.*

While the clean air benefits associated with RNG as compared to conventional natural gas are limited, regardless of application, the lifecycle GHG reduction benefits associated with displacement of conventional gas are significant across all end-use sectors. According to California's CA GREET 3.0 model, which provides a good basis for preliminary assessment, the average lifecycle carbon intensity of North American natural gas (compressed and used in a vehicle) is approximately 79.2. Using existing CARB fuel pathway data, the approximate weighted average lifecycle carbon intensity for RNG production sources in Colorado is **-82.9— significantly *carbon negative***—across all four major organic waste feedstocks: landfill, wastewater, agricultural manure and food and green waste.[128]

Because the weighted average carbon intensity for RNG is net-negative, displacement of just 19.4 million MMBTU (4.6%) of Colorado's total natural gas consumption, or of a larger portion of one or multiple segments of natural gas demand (assuming the same CI score for natural gas regardless of end-use), would reduce lifecycle in-state greenhouse gas emissions from current natural gas usage by approximately 9.7%, or 2.17 million metric tons of CO2e per year.[129]

The opportunity to displace conventional natural gas with RNG in Colorado is not insignificant. In fact, doing so offers substantial GHG reduction benefits. But because the molecules are interchangeable and practically indistinguishable, and conventional natural gas is the cleanest burning fossil fuel that exists, another end-use option for RNG would offer even greater climate benefits, as well as significant clean air benefits, to the state – the replacement of on-road diesel vehicles/fuel with RNG and near-zero emission natural gas engines.

Colorado has supported the adoption and deployment of natural gas vehicles and related infrastructure through various programs and policies. The state's 37 natural gas fueling stations currently dispense between 3.5 and 7.6 million DGEs, depending on the assessment (EIA vs Colorado's Clean Cities Coalitions). By either estimate, RNG production potential in Colorado vastly exceeds current natural gas demand within the on-road transportation sector. Much like displacing conventional natural gas with RNG for stationary applications, transitioning from CNG to RNG in a vehicle does not offer enhanced clean air or "tailpipe" benefits, but does achieve substantial greenhouse gas reductions. Table 34 highlights the magnitude of the climate benefits of a transition to RNG based on the current CNG demand (including both estimates) and the same average carbon intensity values referenced above, 79.2 and -82.9 for N.A. average natural gas and RNG, respectively.

The transition from CNG to RNG offers a here-and-now solution toward transportation sector decarbonization. However, known in-state RNG potential exceeds existing natural gas vehicle demand by a wide margin – 136.25 million DGEs of annual excess capacity (based on average existing CNG fuel use).

TABLE 34. Lifecycle Emissions Reduction Potential by Transitioning Colorado's Existing CNG Fleet to Average, In-State Generated RNG

Current CNG Demand (MMBTU)	RNG Emission Reduction Potential (Metric Tons CO2e)[130]
461,000 (EIA Estimate)	51,520
1,052,000 (CO Clean Cities)	117,559

THE FUTURE OF RNG AS A TRANSPORTATION FUEL IN CO: THE OPPORTUNITY TO DISPLACE DIESEL FUEL

Utilizing the full potential of the state's RNG resource in transportation would require a significant shift within medium- and heavy-duty fleets/vehicles operating in the state from the status quo (diesel) to models equipped with natural gas engines. Based on average annual fuel consumption of approximately 10,000 gallons per truck for Class 6-8 vehicles,[131] more than 13,000 diesel units would need to be replaced by natural gas models to match local RNG supply. However, if this shift were made in Colorado (obstacles to doing so will be discussed under Task 4), the climate and clean air benefits would be substantial, as highlighted in Table 35.

TABLE 35. Estimated Lifecycle Greenhouse Gas Reduction Benefits of a Shift to Locally Produced RNG from Diesel Fuel[132]

Current On-Road Diesel Demand (million gallons)	**Associated GHG Emissions** (million metric tons)	**Diesel Displacement Potential via RNG** (million DGEs)	**Projected Lifecycle Emission Reduction** (million metric tons)
589.6	6	136.25	2.54

Because of the high carbon intensity of diesel fuel, and the overall net-negative carbon intensity of RNG that could be produced in Colorado, using all the in-state RNG production potential to displace diesel would reduce transportation sector greenhouse gas emissions by 2.54 million metric tons per year. In fact, replacing just 23% of current diesel demand would cut total lifecycle emissions from diesel by more than 42%. By comparison, a reduction of approximately 2.17 million metric tons per year was projected for displacement of conventional gas with RNG. The benefit from displacing less than a quarter of all diesel fuel consumption is greater than displacing all natural gas consumption for transportation.

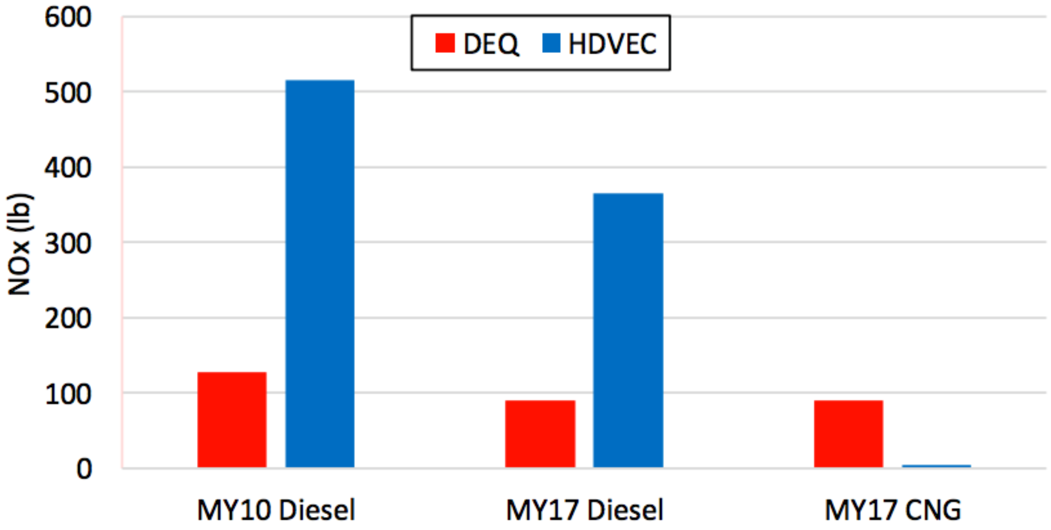
While the GHG emission benefits for displacing diesel fuel are more significant than for displacing natural gas, the conversion of existing diesel vehicles to RNG offers even clearer and substantial *clean air and public health benefits*. In fact, diesel-powered vehicles and equipment account for nearly half of all nitrogen oxides (NOx) and more than two-thirds of all particulate matter (PM) emissions from US transportation sources.[133]

As a primary culprit in ozone formation, there is a clear and direct link between NOx, air quality and non-attainment. Similarly, there is an environmental and economic benefit to reducing these emissions, according to research by the International Council for Clean Transportation and others, particularly in relation to reduced health impacts and costs.[134,135] In Colorado, the Denver region was recently ranked 12th worst in the country for ozone by the American Lung Association in its 2019 "State of the Air" report.[136]

Advanced “near-zero” emission natural gas engines have been certified, by the US EPA and CARB, to drastically reduce tailpipe NOx emissions. In fact, these engines (9L and 12L) have been certified to exceed the most stringent 2010 emissions standard—0.2 grams per brake horsepower hour (g/bhp)—by 90% or more, with official test results coming in at or below 0.02 g/bhp for NOx.[137] While difficult to quantify as part of this preliminary assessment, empirical testing data collected from in-use vehicles across different duty cycles—both diesel and natural gas—further demonstrates the tangible tailpipe emission benefits new natural gas engines provide versus diesel.

In fact, the data clearly shows that NOx emissions from “near-zero” natural gas engines consistently come in well below the nameplate certification, whereas diesel vehicles often emit considerably higher amounts of NOx under real-world conditions. Figure 17 below summarizes some of these findings from Argonne National Lab’s new (2018) Heavy-Duty Vehicle Emissions Calculator (HDVEC), available as part of its Alternative Fuel Life-Cycle Environmental & Economic Transportation tool (AFLEET), compared to the older EPA Diesel Emissions Quantifier (DEQ) tool.[138]

FIGURE 17. Pounds of NOx Emissions per Year for Model Year 2010/2017 Transit Buses: Diesel Emission Quantifier (DEQ) vs. Heavy Duty Vehicle Emissions Calculator (HDVEC) Measurements[139]



While a more detailed assessment and quantification of the climate and clean air benefits of local RNG production and end use options may be warranted, this preliminary analysis highlights a largely untapped opportunity. Based on resource potential projections, there is no shortage of end use demand across the range of current natural gas consumption, all of which would achieve significant annual greenhouse gas reductions. However, the greatest climate and clean air benefit would be achieved by using RNG to fuel medium- and heavy-duty vehicles (Class 6-8) currently powered by diesel.

Ultimately, RNG’s potential in Colorado will be largely dependent on economic, policy, regulatory, operational and other factors that will be discussed in Task 4.

Task 4: Current and Future Barriers to Developing RNG in Colorado for use in the Transportation Market

The technologies to produce and capture biogas from various organic waste feedstocks, refine that gas to meet vehicle and pipeline quality standards, and deliver the resultant RNG to end users are all commercially available, as demonstrated by numerous projects across North America, Europe and Asia. In the US alone, there are more than 90 operational RNG projects with dozens more under construction and in planning (see Table 36). However, challenges that continue to impede RNG project development across the US pose challenges for Colorado as well.

TABLE 36. Verified US RNG Projects by Type & Status (through Q1 2019)[140]

	Operational	**Construction**	**Planned**
Landfills	58	8	14
Farm Digesters	11	21	63
Food Waste Digesters	7	2	5
Wastewater Facilities	13	7	11
Total	**89**	***38***	***93***

Barriers to realizing the untapped potential of Colorado's in-state RNG resource—for the transportation sector, or for natural gas grid decarbonization—can be largely categorized in three different overlapping forms: economics, policy and regulation. The following sections will detail the current programs and policies driving RNG development to provide context, followed by a focus on how existing incentives may or may not benefit RNG production and use in Colorado, and the economic and regulatory factors impeding industry growth.

