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Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model

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WASTE-TO-WHEEL ANALYSIS OF ANAEROBIC-DIGESTION-BASED RENEWABLE NATURAL GAS PATHWAYS WITH THE GREET MODEL

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ABSTRACT

In 2009, manure management accounted for 2,356 Gg or 107 billion standard cubic ft of methane (CH_4) emissions in the United States, equivalent to 0.5% of U.S. natural gas (NG) consumption. Owing to the high global warming potential of methane, capturing and utilizing this methane source could reduce greenhouse gas (GHG) emissions. The extent of that reduction depends on several factors—most notably, how much of this manure-based methane can be captured, how much GHG is produced in the course of converting it to vehicular fuel, and how much GHG was produced by the fossil fuel it might displace.

A life-cycle analysis was conducted to quantify these factors and, in so doing, assess the impact of converting methane from animal manure into renewable NG (RNG) and utilizing the gas in vehicles. Several manure-based RNG pathways were characterized in the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model, and their fuel-cycle energy use and GHG emissions were compared to petroleum-based pathways as well as to conventional fossil NG pathways. Results show that despite increased total energy use, both fossil fuel use and GHG emissions decline for most RNG pathways as compared with fossil NG and petroleum. However, GHG emissions for RNG pathways are highly dependent on the specifics of the reference case, as well as on the process energy emissions and methane conversion factors assumed for the RNG pathways. The most critical factors are the share of flared controllable CH_4 and the quantity of CH_4 lost during NG extraction in the reference case, the magnitude of N_2O lost in the anaerobic digestion (AD) process and in AD residue, and the amount of carbon sequestered in AD residue. In many cases, data for these parameters are limited and uncertain. Therefore, more research is needed to gain a better understanding of the range and magnitude of environmental benefits from converting animal manure to RNG via AD.

1 INTRODUCTION

In 2009, the United States consumed 23.4 quadrillion Btu of natural gas (NG) for energy, equivalent to 25% of total primary energy consumption, according to the U.S. Energy Information Administration (U.S. EIA, 2011). In the process, 1,221 million metric tons (MMT) of carbon dioxide equivalent (CO_2e) were released to the atmosphere, accounting for 22.6% of U.S. greenhouse gas (GHG) emissions from energy consumption (U.S. EIA, 2011). In addition to its use as a fuel for boilers and other combustion equipment, NG is also used as a feedstock in the production of ammonia, plastics and other products, as a dehumidifier or desiccant, and for various other industrial processes. Although GHG emissions are also produced from these uses, they are at a much lower level (e.g., <0.01 MMT in ammonia production, according to the U.S. Environmental Protection Agency [U.S. EPA], 2011b).

While most of the NG consumed in the United States is from conventional wells located in North America, an increasing portion comes from shale deposits, coal beds and other unconventional sources. The shift to these unconventional sources of fossil NG has raised a number of environmental concerns, including the effect of effluent discharges from production fluids on groundwater and the potential for increased GHG emissions.

Newly revised results obtained with the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model show less relative advantage for fossil NG as compared with conventional gasoline in vehicular applications. This is primarily because of upward revisions to EPA's methane leakage and venting assumptions for conventional gas production. Renewable NG or RNG (also known as biogas, landfill gas [LFG] or digester gas) typically contains 50% or more methane and is itself a significant source of GHG emissions that may be released to the atmosphere—either as a mixture of methane (CH_4), CO_2 and other gases, or as the CO_2 combustion product from the flaring of those gases. EPA estimates that in 2009 over 190 MMT of CO_2e emissions came from landfills, animal manure and wastewater treatment (WWT) facilities (U.S. EPA, 2011b), while another 98 MMT and 16 MMT, respectively, were avoided by LFG-to-energy and manure biogas recovery projects (U.S. EPA, 2011b, 2011c). By avoiding the release of CH_4 and instead recovering and using the RNG in vehicles, very large reductions in GHG emissions can be realized relative to petroleum gasoline.

At present, there is no generally accepted estimate of the potential RNG resource base, although several sources have investigated portions of it (QSS Group Inc., 1998; Milbrandt, 2005; Saber and Takach, 2009). Hamberg (2011) reports that in the 2035–2050 timeframe, RNG production could reach 4.84 tcf, with 0.54 tcf coming from LFG, municipal wastewater, and livestock manures.[1].The RNG potential from the anaerobic digestion (AD) of food waste is highly speculative. Assuming that it could double production from municipal wastewater and livestock manures, the resulting renewable gas resource base (excluding gasification) could be

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[1] The bulk of the 4.84 tcf comes from the gasification of energy crops, agricultural waste, and other waste. Although the 0.5 tcf from anaerobic digestion does not explicitly include food waste, some may be included as a co-digestate. More complete estimates are currently under development and may be available later in 2011.

0.74 tcf per year, which is comparable to the American Gas Foundation (2011) estimate of 0.34–0.87 tcf per year.

Although the resource base may be limited, an understanding of RNG pathways and their GHG reduction potential has important policy implications. Because it is chemically identical to fossil NG yet produces far fewer GHG emissions, the blending of relatively small quantities of RNG with fossil gas can provide significant GHG benefits. For example, our previous analysis of compressed NG (CNG) and liquefied NG (LNG) from LFG showed 77‒101% reductions in GHG emissions as compared with petroleum gasoline (Mintz et al., 2010). Even blends of 20% RNG and 80% fossil NG were found to yield reductions of 30% or more (Mintz and Han, 2011). In those analyses, individual pathways differentiated by the source of process electricity and the method of distributing the CNG/LNG produced substantially different results. Likewise, for manure-based pathways, reductions in GHG emissions and fossil fuel use are likely to differ by feedstock and pathway because collection, composition, conversion and purification processes differ by type of manure as well as by climate, the composition of digester residue and the fate of that residue. Thus, typical pathways must be defined and analyzed on a life-cycle basis, and compared using a tool like GREET.

1.1 FUEL CYCLE ANALYSIS

Understanding the impacts of a fuel on energy use and emissions requires life-cycle analysis (LCA), a systematic accounting of the energy use and emissions at every stage of the fuel's production and use. The stages included in LCA are raw-material acquisition, transportation and processing and product manufacturing, distribution, use and disposal or recycling. LCA of a fuel is also called fuel-cycle analysis. A fuel cycle typically includes feedstock recovery and transportation, fuel production, transportation and distribution, and combustion as an end use. For example, as shown in Figure 1, a CNG pathway for today's CNG-fueled vehicles includes stages corresponding to gas exploration and recovery, gas venting and flaring and NG upgrading and compression, as well as stages accounting for non-NG inputs like petroleum, coal, and renewables. The stages from exploration and recovery (well) to transportation and distribution (pump) are collectively called well-to-pump (WTP), while the last stage, corresponding to combustion by an internal combustion engine (ICE), is called pump-to-wheel (PTW). The entire pathway is known as well-to-wheel or, in the case of RNG, waste-to-wheel (WTW). In other words, WTW is a term specific to a fuel-cycle analysis of transportation fuel, and a WTW analysis is a LCA of transportation fuels.

To conduct fuel-cycle analyses, Argonne National Laboratory has developed and continuously updated the GREET model. Since 1995, GREET improvements have been supported with funding from several programs within DOE's Office of Energy Efficiency and Renewable Energy. Developed in Microsoft® Excel with a graphical user interface, GREET is structured to systematically account for a range of potential feedstocks, fuels and conversion processes for any defined WTW pathway. GREET calculates emissions of three GHGs (CO_2, CH_4 and N_2O) and six criteria pollutants (VOCs, CO, NO_x, SO_x, PM_{10} and $PM_{2.5}$), and consumption of each of the following: total energy, fossil fuel, petroleum, NG, and coal.

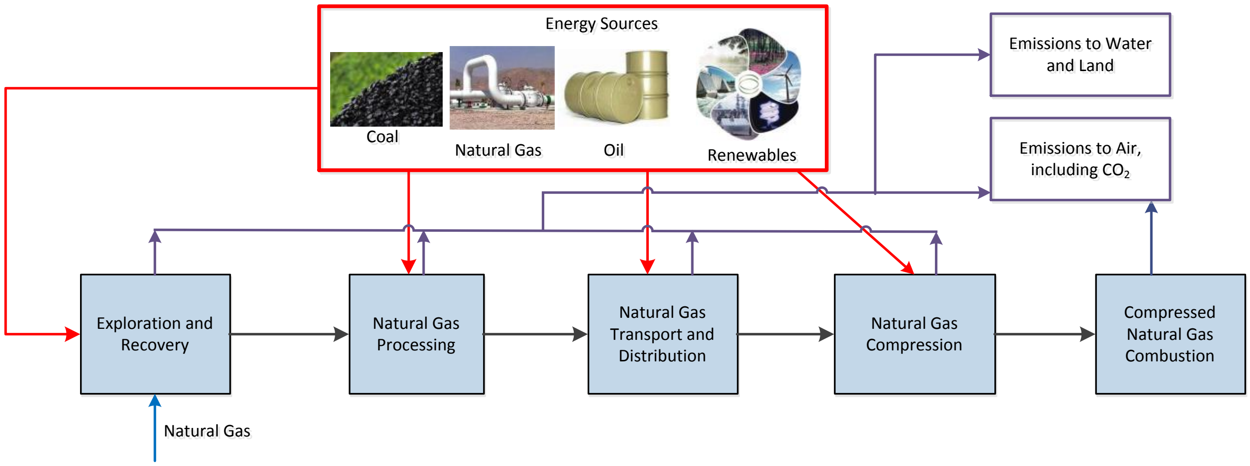

FIGURE 1 Stages in a CNG Pathway

Downloadable at http://greet.es.anl.gov/, GREET currently has more than 15,000 registered users worldwide from academia, industry and government.

1.2 FUEL CYCLE ANALYSIS OF RENEWABLE NATURAL GAS

Figure 2 illustrates the carbon cycle corresponding to RNG produced from the AD of animal waste. Currently, manure management systems treat most animal waste, recovering some energy in the form of a nutrient-rich residue but typically not producing energy. With AD, RNG also can be produced from animal waste and used to fuel vehicles or generate electricity.

