A review of the scientific literature on greenhouse gas and co-pollutant emissions from waste- and coproduct-derived biomass-based diesel and renewable natural gas

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Executive summary

The United States' goal of net zero emissions by 2050 urges state governments to take immediate and deep decarbonization actions (Flatt, 2021; LCSL, 2021). Correspondingly, New York State's Climate Leadership and Community Protection Act (CLCPA) mandates to achieve at least 85% state-wide carbon reduction of greenhouse gas (GHG) emissions by 2050 (Anon, 2020a). Biomass-based diesel (BBD) and renewable natural gas (RNG) have been identified in the law as alternative biofuels that have the potential to displace fossil fuels (CARB, 2021; EPA, 2020). As such, it is important to assess their life cycle carbon intensities (CIs) and co-pollutant emissions, which this paper delivers as key findings from a review of the scientific literature. Simultaneously, comparisons of inputs and outputs of both the CA-GREET3.0 and Argonne GREET models provide information that help develop biofuel pathways appropriate for the New York State's context.

BBD and RNG can achieve substantial reductions of GHG emissions. The CIs of BBD from waste- and coproduct-based feedstocks (e.g., used cooking oil, tallow) are 66%-81% lower than those of petroleum diesel (CARB, 2021, 2018a; Chen et al., 2018; EPA, 2020). The RNG's compressed and liquified form produced from landfill gas has CIs with a range of 48.01-64.37 g CO_2eq/MJ which is 30%-44% lower than counterpart fossil fuels. The identical forms generated from swine manure feedstock range in negative emissions (-332.21 to -387.43 g CO_2eq/MJ) (CARB, 2021, 2019a). While the literature reports fugitive methane emissions from anaerobic digestion (AD) and biogas upgrading systems, the total supply chain methane emissions of the systems that produce compressed or liquified form are negative, reflecting the potential to achieve large reductions to GHG emissions when displacing counterpart fossil fuels.

Similarly, BBD and RNG have the potential to reduce co-pollutant emissions. After switching to unblended form of biodiesel (B100) from petroleum diesel, 47%-100% reductions of emissions are reported depending on co-pollutants, except for the slight increase in NOx emissions (Caetano et al., 2019). The GREET models show that the RNG supply chains achieve low-to-negative co-pollutant emissions, although the emissions typically depend on key factors such as AD system's feedstock type, counterfactual case's emissions, and the way of RNG being consumed.

The current findings of this report reveal that both BBD and RNG have the potential to make meaningful contributions to New York State's climate and human health targets under the CLCAP. As such, it is important that the state policymakers accurately identify and spur the conditions where both the biofuels achieve the largest reductions to GHG and co-pollutant emissions. The findings suggest that the use of waste/residue feedstocks, development of domestic supply chains, and prioritization of biogenic methane capture and destruction will enable both the biofuels to achieve their maximum climate and human health benefits as New York State decarbonizes.

List of abbreviations and acronyms

AD	anaerobic digestion
AS DEA	amine scrubbing with diethanolamine
AS MEA	amine scrubbing with monoethanolamine
ASTM	American Society of Testing and Materials
AwR	alkaline with regeneration
B100	unblended form of biodiesel
B20	20% blend of biodiesel with ultra-low sulfur diesel
BBD	biomass-based diesel
CA-GREET	California-specific version of Greenhouse gases, Regulated Emissions, and Energy use in Technologies
CCLUB	Carbon Calculator for Land Use Change from Biofuels Production
CH_4	methane
CHP	combined heat and power
CI	carbon intensity
CIDI	compression ignition direct injection engine
CLCPA	Climate Leadership and Community Protection Act
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
CO_{2eq}	carbon dioxide equivalent
Cry	cryogenic separation
DME	dimethyl ether
DWT	deadweight tonnage
EPA	U.S. Environmental Protection Agency
FAME	fatty acid methyl ester
FOG	fats, oil, and grease
FS	feedstock production stage
FU	fuel production stage
g	gram
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWP	global warming potential
HPWS	high-pressure water scrubbing
ILUC	indirect land use change
LCA	life cycle assessment
LCFS	Low Carbon Fuel Standard
L-CNG	liquefied-compressed natural gas
LNG	liquified natural gas
MJ	megajoule

MMBtu	million British thermal units
MSW	municipal solid waste
NG	natural gas
NOx	nitrogen oxides
nPAH	nitrated polycyclic aromatic hydrocarbon
OFP	ozone-forming potential
OPS	organic physical scrubbing
PAH	polycyclic aromatic hydrocarbon
PM	particulate matter
PSA	pressure swing adsorption
RD	renewable diesel
RFS	Renewable Fuel Standard
RNG	renewable natural gas
SE	substitution elasticity
SI	spark ignition engine
SMR	steam methane reforming
SO_2	sulfur dioxide
SOx	sulfur oxides
T&D	transportation and distribution
ULSD	ultra-low sulfur diesel
VO	vehicle operation stage
VOC	volatile organic compounds

Introduction

New York State's Climate Leadership and Community Protection Act (CLCPA) requires the state to achieve economywide reductions to its greenhouse gas (GHG) emissions of at least 85% by 2050. The law also requires state policymakers to account for emissions of co-pollutants (e.g., particulate matter, nitrogen oxides, sulfur oxide, etc.) when determining how to achieve the GHG emission reduction target (*Climate Leadership and Community Protection Act*, 2019). Bioenergy pathways such as anaerobic digestion (AD) and biomass-based diesel (BBD) have been identified through the CLCPA's implementation process as potential low-carbon fuels available for use through the law's decarbonization target (Anon, 2020a). This determination has prompted debate over the ability, if any, of these low-carbon fuels to achieve reduced GHG and co-pollutant emissions on a life cycle basis compared to fossil fuels and thereby contribute to the CLCPA's climate and human health objectives (Anon, 2021).

Life cycle assessment (LCA) is an accounting methodology that quantifies the GHG and co-pollutant emissions of a product over its full life cycle (e.g., well-to-wheel, cradle-to-grave, etc.). When applied to fuel products LCA accounts for the full supply chain, up to and including combustion of the final product. Two factors frequently cause a fuel's life cycle emissions to be greater than its tailpipe/smokestack emissions alone: (1) the inclusion of indirect land use change emissions and energy inputs, often fossil-based, in the supply chain (e.g., transportation of the fuel from the point of location to the point of end-use), and (2) the inclusion of non-combustion GHG emissions across the supply chain (e.g., leakage of the potent GHG methane from anaerobic digesters).

Originally an academic methodology, LCA is now widely employed outside of academic institutions due to its mandatory use under government policies such as the federal Renewable Fuel Standard (RFS) and state policies such as California's Low Carbon Fuel Standard (LCFS). The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model (ANL, 2020), which was developed through the sponsorship of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, plays a critical role in the use of LCA in support of both of these types of policies. Two variants of the model are now in use in the U.S.: the CA-GREET3.0 Model (CARB, 2019a), which is employed to conduct LCA under California and Oregon's respective LCFS policies, and the Argonne GREET model, an early version of which was employed by the U.S. Environmental Protection Agency (EPA) during its implementation of the federal RFS.