EXISTING COLORADO INCENTIVES RELATIVE TO BIOGAS/RNG PRODUCTION

While biogas produced via anaerobic digestion is included in Colorado's renewable portfolio standard, the state and its municipalities appear to offer little in the way of general financial support for its development. As a local government effort, the Longmont WWTP project has received a $1 million grant from the Energy/Mineral Impact Assistance Fund of the Colorado Department of Local Affairs.[141] Beyond this sort of grant to local government, however, the totality of direct support for digester projects in the state appears to be a sales tax exemption for components used in biogas production systems, which expires in July 2019.[142]

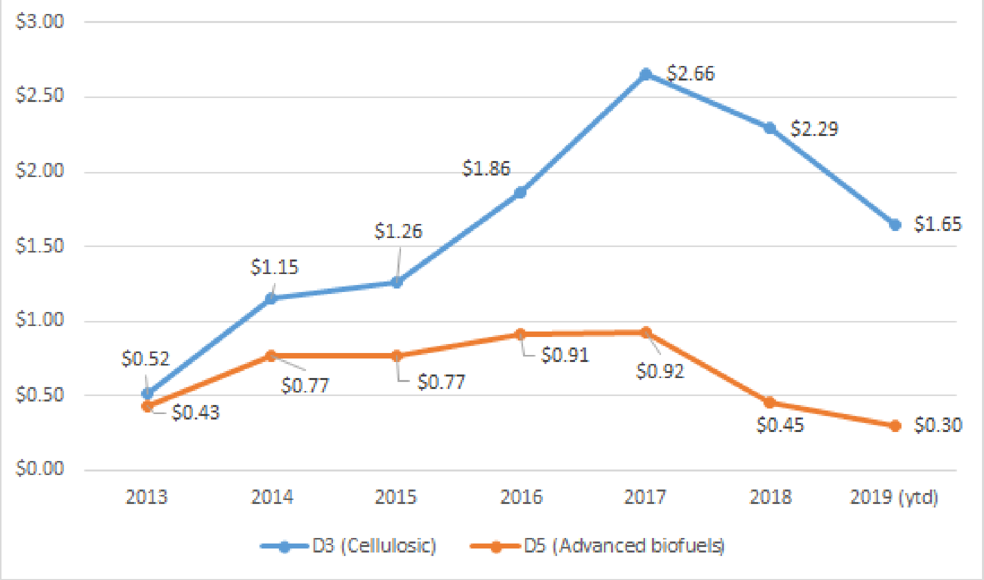
Industry participants with experience developing and financing anaerobic digester projects commented that to get digesters built in Colorado, the state needs to be more "creative" about incentives and offer something more "meaningful." Those willing to discuss this issue referred to the sales tax exemption as "nominal", and "insignificant" to the point that it has not provided enough of an incentive to drive digester project development in Colorado as opposed to elsewhere.[143]

BACKGROUND: THE RENEWABLE FUEL STANDARD (RFS)

The United States Environmental Protection Agency's (EPA) Renewable Fuel Standard (RFS) has driven a major uptick in interest and investment in projects/facilities "upgrading" biogas to pipeline or vehicle grade RNG. That's largely because the credits generated under this program—Renewable Identification Numbers (RINs)—are particularly valuable for RNG made from cellulosic sources such as wastewater, landfill, and agricultural (e.g., dairy or hog manure) waste-derived biogas and delivered to the transportation market. To be eligible under this program, a project must show both a physical and contractual "pathway" from RNG production to combustion of the fuel (compressed or liquefied) in a natural gas vehicle.[144]

Over the past five years, the RFS has been the largest single economic/policy driver influencing RNG project investment and development. That's because since 2014, RNG made from wastewater, landfill, or livestock manure biogas has been an approved "cellulosic" feedstock for fuel production under the EPA's RFS, making RNG produced from these sources eligible to generate the highest value environmental attributes (RINs). The value of RIN credits has enabled RNG producers to overcome fuel production costs greater than the continued low price of conventional natural gas in the US. Figure 18 highlights the average annual value of the two types of RINs (cellulosic vs. advanced) that apply to biogas-derived RNG through Q1 2019.

FIGURE 18. Average Cellulosic (D3) and Advanced (D5) RIN Prices: 2013-2019



D3 Cellulosic RINs are generated by landfill, wastewater and animal manure RNG.
D5 Advanced RINs are generated by food waste or other "non-cellulosic" RNG feedstocks.

For projects approved under the EPA's RFS, one RIN credit is generated for the equivalent energy content of one gallon of ethanol, or 77,000 BTUs. For RNG, each MMBTU of gas delivered to a transportation fuel end user generates approximately 11.7 RINs (which is based on the Lower Heating Value of the fuel).[145] Table 37 provides an overview of the total value of RNG (RIN + commodity) as a function of RIN price, recognizing the credit value volatility can be quite significant and an RNG producer will typically retain approximately 70% of the total RIN value. Since mid-May 2019, RIN prices have fallen even further due to a combination of factors that the EPA and White House now recognize as problematic, but have vowed to address this summer.[146]

TABLE 37. RNG Value (Commodity + RIN) as a Function of Credit Price

4 Different RIN Price Scenarios (Based on Recent Historic Value)	1	2	3	4
Commodity Value (per MMBTU)	$3.00	$3.00	$3.00	$3.00
D3 RIN Price (per credit)	$1.00	$1.50	$2.00	$2.50
Total RNG Value (per MMBTU)	**$14.70**	**$20.55**	**$26.40**	**$32.25**

Under all scenarios, combined RNG value is significantly greater than the price of commodity natural gas, providing a strong economic incentive for developers to produce the fuel and make contractual arrangements to deliver RNG to the transportation market. Because the RFS is a federal program, RNG produced in Colorado can be sold to a fleet in any other US state, provided there is a physical and contractual pathway in place. Most commonly this is achieved by injecting RNG into a gas pipeline at or near the site of production, and wheeling the gas to a local or distant fleet user.

BACKGROUND: STATE LEVEL LOW CARBON FUEL STANDARDS IN CALIFORNIA & OREGON

In 2009, California adopted a statewide *Low Carbon Fuel Standard (LCFS)* program to contribute to state greenhouse gas (GHG) emission reduction goals under the Global Warming Solutions Act of 2006 (AB 32). In 2016, Oregon adopted the nearly identical *Clean Fuels Program.* (For the purposes of this discussion, the two programs will be discussed interchangeably.) The LCFS was designed as a performance-based regulation, so that the program incentivizes adoption of low-carbon transportation fuels based on a given fuel's lifecycle GHG emissions per unit of energy—or carbon intensity (CI) as rated by the program. As discussed throughout this report, carbon intensity is measured as grams of CO2e per megajoule (MJ) of energy.

An LCFS system pegs all fuels to a carbon intensity benchmark for gasoline/diesel; those with a CI below the benchmark earn more credits the further they get from the benchmark, while those with CI's above the threshold generate deficits that increase as carbon intensity does. (The CI's of fuels are measured and certified by program -accredited verifiers.) To meet their obligations under the standard, providers of higher CI fuels buy credits from producers of lower CI fuels who have a surplus—meaning that producers of higher-CI fuels are effectively funding development of cleaner options. The system emphasizes total carbon reduction, and is more technology agnostic about how reductions are achieved than the Federal RFS. As noted, it also focuses on life cycle emissions, not just tailpipe emissions.

The California regulation initially laid out annually-declining CI benchmarks for the average transportation fuel mix from 2011 through 2020. In September 2018, CARB adopted regulatory amendments to extend the LCFS for an additional ten years with a target of an overall 20% CI reduction for all transportation fuels used in the state from 2010 levels by 2030.

Under the program, RNG derived from all sources of biogas is considered an ultra-low-carbon fuel option with CI scores ranging from the high (positive) 40's for average landfill gas to net-negative 264 for dairy manure. Unlike the federal RFS, where fuel can be delivered and used by natural gas vehicles in any US state, under the LCFS fuel can be produced out of state but must be delivered and consumed in California (or Oregon).

One LCFS credit is generated for every metric ton of reduction of CO2e emissions. Due to the range of fuel pathways for RNG and associated CI scores, this produces a range of potential values. By way of example, with CA LCFS credits trading at $196 each, RNG value per MMBTU ranges from $8.30/MMBTU for landfill gas (at an average CI of +47) at the low end, to $63/MMBTU for dairy digester gas (at an average CI of -264). For the total RNG production potential in Colorado (based on the projected weighted average CI of-82), California's LCFS credits would add an average of $31/MMBTU in additional value.[147]

COMBINED IMPACT OF THE RFS & LCFS PROGRAMS ON USE OF RNG IN NON-LCFS STATES

The US EPA's RFS and state-level LCFS programs in California and Oregon are similar in that each provides a market-based incentive to producers of renewable, lower carbon fuels. But the mechanics and compliance under each (federal vs. state) is different, and renewable fuel production facilities—including RNG—have the ability to register and generate credits under both, creating an even greater financial incentive. Table 38 provides a simplified summary of the combined economic value created by the state and federal programs directly benefitting the production and use of RNG as a transportation fuel. Because LCFS credit value is directly linked to the carbon intensity of a particular project/pathway, whereas RIN value is determined only by feedstock (cellulosic vs. advanced), value is illustrated as a function of average CI for different RNG resources, and fixed RIN prices.

TABLE 38. Combined RNG Value (Commodity + RIN + LCFS) as a Function of Feedstock*

Biogas Feedstock	*Landfill Avg. CI=47*	*Wastewater Avg. CI=27*	*Food Waste Avg. CI=-23*	*Ag Manure Avg. CI=-264*
Commodity Value (per MMBTU)	$3.00	$3.00	$3.00	$3.00
RIN Price (per MMBTU) *D3=$1.50/RIN; D5=$.40/RIN*	D3 $17.55	D3 $17.55	D5 $4.68	D3 $17.55
LCFS Credit Value (per MMBTU)	$8.30	$11.76	$20.59	$63
Total RNG Value (per MMBTU)	**$28.85**	**$32.31**	**$28.27**	**$83.55**

**Based on CARB Certified Pathway CI Scores and Recent Historical RIN Pricing*

Because of the additive value of the RFS and LCFS programs, it is not difficult to understand why most US RNG production facilities have opted to deliver gas into the California transportation market. However, the opportunity to send RNG to California (and more recently, Oregon) has also proven to be a barrier for other states that want to decarbonize and diversify their transportation fuel mix but do not have similar market-based incentives in place—which is why it's important to provide this context when discussing barriers to bringing RNG to the Colorado transportation market.

In sum, if an RNG producer in Colorado were to deliver its fuel to a Colorado-based fleet, they would *only* be eligible to generate federal RIN credits. If the same producer were to contract with a California or Oregon-based vehicle fleet, the total fuel value would be considerably higher. This means that RNG kept in state represents major lost revenue opportunities for all sources of RNG, but particularly for agricultural digester-derived RNG, which has the lowest CI and attracts the most credits out of state. Thus a major consideration for Colorado in developing its RNG capacity is how to improve the economics of keeping RNG in-state.

MARKET VOLATILITY & IMPENDING SUPPLY/DEMAND

Economic Uncertainty & Financing Challenges

The combined value afforded by the RFS and LCFS programs has generated significant recent interest in producing and delivering RNG to the transportation market, as evidenced by the significant uptick in projects/production since 2014 (more than doubling from less than 45). However, because so much of the value is linked to environmental attributes (RINs + LCFS) that exist because of legislation, there has been persistent fear from developers, investors and other RNG market participants regarding the fate and longevity of these programs. One current example is the precipitous drop in RIN prices (D3 and D5) since January of 2019—from $1.65 to $0.95—due to a recent oversupply of credits related to the combined effect of increased production and changing EPA interpretation(s) of the RFS program.

Despite the immense economic opportunity in producing RNG, the recent and historic volatility of credit prices under the RFS—and to a lesser extent, the LCFS—has left developers with somewhat limited financing options, particularly in the debt markets. Equity investors with higher appetites for risk have been more willing to participate in the RNG market, but even so, many developers cite project financing as the single greatest challenge to expanding the production capacity of RNG in the US.[148] Nonetheless, there appears to be steady and growing interest from the financial community, particularly in relation to farm digesters that can show a highly net-negative carbon intensity score and have the ability to move gas into California, which may soon pose other supply/demand imbalance challenges.