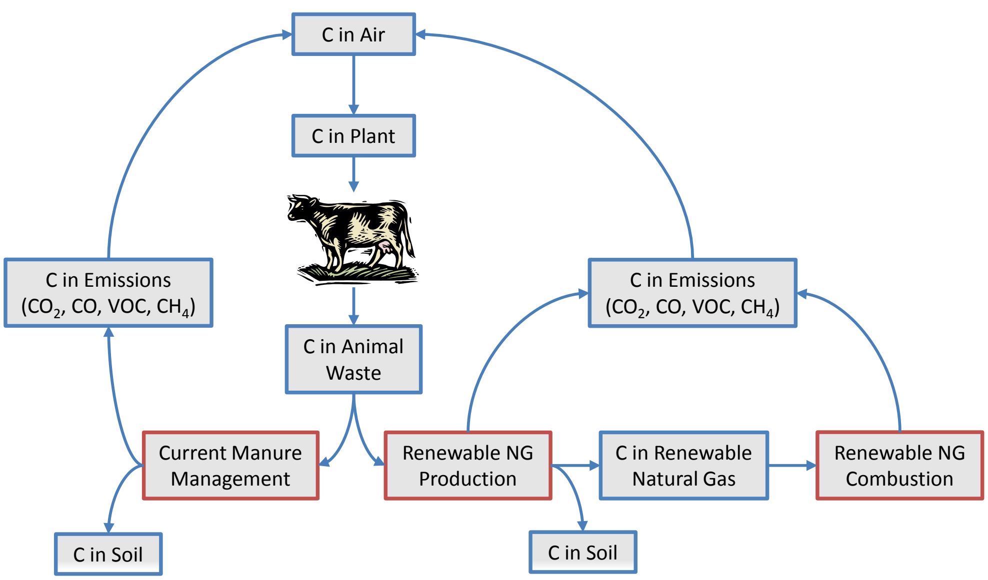

FIGURE 2 Carbon Cycle of Anaerobic Digestion-Based RNG from Animal Waste

This study examines the fuel cycle of animal waste conversion to CNG and LNG vehicle fuels. As compared with fossil NG (shown in Figure 1), WTW analysis of RNG is more complicated, since it must account for energy use and emissions in a reference or base case as well as in a "new" pathway (i.e., conversion of AD gas to RNG and its use in vehicles). Unlike fossil fuels, where no fossil carbon-associated emissions occur if the fuel stays in the ground, renewable fuels involve a recycling of carbon and emissions in both a reference case and a "new" pathway that is being modeled. The reference-case pathway consumes energy and generates emissions in the absence of conversion to vehicular fuel. These reference-case emissions must be subtracted from emissions that occur in the "new" pathway being modeled. Portions (or stages) of the reference and "new" pathway that are unchanged can be ignored, since they do not affect the calculation.

Constructing an appropriate reference case for RNG pathways is further complicated by current and future diversity in manure management systems and energy recovery. For example, only 167 of the more than 2 million farms in the United States currently recover AD-based RNG to produce electricity for on-site consumption or export to the grid, a handful produce pipeline-quality gas for injection to the natural gas system, and only one farm currently produces NG as a vehicle fuel from animal waste because of the technical and financial difficulties of producing and injecting RNG into a NG pipeline (U.S. EPA, 2011a).[2] Even if AD gas-based CNG/LNG for vehicle fuels is not developed in the future, the number of farms producing electricity from AD gas could increase as illustrated by the solid blue line in Figure 3. Thus, if AD gas-based CNG/LNG were introduced as a transport fuel, the reference-case feedstock for the CNG/LNG would include not only the animal waste traditionally treated by manure management (the pale red area in the figure) but also animal waste that is converted to electricity (the pale blue area in the figure). Therefore, following the introduction of AD gas-based CNG/LNG, the share of animal waste for electricity generation with AD gas-based CNG/LNG would be smaller than that without AD gas-based CNG/LNG.

Either *marginal analysis* or *energy allocation* can be applied to deal with this issue. In *marginal analysis*, the reference case is assumed to include a mix of animal waste disposal options with some waste treated by conventional manure management and some converted to electricity, with the actual share illustrated by the solid blue line in Figure 3 and the amount of animal waste that otherwise would generate electricity noted as A in the figure. If "A" were to be used for RNG, then conventional fuel (such as fossil NG) would be needed to replace the electricity that otherwise would be produced from animal waste. This fuel should be added to the calculation for the RNG pathway. However, the size of "A" is difficult to measure. Moreover, it depends on various factors (such as policy incentives, regulation, relative NG and electricity prices, and technology development) that change over time. Thus, estimating the mix of supplemental electricity generation is highly uncertain.

[2] Another, Fair Oaks Dairy, is expected to begin production by the end of 2011.

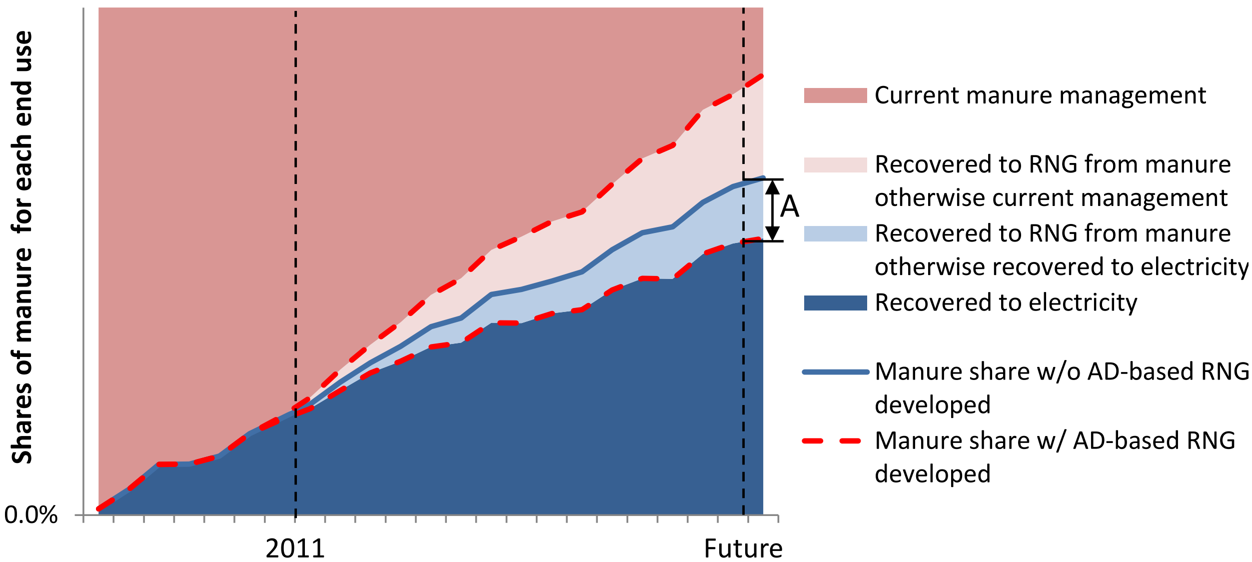

FIGURE 3 Disposition of Animal Waste

On the other hand, using the *energy allocation* approach, the reference case is considered to be simply traditional manure management and both CNG/LNG and electricity are considered to be products of the "new" pathway. Then, energy and emissions associated with the avoided emissions from manure management can be allocated to LFG-based electricity and RNG by their respective energy shares. Since energy allocation does not require uncertain projections (e.g., future shares of waste-to-electricity conversion and the marginal supplies used to offset waste-to-electricity conversion displaced by RNG conversion), this study uses that approach.

Once WTW results for a given fuel pathway are estimated, they should be compared with those for baseline or reference-case pathways that the examined fuel may displace. Since CNG is expected to be used primarily in light-duty vehicles (LDVs), the baseline pathway for CNG should be petroleum gasoline, which is used widely for passenger cars in the United States. Similarly, since LNG is expected to be used in heavy-duty vehicles (HDVs), the baseline pathway for LNG should be petroleum diesel. Table 1 summarizes some of the parameters of "new" and reference-case AD gas-, LFG- and fossil NG-to-CNG/LNG pathways.

1.3 SCOPE

This report summarizes WTW analyses of RNG produced from the AD of animal waste. It describes the pathways, feedstock characteristics, conversion processes and efficiencies, co-products and indirect emissions assumed for the analysis and presents results.

The report is organized into four sections. Following this introduction, Section 2 describes the RNG pathways, their key stages and important features of the fuel cycle analysis. In Sections 3 and 4, estimates of WTW energy use and GHG emissions are presented and conclusions are discussed.

TABLE 1 "New" RNG Pathways and Reference-Case Parameters in the GREET Model

RNG ("New") Pathway and Fuel	Reference Case of Feedstock and Fuel Displaced	
AD gas-based CNG	Current manure management[1]	Petroleum gasoline
AD gas-based LNG	Current manure management[1]	Petroleum diesel
LFG-based CNG	Flaring LFG[1]	Petroleum gasoline
LFG-based LNG	Flaring LFG[1]	Petroleum diesel
Fossil CNG	No activity	Petroleum gasoline
Fossil LNG	No activity	Petroleum diesel

[1] With the energy allocation methodology, the reference case does not include competing pathways (e.g., electricity generation from AD gas or LFG).

2 FUEL CYCLE ANALYSIS OF RENEWABLE NATURAL GAS FROM ANAEROBIC DIGESTION OF ANIMAL WASTE

Figure 4 shows the system boundary of RNG pathways from animal waste. The system begins with collected animal waste because waste is collected in both the reference case (current manure management) and the "new" AD cases. In the latter, collected waste is transported to an AD facility where biogas and AD residue are produced. Some biogas is combusted to produce electricity and heat for the digestion process, biogas cleanup, and on-site liquefaction, while the rest is purified to produce commercial-grade NG. The produced NG is then either 1) transported as a gas to off-site refueling stations, compressed to 3,600 psi and dispensed to CNG vehicles or 2) liquefied on-site, transported as a liquid to off-site stations, and dispensed to LNG vehicles.[3]