While both the CA-GREET3.0 and Argonne GREET models derive from a common predecessor, important differences have arisen between them that are relevant to New York State's own interest in understanding the life cycle emissions of low-carbon fuels. A substantial fraction of the low-carbon fuels that are consumed in California in compliance with that state's LCFS are sourced from production facilities that are up to thousands of miles away from the state. GHG and co-pollutant emissions associated with the transportation of these fuels over great distances are often reflected in the CA-GREET3.0 model but not the Argonne GREET model due to the latter's focus on domestic low-carbon fuels production. Both models also utilize a broad range of LCA results from the scientific literature as inputs that are constantly being updated as new data is made available, and differences in their results also arise due to location variability (i.e., the CA-GREET3.0 model is necessarily focused on only those energy systems that participate in California's LCFS).

The primary objective of this white paper is to review the scientific literature on the GHG and co-pollutant emissions of the AD and BBD pathways. The literature review focuses on the CA-GREET3.0 and Argonne GREET models, although the results of these models are cross-referenced with LCA results from refereed scientific publications where appropriate. This review has three limitations of scope that result from three specific provisions within the CLCPA.

First, the review focuses primarily on GHG and co-pollutant emissions that are upstream of the final product's combustion due to the CLCPA's lack of distinction between fossil and biogenic carbon for GHG accounting purposes. While this failure to account for the biogenic carbon cycle is at odds with the scientific consensus on the global warming potential of bioenergy (Withey et al., 2019), it does necessarily affect the scope of this review.

Second, the scientific literature commonly quantifies methane's CO2 equivalence value using a 100-year global warming potential (GWP), whereas the CLCPA requires methane's GWP to be accounted for on a 20-year basis (*Climate Leadership and Community Protection Act*, 2019). As a relatively short-lived GHG, methane has a GWP on a 20-year basis that is 2.5-3 times greater than its GWP on a 100-year basis (ERCE, 2021). This review focuses on the reporting of methane leakage rather than CO_2-equivalence values to avoid confusion about the difference of assumed GWP values between the CLCPA and the scientific literature. When the review does report certified carbon intensities for AD pathways from the CA-GREET3.0 model inclusive of combustion, it should be noted that the use of the 20-year GWP basis would result in lower values where the intensities are negative were a 100-year basis to be employed instead.

Finally, this review's scope primarily focuses on the results of LCAs in the literature that assess waste and coproduct feedstocks within the BBD and AD pathways (see Table 1). This reflects the CLCPA's emphasis on deep decarbonization in the form of its 85% minimum economywide GHG emission threshold. These feedstocks' characteristics can minimize land use impact, food security issue, and water scarce regional issue when producing biofuels (Popp et al., 2016). Waste and coproduct BBD feedstocks (e.g., animal tallow, used cooking oil) are reported in the LCA literature to have carbon intensities that are near or at the 85% GHG emission reduction threshold, whereas conventional agricultural feedstocks (e.g., soybean oil, canola oil) do not because of their carbon-intensive inputs (California Air Resources Board, 2021). AD feedstocks, on the other hand, are primarily waste-based (e.g., manure, wastewater, landfill contents) due to the technological characteristics of the AD pathway.

Table 1. Summary of studied fuels

Types of fuels	Diesel	Natural gas
Fossil	Petroleum diesel (ULSD, conventional)	NG, CNG, LNG
Renewable	Biomass-based diesel (BD, RD)	NG, CNG, LNG

(Note: BD = biodiesel; RD = renewable diesel; ULSD = ultra-low sulfur diesel; NG = natural gas; CNG = compressed natural gas; LNG = liquified natural gas).

Pathway overviews

BBD is primarily consumed in the U.S. in one of two forms: (1) biodiesel, or (2) renewable diesel. The two biofuels' characteristics, while similar in terms of both technical performance and climate and similar human health impacts when combusted in a new technology diesel engine (NTDE), do have important differences. Biodiesel is most commonly a fatty acid methyl ester (FAME) that is produced by reacting a lipid feedstock such as used cooking oil with methanol. Biodiesel is not a hydrocarbon fuel, but it is widely used for transportation and building heat applications in blends of up to 20% with ultra-low sulfur diesel (ULSD). Biodiesel is frequently produced from waste/residue vegetable oil feedstocks such as distillers corn oil and used cooking oil.

Like biodiesel, renewable diesel is commonly produced from lipid feedstocks, although renewable diesel producers often favor waste/residue feedstocks with a high saturated fat content such as animal processing waste. Renewable diesel production also can utilize lignocellulosic feedstocks such as municipal solid waste (MSW), although this is at a much earlier stage of commercialization (e.g., Fulcrum Bioenergy, 2021; Tepper, 2017). Regardless of feedstock, renewable diesel is produced by reacting the feedstock with hydrogen. The result is a hydrocarbon fuel that meets the same ASTM D975 specification in unblended form as ULSD, albeit one with very different climate and human health impacts than ULSD (see below) (Brown, 2020).

The AD pathway causes organic matter such as manure and wastewater to be broken down by anaerobic microorganisms to a mixture of carbon dioxide (CO_2) and methane (CH_4) known as biogas. Unlike BBD, which is only produced intentionally, methane production can (and often does) occur in the absence of human intervention due to the widespread presence of anaerobic microorganisms in the environment. The storage of organic matter under anaerobic conditions, such as occurs at manure lagoons and landfills, naturally yields methane as a result. From a technological standpoint, then, AD is properly viewed as the capture of methane that is already being emitted naturally; the intentional creation of methane from purpose-grown feedstocks via AD is rare due to the comparative economic disadvantage of not utilizing a waste product as feedstock.

When captured in an AD system, biogas is a versatile renewable energy product that can be utilized in several different applications. The simplest is the on-site combustion of biogas to produce heat and displace natural gas consumption. A higher-value application requires the upgrading of the biogas via a process that removes carbon dioxide and any contaminants such as hydrogen sulfide. The resulting product can be injected into the existing natural gas grid and is consequently known as renewable natural gas (RNG). This RNG is capable of use in a wide range of applications, including combined heat and power systems and compressed/liquefied natural gas vehicles, in the latter use following compression to compressed natural gas (CNG) or liquefaction to liquefied natural gas (LNG), respectively (Lee et al., 2016). The biogas from AD can be used for electricity generation to meet on-site electricity demand or to sell to the power grid (Dalke et al., 2021; Kraemer and Gamble, 2014; Pfluger et al., 2019). Alternatively, RNG can also be further upgraded to hydrogen for use in fuel cells (Lackey et al., 2017; Saadabadi et al., 2019). The conversion of biogas to electricity or hydrogen is outside of the scope of this report. As with BBD, RNG's technical performance characteristics are very similar to those of natural gas, but its climate and human health impacts are substantially different.

Results

Carbon intensities of biomass-based diesel and renewable natural gas supply chains

BBD combustion results in the oxidization of its carbon content and tailpipe emissions in the form of CO_2. Its climate impacts are not limited to tailpipe emissions, due to the use of carbon-intensive inputs, like gasoline, diesel, and natural gas during feedstock production/collection and biofuel production (while methanol and hydrogen can both be sourced from renewable feedstocks, they are mostly produced from natural gas in the U.S. today). Emissions estimated to be associated with direct and indirect land use change in the production of certain first-generation agricultural commodity feedstocks are largely avoided by the use of waste/residue feedstocks (Cai et al., 2021; Chen et al., 2018). Furthermore, more recent estimates of land-use change emissions for coproduct feedstocks grown in the United States (e.g., soybean oil) have found drastically reduced earlier emissions estimates (Taheripour and Tyner, 2020). These distinct production characteristics result in substantial differences in life cycle carbon intensities of biodiesel and renewable diesel (see Figure 1) as reported to the California Air Resources Board for low-carbon fuels participating in that state's LCFS that are sourced from either waste (e.g., tallow, used cooking oil) or coproduct (e.g., soybean oil, distillers corn oil) feedstocks. Furthermore, the ULSD benchmark against which BBD's carbon intensity is compared also varies due to the use of different petroleum feedstocks in different parts of the U.S., with light/sweet crudes producing ULSD with a lower carbon intensity than heavy/sour crudes.