Limited Existing Natural Gas Vehicle Fuel Demand

Recent industry data indicates that RNG now accounts for approximately 32% of total natural gas vehicle fuel use nationwide as of 2018, or 204 million gasoline gallon equivalents (GGEs).[149] In California, the first and largest market for natural gas vehicles in the US, fleet demand is estimated at approximately 160 million GGEs annually, or about 25% of total US demand.[150] Because of California's LCFS, the vast majority of the in-state natural gas vehicle fuel consumption is already being met by RNG. While there will be opportunities to displace higher carbon intensity RNG (e.g. from landfills) with low- and negative-CI RNG, the overall supply of RNG is growing much faster than the total natural gas vehicle demand pool, in California and nationally.

For Colorado, a similar supply/demand imbalance would manifest rather quickly based on the rather limited existing natural gas vehicle fuel use in the state – between 3.5 and 7.8 million DGE's based on US EIA and Clean Cities data, as highlighted in Task 3. Put simply, a handful of local RNG production facilities could make enough fuel to supply the entire existing natural gas fleet in the state, which would barely scratch the surface of Colorado's potential RNG production. Therefore, *limited in-state RNG demand* is another clear barrier to expanded production and use in Colorado.

While known resource potential and existing infrastructure—extensive gas distribution and transmission pipelines, plus 37 natural gas refueling stations—suggests Colorado has many of the pieces in place to expand natural gas vehicle fuel demand, economic challenges will likely persist without incentives or greater certainty. The slow pace of market penetration for natural gas vehicle technology remains perhaps the greatest challenge to growing the potential RNG demand pool in Colorado.

Despite proven technology and various case studies detailing the benefits of natural gas for heavy-duty applications (as compared to diesel)[151], the higher capital cost—approximately $40,000 per vehicle—and other associated infrastructure requirements remain challenging.[152] Beyond the refuse sector, where close to 60% of new vehicle orders have been for natural gas (nationally) since 2016[153]—largely due to major commitments by Waste Management and Republic Services—natural gas vehicle adoption appears to be relatively stagnant in Colorado and nationwide as diesel prices have remained relatively low, and state/federal incentives for NGV adoption have mostly disappeared over the past few years.[154] The private sector has stepped in to bridge this gap by offering low- or no-cost financing for NGVs to level the playing field with diesel. The initial results suggest this approach has generated renewed interest from private fleets, but the total funds being made available are relatively limited.[155]

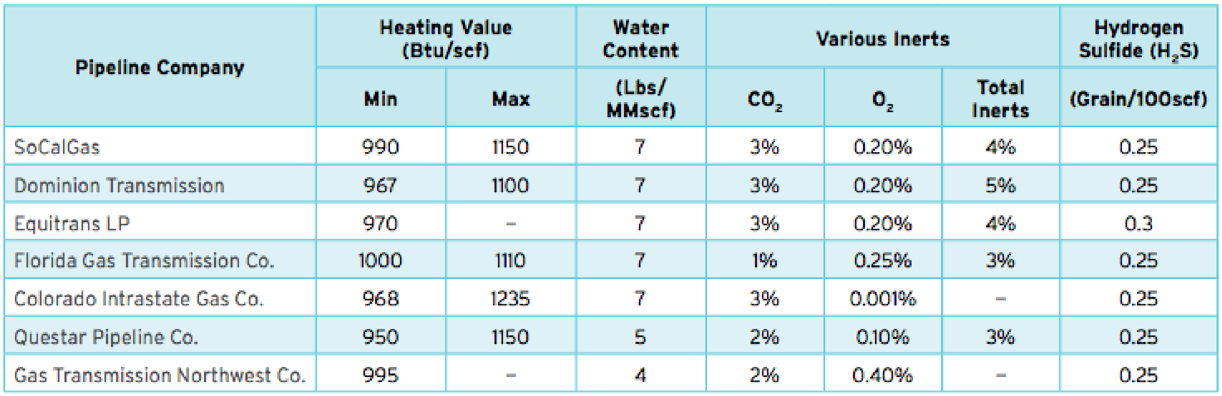
OVERVIEW: DELIVERING RNG TO END USE MARKETS VIA EXISTING INFRASTRUCTURE

Successful RNG project development, regardless of end use, requires the ability to link production with demand – as seen by the ~90 operational facilities in the US. Most often, this means tapping into an existing natural gas pipeline to deliver RNG to customers. For example, of the roughly 90 projects up and running today, approximately 78 tie directly into a natural gas pipeline, whereas the rest—mostly small facilities—utilize RNG on-site or nearby.

The first RNG project in the US was developed in New York State at the Fresh Kills landfill on Staten Island in 1982 through the collaborative efforts of the Brooklyn Union Gas Company (now National Grid) and the NYC Department of Sanitation. Since its inception, the biogas produced at the landfill has been collected and refined to meet gas quality specifications for the pipeline, and then odorized, compressed and directly injected into the natural gas grid. Despite this example of nearly 40 years of successful, near continuous operation, utility, pipeline operator and regulator concerns about gas quality have often made it difficult and/or prohibitively expensive for projects to inject RNG into the natural gas grid.

Nonetheless, in the last five years alone, numerous gas utilities and pipeline operators have recognized the need to decarbonize the natural gas network, and the clear role that RNG can play. As a result, a growing number of gas utilities and pipeline operators have developed—or are currently developing—biomethane quality and interconnection standards. (Due to local, regional and even national differences, there is no federal gas quality standard.) However, as interest has grown in RNG and inquiries have skyrocketed, numerous state and federal agencies, industry groups and others have collaborated to develop guidelines for RNG. Table 39 provides a selection of those that have published/established specifications for RNG gas quality; this is not a comprehensive list, nor does it include details on interconnection cost(s), which can also be prohibitive.

TABLE 39. Overview of RNG Gas Quality Specifications from Across the US[156]



Pipeline Company	Heating Value (Btu/scf)		Water Content	Various Inerts			Hydrogen Sulfide (H_2S)
	Min	Max	(Lbs/ MMscf)	CO_2	O_2	Total Inerts	(Grain/100scf)
SoCalGas	990	1150	7	3%	0.20%	4%	0.25
Dominion Transmission	967	1100	7	3%	0.20%	5%	0.25
Equitrans LP	970	–	7	3%	0.20%	4%	0.3
Florida Gas Transmission Co.	1000	1110	7	1%	0.25%	3%	0.25
Colorado Intrastate Gas Co.	968	1235	7	3%	0.001%	–	0.25
Questar Pipeline Co.	950	1150	5	2%	0.10%	3%	0.25
Gas Transmission Northwest Co.	995	–	4	2%	0.40%	–	0.25

**A recent decision by the California Public Utilities Commission (CPUC rulemaking R 13-02-008) lowered the minimum heating value for the acceptance of RNG from 990 to 970.*

ACCESSING EXISTING PIPELINE INFRASTRUCTURE IN COLORADO

In Colorado, natural gas is provided to residential, commercial and industrial customers by Xcel Energy, Black Hills Energy, Colorado Natural Gas and Atmos Energy, as well as eight municipal utilities.[157] Preliminary research and outreach indicates that the only successful example of RNG pipeline injection in Colorado to date was demonstrated by the Heartland Biogas project in Weld County. While operational, the RNG being produced was injected into a nearby high-pressure transmission line owned and operated by Colorado Interstate Gas (CIG), a subsidiary of Kinder Morgan.

Public information regarding biomethane quality specifications for the aforementioned natural gas utilities in Colorado proved difficult to attain. Consistent with similar state-level assessments across the US, conversations with developers and utilities in Colorado provided a wide range of perspectives and the basis for further inquiry/exploration.

Overall, the general lack of transparency when it comes to RNG is viewed by some as a barrier. Nonetheless, it's also clear that one utility—Black Hills Energy—is quite supportive of RNG development and interconnection to its network across its service territory, which includes parts of western, southern and northeastern Colorado. Even so, Black Hills' biomethane quality specifications or standard interconnection agreement is not publicly available at this time, and information regarding other utilities and pipeline operators is also difficult to find.

Further/expanded development of RNG in Colorado may be hindered by the lack of transparency around biomethane quality, interconnection costs, anticipated timelines and more. However, as interest in RNG grows, utilities, regulators, developers and others will have an opportunity to improve/standardize the systems in place such that all parties involved know exactly what is required and expected. The evolution of RNG in California and ongoing efforts by utilities and pipeline operators across the country have shown what is possible through education and collaboration.

REGULATORY BARRIERS TO GREATER RNG PRODUCTION/ADOPTION IN COLORADO

Colorado is one of 19 states that does not currently offer natural gas customer choice programs (i.e the ability to buy energy from third party suppliers which is then delivered by existing utilities), although the Colorado Public Utilities Commission has approved regulated gas utilities in the state to do so.[158] This is potentially important for RNG producers and end users (transportation or otherwise), because it means that without gas utility collaboration/participation, there is no way to deliver RNG to end-use customers in Colorado. (By some accounts, third party sourcing is available for particularly large natural gas users; clarification of this point and of the reasons for such limitations merit additional review.)

Further complicating matters for potential Colorado RNG producers interested in selling gas in the state, regulated gas utilities must also be willing to accept the gas into their systems. A reluctance to do so often manifests in the form of stringent purity requirements for RNG. As a result, connecting local RNG supply with the Colorado market may prove difficult, even if there is consumer demand.

While there are other economic and policy factors at play, the lack of natural gas customer choice—which is driven by limited gas utility interest—has been cited as a significant barrier, evidenced at least in part by the fact that there are currently no large public or private fleets using RNG, beyond the handful of municipalities that have access to local wastewater RNG supply.

Task 5: *Next Steps and RNG Roadmap*

This preliminary statewide assessment of RNG potential for Colorado highlights various opportunities and obstacles that would benefit from further research and analysis. The following section provides a detailed summary of topics that may be considered in the development of an RNG Roadmap.

1. **Perform an in-depth analysis of RNG feedstocks in Colorado**
    - *1.1.* Statewide or Front Range audit of food waste available for anaerobic digestion. *(As noted in the "Food Waste" section, composting may prove to be more appropriate in some areas. This should be taken into account as part of a food waste audit.)*
        - 1.1.1. Assess residential food waste resource
            - 1.1.1.1. In tandem with or following inventory, evaluate incentives or policies to encourage recovery of residential food waste
        - 1.1.2. Assess commercial food waste resource
            - 1.1.2.1. In tandem with or following inventory, evaluate incentives or policies to encourage recovery of commercial food waste
        - 1.1.3. Assess manufacturing/food processing industry organic waste resource
            - 1.1.3.1. In tandem with or following inventory, evaluate incentives or policies to encourage recovery of manufacturing food waste
        - 1.1.4. Assess additional food waste sources in Colorado
            - 1.1.4.1. In tandem with or following inventory, evaluate incentives or policies to encourage recovery of other sources of food waste
        - 1.1.5. Evaluate water requirements for successful anaerobic digestion of food waste. Periodic water shortages and competition for water have been identified as a potential impediment to AD
    - 1.2. Audit the design and operation of cattle feedlots with an eye to improving recovery of beef cattle manure for anaerobic digestion
        - 1.2.1. Based on field research and dialogue with industry, evaluate techniques and practices for facilitating regular collection of manure from cattle feed lots, such as:
            - 1.2.1.1. More frequent pen rotation of cattle in feed lots
            - 1.2.1.2. Use of slotted floors to capture manure without moving cattle
            - 1.2.1.3. Design of feed lot facilities to more closely replicate milking barns
            - 1.2.1.4. Provision of basic structures protecting animals and manure from the elements

        1.2.2. Evaluate water requirements for successful anaerobic digestion of beef manure. Periodic water shortages and competition for water have been identified as a potential impediment to AD.