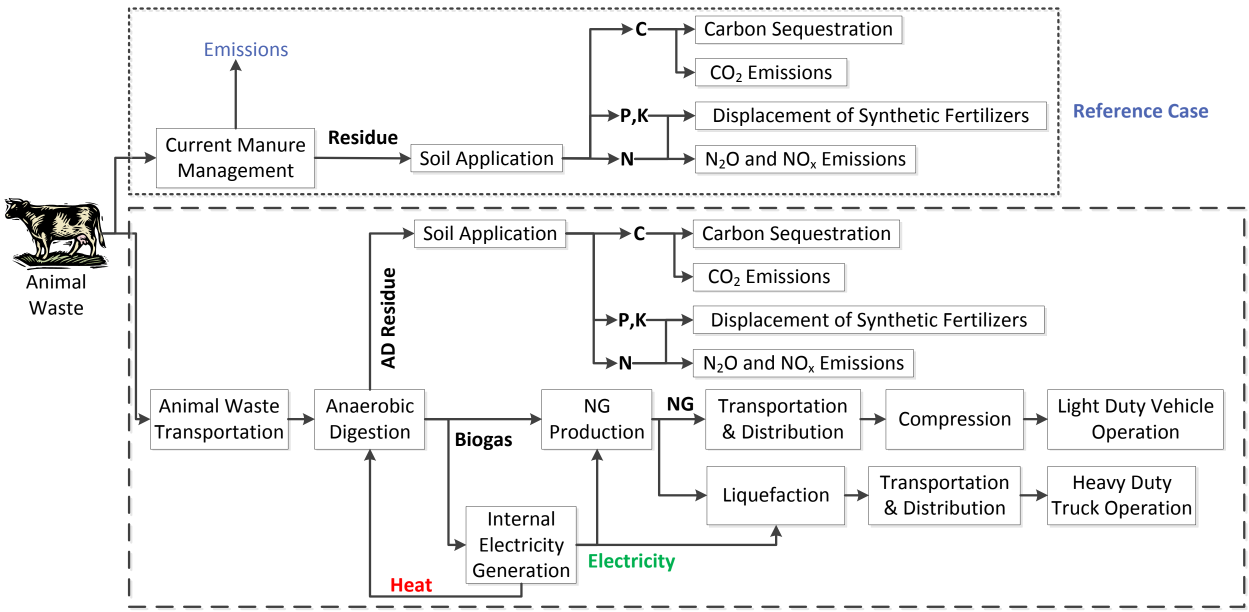

FIGURE 4 System Boundary of Renewable Gas Production from AD of Animal Waste

The liquid AD residue from the digestion process contains significant quantities of N, P and K. It is transported off-site and applied to soil to displace synthetic fertilizers. The solid portion of the residue may be recycled for animal bedding or as a soil amendment, but this is not considered in our analysis.

[3] Alternatively, the gas could be injected into a pipeline and liquefied off-site. This pathway is not modeled explicitly in GREET.

2.1 BIOGAS PRODUCTION IN AD PATHWAYS AND REFERENCE CASE

Unlike the LFG pathways already contained in GREET (see Mintz et al., 2010), AD pathways include the bio-methane production step and soil application of AD residue. Therefore, the amount of bio-methane produced is important and can be estimated for a given livestock type as follows:

$$CH_{4,Manure} = \sum_{S} \sum_{k} B_O \times MCF_{S,k} \times MS_{S,k} \ ,$$

where $CH_{4,Manure}$ is the amount of CH_4 produced in ft^3/lb of volatile solid (VS), B_0 is the maximum methane-producing capacity for manure of a given livestock type in ft^3/lb of VS, $MCF_{S,k}$ is the methane conversion factor (MCF) for each manure management technology S by climate region k in %, and $MS_{S,k}$ is the manure share (MS) handled by manure management technology S by climate region k (IPCC, 2007). B_0 depends on species and diet; the MCF of conventional manure management varies by technology and climate while the MCF of anaerobic digesters depends on technology, residence time and temperature.

The energy use and emissions associated with current manure management should be taken as a credit, which depends not only on the manure management system but also on climate, livestock species and diet. IPCC provides recommended values for B_0 and MS for nine regions (i.e. North America, Latin America, Western Europe, Eastern Europe, Oceania, Africa, Middle East, Asia, and Indian Subcontinent) and MCFs for a range of annual average temperatures from 10°C to 28°C (IPCC, 2007). The U.S. EPA summarizes B_0 for livestock in the United States from various sources in the literature, and estimates MS for manure management systems used in the United States by state (U.S. EPA, 2011a). EPA also estimates MCFs of wet (e.g. anaerobic lagoon, liquid slurry and deep pit) and dry (e.g. daily spread and pasture) manure management systems for cool, temperate and warm climate zones. EPA uses the same climate zone definitions as the IPCC (i.e., cool climate zone: 10–14°C, temperate climate zone: 15–25°C and warm climate zone: 26–28°C) and annual average temperatures reported by the U.S. National Oceanic and Atmospheric Administration (NOAA, 2011). Average MS and MCF values for the United States as a whole are obtained using the livestock population from the U.S. Department of Agriculture (USDA, 2011). All data available from IPCC, EPA, NOAA and USDA are included in GREET. For this study, we use average U.S. values for dairies as reported by U.S. EPA and USDA, and conduct sensitivity analyses using data for California and Wisconsin, the two states with the largest dairy populations. Table 2 summarizes average MSs and MCFs for the United States, California, and Wisconsin. Note that in Wisconsin, solid storage is used for a larger share and anaerobic lagoons for a smaller share of manure than in the United States as a whole, while in California more than 50% of manure is treated by anaerobic lagoon. B_0 for dairy cows is 0.24 m^3 CH_4/kg of VS (USDA, 2011).

According to EPA's AgSTAR Program, 167 farm-based AD projects are currently recovering energy in the United States, reducing CH_4 emissions by 1.1 Tg CO_2e, as shown in Table 3 TABLE 3(U.S. EPA, 2011b). Despite this reduction, EPA estimates that total methane emissions from manure management in the United States were still 49.5 Tg CO_2e in 2009, which is significant compared to other sectors (U.S. EPA, 2011a). For example, in 2009, NG systems in the United States generated 130.3, 17.5, 44.4 and 29.0 Tg CO_2e emissions from field production, processing, transmission, and storage and distribution, respectively. Owing to increasing concerns about global warming, manure management systems are expected to capture or flare an increasing share of CH_4 from manure. Therefore, we assume that CH_4 from all manure management systems except pasture and daily spread will be flared, and provide a sensitivity analysis for the share of flared CH_4 from current manure management (see Sec. 3.3). Pasture and daily spread are excluded from this assumption because of the difficulty in collecting CH_4 from land application.

TABLE 2 Manure Share (MS) and Methane Conversion Factor (MCF) of Manure Management Systems

Waste Management System	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit
MS by system and location						
U.S. Average	7%	15%	23%	21%	32%	2%
California	1%	11%	9%	21%	58%	0%
Wisconsin	7%	12%	42%	24%	12%	4%
MCF by system and location						
U.S. Average	1.2%	0.2%	2.6%	28.6%	69.9%	28.6%
California	1.5%	0.5%	4.0%	35%	75%	35%
Wisconsin	1.0%	0.1%	2.0%	22%	66%	22%

TABLE 3 Operational Anaerobic Digesters and Methane Reduction by Livestock Type and Biogas End Use in the United States

	Dairy		Beef		Swine		Poultry	
	No. of Projects	Methane Reduction (Gg CO_2e/yr)	No. of Projects	Methane Reduction (Gg CO_2e/yr)	No. of Projects	Methane Reduction (Gg CO_2e/yr)	No. of Projects	Methane Reduction (Gg CO_2e/yr)
Heat	6	31			2	84		
Electricity	38	284			7	102	2	2.2
Cogeneration	78	392	1	2.7	7	20	3	15
Vehicle Fuel	1	1.9						
Pipeline NG	1	1.4						
Flared	11	123			5	17		
Not Specified	2	27	1		2	7		
Total	137	861	2	2.7	23	230	5	17

MCFs for AD pathways are estimated from EPA's AgStar project database (U.S. EPA, 2011b). From a consideration of 92 projects without co-digestion among the 137 active dairy projects in the United States, total CH_4 emissions are estimated by subtracting CH_4 emission reductions from baseline CH_4 emissions. Here, the baseline CH_4 emissions are estimated from the baseline MCFs by states provided in the GHG Inventory (U.S. EPA, 2011a) while the CH_4 emission reductions are converted from metric tons of CH_4/yr to m^3/kg VS using the livestock population feeding the digester and the VS production rate provided in the GHG Inventory (U.S. EPA, 2011a). Then, MCFs of AD are estimated as follows:

$$\text{MCF (\%)} = \frac{\text{B}_0 - [\text{Total CH}_4 \text{ Emission}]}{B_0} .$$

Table 4 summarizes MCFs estimated from the AgStar project database along with those from two other sources. The values of Frost and Gilkinson (2011) are based on measured AD yields from dairy cow slurry at Hillsborough, UK, while the values of Berglund and Börjesson (2006) are based on several reports from Sweden. Values within parentheses represent minimum and maximum values reported in the literature, which show large variations in MCFs. Typically, covered lagoon systems have a lower average and a wider range of MCFs than other systems because the temperature and homogeneity of the mixture in the reactor are less controllable.

TABLE 4 Methane Conversion Factors (MCFs) of Anaerobic Digesters

Source	Covered Lagoon	Complete Mix	Horizontal Plug Flow	Mixed Plug Flow
AgStar (U.S. EPA, 2011b)	70% (37%–90%)	85% (61%–92%)	82% (69%–97%)	81% (53%–97%)
Frost and Gilkinson (2011)		65% (54%–72%)		
Berglund and Börjesson(2006)	81% (63%–99%)			

2.2 ANIMAL WASTE TRANSPORTATION AND OPERATION OF ANAEROBIC DIGESTER

From the CH_4 production estimated using the equation above, the VS required to produce 1 mmBtu of NG can be calculated. When VS is transported,[4] other solids and water are also transported. Therefore, the total mass, in lb, to be transported (M_T) per 1 mmBtu of methane produced can be expressed as

$$M_T = \frac{1{,}000{,}000}{r_{VS/TS} \times (1 - r_{moisture}) \times CH_{4,Manure}^{AD} \times LHV_{CH_4}} ,$$

4 In the reference case, manure is not transported off site. In our analysis, transportation may occur as part of the collection process.

where $r_{VS/TS}$ and $r_{moisture}$ are the ratios of VS to total solids (TS) and the moisture content is calculated using the values summarized in Table 5. Also, $CH_{4,Manure}^{AD}$ is the CH_4 produced from AD in ft^3/lb VS and LHV_{CH4} is the lower heating value of methane in Btu/ft^3. In this study, the default assumption is that all manure is transported by truck for 3 miles to a central digester. Depending on the scale of the AD project, pipeline transportation of manure can be used to reduce the process energy inputs and operating costs, negating large capital costs (Ghafoori et al., 2007).