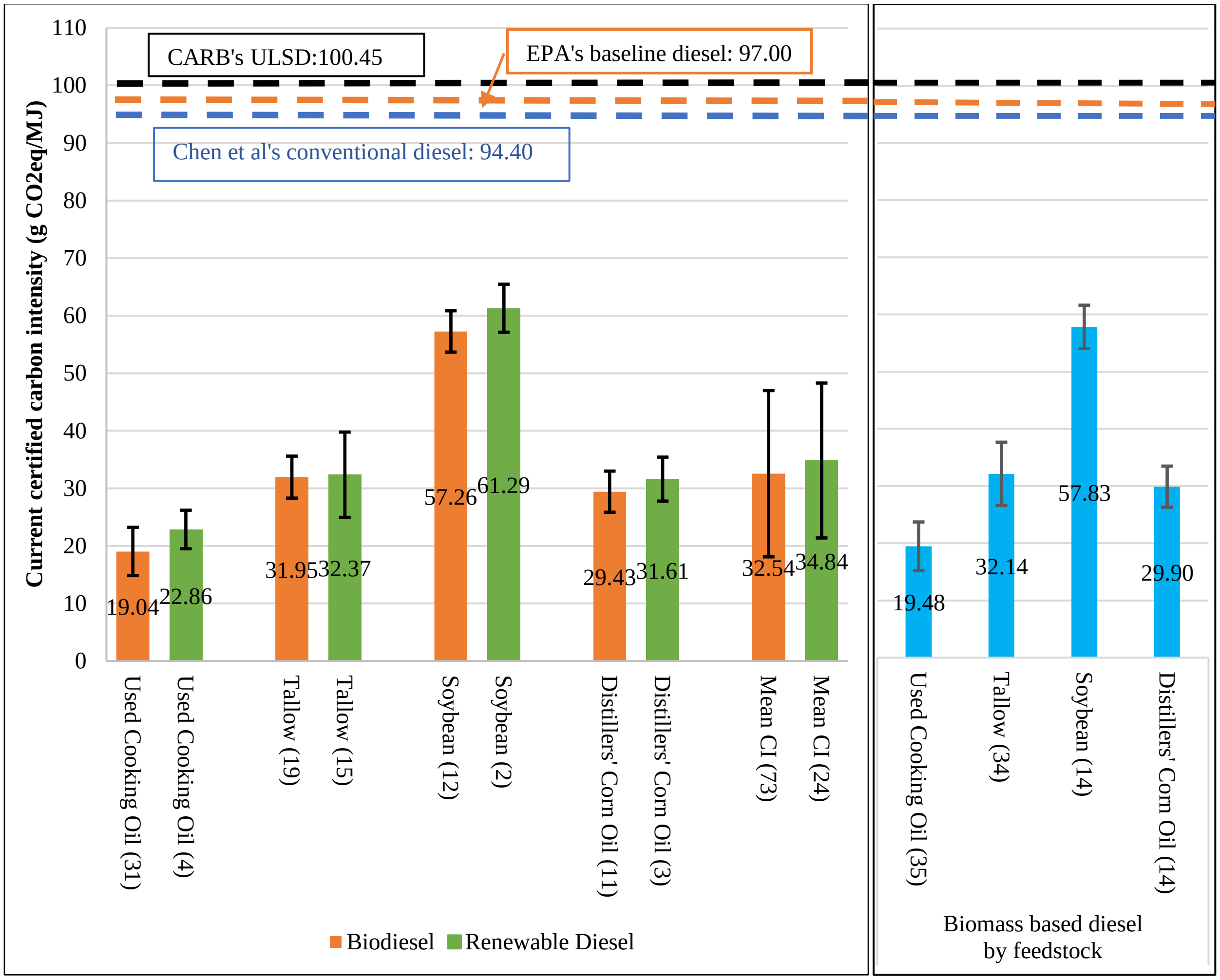


Figure 1. Carbon intensities of biomass-based diesel and petroleum diesel, sourced from (CARB, 2021, 2018a; Chen et al., 2018; EPA, 2020). Numbers in parentheses represent the number of carbon intensity scores surveyed. (Note: CARB = California Air Resources Board; EPA = US Environmental Protection Agency).

Despite these differences, however, a review of the carbon intensities that have been calculated for the BBD fuels that participate in California's LCFS provides three important findings. First, the differences between BBD fuels produced from waste feedstocks are limited compared to the level of carbon intensity reductions achieved, with actual carbon intensities ranging from a minimum of 19.04 g CO_2eq/MJ (biodiesel from used cooking oil) to a high of 32.37 g CO_2eq/MJ (renewable diesel from tallow), as compared to 94.4-100.85 g CO_2eq/MJ for ULSD. Second, there is very little difference between the carbon intensities of biodiesel and renewable diesel when produced from the same feedstocks, with those of renewable diesel being slightly higher than those of biodiesel due to the former's isomerization requirement. Including coproduct feedstocks, the carbon intensity reductions of LCFS-certified BBD fuels relative to ULSD are 38%-91% for biodiesel and 44%-83% for renewable diesel (Brown, 2020). Third, the current ILUC emission value (29.10 g CO_2eq/MJ) that is used in California's LCFS pathway certified CI values for soy oil biodiesel is much higher than estimates found in the recent scientific literature (see Figure 2a and 2b). We calculate CI values for soy oil biodiesel of 38.73 and 46.23 g CO2eq/MJ with selected ILUC emission values of 10 and 17.5 g CO2eq/MJ, respectively (Chen et al., 2018; Taheripour and Tyner, 2020).