        1.2.3. In tandem with or following the evaluation of techniques and practices, assess incentives/policies/mandates to encourage adoption of those techniques and practices

    1.3. Audit the potential biogas production of Colorado landfills

        1.3.1. Measure output of all landfills already equipped with gas recovery systems (especially those currently flaring) and quantify potential production of RNG

        1.3.2. Evaluate the potential for gas production from landfills currently not collecting gas

            1.3.2.1. To avoid off-gassing of methane from landfills, evaluate regulations that allow landfills to forego installation of gas collection systems

        1.3.3. In tandem with or following the evaluation of gas potential at landfills, assess incentives/ policies/mandates to encourage installation of gas collection systems and/or upgrading equipment

    1.4. Perform a study of the one sector that has been adopting RNG in Colorado—wastewater—to assess why some facilities have RNG projects in operation/under construction/planned and why others do not

        1.4.1. Assess incentives/policies/mandates to encourage development of RNG at wastewater facilities

    1.5. Following or in tandem with each feedstock assessment, identify potential local users for RNG output

2. **Following or in tandem with feedstock assessments, evaluate effective transportation models for both ends of the process (feedstocks and gas products), which may include**:

    2.1. For food waste and animal manure, do localized digesters make sense? Or should food waste be agglomerated at more centralized facilities?

        2.1.1. For local and centralized digester assessments, explore opportunities for hub-and-spoke approaches to gas collection and clean-up

        2.1.2. Assess the comparative economics and logistics of pipeline interconnection via physical vs. virtual pipeline.

    2.2. At landfills, upgrading facilities are usually located on site.

        2.2.1. Assess the comparative economics and logistics of connecting these facilities to local pipelines via physical or virtual pipeline.

        2.2.2. Assess the potential for developing on-site fueling facilities at landfills that could be used by haulers and other vehicles.

3. **Development of public education campaigns**

    3.1. Public acceptance requires public understanding. Efforts to educate the public about biogas and renewable natural gas should be introduced across the state. Everywhere there is organic waste, there is the potential opportunity to transform these materials into energy and nutrient co-products. These efforts would highlight this opportunity by implementing education at schools, appropriate local and state agencies and even the private sector.

        3.1.1. The failure of the Heartland Biogas project was highly visible and is considered by many to have turned public sentiment against anaerobic digestion in Colorado. Without acceptance of/support for anaerobic digesters, development of the state's RNG potential could be significantly hampered. If it hasn't already been done, a complete, clear and simple evaluation of what went wrong at Heartland, and any other relevant findings, would be invaluable in addressing public concerns and raising public awareness and understanding.

    3.2. Colorado has both GHG emissions goals and MSW diversion goals. As appropriate, awareness of these goals should be raised, along with the potential role of anaerobic digestion and RNG in addressing them.

        3.2.1. Educational efforts should place appropriate emphasis on RNG as a way of capturing of methane that would otherwise escape into the atmosphere, not just a clean fuel alternative.

    3.3. Much of anti-CAFO sentiment in Colorado appears to stem from pollution concerns (groundwater and other bodies of water) and odor issues. The role of anaerobic digestion in manure management / reducing odors should be publicized.

4. **Identify fleets that are already using conventional natural gas and could readily switch to RNG**

    4.1. Government and private fleets (all levels)

    4.2. Utility fleets

    4.3. Local transit fleets

    4.4. Local waste hauling fleets

5. **Explore incentives/mandates specific to encouraging biogas production and utilization**

    5.1. Assess programs, policies or requirements to capture and utilize organic waste-generated methane emissions in Colorado

6. **Explore incentives/mandates to encourage greater use of low-carbon fuels to replace gasoline and diesel, including the production and use of RNG as a transportation fuel option**

6.1. Explore the viability of a state-wide or regional low carbon fuel standard in Colorado. Existing programs in California, Oregon and British Columbia as well as efforts in Washington, the Midwest and Northeast should provide ample opportunity for research and collaboration around program compliance, fuel pathways, enforcement, etc.

7. **Further explore and assess gas quality and practical interconnection standards (which may include costs) for injecting RNG into Colorado pipelines and delivering biomethane to Colorado customers, towards achieving greater transparency and standardization.**

7.1. Regulated natural gas utilities and pipeline operators in Colorado have shown initial interest in integration of RNG, but public details around gas standards and interconnection as well as associated costs and timelines are not readily apparent. Further exploration of these details would provide interested RNG developers greater clarity to help inform important decisions.

Engagement with the Colorado Public Utility Commission on various elements of RNG development and end use opportunities should also be explored. In particular, the lack of natural gas customer choice appears to be an obstacle for both potential producers and end users of RNG.

APPENDICES AND REFERENCES

APPENDIX 1

COMMENTS ON BEEF CATTLE MANURE

Producing biogas from beef manure is more challenging than for dairy manure, and literature on it is extremely limited.

Dairy cows tend to be larger, producing more manure and therefore more biogas. The USDA's Natural Resources Conservation Service assumes an average dairy cow to weigh 1,400 pounds, vs. 1000 pounds for a beef steer, and estimates 112 pounds of dairy per animal per day, against the 59.1 for beef cattle.[159] Per pound of volatile solids, the energy content of dairy and beef manure is very similar,[160] and some place that of beef manure slightly higher.[161]

In addition to size and daily manure production, dairy cattle have a longer life span over which to produce manure; a dairy cow's life averages about 6 years,[162] compared to less than 2 for beef "feeder" cattle (cattle destined for feedlots).[163]

There are other factors, including manure recovery. Dairy animals spend more of their lives in a barn environment that has probably been designed to facilitate manure recovery. Beef cattle spend their youth in pasture, where manure recovery is not practical, before going to feedlots for roughly the last five months of their lives.[164] The USDA puts potential manure recovery for dairy cattle in the Western region that includes Colorado at 80%; manure recovery for grazing beef cattle in that region is 5%. Once beef cattle are in a feedlot, potential recovery jumps to 85%.[165] But as noted, feedlot animals are only there for about 5 months, creating a relatively narrow window for manure recovery.

However, the feedlot recovery rate may be deceptive. Feedlot cattle are generally spending their time in an unsheltered, outdoor environment, on dirt or even concrete. Manure may not be collected from individual pens for weeks at a time, thus drying out and losing a portion of its energy content, or getting washed away by precipitation.[166] Manure that is recovered is contaminated with dirt, stones and windblown debris, which cause problems in the operations of digesters.

In short, beef cattle produce less manure and biogas on a daily basis; spend less time in an environment (a feedlot) where their manure is recoverable; and the manure from that environment is often contaminated. These cumulative factors help explain why the EPA's AgSTAR database of anaerobic digester projects lists 8 beef cattle projects—2 codigesting with food waste, 4 codigesting with swine manure—as opposed to 194 dairy projects.[167]

The main opportunity for biogas/RNG production from beef manure in Colorado is at feedlots. However, maximizing this potential would require operational, and potentially physical, changes to how these facilities operate, as discussed in "Areas for Further Research," above.