TABLE 5 Characteristics of Manure (USDA, 2010)

wt%	Dairy Cow	Other Cattle	Market Swine	Breeding Cattle
Moisture	88%	88%	90%	90%
VS/TS	85%	50%	54%	54%
N/TS	3.9%	2.6%	4.2%	4.7%
P/TS	0.6%	0.9%	1.6%	1.5%
K/TS	2.5%	1.9%	2.2%	3.0%
C/TS	47%	28%	29%	28%

As shown in Table 6, heat and electricity demands of AD facilities vary significantly depending on feedstock characteristics, plant size and technology (mesophilic vs. thermophilic, batch vs. continuous, and single stage vs. multiple stages). For example, mesophilic digesters operating at ambient temperature (65–110°F) require less heat than thermophilic ones operating at elevated temperature (120–160°F). Mesophilic digesters are typically more stable but less productive than thermophilic. On the other hand, simple batch reactors (e.g. covered lagoon) require much smaller energy inputs than continuous reactors (e.g. continuously stirred tank reactors [CSTRs] and plug-flow reactors). Continuous reactors typically produce more biogas faster because of the homogeneity of manure in reactors. Moreover, it is possible to use multiple vessels for different stages of digestion, such as hydrolysis, acidogenesis, acetogenesis and methanogenesis, so that each stage can occur under optimal conditions. In a typical two-stage reactor, hydrolysis, acidogenesis and acetogenesis occur in the first vessel while methanogenesis occurs in the second vessel. Even though the biogas yields are higher, multistage reactors are more complex and require more energy.

The AD systems reported by Frost and Gilkinson (2011) and Berglund and Börjesson (2006) are a CSTR and a continuous-tank reactor operating at mesophilic temperature, respectively, while Börjesson and Berglund (2006) do not specify the type of reactor. This study assumes average values for AD except for covered lagoons. Since covered lagoons have little maintenance cost, they are assumed to consume half the heat required by the other systems and no electricity. For reference manure management, no energy inputs are assumed because major

TABLE 6 Process Heat and Electricity Inputs for Anaerobic Digesters of Manure

		Heat (Btu/wet ton of manure)	Electricity (kWh/wet ton of manure)
Frost and Gilkinson (2011)	Farm Scale	96,000 (68,000–121,000)[1]	4.9
Berglund and Börjesson (2006)	Farm Scale	215,000	8.3
	Large Scale	94,600 (60,000–155,000)	16.6 (13.9–20.2)
Börjesson and Berglund (2006)	Farm Scale	163,000	6.5
	Large Scale	73,000	13.4
Average		116,000	12.0

[1] Values within parentheses indicate the range observed in the literature.

waste management practices in the United States (daily spread, solid storage, liquid/slurry storage, anaerobic lagoon and deep pit) require negligible amounts of energy other than for transferring the waste.[5]

In this study it is assumed that all on-site electricity and heat demands for AD, NG production, and on-site liquefaction are supplied by an on-site generator powered by RNG. If the heat produced from an on-site generator meets the heat demand and produces excess electricity, the electricity is assumed to be exported, displacing the U.S. average generation mix. On the other hand, if excess heat is produced, it is assumed to be discarded.

2.3 APPLICATION OF AD RESIDUE TO SOIL

Regardless of manure management system, residue from manure management or anaerobic digesters is eventually applied to soil. AD residue is assumed to be backhauled by the same trucks that transport animal waste. Since residue still contains VS, AD still occurs, emitting a small amount of CH_4. This study assumes the same MCF for CH_4 emissions from residue as from manure daily spread. Also, the carbon in the residue is not stable and is easily oxidized to CO_2. Bruun et al. (2006) estimate that 14–37%, 63–83% and 84–98% of C applied becomes CO_2 in 10, 50 and 100 years, respectively (Figure 5). Using the data in Bruun et al. (2006) and averaging over a 100-year time horizon, 62% of the C in the residue is assumed to become CO_2, and the rest (38%) is assumed to remain stored in the soil. The C in the residue is calculated by subtracting the C converted to CH_4 from the total C in the manure.

The typical nitrogen (N), phosphorus (P) and potassium (K) contents of manure were shown in Table 5. Since there is little loss of nutrients during manure management, the nutrients are applied to the soil when residue is applied, displacing synthetic fertilizers. However, when N

[5] This assumption is also consistent with longer retention times which would provide more opportunity for methane leakage.

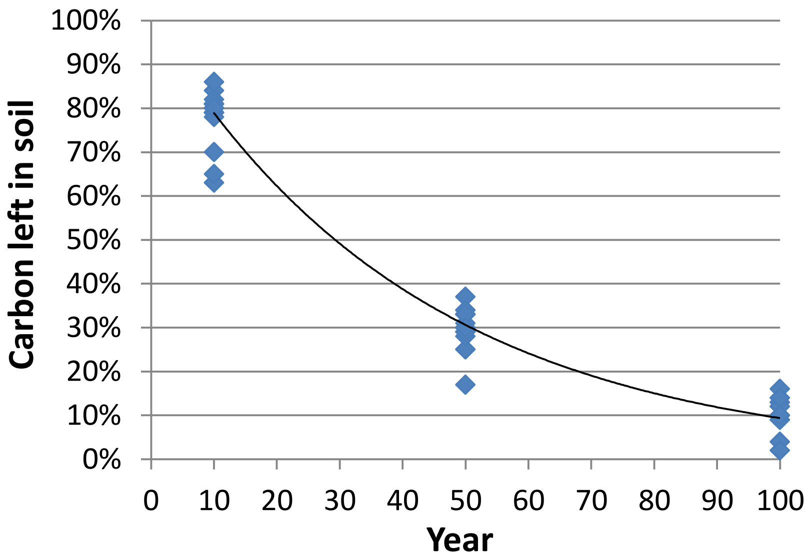

FIGURE 5 Carbon Left in Soil After AD Residue is Applied to Soil[6]

is applied, N_2O and NO_x are emitted. These impacts—that is, synthetic fertilizer displacement and N_2O and NO_x emissions—should be included in LCAs of AD pathways. N_2O emissions can occur (1) by nitrification and denitrification, (2) by volatilization as nitrate (some of which is then converted to N_2O), and (3) by leaching as nitrate from soil to streams and groundwater via runoff (some of which is then converted to N_2O). This study applies the emission factors set by the IPCC and adapted in EPA's GHG Inventory. These are summarized in Table 7. Note that while the emission factors for direct N_2O emissions by nitrification and denitrification are defined as kg (N_2O – N)/kg excreted N, those for indirect N_2O emissions are defined as kg (N_2O – N)/kg volatilized or leached N. Thus, in order to calculate indirect N_2O emissions by volatilization and leaching, the fraction of N lost through volatilization and leaching should be determined (see Table 7). For AD, EPA specifies no direct N_2O emissions because nitrification requires oxygen.

Little information is available for indirect N_2O emissions from AD and AD residue. Therefore, we assume that the volatilization and runoff/leaching N_2O loss factors are 43% and 0.6%, respectively, which are consistent with those for open anaerobic lagoons. With N_2O emissions calculated for the reference case and the AD pathways, the differences in N stored in the soil between the reference case and the AD pathways can be estimated. The stored N is taken by plants, displacing synthetic fertilizers. Therefore, the differences in the stored N can be used to estimate the amount of displaced N fertilizers. In this study, we assume 50% of the stored N

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6 Note that the percent of carbon stored in soil could asymptote over time with repeated application of AD residue. However, since we assume systematic rotation of the soil to which AD residue is applied, we do not adjust carbon uptake assumptions.

TABLE 7 Direct and Indirect N_2O Emission Factors and Indirect N_2O Loss Factors

	Pasture	Daily Spread	Solid Storage	Liquid/ Slurry	Anaerobic Lagoon	Deep Pit
Direct N_2O Emission Factors (kg [N_2O – N]/kg N)	0	0	0.005	0.005	0	0.002
Volatilization Indirect N_2O Emission Factors	0.010 kg (N_2O – N)/kg N Volatilized					
Volatilization Indirect N_2O Loss Factor	0%	10%	27%	26%	43%	24%
Runoff/Leaching Indirect N_2O Emission Factor	0.010 kg (N_2O – N)/kg N from Runoff/Leaching					
Runoff/Leaching Indirect N_2O Loss Factor						
Central	0.0%	0.0%	0.2%	0.2%	0.2%	0.0%
Pacific	0.0%	0.0%	0.0%	0.8%	0.8%	0.0%
Mid-Atlantic	0.0%	0.0%	0.0%	0.7%	0.7%	0.0%
Midwest	0.0%	0.0%	0.0%	0.4%	0.4%	0.0%
South	0.0%	0.0%	0.0%	0.9%	0.9%	0.0%
U.S. Average	0.0%	0.0%	0.0%	0.6%	0.6%	0.0%

displaces synthetic N fertilizers for the reference case and AD pathways.[7] Therefore, this study includes the energy and emissions associated with synthetic fertilizers displaced, assuming the soil is cornfield.

2.4 BIOGAS PROCESSING FOR RNG PRODUCTION

In NG production, biogas from an anaerobic digester is converted into pipeline-quality NG through pre-purification and purification processes. Pre-purification removes impurities including corrosive hydrogen compounds, low concentrations (parts per million) of non-methane organic compounds, and water; purification removes CO_2 and increases CH_4 concentration. We examine four major technologies (membrane separation, adsorption, absorption, and cryogenic distillation) and define the process efficiency of NG production, i.e., the energy in the produced NG divided by the sum of the energy in the biogas feed to the pre-purification step and the process energy for pre-purification and purification (Mintz et al., 2010). The electricity for NG production and subsequent processes is assumed to be generated from ICEs powered by pre-purified biogas. The efficiency of ICEs is assumed to be 35% (Mintz et al., 2010).

CH_4 vented or leaked from equipment during AD, NG production or upgrading is a major source of GHG emissions. On the basis of several Swedish reports, Börjesson and Berglund (2006) estimate that 2% of the biogas produced is vented or leaked during these stages. This value is significantly larger than the 0.15% emission rate for conventional NG upgrading

[7] Lack of oxygen in AD keeps ammonia from being nitrified, thereby increasing its ammonia content. Thus, AD residue might displace more N fertilizer than manure in the reference case. Moreover, N uptake occurs over a longer portion of the growing season, permitting multiple applications of residue to nearby (and perhaps more distant) fields. However, since data on actual application rates and travel distances from residue storage tanks to fields are not available, displacement ratios are assumed to be the same for the reference case and the AD pathways.

facilities, but could be attributed to differences in scale (Burnham et al., 2011). Therefore, this study assumes that 2% of the produced renewable gas is leaked. As indicated by Börjesson and Berglund (2006), more research on CH_4 emissions from anaerobic digesters and small-scale NG processing facilities is warranted for a more comprehensive understanding of biogas-based pathways.