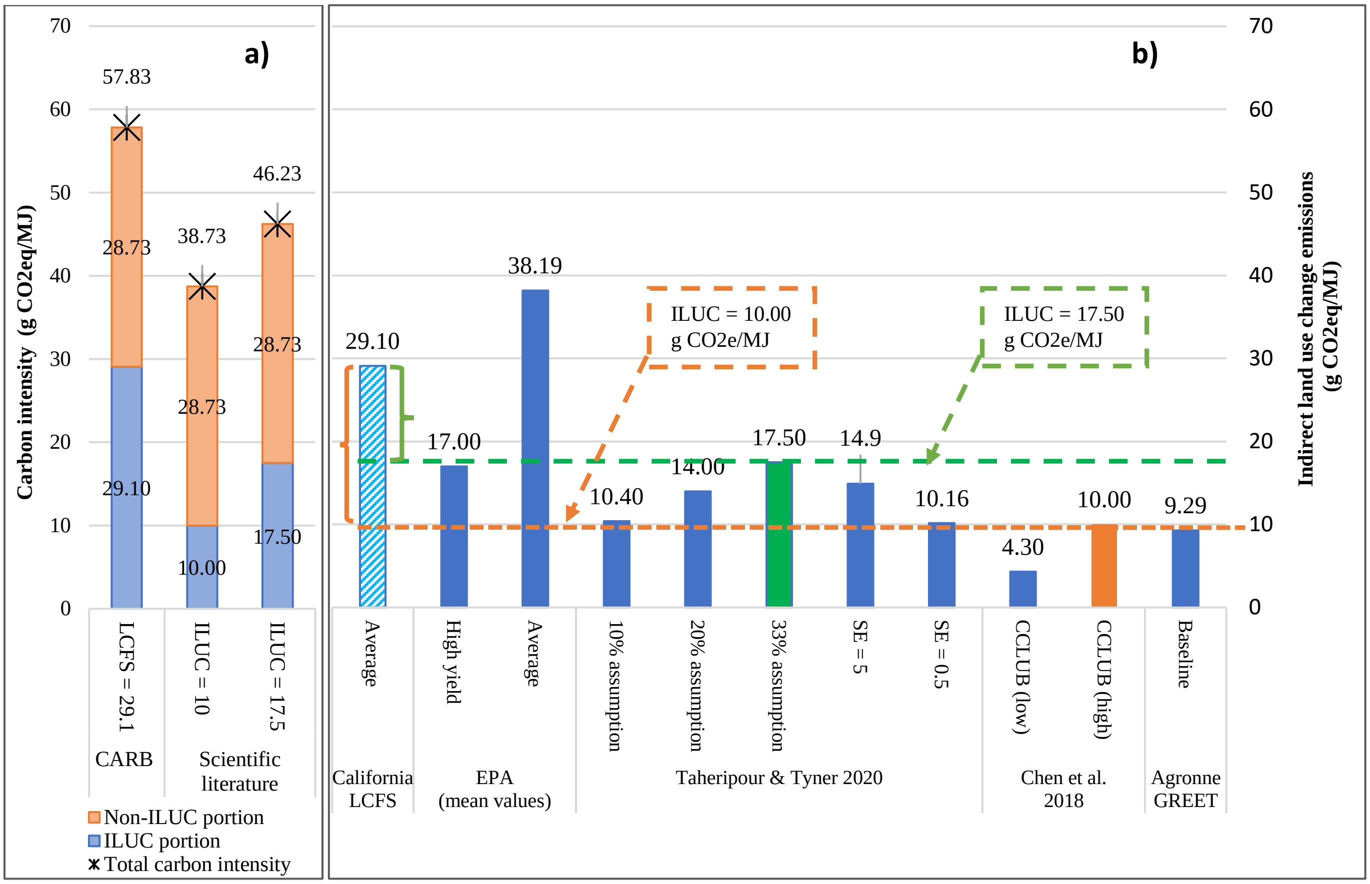


Figure 2. CI values based on California's Low Carbon Fuel Standard and ILUC estimated emissions from the scientific literature (ANL, 2020; CARB, 2021, 2015; Chen et al., 2018; EPA, 2020; Taheripour and Tyner, 2020). (Note: LCFS = Low Carbon Fuel Standard; ILUC = Indirect land use change; SE = substitution elasticity; CCLUB = Carbon Calculator for Land Use Change from Biofuels Production).

Greater variation exists in the carbon intensities for the different pathways that produce RNG under California's LCFS (see Figure 3) (CARB, 2021, 2020, 2019a). (Note that California's data is reported for the fuel in compressed and liquefied forms due to the LCFS's focus on the transportation sector.) The highest carbon intensities inclusive of combustion are reported for landfill gas, with liquefied landfill RNG having a higher carbon intensity than compressed due to the high energy requirements of the liquefaction process relative to the compression process. Regardless of form, though, landfill RNG's carbon intensity (48.01-64.37 g CO_2eq/MJ) is lower than that of fossil natural gas in either compressed (81.71 g CO_2eq/MJ),liquified form (86.94 g CO_2eq/MJ), or liquefied-compressed natural gas (92.53 g CO_2eq/MJ) (CARB, 2021, 2019a). The carbon intensities of RNG produced from wastewater sludge are lower still, albeit positive, ranging from 35.12 g CO_2eq/MJ for compressed to 48.17 g CO_2eq/MJ and 51.26 g CO_2eq/MJ for liquified forms. The positive carbon intensities reported for wastewater sludge are due to the assumption that biogas is already being produced, captured, and flared as part of the wastewater treatment process (Lee et al., 2016), thus preventing the allocation of negative emissions to RNG produced from wastewater sludge within the CA-GREET3.0 model. A 2007 analysis found that only 20% of New York's wastewater treatment plants had AD facilities in place (Pirnie, 2007), though, and it would be correct to allocate negative emissions to those plants without existing AD facilities. RNG produced from landfill gas has a positive carbon intensity score under California's LCFS for a similar reason, and both numbers would be lower in a location where methane capture due to AD would be additional to existing processes. Even in the case of RNG from landfill gas, however, RNG's carbon intensity is reported to be lower than that of natural gas by an average of 40% (CARB, 2021).