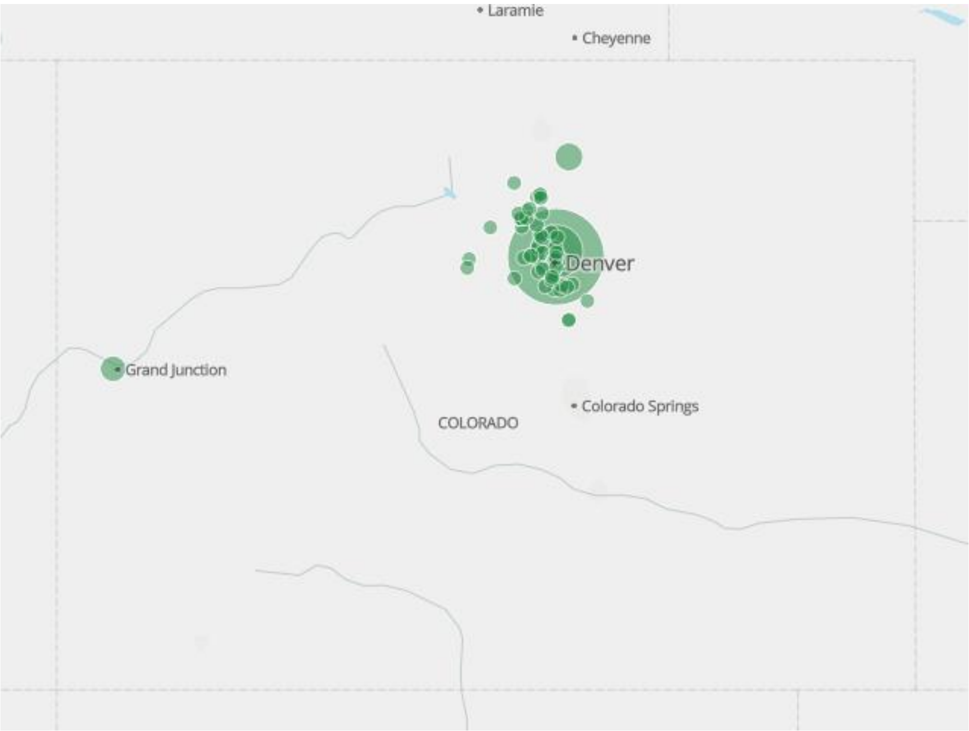
APPENDIX 2: FOOD MANUFACTURERS BY COUNTY AND NAICS CODE

County, total	**2012 NAICS code**	**Definition of NAICS code**	**Number of**
Adams, 37	3111	Animal food manufacturing	4
	3112	Grain and oilseed milling	3
	3116	Animal slaughtering and processing	12
	3118	Bakeries and tortilla manufacturing	15
	3119	Other food manufacturing	3
Arapahoe, 28	3116	Animal slaughtering and processing	3
	3118	Bakeries and tortilla manufacturing	20
	3121	Beverage manufacturing	5
Boulder, 75	3113	Sugar and confectionery product manufacturing	7
	3114	Fruit and vegetable preserving and specialty food manufacturing	7
	3115	Dairy product manufacturing	4
	3116	Animal slaughtering and processing	4
	3118	Bakeries and tortilla manufacturing	20
	3119	Other food manufacturing	19
	3121	Beverage manufacturing	14
Delta, 3	3116	Animal slaughtering and processing	3
Denver, 122	3111	Animal food manufacturing	5
	3113	Sugar and confectionery product manufacturing	6
	3114	Fruit and vegetable preserving and specialty food manufacturing	10
	3115	Dairy product manufacturing	4
	3116	Animal slaughtering and processing	10
	3118	Bakeries and tortilla manufacturing	50
	3119	Other food manufacturing	14
	3121	Beverage manufacturing	23
Douglas, 9	3118	Bakeries and tortilla manufacturing	5
	3121	Beverage manufacturing	4
Eagle, 8	3118	Bakeries and tortilla manufacturing	5
	3121	Beverage manufacturing	3
El Paso, 30	3113	Sugar and confectionery product manufacturing	7
	3116	Animal slaughtering and processing	4
	3118	Bakeries and tortilla manufacturing	14
	3121	Beverage manufacturing	5
Jefferson, 26	3115	Dairy product manufacturing	4
	3118	Bakeries and tortilla manufacturing	11
	3119	Other food manufacturing	4
	3121	Beverage manufacturing	7
La Plata, 5	3121	Beverage manufacturing	5
Larimer, 47	3111	Animal food manufacturing	3
	3113	Sugar and confectionery product manufacturing	6
	3114	Fruit and vegetable preserving and specialty food manufacturing	3
	3115	Dairy product manufacturing	4
	3118	Bakeries and tortilla manufacturing	6
	3119	Other food manufacturing	7
	3121	Beverage manufacturing	18
Mesa, 22	3118	Bakeries and tortilla manufacturing	6
	3121	Beverage manufacturing	16
Moffat, 3	3116	Animal slaughtering and processing	3
Montezuma, 3	3121	Beverage manufacturing	3
Morgan, 6	3116	Animal slaughtering and processing	6
Prowers, 3	3111	Animal food manufacturing	3
Pueblo, 9	3113	Sugar and confectionery product manufacturing	3
	3118	Bakeries and tortilla manufacturing	6
Summit, 3	3121	Beverage manufacturing	3
Teller, 3	3121	Beverage manufacturing	3
Weld, 26	3111	Animal food manufacturing	6
	3115	Dairy product manufacturing	3
	3116	Animal slaughtering and processing	9
	3118	Bakeries and tortilla manufacturing	5
	3121	Beverage manufacturing	3
TOTAL FIRMS			**468**

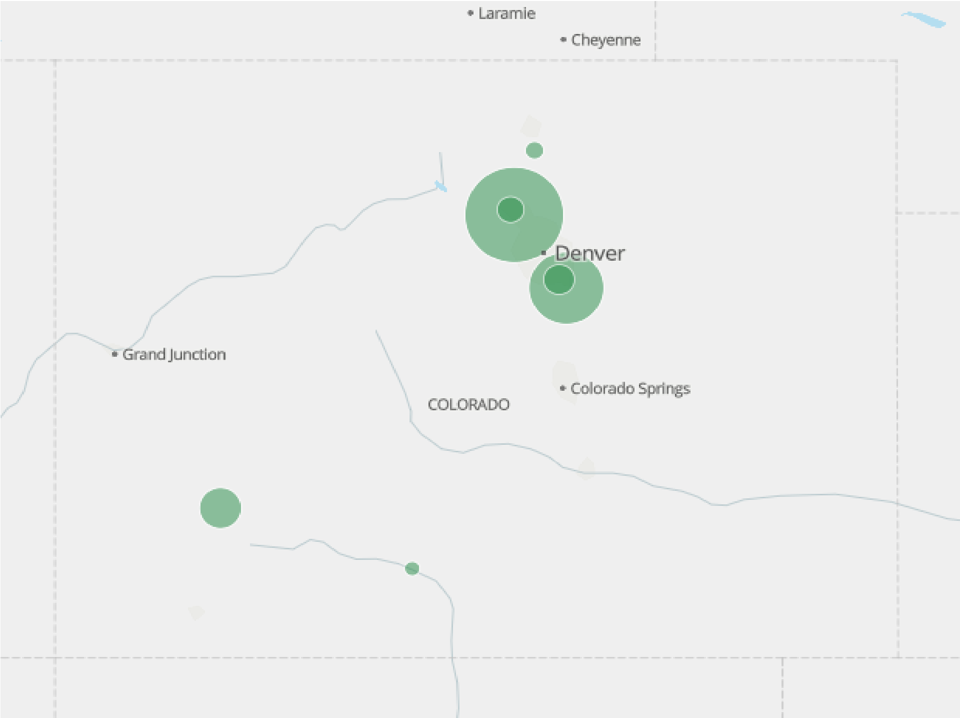
APPENDIX 2 CONTINUED: GEOGRAPHICAL CLUSTERING OF FOOD & BEVERAGE MANUFACTURERS

(Maps courtesy of Colorado Office of Economic Development & International Trade)

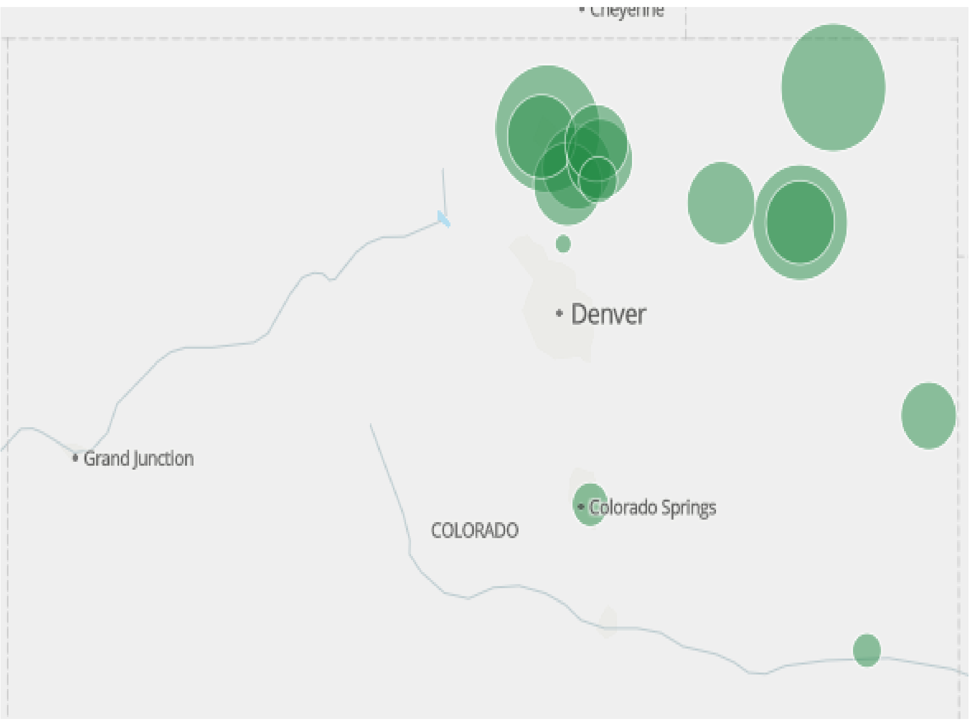
BEVERAGES (NAICS 3121)



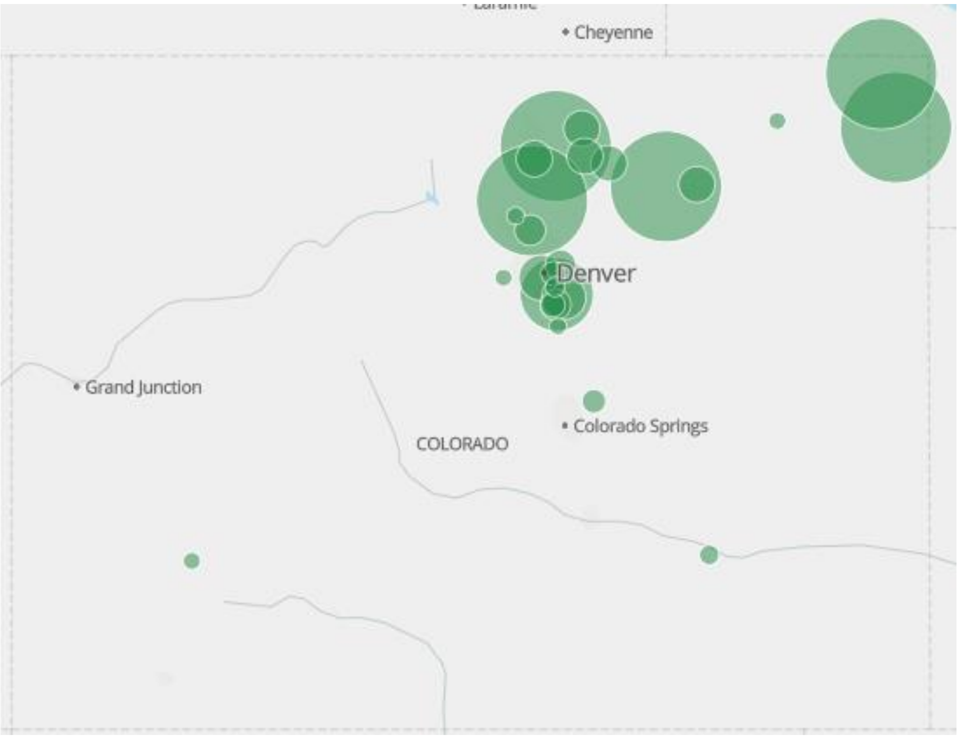
GRAIN & OILSEED (3112)



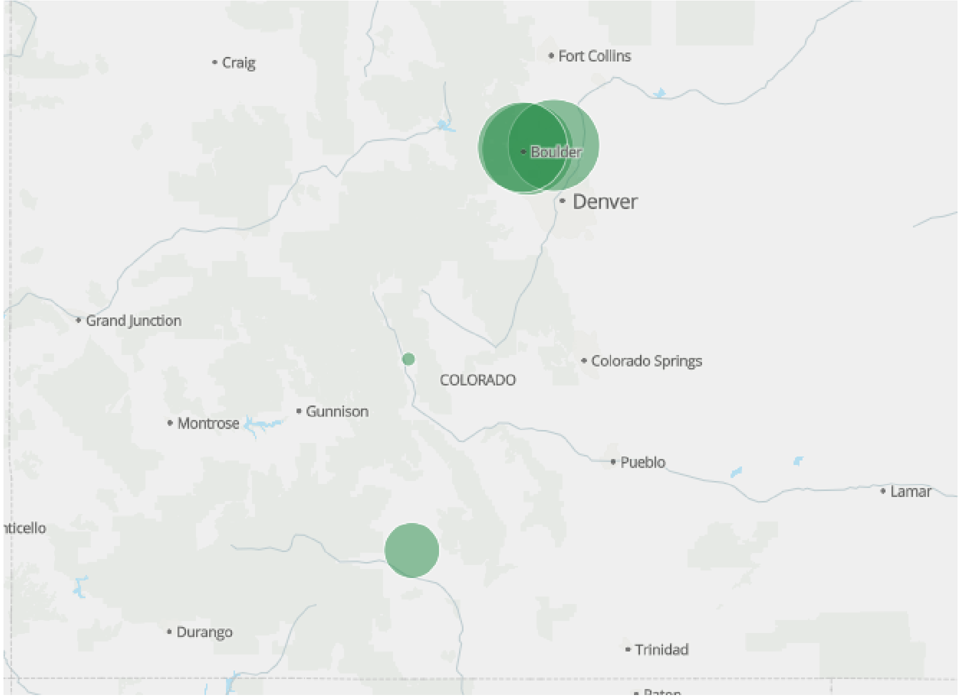
ANIMAL FOOD (3111)