A substantial amount of methane, which could correspond to 5–10% or even up to 20% of produced renewable gas, could also leak during the storage and transport of waste to the digester or as AD residue and during digester maintenance (Börjesson and Berglund, 2006). Assuming an 80% MCF for AD, 5–10% CH_4 emission during storage means that MCFs for AD residue storage could be 20–40%, which corresponds to the range of MCFs for liquid/slurry, deep pit and anaerobic lagoon storage. Because AD residue is not stored as long as manure in liquid/slurry, deep pit and anaerobic lagoons (typically more than 2–3 months), MCFs of 20–40% may be too high (particularly if GHG reduction measures become widely adopted). Moreover, most losses can be reduced by reducing the storage period or collecting the gas during transport, storage and maintenance. Owing to the uncertainty of the leakage rate and the possibility of reducing it, this study does not include potential losses from leakage during transport, storage, or maintenance.

2.5 RNG COMPRESSION, LIQUEFACTION, TRANSPORTATION, DISTRIBUTION AND VEHICLE USE

In GREET, RNG can be dispensed as a gas to CNG LDVs or as a cryogenic liquid to LNG HDVs. For the former, RNG is assumed to be shipped 50 miles[8] by pipeline to off-site refueling stations where it is compressed to 4,000 psia by electric compressors powered by grid electricity. For the latter, RNG is liquefied by on-site liquefiers (whose efficiency is assumed to be 89%, assuming single mixed refrigerant and expander processes) and then trucked to off-site stations located 50 miles from the RNG production site.

This study assumes that LDVs operate on CNG while HDVs operate on LNG. Thus, results for CNG- and LNG-fueled vehicles are compared to those for petroleum gasoline cars and diesel HDVs, respectively. We also assume that gasoline cars achieve the GREET default fuel economy, which is 23.4 mpgge (miles per gallon gasoline equivalent), and that CNG cars are as efficient as gasoline cars (Mintz et al., 2010). For HDVs, we reviewed several sources. The 2002 Vehicle Inventory and Use Survey conducted by the U.S. Census Bureau (2002) reports that class 7–8 diesel trucks achieve 5.92 mpgde (miles per gallon diesel equivalent) in regional service while on-road driving data from manufacturers suggest a value of 6.2 mpgde for long-haul heavy-duty diesel trucks.(Vyas et al., 2002). By contrast, recent EPA and NHTSA estimates, using a vehicle simulation model for their regulation impact analysis of Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles (2011), report a value of 4.95 mpgde. This study assumes that class 7-8 diesel trucks achieve an average fuel economy of 6 mpgde and that LNG trucks are 10% less fuel-efficient than diesel trucks (Mintz et al., 2010).

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8 The distance is estimated by assuming a local refueling station, and can vary by scenario.

3 RESULTS

WTW results, in units of total energy and fossil energy consumption per MJ and per mi and in GHG emissions per MJ and per mi, are presented below. Key parameters are summarized in Table 8. Results of sensitivity analyses for seven key parameters related to AD pathways are presented in Section 3.3. These parameters include percent of controllable CH_4 that is flared in the reference case, MCF of the anaerobic digester, process energy demand for AD, MCF of the AD residue, percent of C in the AD residue applied to the soil that is sequestered, indirect N_2O loss factors, and CH_4 losses in NG processing.

TABLE 8 Key Parametric Assumptions

Parameter	Unit	Value
Animal Waste Transportation		
Animal Waste Transportation Distance	mile	3
Animal Waste Moisture Content	%	88%
AD and Reference Case		
B_0	m^3 CH_4/kg of VS	0.24
MS and MCF of Reference Case	%	See Table 2
% of Flaring Controllable CH_4 in Reference Case	%	100%
MCF of Anaerobic Digester	%	See Table 4
Heat Demand for AD	Btu/wet ton of manure	See Table 6
Electricity Demand for AD	kWh/wet ton of manure	See Table 6
AD Residue		
MCF of AD Residue	%	0.2%
% of Sequestration of C in AD Residue Applied to Soil	%	38%
Volatilization Indirect N_2O Loss Factor	%	43%
Runoff/Leaching Indirect N_2O Loss Factor	%	0.6%
NG Processing and Upgrading		
NG Processing Efficiency	%	94%
CH_4 Loss Rate from NG Processing	%	2%[1]
Internal Engine Generation Efficiency	%	35%
Heat Recovery Efficiency of Internal Engine Generation	%	80%
Compression Efficiency	%	97%
Liquefaction Efficiency	%	89%
NG Transportation/Distribution and Vehicle Operation		
Distance to CNG/LNG Refueling Stations	mi	50
Fuel Economy of Baseline Gasoline Cars	mpgge	23.4
Ratio of CNGV Fuel Economy to That of Gasoline Cars	%	100%
Fuel Economy of Baseline Diesel HDVs	mpgde	6
Ratio of LNGV Fuel Economy to That of Diesel HDVs	%	90%

[1] Percent of CH4 produced that is lost in processing.

3.1 ENERGY AND GHG EMISSIONS PER MJ

Figure 6 compares WTW total energy use for each RNG pathway with similar results for CNG from conventional North American Natural Gas (NA NG), LNG from NA NG, petroleum gasoline, and petroleum diesel. WTW total energy use depends largely on system efficiency. Thus, RNG-based pathways typically require more total energy than conventional NG, gasoline or diesel. Moreover, LNG requires more total energy than CNG because compression is more energy efficient than liquefaction.

Figure 7 compares WTW fossil fuel use for the pathways, and shows a significant reduction for RNG-based pathways relative to fossil-based pathways. Note that for RNG pathways, vehicle operation (PTW) uses no fossil fuel (since RNG-based fuels are renewable), while RNG processing and liquefaction require little or no fossil fuel and only a small amount of fossil fuel is needed for animal waste and AD residue transport and RNG transportation and distribution. For CNG, RNG is compressed at off-site refueling stations using electricity produced by the U.S. average electricity mix; for LNG, RNG is liquefied on site using electricity generated by biogas from the digestion process itself. Therefore, AD-based renewable LNG consumes much less fossil energy than does CNG. Among AD-based pathways, covered lagoons use less total and fossil fuel because of their smaller process energy demands.

Figure 8 shows WTW GHG emissions for RNG pathways, as compared with petroleum gasoline, petroleum diesel, fossil CNG (from NA NG) and fossil LNG (from NA NG) pathways. Note that GHG emissions are expressed as g CO_2e per unit energy produced and used, and include CO^{-}, CH_4 and N_2O. Because of credits from manure management in the reference case, RNG pathways generate far fewer GHG emissions than fossil fuel pathways. Similar to the fossil energy results, AD-based renewable LNG emits much less GHG than CNG because RNG is liquefied on-site using electricity produced from biogas. Also, the smaller process energy demands of anaerobic lagoons result in lower GHG emissions.

Tables 9 and 10 provide detailed WTW results for total energy use, fossil fuel use and GHG emissions for CNG and LNG pathways, respectively. In the GHG calculations, GHGs are assumed to be captured and stored in the fuel during fuel production and released during vehicle operation. Thus, GHG emissions for WTP are largely negative.

Figure 9 shows GHG emissions from AD-based renewable CNG, fossil CNG and petroleum gasoline pathways by stage. For AD-based renewable CNG, results are shown for the mixed plug flow digester. Excluding emissions from vehicle operation, the largest share of GHG emission in all three pathways occurs during the recovery and processing stages. For fossil CNG, recovery generates large GHG emissions because of methane leakage and venting during well workovers (Burnham et al., 2011). For AD-based renewable CNG, processing accounts for a larger share of emissions because of our 2% leakage assumption (discussed in Section 0) as well as the lower processing efficiency of the relatively small-scale reactors.

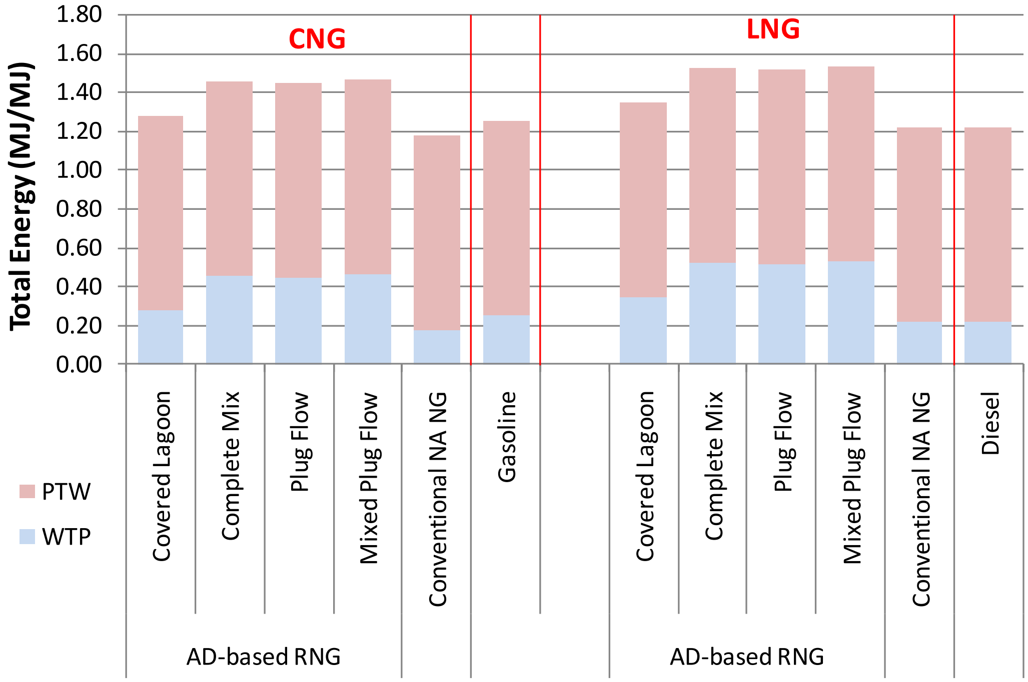

FIGURE 6 WTW Total Energy Use for AD-Based RNG Pathways Compared to Conventional NG, Gasoline and Diesel Pathways (MJ/MJ Produced and Used)