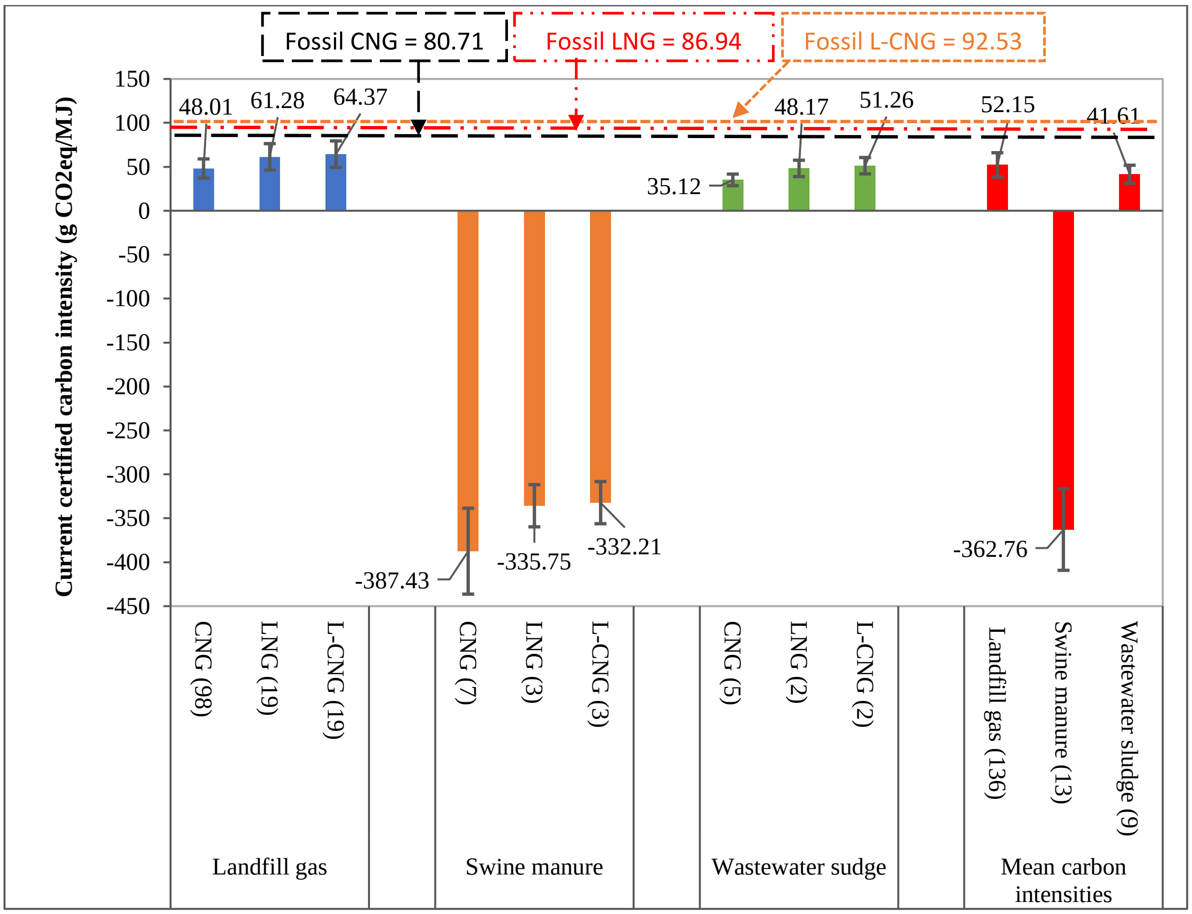


Figure 3. CI values of renewable natural gas and fossil natural gas (CARB, 2021, 2019a). Numbers in parentheses represent the number of carbon intensity scores surveyed. (Note: L-CNG = liquefied-compressed natural gas).

Uniquely, RNG that is produced from swine manure achieves very negative carbon intensities. The compressed form has the lowest carbon intensity at -387.43 g CO_2eq/MJ, followed by the liquified forms at -335.75 g CO_2eq/MJ and -332.21 g CO_2eq/MJ. While a negative carbon intensity can represent net carbon sequestration, in this case it reflects the fact that the pathway's actual emissions take the form of carbon dioxide, whereas its avoided emissions take the form of the much more potent GHG methane. Furthermore, whereas methane emissions from landfills and wastewater treatment plants are already mitigated in California, those from manure lagoons are not (CARB, 2020, 2019a), providing RNG with much greater emissions mitigation additionality when produced from manure.

Fugitive methane emissions from the natural gas supply chain

An important component of the carbon intensities of both natural gas and AD systems is fugitive methane emissions. Methane leakage is a potential major contributor to the carbon intensity of RNG due to methane's high global warming potential, especially under a 20-year GWP. The escape of methane from an anaerobic digestion system or a subsequent stage of the RNG supply chain either decreases RNG's carbon intensity reduction (for manure) or contributes to a positive carbon intensity (when derived from a mitigated methane source such as a wastewater treatment facility). Methane leakage from the natural gas supply chain is a relatively recent concern (Howarth et al., 2011), however, and has not been as well-studied as many other forms of GHG emissions. This uncertainty can cause RNG to be overlooked by policymakers as a means of mitigating GHG emissions under strict applications of the precautionary principle. This review, however, finds that differences in technologies and their corresponding fugitive methane emission rates makes it inappropriate to apply reported methane leakage rates in aging natural gas infrastructure to new RNG infrastructure that utilizes modern materials and leakage mitigation procedures.

The potential for fugitive methane emissions exists along the entire natural gas (and RNG) supply chain, although the amount of leakage that occurs is reported to vary widely (Alvarez et al., 2018). One reason for confusion regarding the amount of actual methane leakage is due to a lack of uniformity of natural gas infrastructure characteristics (e.g., materials, transportation distance, etc.) across U.S. regions that leads to a wide range of fugitive emissions estimates. Alvarez et al. (2018) shows methane emission rates (as a percent of production throughput) in the natural gas supply chain to vary from 0.4% to 9.1% of natural gas production, depending on the petroleum and natural gas basins in question and infrastructure age (Alvarez et al., 2018; NYSERDA, 2019). Howarth (2014) reports methane emissions as a percentage of natural gas throughput of 0.47%-5.8% (Howarth and Robert Howarth, 2014; NYSERDA, 2019). According to a more recent analysis (Howarth, 2020), methane emissions from natural gas are equal to 3.6% of the methane in the natural gas that is consumed, based on the full life cycle of the natural gas supply chain.

Both the CA-GREET3.0 and Argonne GREET models provide estimated fugitive methane emission rates for natural gas produced via either conventional extraction and shale hydraulic fracturing (see Table 2). These models, too, report different leakage rates despite their underlying similarities. Both models find methane venting and leakage from wellhead equipment to account for over half of the supply chains' total leakage, followed by the transmission/storage, processing, and distribution steps. The Argonne GREET model calculates a total leakage rate that is almost 50% lower than that of the CA-GREET3.0 model, however, due to the latter's finding of substantially higher leakage occurring at the well equipment from which California's natural gas is sourced.

Table 2. Fugitive methane emissions via leakage and venting from natural gas production in GREET models (volumetric percentage of methane over NG throughput) (ANL, 2020; CARB, 2019a).

GREET models	CA-GREET3.0		Argonne GREET	
Stages	Conventional NG (%)	Shale gas (%)	Conventional NG (%)	Shale gas (%)
Recovery - completion CH_4 venting	0.00%	0.06%	0.00%	0.02%
Recovery - workover CH_4 venting	0.00%	0.01%	0.00%	0.00%
Recovery - liquid unloading CH_4 venting	0.04%	0.04%	0.02%	0.02%
Well Equipment - CH_4 venting and leakage	0.65%	0.65%	0.35%	0.35%
Processing - CH_4 venting and leakage	0.13%	0.13%	0.03%	0.03%
Transmission and storage - CH_4 venting and leakage	0.23%	0.23%	0.19%	0.19%
Distribution - CH_4 venting and leakage	0.09%	0.09%	0.08%	0.08%
SUM	1.14%	1.21%	0.67%	0.70%

The GREET models also report sizeable methane leakage rates from the vehicle operation stage when natural gas is used to fuel either CNG or LNG vehicles. The Argonne GREET model reports larger leakage from that end-use stage in both CNG and LNG vehicles than from any other stage of the supply chain, including natural gas production (see Table 3). The CA-GREET3.0 model shows lower fugitive methane emissions from the vehicle operation stage, although that is in part due to its higher assumed fugitive methane emissions during the natural gas production stage. Finally, both models report much larger fugitive methane emissions during the natural gas liquefaction step than during the natural gas compression step due to the former's greater complexity and energy inputs.