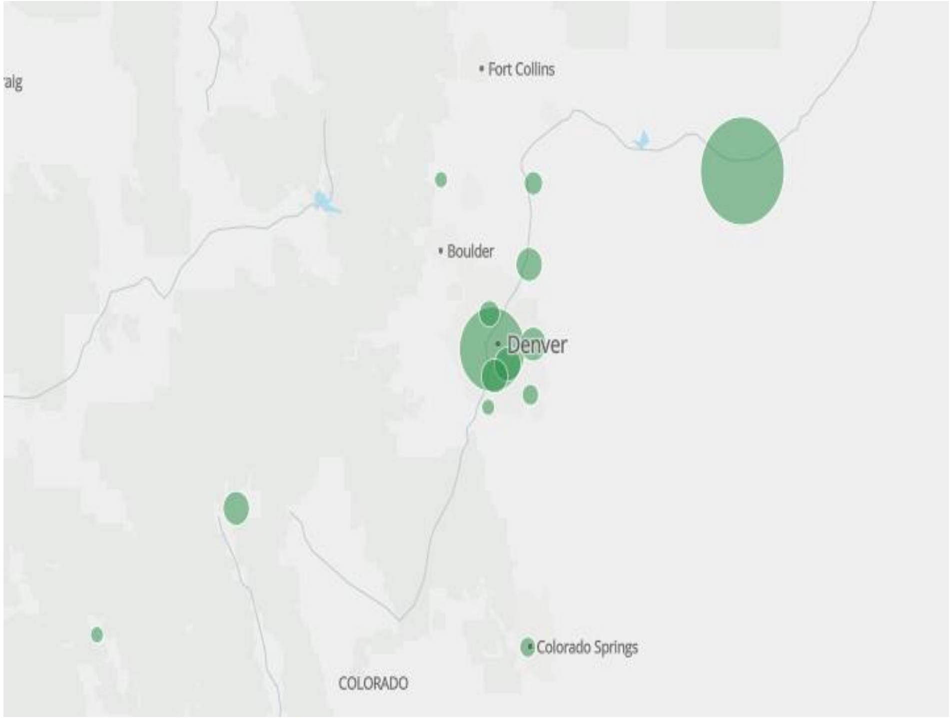
SUGAR & CONFECTIONARY PRODUCTS (3113)



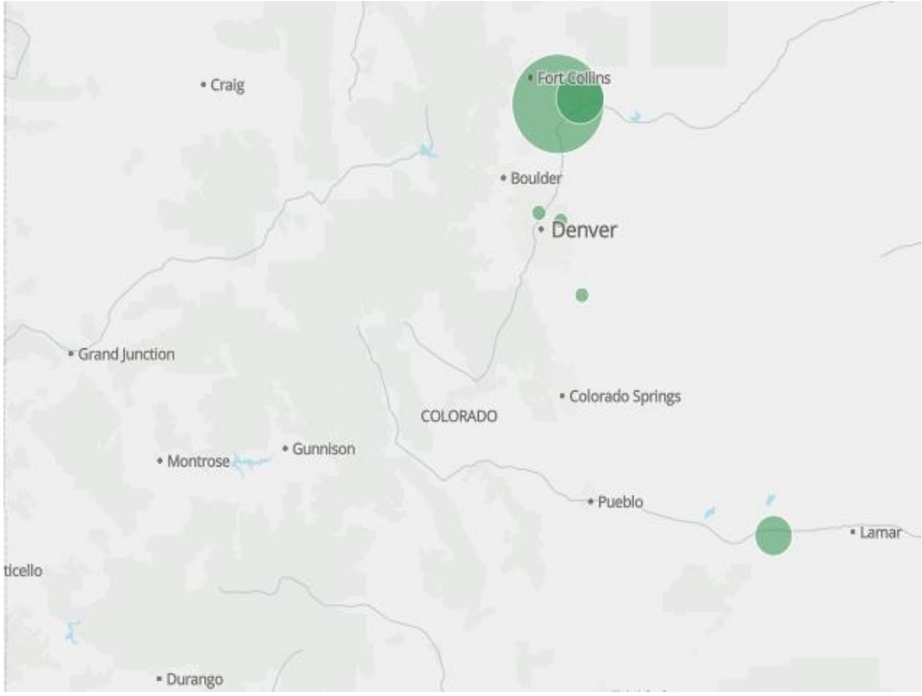
FRUIT & VEGETABLE PRESERVING & SPECIALTY FOOD (3114)



DAIRY PRODUCT (3115)

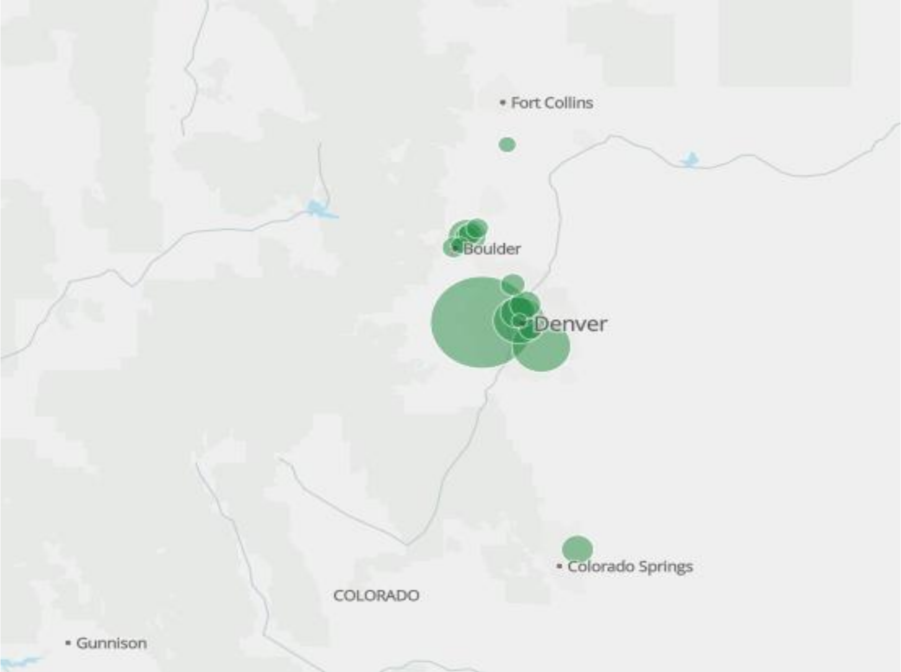


ANIMAL SLAUGHTERING & PROCESSING (3116)



BAKERIES & TORTILLAS (3118)

OTHER FOOD (3119)



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[2] CARB, “LCFS Pathway Certified Carbon Intensities,” https://www.arb.ca.gov/fuels/lcfs/fuelpathways/pathwaytable.htm. Based on average of CI values for all entries of each fuel. Because 2019 database includes only one wastewater sample, we have averaged that against internally generated CARB numbers for wastewater sludge from 2017.

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[13] Based on US Energy Information Administration, Colorado State Energy Profile, https://www.eia.gov/state/?sid=CO#tabs-2

[14] US EIA, data download from “Colorado Net Electricity Generation by Source, Jan. 2019,” www.eia.gov/state/?sid=CO#tabs-4

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[16] Does not include coal, aviation gasoline, jet fuel, lubricants or residual fuel oil (grades 5 and 6).

[17] Diesel, motor gasoline and propane from US Energy Information Administration, “Transportation Sector Energy Consumption Estimates for Colorado, 1960-2016,” https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_use/tra/use_tra_CO.html&sid=CO;

[18] Calculated based on MMBTUs. A “diesel gallon equivalent” refers to the amount of energy contained in one gallon of diesel (distillate) fuel, measured in BTUs. US EIA considers this value to be 137,381 BTUs.

[19] Electricity use for transportations based on US EIA, “Electricity Sales, Revenue and Average Price,” https://www.eia.gov/electricity/sales_revenue_price/xls/table9.xlsx. MMBTUs calculation based on 3,412,141 .48 BTUs per MWh.

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[24] Based on US EIA, “Colorado Natural Gas Vehicle Fuel Consumption,” https://www.eia.gov/dnav/ng/hist/na1570_sco_2a.htm US EIA values are in million cubic feet, MMBTUs are an Energy Vision calculation based on US EIA 1,037 BTU per cf of natural gas

[25] Based on reported fleet use by Federal and state agencies, transit agencies, natural gas and electricity providers. US EIA, “Alternative fuel vehicle data,” www.eia.gov/renewable/afv/users.php?fs=A&ufueltype=CNG&ustate=CO#tabs_charts-3

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[27] According to the “Technical Response” desk for the Clean Cities Coalition Network, Coalition emissions reductions are calculated on a lifecycle basis using a GWP of 30. Recalculating the well-to-pump component of the referenced emissions reductions based on AR5’s short term GWP would affect the values in this table, and may warrant further exploration.

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[45] Wastewater values are based on the Metro Wastewater Reclamation District, which includes 6 of Colorado’s 10 largest cities-- Denver, Aurora, Lakewood, Thornton, Arvada and Westminster (as well as smaller municipalities)—and Fort Collins, Colorado Springs, Pueblo and Greeley. Also includes known WWTP renewable natural gas projects at Grand Junction, Longmont and Englewood, for which Energy Vision has output data based on the database of RNG projects in the US which it curates for the US Department of Energy. MMBTU per year based on personal communication with the relevant utilities regarding daily gas flow and methane content of gas.

[46] Diesel emissions based on US EIA’s estimated 22.4 pounds of CO2e per gallon of diesel fuel consumed, www.eia.gov/environment/emissions/co2_vol_mass.php. Assumes average 80% reduction in lifecycle emissions from using RNG.

[47] US EPA, “Fast Facts, US Transportation Sector Greenhouse Gas Emissions,” https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100USI5.pdf

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[51] Ibid, Page 3.

[52] Bates White, “Renewable Natural Gas Supply and Demand for Transportation.”

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[63] Intergovernmental Panel on Climate Change, "Climate Change 2013: The Physical Science Basis." Chapter 8, "Anthropogenic and Natural Radiative Forcing."

[64] US EPA, "Inventory of Greenhouse Gas Emissions and Sinks, 1990-2017," Section 3.7, Natural Gas Systems. https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf The inventory provides a total emissions figure for methane released to the atmosphere for all US natural gas production, which was compared to US EIA gross withdrawals for the United States (https://www.eia.gov/dnav/ng/ng_prod_sum_dc_NUS_mmcf_a.htm) to establish an emissions level per million cubic feet extracted (an average of 5.2 MT). This average was then applied to recent Colorado gross withdrawals of natural gas over the time period. US emissions for 2018 were not available in the inventory, but the average was applied to 2018 gross gas withdrawals. (Energy Vision initially attempted to do the calculations using the "Colorado Greenhouse Gas Inventory – 2014." However, that report's data on natural gas and oil field emissions ends at 2010, requiring extrapolation forward from that year; those estimates also generated emissions values significantly higher for natural gas, and significantly lower for oil, than from the EPA numbers. Ultimately Energy Vision chose to use the EPA/EIA method described above.)