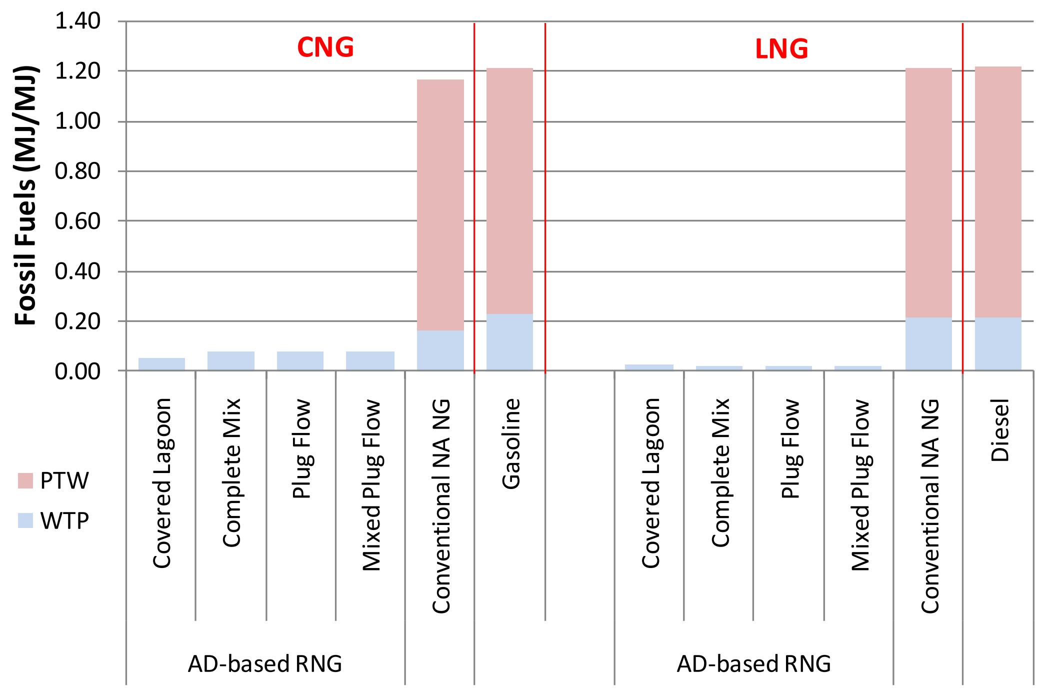

FIGURE 7 WTW Fossil Fuel Use for AD-Based RNG Pathways Compared to Conventional NG, Gasoline and Diesel Pathways (MJ/MJ Produced and Used)

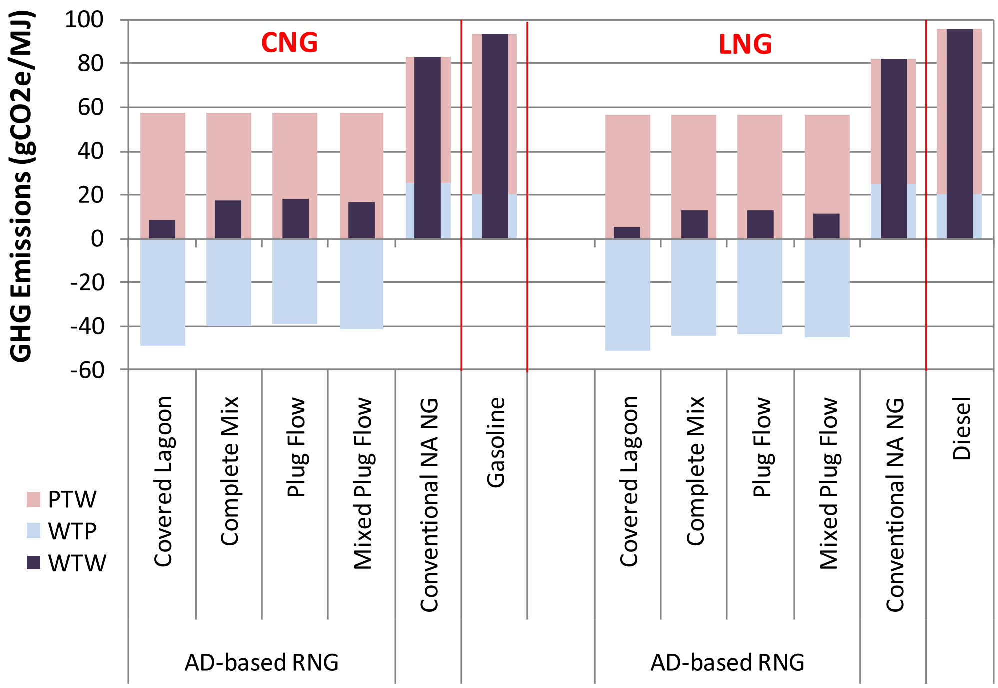

FIGURE 8 WTW GHG Emissions for AD-Based RNG Pathways Compared to Conventional NG, Gasoline and Diesel Pathways (g CO_2e/MJ Produced and Used)

TABLE 9 WTW Results for AD-Based Renewable CNG Pathways Compared to Conventional CNG and Gasoline Pathways (MJ or g CO_2e/MJ Produced and Used)

Fuel		**CNG**					**Gasoline**
Feedstock		AD Gas				NA NG	
AD Type		Covered Lagoon	Complete Mix	Horizontal Plug Flow	Mixed Plug Flow		
Total Energy (MJ/MJ)	WTP	0.28	0.45	0.45	0.46	0.18	0.25
	PTW	1.00	1.00	1.00	1.00	1.00	1.00
	WTW	1.28	1.45	1.45	1.46	1.18	1.25
Fossil Fuels (MJ/MJ)	WTP	0.05	0.08	0.08	0.08	0.17	0.23
	PTW	0.00	0.00	0.00	0.00	1.00	0.98
	WTW	0.05	0.08	0.08	0.08	1.17	1.21
GHGs (g CO2e/MJ)	WTP	-49	-40	-39	-41	26	20
	PTW	58	58	58	58	58	74
	WTW	9	18	18	17	83	94
GHG Emissions Reduction Relative to Gasoline Vehicles		-91%	-81%	-81%	-82%	-11%	

TABLE 10 WTW Results for AD-Based Renewable LNG Pathways Compared to Conventional LNG and Diesel Pathways (MJ or g CO_2e/MJ Produced and Used)

Fuel		LNG					Diesel
Feedstock		AD Gas				NA NG	
AD Type		Covered Lagoon	Complete Mix	Horizontal Plug Flow	Mixed Plug Flow		
Total Energy (MJ/MJ)	WTP	0.34	0.52	0.52	0.53	0.22	0.22
	PTW	1.00	1.00	1.00	1.00	1.00	1.00
	WTW	1.34	1.52	1.52	1.53	1.22	1.22
Fossil Fuels (MJ/MJ)	WTP	0.02	0.02	0.02	0.02	0.22	0.22
	PTW	0.00	0.00	0.00	0.00	1.00	1.00
	WTW	0.02	0.02	0.02	0.02	1.22	1.22
GHGs (g CO2e/MJ)	WTP	-51	-44	-44	-45	25	20
	PTW	57	57	57	57	57	75
	WTW	5	13	13	11	82	96
GHG Emissions Reduction Relative to Diesel Vehicles		-94%	-87%	-86%	-88%	-14%	

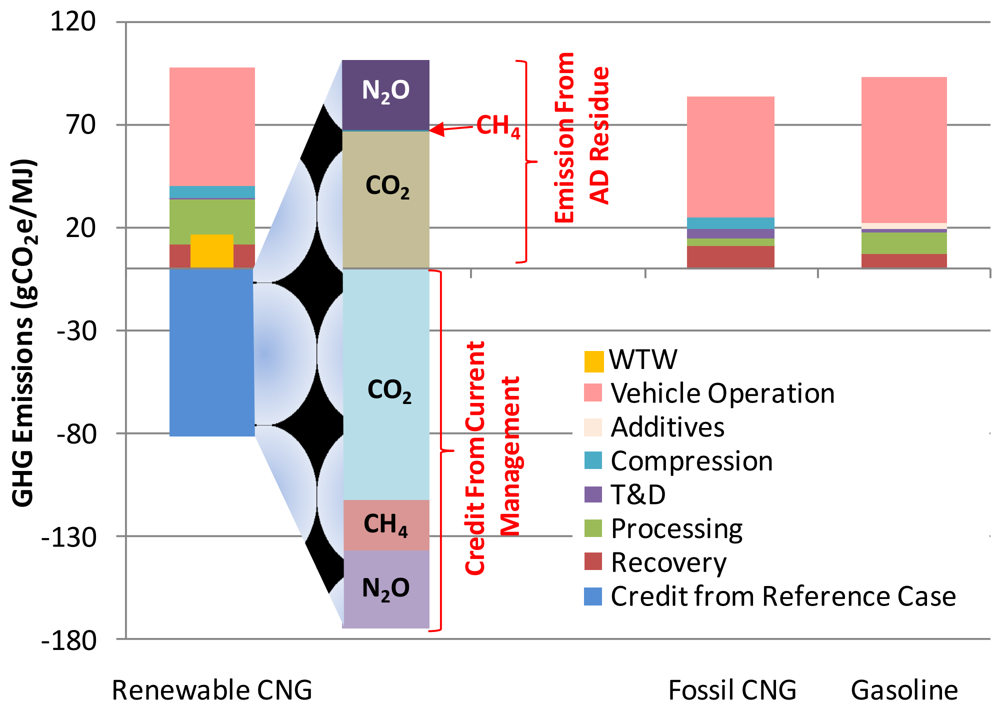

FIGURE 9 GHG Emissions from Renewable CNG, Fossil CNG and Petroleum Gasoline Pathways (g CO_2e/MJ)

Figure 9 also breaks down the emission credits and burdens for the AD-based renewable CNG pathway. All GHG credits result from the reference case (i.e., the difference between the emissions generated by current manure management and the emission burdens from AD residue). Compared to CH_4 emissions from current manure management, the CH_4 emissions from AD residue are significantly smaller because most digestible carbon is recovered by AD, and AD residue is applied to soil, where much of the remainder is digested aerobically. The CO_2 emissions from AD residue are also much smaller than the CO_2 credits from current manure management because a large amount of carbon is converted into RNG, as shown in Figure 10. Even though the difference is small, N_2O emissions from the AD residue are also smaller than those produced from current manure management.