Table 3. CNG and LNG combination long-haul truck's life cycle methane emissions in CA-GREET3.0 and Argonne GREET models (ANL, 2020; CARB, 2019a)

Three main life cycle stages of GREET models	CNG in spark ignition engine (g CH_4/mmBtu of fuel throughput)		LNG in spark ignition engine (g CH_4/mmBtu of fuel throughput)	
	CA-GREET	Argonne GREET	CA-GREET	Argonne GREET

Total methane emissions for natural gas production stage	310.2	174.2	295.1	100.6
Total methane emissions for fuel stage	10.4	15.7	135.8	136
Total methane emissions for vehicle operation stage	190.7	248.9	190.7	248.9
SUM	511.4	438.9	621.6	485.5

Fugitive methane emissions from anaerobic digestion and biogas upgrading

The production of biogas and/or RNG presents a different fugitive methane emissions profile than the natural gas supply chain does. In addition to utilizing different types of equipment (e.g., an anaerobic digester versus a natural gas well), most AD systems have the benefit of being of comparatively recent construction utilizing materials that are characterized by lower leakage rates. Studies, including those conducted by Argonne National Laboratory for use with the Argonne GREET model, have found fugitive methane emission rates from anaerobic digesters to be comparable to those from natural gas production systems, although this is sensitive to the choice of AD feedstock. A 2016 study of the Baltic Biogas Bus project, for example, found that methane leakage from the AD step was as low as 0.20% with industrial waste as feedstock and as high as 3.1% with wastewater sewage sludge as feedstock (Odeh and Abu-Ebid, 2016a) (see Table 4a). The Argonne GREET model utilizes a 1% fugitive methane emissions rate for the AD process, although this rises to 3% after the biogas upgrading and RNG pipeline injection steps are accounted for due to leakage during the additional process steps (ANL, 2020; Lee et al., 2021, 2016).

Table 4. a) methane emissions from anaerobic digestion (AD) processing, biogas upgrading, and b) methane emissions CH_4 loss and purity/recovery by biogas upgrading technologies (ANL, 2020; Lee et al., 2021; Odeh & Abu-Ebid, 2016).

Table 4a. AD stage	Ricardo's Baltic Biogas Bus project: AD processing only	Argonne study (Lee et al., 2021) AD processing only	Argonne GREET including AD processing and biogas upgrading
Sewage sludge from wastewater treatment	3.10%	1%	3%
Municipal solid waste	1.70%		3%
Industrial waste	0.20%		x
Animal manure	x		3%

Table 4b. Biogas upgrading stage	Methane loss and recovery \ upgrading technologies	Membrane	AwR	HPWS	PSA	AS MEA	AS DEA	OPS	Cry
Agronne study (Lee et al., 2021)	CH_4 loss	x	2.3%	1.0%	3.5%	0.1%	0.1%	4.0%	0.7%
	CH_4 recovery	x	96.7 %	98.0%	97.5%	99.0%	99.0%	97.0%	98.0%

Odeh and Abu-Ebid (Odeh and Abu-Ebid, 2016b)	CH_4 loss	5 – 15%	x	1 – 2%	1 – 10%	0.1 – 0.5%	x	x
	CH_4 loss (AD plant with CHP)	x	x	3.1%	1.5%	0.4%	x	x
	CH_4 recovery	80 – 95%	x	95 – 98%	95 – 98%	96 – 99.9%	x	x

(Note: PSA = pressure swing adsorption; AwR = Alkaline with regeneration; HPWS = high-pressure water scrubbing; AS MEA = amine scrubbing with monoethanolamine; AS DEA = amine scrubbing with diethanolamine; OPS = organic physical scrubbing; Cry = cryogenic separation; AD = anaerobic digestion; CHP =combined heat and power; x = not applicable).

Not reflected in the Argonne GREET model's reported 2% leakage rate for the biogas upgrading stage is the wide range of leakage rates that has been reported across biogas upgrading technologies (see Table 4b). The lowest biogas upgrading fugitive methane emissions rates of 0.1%-0.5% are reported for amine scrubbing technologies. The reported leakage rate increases to as high as 5-15% for membrane technology, however. A Danish study that investigated methane emissions rates and losses from 23 biogas plants reported methane leakage of between 0.4% and 14.9% of methane in the RNG produced with an average of 4.6% (Scheutz and Fredenslund, 2019). That same study found wastewater treatment AD systems, which are often older, to have higher methane leakage rates (7.5% on average) than newer agricultural AD systems (2.4% on average) (Scheutz and Fredenslund, 2019). The surveyed AD systems employed several different upgrading technologies, however, contributing to the variability in reported fugitive methane emission rates.

The notable effect of feedstock and equipment on methane leakage rates ensures that these rates ultimately vary widely across the RNG supply chain (Lee et al., 2021). Feedstock type has a much smaller impact on the reported fugitive methane emission rate for the RNG supply chain than does the type of equipment employed for the upgrading of biogas to RNG, and leakage during the transportation and distribution stage is minimal (similar to the above findings for natural gas). The average difference of methane leakage rates between feedstock types is 32 g CH_4/MMBtu. The average difference across different upgrading equipment types is much larger at 853 g CH_4/MMBtu. Generally, methane leakage from wastewater sludge systems is higher than from other feedstock types because of the greater complexity of wastewater systems (Scheutz and Fredenslund, 2019) (see Figures Figure *4* and Figure 6). Total methane leakage rates across the supply chain (excluding final use) range from a low of 249 g CH_4/MMBtu RNG (food waste with amine scrubbing upgrading) to a high of 1,133 g CH_4/MMBtu RNG (sludge with organic physical scrubbing upgrading) (see Figure *4*). Importantly, though, methane leakage rates can be minimized through the use of specific biogas upgrading technologies, with cryogenic separation and high-pressure water scrubbing also achieving methane leakage rates that are at least 50% lower than those reported for organic physical scrubbing, regardless of feedstock.