[65] US EPA, Inventory of Greenhouse Gas Emissions and Sinks, 1990-2017," Section 3.6, Petroleum Systems. https://www.epa.gov/sites/production/files/2019-04/documents/us-ghg-inventory-2019-main-text.pdf As with natural gas, the inventory provides a total methane emissions figure all US petroleum production, which was compared to US EIA total production for the United States (https://www.eia.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm) to establish an emissions level per thousand barrels (an average of 12.55 MT). This average was then applied to recent Colorado crude production over the time period. US emissions for 2018 were not available in the inventory, but the average was applied to 2018 oil production.

[66] Equivalencies based on 5,772,000 BTU per barrel of oil (https://www.eia.gov/energyexplained/index.php?page=about_energy_units) and assumes 1,000 BTU per cubic foot of unprocessed conventional natural gas.

[67] US EIA, "Total Petroleum Consumption Estimates, 2017," www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_use_pa.html&sid=US, and "Colorado Field Production of Crude Oil," https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPCO1&f=M

[68] Production of diesel fuel and gasoline calculated on the basis of crude oil production of 116,481,000 barrels, US EIA , "Colorado Field Production of Crude Oil," https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCRFPCO1&f=M, and 11 gallons of distillate fuel and 20 gallons of gasoline produced from each barrel, US EIA, frequently Asked Questions," https://www.eia.gov/tools/faqs/faq.php?id=327&t=9

[69] Distillate and motor gasoline consumption estimates based on US EIA, "Primary Energy Consumption Estimates, 2016," https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_sum/html/sum_btu_totcb.html&sid=US&sid=CO. "Primary energy" refers to fossil fuels to which supplemental fuels-- e.g ethanol-- have **not** been added, so this does not account for additional volume provided by such supplements.

[70] US EIA, Natural Gas Summary for Colorado, https://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_SCO_a.htm. All values have been converted from MMCF to MMBTUs. Production is based on "Marketed Production" for 2017, meaning all gas extracted from gas well, oil wells, shale gas sources and coal beds "less gas used for repressuring, quantities vented and flared, and nonhydrocarbon gases removed in treating or processing operations. Includes all quantities of gas used in field and processing plant operations."

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[71] Ibid, “Total consumption” for 2017. Total consumption includes natural gas used by production facilities, processing plants and in pipeline and distribution use. Pipeline and distribution use is often included under the general heading of “Transportation” in US EIA data, and brings the total well above the amount of gas actually used in vehicles.

[72] Ibid. Gas delivered to consumers in the residential, commercial, industrial, vehicle and electricity generation sectors.

[73] Solar Energy Industries Association, “Colorado Solar,” https://www.seia.org/state-solar-policy/colorado-solar

[74] American Wind Energy Association, state fact sheet for Colorado, https://www.awea.org/resources/fact-sheets/state-facts-sheets

[75] Values for renewable energy: Colorado Energy Office, “Renewable Energy,” links for solar, woody biomass, landfill gas and hydropower at https://www.colorado.gov/pacific/energyoffice/renewable-energy-1; values for wind energy, American Wind Energy Association

[76] Based on 19,482,567 MMBTU of energy from RNG and 3.412 MMBTU per MWh, averaged across the number of hours in a year.

[77] Based on data collected by Energy Vision for its ongoing updates of a database of RNG projects for the US Department of Energy/Argonne National Laboratory.

[78] Personal Communication, Chris Douville, Wastewater Treatment Manager, City of Boulder.

[79] Personal communication with John Gage, project manager for City of Longmont, May 8 2019.

[80] The outlines of pipeline systems are taken from USEIA, and added as an overlay to Google maps to allow for plotting of specific facilities. US EIA, “US Energy Mapping System,” https://www.eia.gov/state/maps.php?v=Natural%20Gas

[81] Information on DADS project based on presentation by Gregg Thomas, Director, Environmental Quality Division of Denver Department of Public Health and the Environment (DDPHE) to Colorado Energy Office RNG working group, May 17, 2019; and subsequent phone conversations with Dave Wilmoth, Senior Environmental Public Health Program Administrator at DDPHE, May 23 and June 3.

[82] 500 BTU/cf: personal communication, Dave Wilmoth, City and County of Denver.

[83] The Yuma Pioneer, “Anaerobic digester being planned south of Yuma,” February 18, 2018, https://yumapioneer.com/local_news/anaerobic-digester-planned-south-yuma/

[84] Output estimates based on personal communication with Sheldon Kye Energy, June 3, 2018.

[85] Personal communications.

[86] “Leachate” refers to moisture trickling down through a landfill, usually as a result of precipitation. This liquid can be collected and recirculated through the landfill to maintain moisture.

[87] US EPA, Landfill Methane Outreach Program (LMOP), Landfill Gas Energy Project Data, https://www.epa.gov/lmop/landfill-gas-energy-project-data

[88] Ibid.

[89] Landfill information based on EPA Landfill Methane Outreach Program data from February 2019, accessed via https://www.epa.gov/lmop/project-and-landfill-data-state, and potential gas output based on EPA “LFGcost” tool, https://www.epa.gov/lmop/lfgcost-web-landfill-gas-energy-cost-model. Where unavailable: 1) landfill acreage is based on an “average” size established for the sample; 2) “waste in place” is based on an average for the sample; 3) annual tons waste delivered is based on “waste in place” divided by the number of years the landfill had been open at time waste in place value established; 4) lifespan of landfills based on an average of the sample.

[90] Map from “CO Hometown Locator,” https://colorado.hometownlocator.com/maps/statecountymap.cfm

[91] Estimates of poultry manure production based on manure per “1000 pound animal unit” per USDA Natural Resources Conservation Service, “Animal Manure Management RCA Brief #7”; weight per layer chicken based on Poultry Hub, “Nutrient Requirements of egg-laying chickens,” http://www.poultryhub.org/nutrition/nutrient-requirements/nutrient-requirements-of-egg-laying-chickens/. These potential outputs were then compared to poultry RNG projects in the US DOE database curated by Energy Vision and to “rules of thumb” for output provided by a poultry RNG project developer.

[92] Based on Colorado General Assembly website, www.colorado.gov/pacific/sites/default/files/Colorado%20General%20Assembly98_3.pdf, and personal communication with an agricultural digester project developer and a representative of CDPHE’s Environmental Agriculture unit.

[93] Non-transferability, restrictions on digestate: according to the two contacts referenced, this is the interpretation applied by Colorado’s Attorney General, in response to a request for an exemption to process swine manure from a merchant digester developer. That digestate from swine manure could probably be transferred for use out of state was the informed opinion of the CDPHE representative.

[94] Energy potential based on personal communication with a swine project developer, who puts annual energy production per animal at between .8 and 1 MMBTU per year. .9 MMBTU was used to calculate this table.

[95] USDA National Agricultural Statistics Service, Census of Agriculture, https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_2_County_Level/Colorado/

[96] Biogas production based on Stanley Weeks, “Experience with Three On-Farm Digester Systems Using Additional Off-Farm Organic Substrates,” http://www.manuremanagement.cornell.edu/Pages/General_Docs/Events/10.Stan.Weeks.pdf; 70% manure recovery based on average of regional dairy cattle manure recovery ratios, per USDA Natural Resources Conservation Service, “Animal Manure Management RCA Issue Brief #7,” www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211

[97] Personal communication.

[98] Weeks, “Experience with Three On-Farm Digester Systems Using Additional Off-Farm Organic Substrates.” Weeks’ biogas production estimates are for dairy cattle; for beef cattle, ratio of biogas produced is assumed to be the same as ratio of manure produced, per USDA Natural Resources Conservation Service, “Animal Manure Management RCA Issue Brief #7,” www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211.

Assumes 25% of feedlot cattle manure is recovered on at least a daily basis.

[99] Personal communication with Colorado Livestock Association. The old maps were no longer available for review.

[100] Kraemer and Gamble, "Integrating Anaerobic Digestion with Composting," Biocycle, November 2014. https://www.biocycle.net/2014/11/18/integrating-anaerobic-digestion-with-composting/

[101] Burns & McDonnell and Skumatz Economic Research Associates, "Colorado Integrated Solid Waste & Materials Management Plan," June 2016. Appendix G, "Estimated 2016 tonnages By Region." https://environmentalrecords.colorado.gov/HPRMWebDrawerHM/RecordView/410058

[102] Energy estimates referenced based on 35% diversion.

[103] Personal communication, Scott Pasternak, Burns & McDonnell, May 23, 2019.

[104] Southwest Colorado Council of Governments, "Southwest Colorado Waste Study," 2015, https://www.colorado.gov/pacific/sites/default/files/DEHS_RREO_SWCCOGFinalReport_2015rev1.pdf

[105] US EPA Excess Food Opportunities map and dataset, https://www.epa.gov/sustainable-management-food/excess-food-opportunities-map. From FAQ section, "For the map, the phrase 'excess food' generally refers to post-harvest food that is intended for human consumption but removed from the supply chain to be recovered, recycled or disposed." Dataset does not include "unharvested crops or on-farm loss and excess food and other organic material disposed of by the residential sector, other than that which is captured by Source Separated Organics collection programs."

[106] EPA's Excess Food database provides a high and a low estimate for annual excess food. The number used here is an average of those two values. Only establishments institutions with at least a half ton a week of food waste were included.

[107] United States Census Bureau, "American Fact Finder," 'guided search' by food and beverage NAICS codes and state, https://factfinder.census.gov/faces/tableservices/jsf/pages/productview.xhtml?pid=SBO_2012_00CSA01&prodType=table

[108] Personal communication.

[109] According to the "Integrated Solid Waste and Materials Management Plan," under the Colorado Solid Waste Act CDPHE has authority over landfills, but its "enforceable authorities" beyond that effectively "do not exist" (page 6.1).

[110] Burns & McDonnell and Skumatz, "Colorado Integrated Solid Waste and Materials Management Plan."

[111] Colorado Solid and Hazardous Waste Commission, "Resolution of the Solid and Hazardous Waste Commission to Adopt Statewide and Regional Municipal Solid Waste Diversion Goals for Colorado." Adopted August 15, 2017. https://www.colorado.gov/pacific/sites/default/files/Waste_Diversion_Goals_Resolution08-15-17.pdf

[112] Colorado General Assembly, SB19-192, "Front Range Waste Diversion Enterprise Grant Program." https://leg.colorado.gov/bills/sb19-192

[113] "Resolution of the Solid and Hazardous Waste Commission."

[114] The "Integrated Plan" also included suggested commercial food waste diversion requirements, should the state in the future "acquire real authority in materials management beyond [landfill] disposal." Under these guidelines, food waste would have to be diverted to any certified facility within 20 miles, starting with generators of two tons per week in the first year and including all by the fifth year. Page 6-24.

[115] CDPHE, "About the RREO Grant Program," www.colorado.gov/pacific/sites/default/files/DEHS_RREO_MktTlkt_AboutRREOFund.pdf; "Recycling grants and rebates," www.colorado.gov/cdphe/recycling-grants-and-rebates; personal communication with RREO program office. Not all financial for AD has been direct; for instance, one RREO grant was for de-packaging equipment associated with the now-closed Heartland project.