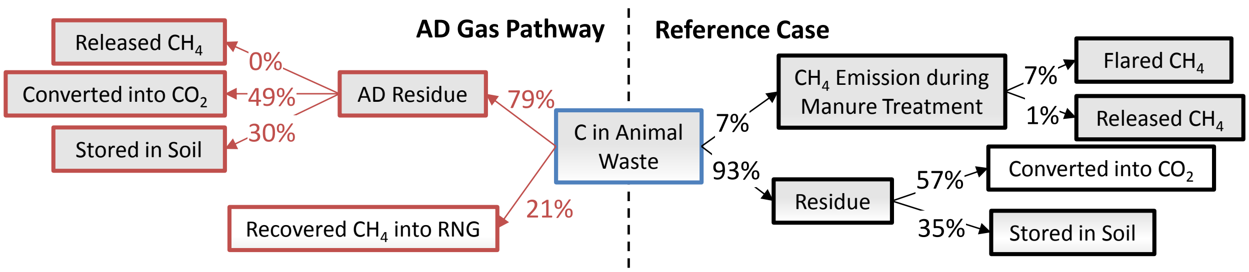

FIGURE 10 Disposition of Carbon from Animal Waste in AD Gas Pathways and the Reference Case

3.2 ENERGY AND GHG EMISSIONS PER MILE

Figures 11–13 show WTW total energy use, fossil fuel use and GHG emissions on a per-mile basis for AD-based RNG pathways. Separate comparisons highlight differences for cars fueled with AD-based renewable CNG versus petroleum gasoline and fossil CNG (from NA NG), and for HDVs fueled with AD-based renewable LNG versus petroleum diesel and fossil LNG (from NA NG). Tables 10 and 11 provide detailed results for WTW total energy and fossil fuel use and GHG emissions for CNG cars and LNG trucks as compared to gasoline cars and diesel trucks.

Since automobile fuel economy is about 10 times better than HDV fuel economy (in mpg equivalent), WTW results for cars are about 10-fold smaller than for HDVs. Note that in Figures 11–13, the units on the right vertical axis (for HDVs) are 5 times those on the left vertical axis (for cars).

Because CNG cars are as efficient as gasoline cars, their per-mile PTW energy use and GHG emissions look very similar to the per-MJ results shown in Figures 6–8. However, owing to the 10% fuel economy advantage of diesels over NG-fueled trucks, total energy use and fossil fuel use for diesel HDVs are smaller than for fossil LNG HDVs. Nonetheless, the advantages of renewable LNG pathways with respect to fossil fuel use and GHG emissions result in significant reductions in WTW fossil fuel use and GHG emissions (Figures 12 and 13).

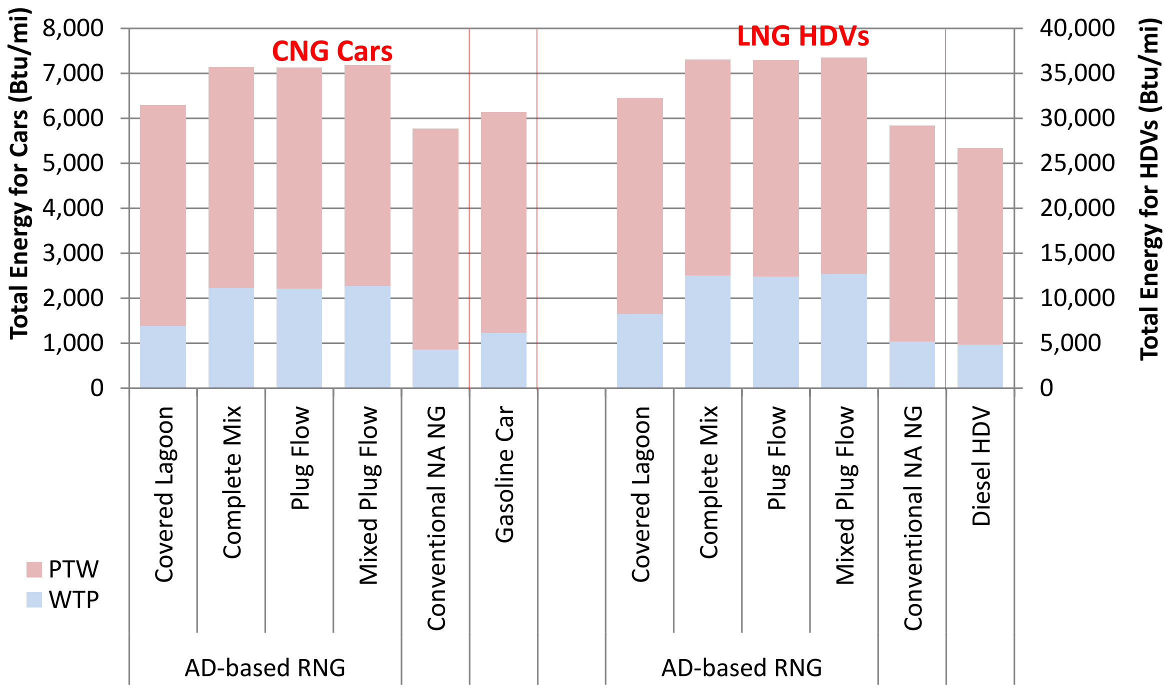

FIGURE 11 WTW Total Energy Use for AD-Based RNG Pathways Compared to Conventional NG, Gasoline and Diesel Pathways (Btu/mi)

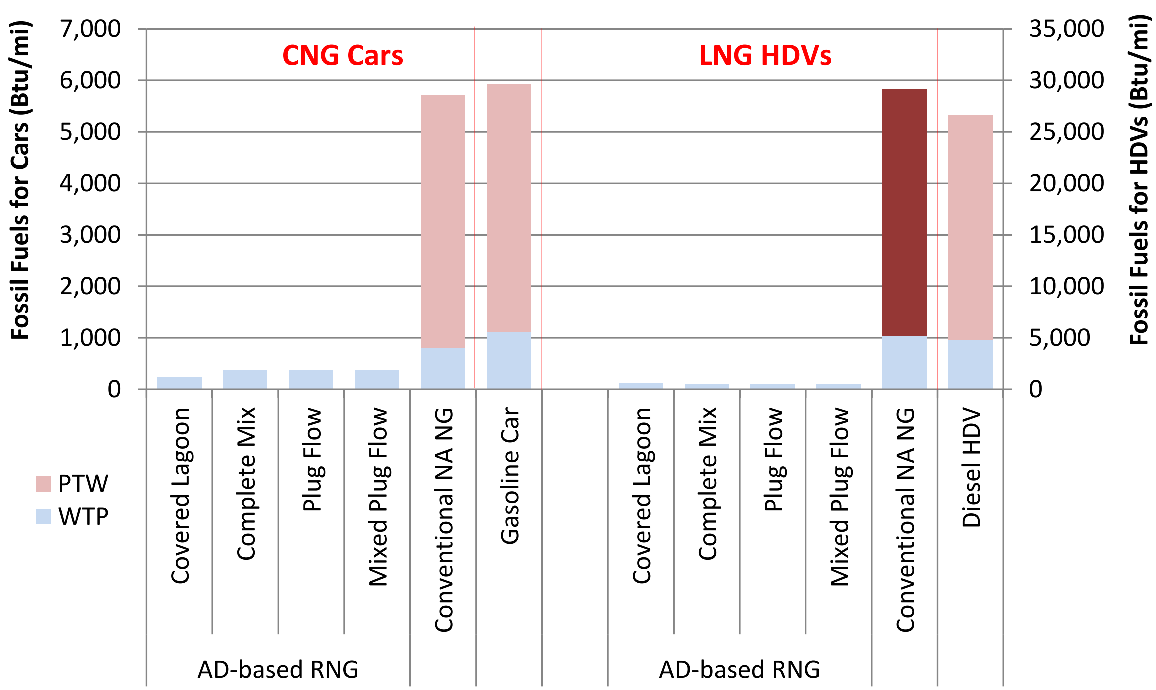

FIGURE 12 WTW Fossil Fuel Use for AD-Based RNG Pathways Compared to Conventional NG, Gasoline, and Diesel Pathways (Btu/mi)

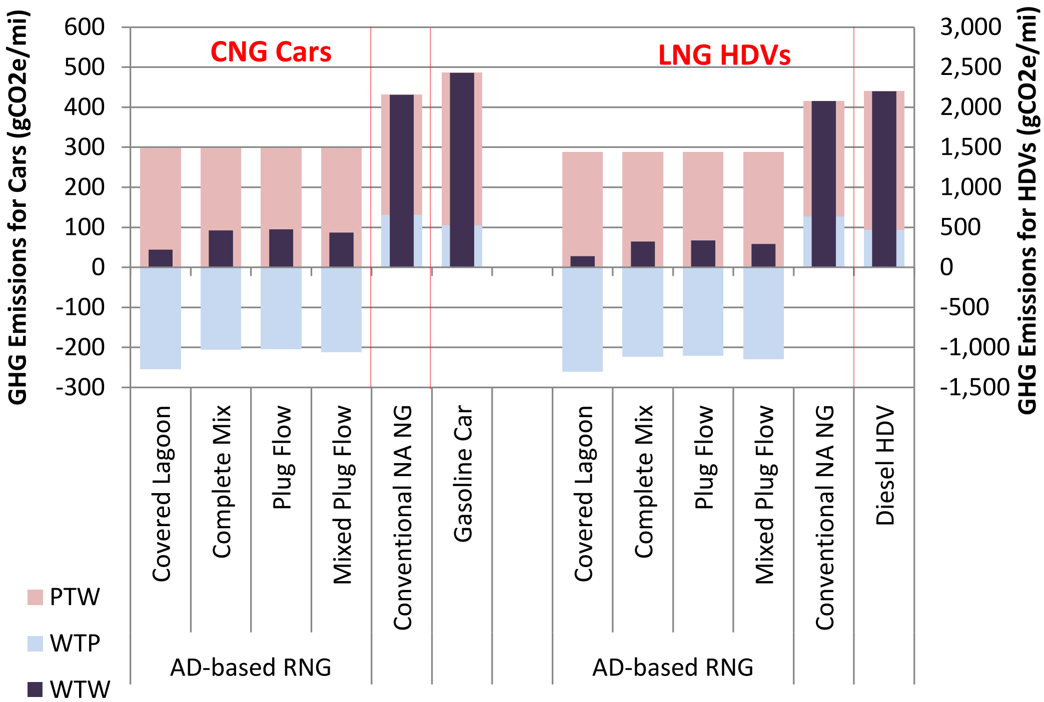

FIGURE 13 WTW GHG Emissions for AD-Based RNG Pathways Compared to Conventional NG, Gasoline and Diesel Pathways (g CO_2e/mi)