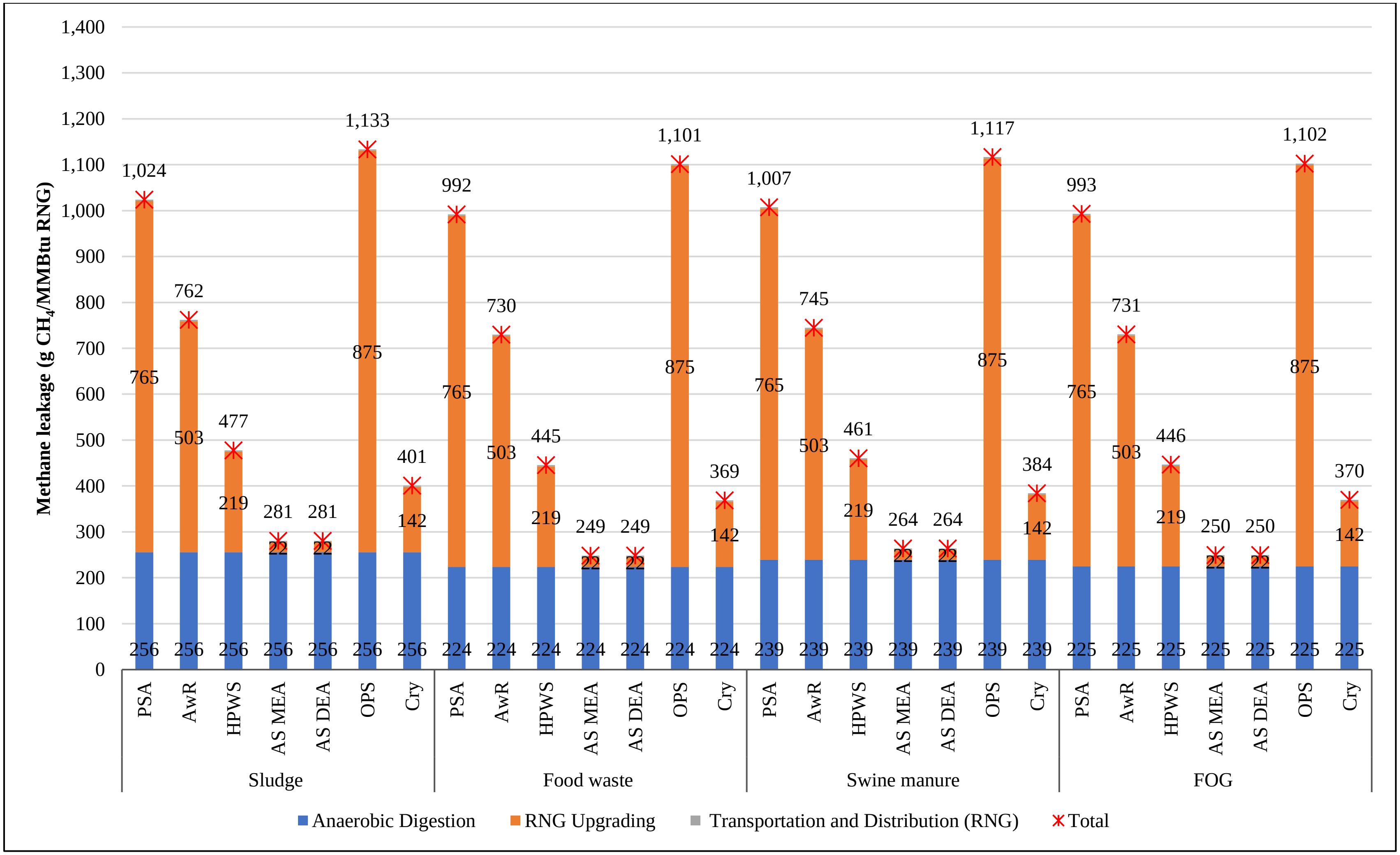


Figure 4. Methane leakage rate patterns for RNG production by different upgrading technologies and feedstocks (Lee et al., 2021). (Note: FOG = fats, oil, and grease; Wet waste feedstock-based anaerobic digesters are assumed to use feedstocks with high moisture contents (>75%)).

The literature is very clear that the fact that fugitive methane emissions occur at AD and biogas upgrading systems does not mean that RNG a similar global warming impact as natural gas, however. Even the highest methane leakage rates across the RNG supply chain are unable to prevent AD systems from achieving very large reductions to GHG emissions when replacing natural gas use, although the magnitude of the reduction is affected by the assumed leakage rate for the competing natural gas system. The RNG supply chain achieves negative methane emissions when produced from food waste, manure, and fats, oils, and greases (FOG) regardless of AD system methane leakage rate due to its mitigation of biogenic methane emissions that would otherwise occur (see Figure 5). That said, the choice of upgrading technology does have an important impact on the RNG supply chain's carbon intensity, with amine scrubbing having methane emissions that are reported to be 700-800 g/MMBtu lower than those of pressure swing absorption and organic physical scrubbing upgrading systems regardless of feedstock type.

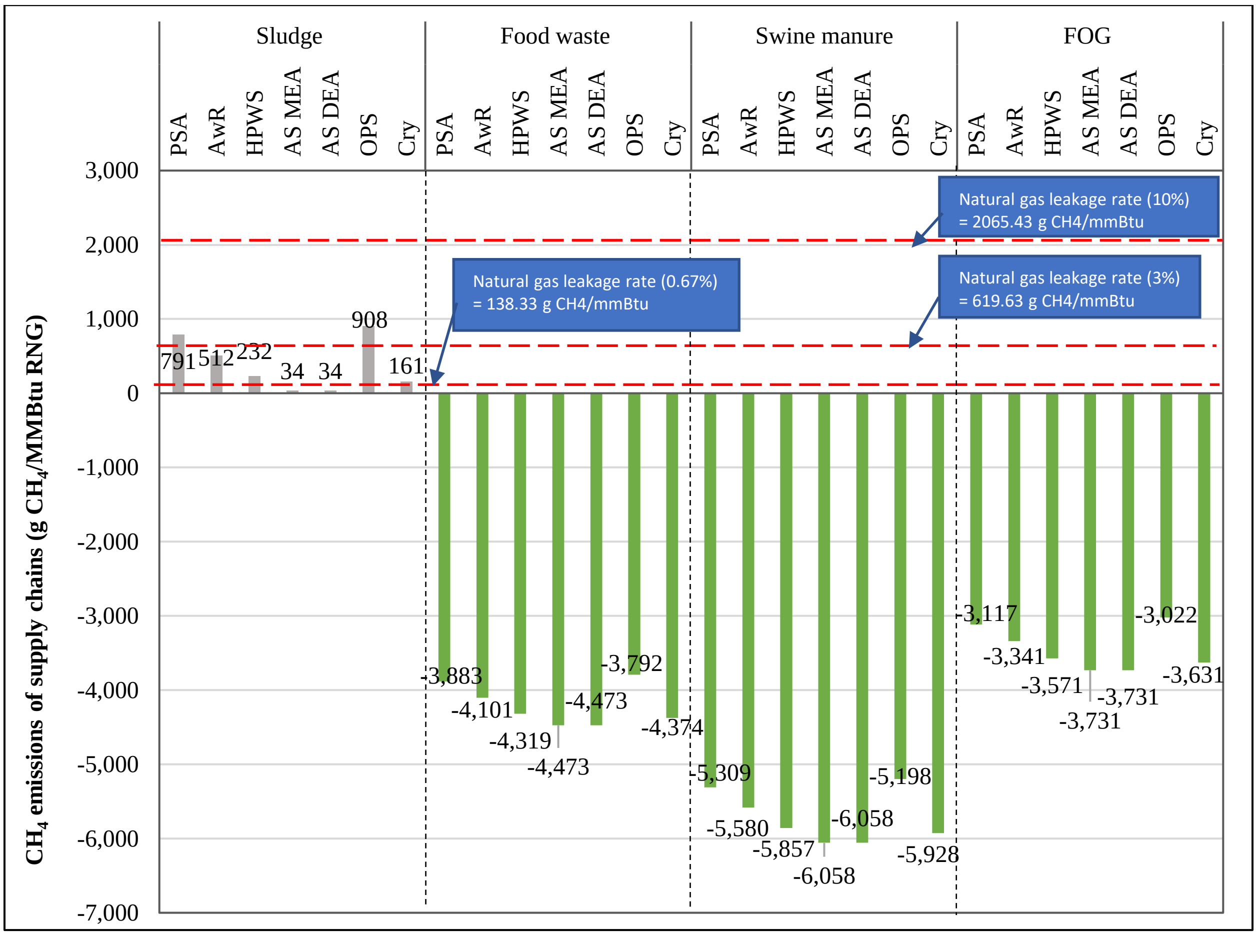


Figure 5. Methane emissions of RNG supply chains including CH_4 leakage and different assumed natural gas leakage rates (ANL, 2020; Lee et al., 2021). (Note: Wet waste feedstock anaerobic digesters are assumed).

An important corollary of this finding is that AD systems are capable of achieving low-to-negative carbon intensities regardless of how the biogas or RNG is ultimately utilized. Indeed, the use of RNG in non-combustion applications (e.g., replacing natural gas as a commodity chemical feedstock) can also contribute to decarbonization policies, especially if the RNG displaces natural gas demand in regions characterized by high fugitive methane leakage rates in the natural gas infrastructure. In the case of both fuel and non-fuel products, however, the primary methane emission reductions achieved by biogas and RNG are the result of biogenic methane emission abatement rather than fugitive fossil methane emission abatement via natural gas displacement. Excepting those that utilize sewage sludge, biogenic methane emission abatement is greater than fugitive fossil methane emission abatement even when displacing natural gas that is characterized by a 10% methane leakage rate (e.g., from very antiquated natural gas infrastructure). This even holds true for those AD systems that are characterized by relatively high fugitive biogenic methane emissions.