[116] City of Boulder, "Zero Waste Regulations," https://bouldercolorado.gov/zero-waste/regulations; City of Boulder Municipal Code, Title 6, Chapter 3, "Trash, Recyclables and Compostables," https://library.municode.com/co/boulder/codes/municipal_code?nodeId=TIT6HESASA_CH3TRRECO_6-3-13PROWRERECOCO; and Title 6, Chapter 12, "Trash, Recyclables and Compostables Hauling."

[117] City and County of Denver, "Recycling, Compost and Trash," https://www.denvergov.org/content/denvergov/en/trash-and-recycling/composting/compost-collection-program.html and "Compost Sign Up," https://www.denvergov.org/compostsignup

[118] Personal communication with Alpine Waste and Recycling, Denver, https://alpinewaste.com/recycling-compost/.

[119] Town of Vail website, "Recycling," https://lovevail.org/programs/recycling/getting-started/

[120] Based on US EPA Emissions Calculator and .053 metric tons CO2e per MMBTU natural gas consumed. https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

[121] Assumes 50% manure capture rate. Production from cattle manure based on populations from USDA National Agricultural Statistics Service, 2017 Census of Agriculture, Chapter 1, Table 15, "Cow Herd by Inventory and Sales," www.nass.usda.gov/Quick_Stats/CDQT/chapter/1/table/15/state/CO.

[122] Weeks, "Experience with Three On-Farm Digester Systems Using Additional Off-Farm Organic Substrates," www.manuremanagement.cornell.edu/Pages/General_Docs/Events/10.Stan.Weeks.pdf; USDA Natural Resources Conservation Service, "Animal Manure Management RCA Issue Brief #7," https://www.nrcs.usda.gov/wps/portal/nrcs/detail/null/?cid=nrcs143_014211

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[123] Food scrap tonnage based on Skumatz Economic Research Associates, "Colorado Integrated Solid Waste & Materials Management Plan," June 2016. Appendix G, "Estimated 2016 tonnages By Region." https://environmentalrecords.colorado.gov/HPRMWebDrawerHM/RecordView/410058. Energy value assumes 35% diversion rate for food waste, based on overall MSW diversion target of 35% by 2026 established by the Solid and Hazardous Waste Commission in August 2017, linked at www.colorado.gov/pacific/cdphe/shwc-rules-resolutions-and-policies

[124] Energy yield from food waste, Energy Vision/Impact Bioenergy calculation. Based on 5000 cubic feet of biogas per ton food waste; 55% gas purity; upgrade to 970 BTU/cubic foot.

[125] Number of open closed landfills based on US EPA Landfill Methane Outreach Program (LMOP) "Landfill Energy Project Data" (www.epa.gov/lmop/landfill-gas-energy-project-data) and "Landfill Technical Data" (www.epa.gov/lmop/landfill-technical-data) databases for February 2019.

[126] Annual and lifetime biogas outputs based on EPA "LFGcost" tool, https://www.epa.gov/lmop/lfgcost-web-landfill-gas-energy-cost-model. The tool is designed to calculate on a project basis, requiring landfill opening and (if applicable) closing dates; landfill acreage; annual average delivery of waste, in tons; total tons of waste in place. To meet these requirements, open landfills and closed landfills were each treated as a "project", with averaged opening and closing years, and averages established for acreage and annual and total tonnage, based on available LMOP data, per note 6. For closed landfills, project start date was assumed to be 2022. For open facilities, project start was also assumed to be 2022, and annual flows set to reflect hypothetical 35% food waste diversion.

[127] Wastewater values are based on the Metro Wastewater Reclamation District, which includes 6 of Colorado's 10 largest cities-- Denver, Aurora, Lakewood, Thornton, Arvada and Westminster (as well as smaller municipalities)—and Fort Collins, Colorado Springs, Pueblo and Greeley. Also includes known WWTP renewable natural gas projects at Grand Junction, Longmont and Englewood, for which Energy Vision has output data, based on the database of RNG projects in the US which it curates for the US Department of Energy. MMBTU per year based on personal communication with the relevant utilities regarding daily gas flow and methane content of gas.

[128] CARB, *LCFS Pathway Certified Carbon Intensities*, op. cit.

[129] This is based on .053 metric tons CO2e/MMBTU per US EPA's GHG Equivalencies Calculator (https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator) , 19.4 million MMBTU displaced, and the "multiplier" assigned to RNG based on the -82.9 CI.

[130] This calculation is based on US EIA estimates for energy content for DGE (137,381 BTU) and GGE (120,333), the US EPA emissions calculator for natural gas (.053 metric tons CO2e/MMBTU) and the "multiplier" assigned to RNG based on the weighted CARB CI value of -82.9.

[131] US Dept. of Energy Alternative Fuels Data Center, Maps and Data – Average Annual Fuel Use of Major Vehicle Categories. https://afdc.energy.gov/data/

[132] This calculation is based on US EIA estimates for diesel tailpipe emissions of 22.4 grams CO2e/gallon, the CARB carbon intensity for average North American diesel fuel of 100.45, and the "multiplier" assigned to RNG based on the weighted CARB CI value of -82.9, recognizing that this is not an exact science but rather an approximation.

[133] Union of Concerned Scientists "Diesel Engines and Public Health," https://www.ucsusa.org/clean-vehicles/vehicles-air-pollution-and-human-health/diesel-engines

[134] US EPA, Ground level ozone basics: https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics

[135] The World Bank, Cleaning up Diesel Exhaust Improves both Health & Climate. http://www.worldbank.org/en/news/feature/2014/04/29/cleaning-up-diesel-exhaust-improves-health-climate

[136] American Lung Association, State of the Air Report 2019: https://www.lung.org/our-initiatives/healthy-air/sota/city-rankings/most-polluted-cities.html

[137] https://www.cumminswestport.com/press-releases/2018/cummins-westport-receives-2018-emissions-certifications-for-isx12n-natural-gas-engine

[138] Argonne National Lab's Heavy-Duty Vehicle Emissions Calculator (HDVEC), available as part of its Alternative Fuel Life-Cycle Environmental & Economic Transportation tool (AFLEET)

[139] "Understanding the Heavy Duty Vehicle Emissions Calculator (HDVEC),"Powerpoint presentation by Andy Burnham, Principal Environmental Scientist, Argonne National Lab. Presented at NGVAmerica Annual Conference, Nov 15, 2018.

[140] Energy Vision and Argonne National Lab 2018-19 RNG Project Assessment Database

[141] Colorado Department of Local Affairs, Energy Mineral Impact Assistance Tier II Grant Awards, November 2017, https://drive.google.com/file/d/19tWga7nOzVZqqr7lTgKDP8q7Pgc2X4Wi/view

[142] Database of Incentives for Renewables and Efficiency (DSIRE), http://www.dsireusa.org/; Colorado Department of Revenue, "Sales 83: Components used to produce energy form renewable sources or in biogas production systems," https://www.colorado.gov/pacific/sites/default/files/Sales83.pdf. Other incentives that seemed at best indirectly applicable to development of e.g a merchant digester included one program offering a 3% tax credit for businesses setting up in economically distressed areas allows those business to receive a payment equal to 80% of that credit if they install a renewable energy system, including anaerobic digestion. Another "Property Assessed Clean Energy Program" allows property owners to get 100% financing of the cost of undefined "other distributed generation technologies" that may or may not include anaerobic digestion and repay the financing over 20 years as part of their property tax assessment.

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[143] Personal communications.

[144] US Dept. of Energy Alternative Fuels Data Center: Renewable Fuel Standard. https://afdc.energy.gov/laws/RFS.html

[145] The higher heating value of a fuel is the amount of heat released by combustion, assuming that the latent heat of water vapor in the combustion products is recovered. Lower heating value assumes that the latent heat of water vapor is *not* recovered.

[146] "Trump orders review of controversial biofuels waiver program: sources," Jarrett Renshaw, Reuters, June 20, 2019: https://www.reuters.com/article/us-usa-biofuel-trump/trump-orders-review-of-controversial-biofuel-waiver-program-sources-idUSKCN1TL1WL

[147] California Air Resources Board: LCFS Credit Price Calculator, 2019. https://www.arb.ca.gov/fuels/lcfs/dashboard/creditpricecalculator.xlsx

[148] First person interviews with private sector RNG project developers

[149] NGV Global News, "RNG Reaches 32% of Natural Gas Fuel Sold in USA," April 16, 2019. https://www.ngvglobal.com/blog/rng-reaches-32-of-natural-gas-fuel-sold-in-usa-0416

[150] California Energy Commission, Transportation Natural Gas in California, 2016. https://www.energy.ca.gov/almanac/transportation_data/cng-lng.html

[151] US Dept. of Energy, Alternative Fuels Data Center: Natural Gas Vehicle Case Studies: https://afdc.energy.gov/case/1064

[152] Oxford Energy, A review of prospects for natural gas as a fuel in road transport, 2019. https://www.oxfordenergy.org/wpcms/wp-content/uploads/2019/04/A-review-of-prospects-for-natural-gas-as-a-fuel-in-road-transport-Insight-50.pdf

[153] NGVAmerica Industry Data, 2019. https://www.ngvamerica.org/vehicles/refuse/

[154] US Dept. of Energy, Alternative Fuels Data Center: Natural Gas Laws & Incentives. https://afdc.energy.gov/fuels/laws/NG?state

[155] Yahoo Finance, "Clean Energy Zero Now Truck Orders Surpass 250 and Climbing," May 7, 2019. https://finance.yahoo.com/news/clean-energy-zero-now-truck-100000616.html

[156] SoCalGas Renewable Natural Gas (RNG) Gas Quality Standards. https://www.socalgas.com/1443740736978/gas-quality-standards-one-sheet.pdf

[157] Southwest Energy Efficiency Project, Colorado Utility Energy Efficiency Programs Overview, 2017. http://swenergy.org/programs/utilities/state/colorado

[158] American Coalition of Competitive Energy Suppliers, State-by-State Information. http://competitiveenergy.org/consumer-tools/state-by-state-links/

[159] USDA NRCS, "Animal Manure Management RCA Brief #7."

[160] Based on personal communication with Andrea Watson, Asst. Professor of Animal Science, University of Nebraska, Lincoln; consultant Shaun Dustin, PhD, Dustin Engineering, formerly adjunct professor of civil and environmental engineering at Utah State University; and an RNG project investor.

[161] Personal communication with Richard Vetter of Agri-Bio Systems, Elgin, Illinois.

[162] Personal communication with Juan Tricorico, PhD, Innovation Center for US Dairy.

[163] Personal communication with Mary Drewnoski, Asst. Professor of Animal Science, University of Nebraska, Lincoln.

[164] Personal communication with Andrea Watson, UNL; Mary Drewnoski, UNL.

[165] USDA NRCS, "Animal Manure Management RCA Brief #7."

[166] Personal communication Drewnoski, Watson, Vetter, investor.

[167] EPA AgSTAR, "Livestock Anaerobic Digester Database," https://www.epa.gov/agstar/livestock-anaerobic-digester-database