TABLE 11 WTW Results for AD-Based Renewable CNG Pathways Compared to Conventional CNG and Gasoline Pathways (Btu or g CO_2e/mi)

Fuel		**CNG**					**Gasoline**
Feedstock		AD Gas				NA NG	
AD Type		Covered Lagoon	Complete Mix	Horizontal Plug Flow	Mixed Plug Flow		
Total Energy (Btu/mi)	WTP	1,387	2,232	2,214	2,273	862	1,230
	PTW	4,908	4,908	4,908	4,908	4,908	4,908
	WTW	6,295	7,140	7,122	7,181	5,770	6,138
Fossil Fuels (Btu/mi)	WTP	241	375	373	379	810	1,125
	PTW	0	0	0	0	4,908	4,806
	WTW	241	375	373	379	5,718	5,931
GHGs (g CO2e/mi)	WTP	-254	-206	-204	-212	132	105
	PTW	298	298	298	298	298	381
	WTW	44	92	95	86	431	486
GHG Emissions Reduction Relative to Gasoline Vehicles		-91%	-81%	-81%	-82%	-11%	

TABLE 12 WTW Results for AD-Based Renewable LNG Pathways Compared to Conventional LNG and Diesel Pathways (Btu or g CO_2e/mi)

Fuel		LNG					Diesel
Feedstock		AD Gas				NA NG	
AD Type		Covered Lagoon	Complete Mix	Horizontal Plug Flow	Mixed Plug Flow		
Total Energy (Btu/mi)	WTP	8,261	12,527	12,438	12,731	5,191	4,869
	PTW	23,999	23,999	23,999	23,999	23,999	21,818
	WTW	32,261	36,527	36,437	36,731	29,190	26,687
Fossil Fuels (Btu/mi)	WTP	551	520	512	540	5,161	4,786
	PTW	0	0	0	0	23,999	21,818
	WTW	551	520	512	540	29,161	26,604
GHGs (g CO2e/mi)	WTP	-1,299	-1,116	-1,102	-1,147	640	471
	PTW	1,439	1,439	1,439	1,439	1,439	1,729
	WTW	139	323	336	292	2,079	2,200
GHG Emissions Reduction Relative to Diesel Vehicles		-94%	-85%	-85%	-87%	-6%	

3.3 SENSITIVITY ANALYSIS

Detailed sensitivity analyses of WTW GHG emissions per MJ from AD-based CNG pathways are presented below. Results are shown for mixed plug flow AD reactors, the most common type currently in use in the United States (U.S. EPA, 2011b). Bars correspond to the deviations in GHG emissions due to replacing GREET default inputs with low and high values for the parameters shown. These values are defined as 90% and 110% of the average values reported.

As shown in Figure 14, two parameters related to the reference case, the share of flared controllable CH_4 and location, dominate impacts on WTW GHG emissions in AD-based renewable CNG pathways. When 81% of the controllable CH_4 in the reference case (from solid storage, liquid/slurry, anaerobic lagoon and deep pit) is flared (10% lower than the baseline), the emission credits in the reference case increase owing to the avoidance of more CH_4 emissions, and WTW GHG emissions from renewable CNG drop by 130% (meaning net GHG sequestration). Conversely, if the share of flared controllable CH_4 in the reference case increases by 10% (to 99%), the emission credits in the reference case decrease, and WTW GHG emissions from renewable CNG increase by 130%. In 2009, only 1.1 Tg CO_2e of methane out of 50.6 Tg CO_2e was eliminated by EPA's AgSTAR program (U.S. EPA, 2011a, 2011b). Owing to the large uncertainty and impact on GHG emissions, the current share of flared controllable CH_4 is a critical environmental issue and the dominant factor affecting GREET results.

Location, which in turn affects MS and MCFs in the reference case, is the second most important factor affecting our results. For California, the reference manure management system emits more GHGs than the baseline case because 1) reference systems are mainly anaerobic lagoons (58%) whose MCF is 75% and 2) annual average temperature is higher than either the

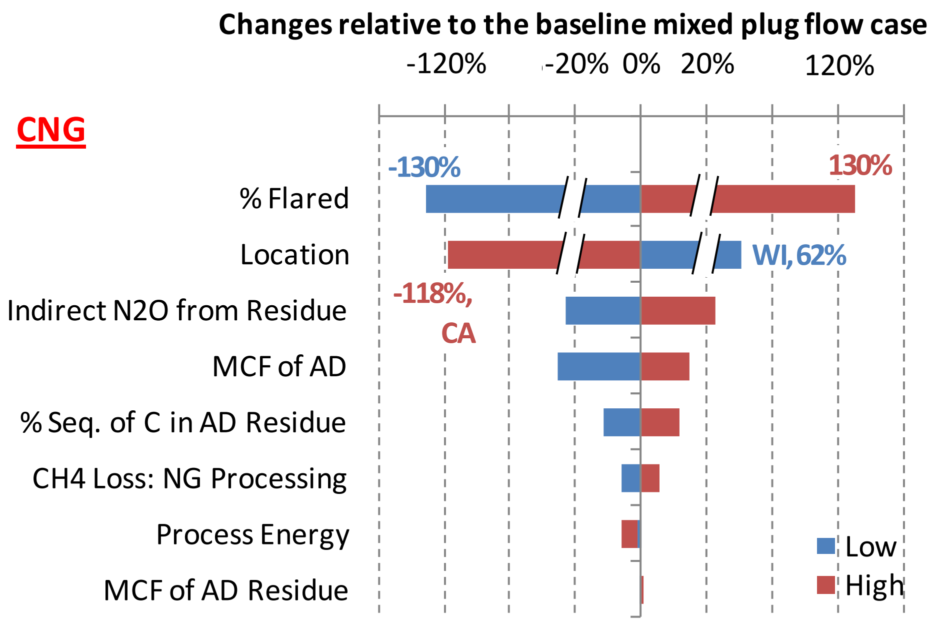

FIGURE 14 Sensitivity of GHG Emissions from AD-Based Renewable CNG Pathways (per MJ)

U.S. average or Wisconsin's average, also resulting in higher MCFs. Owing to the higher GHG emissions from the reference case, AD implemented in California would avoid more GHG emissions than on average in the United States or in Wisconsin, and WTW GHG emissions of AD-based CNG pathways in California result in a 118% decrease in GHG emissions as compared to a California reference case (meaning net GHG sequestration). Conversely, the reference case in Wisconsin emits less GHGs than the average in the United States, which results in WTW GHG emissions in Wisconsin increasing by 62% as compared to the U.S. average case. In addition, AD in Wisconsin would require greater process heat to warm up manure. This study does not take into account the different heat demands by location, which would make the variation wider.

The indirect N_2O loss factor from AD residue also has a large impact on WTW GHG emissions. Even though there are only small differences in N_2O loss factors between the reference case and the AD pathways (shown in Figure 9), the high global warming potential of N_2O (298 times that of CO_2) produces a considerable increase in GHG emissions.

Results for MCFs appear counterintuitive—with lower MCFs producing lower GHG emissions—but can be explained easily. With reduced MCFs, more manure is needed to produce 1 MJ of renewable CNG. As manure input increases, 1) larger emission burdens from increased process energy demands and 2) larger emission credits from the reference case are incurred. Since emission credits are much larger than emission burdens, net WTW GHG emissions decline as MCFs drop. This illustrates a tradeoff between productivity and GHG emissions, an important topic for further analysis.

4 CONCLUSIONS

This report documents a WTW analysis of RNG from animal waste and compares resulting energy use, fossil fuel use and GHG emissions to those for conventional NG and gasoline pathways. A reference case was defined from current manure management practices and differences between it and AD-based pathways were determined. Critical issues, including nutrient recovery and other emissions (N_2O) from soil application, are examined in the context of constructing the reference and AD pathways.

On the basis of data and assumptions from the literature, all RNG pathways show significantly less fossil fuel consumption and GHG emissions than conventional fossil NG and gasoline. Assuming that 90% of controllable CH_4 (from solid storage, liquid/slurry, anaerobic lagoon and deep pit) in current manure management systems is flared and that U.S. average MSs and MCFs are achieved, GHG emission reductions of 81–91% on a per-MJ basis are estimated for AD-based renewable CNG relative to petroleum gasoline, depending on reactor types. Similarly, GHG emission reductions for AD-based renewable LNG relative to petroleum diesel on a per-MJ basis are estimated to be 86–94%.

GHG emission reductions by AD-based pathways vary widely depending on the reference case, the indirect N_2O loss factors from both AD and AD residue, and the MCFs of AD. The most critical factor appears to be the share of flared controllable CH_4 in the reference case because the flaring of bio-methane reduces GHG emission by a factor of nine. Location, which in turn determines MS and MCFs in the reference case, is nearly as important as the share of flared controllable CH_4. Unfortunately, estimates for all these parameters are limited, coverage is spotty and resulting assumptions are highly uncertain. Clearly, more reliable data would provide greater precision and certainty in WTW analysis of AD pathways.

This analysis represents an important step in understanding the environmental benefits of AD and renewable gas. AD is promising not only because of its environmental benefits, but also because of the productivity of biogas. Many other opportunities and pathways, in addition to those based on animal manures, are possible. For example, WWT facilities are a major producer of bio-methane and a major consumer of electricity and heat. In 2007, among over 16,000 WWT facilities operating in the United States, only 544 utilized AD to treat wastewater (U.S. EPA, 2007). Moreover, only 106 WWT facilities produced electricity or heat from AD. If all 544 WWT facilities with anaerobic digesters produced electricity, EPA estimates that approximately 340 MW of renewable electricity could be produced annually reducing 2.3 MMT of CO_2e emissions.

Co-digestion of organic waste with manure or wastewater is another option that has received increasing attention as a means to increase AD productivity despite challenges of contamination and yield variation. In the United States, 44 out of 167 operating AD projects co-digest organic waste (such as crop waste, food waste and food-processing wastewater) with animal waste (U.S. EPA, 2011b). Renewable fuel pathways based on WWT facilities and co-digestion represent important extensions to this work.

Finally, while this study assumes a robust market for RNG-based fuels, market issues are beyond the scope of this analysis. Because there are many renewable sources for electricity but few for NG, RNG may be an increasingly attractive option for entities required to implement low-carbon fuel standards and renewable-portfolio standards. Owing to historically low NG prices and recent advances in shale gas technology, projects to produce pipeline-quality NG are less viable in today's economic climate than they were a few years ago. However, the price differential between NG for stationary applications versus competing motor fuels remains a significant incentive for RNG, as do recently enacted low-carbon fuel standards.

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