Most of the methane leakage that occurs across the RNG supply chain happens during the anaerobic digestion and RNG upgrading stages. Subsequent processing for specialized end-use applications, such as compression for use in a compressed natural gas (CNG) vehicle or liquefaction for use in a liquefied natural gas (LNG) vehicle, results in comparatively low fugitive methane emissions. Both the Argonne GREET and CA-GREET3.0 models report that no additional leakage occurs when RNG is compressed for on-site use in a CNG vehicle (see Figure 6). The conversion of RNG to LNG results in very marginal methane leakage, although additional leakage occurs during the storage of LNG for future use (albeit at amounts that equal a fraction of total fugitive methane emissions across the full supply chain). Other than the AD and biogas upgrading processes, the highest amount of methane leakage occurs when the RNG is transported off-site for use in a CNG vehicle as presented in the CA-GREET model (see Figure 6), although total leakage across the supply chain under that scenario is similar to that for LNG, assuming the same digester and feedstock combination. One important difference between the results of the Argonne GREET and CA-GREET3.0 models is the latter's assumption that RNG is transported 3,600 miles to an off-site refueling station (compared to 50 miles in the Argonne GREET model), which greatly increases the fugitive methane emissions that are reported to occur in the CA-GREET3.0 model during that stage. This characteristic of the CA-GREET3.0 model reflects the unique conditions by which RNG is supplied to California's LCFS and would not be an appropriate assumption for a shorter supply chain.

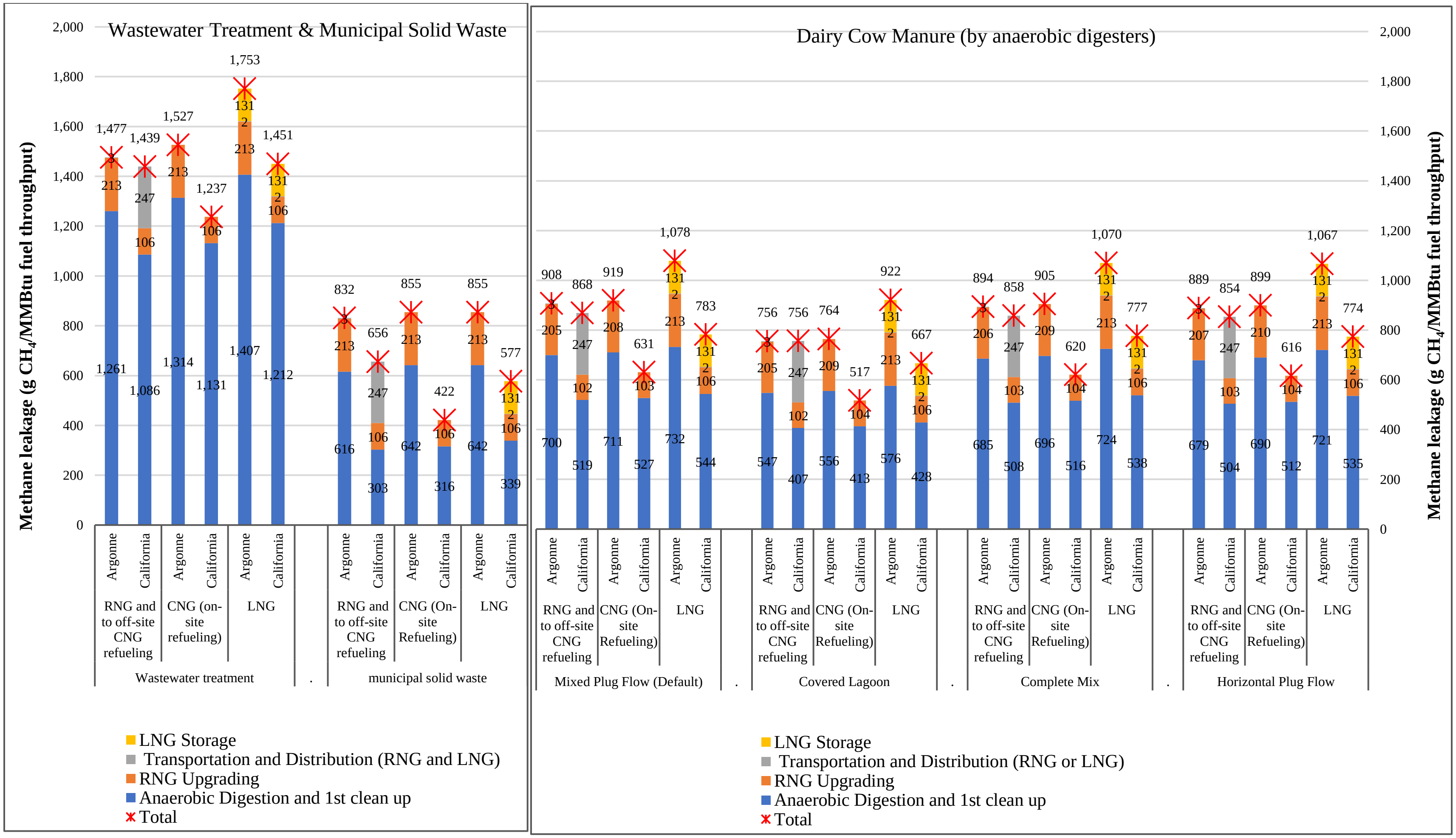


Figure 6. Methane leakage rates of Argonne GREET and CA-GREET3.0 models for RNG, CNG, and LNG production via AD systems (ANL, 2020; CARB, 2019a). (Note: A single-stage mesophilic anaerobic digester with thermohydrolysis treatment is assumed for wastewater treatment pathways; a waste based anaerobic digester is assumed for municipal solid waste pathways; across feedstocks, multiple cleanup processes are applied for upgrading biogas, scrubbing CO_2 to produce pipeline-quality RNG that is used to further produce renewable CNG and LNG (ANL, 2020; CARB, 2019a; Lee et al., 2016); MSW feedstock = yard trimmings which is one of four major organic waste components in MSW (Lee et al., 2017)).

Regardless of RNG's final form, however, total supply chain methane emissions of most AD and biogas upgrading systems are negative even when the RNG undergoes additional process steps to enable use as vehicle fuel (Figure 7). Very large methane emission reductions are achieved when dairy manure is used in AD systems, with smaller reductions being achieved by AD systems at wastewater treatment plants. The Argonne GREET and CA-GREET3.0 models do disagree on the magnitude of methane emission reductions that are achieved when MSW is used in AD systems, however. The CA-GREET3.0 model reports methane emission reductions for MSW that are similar to those of dairy manure, while the Argonne GREET model reports only a minor reduction for MSW. This discrepancy is due to the CA-GREET3.0 model's attribution of a much larger methane emission reduction credit to MSW (3,426 g/MMBtu) than is attributed by the Argonne GREET model (761 g/MMBtu).

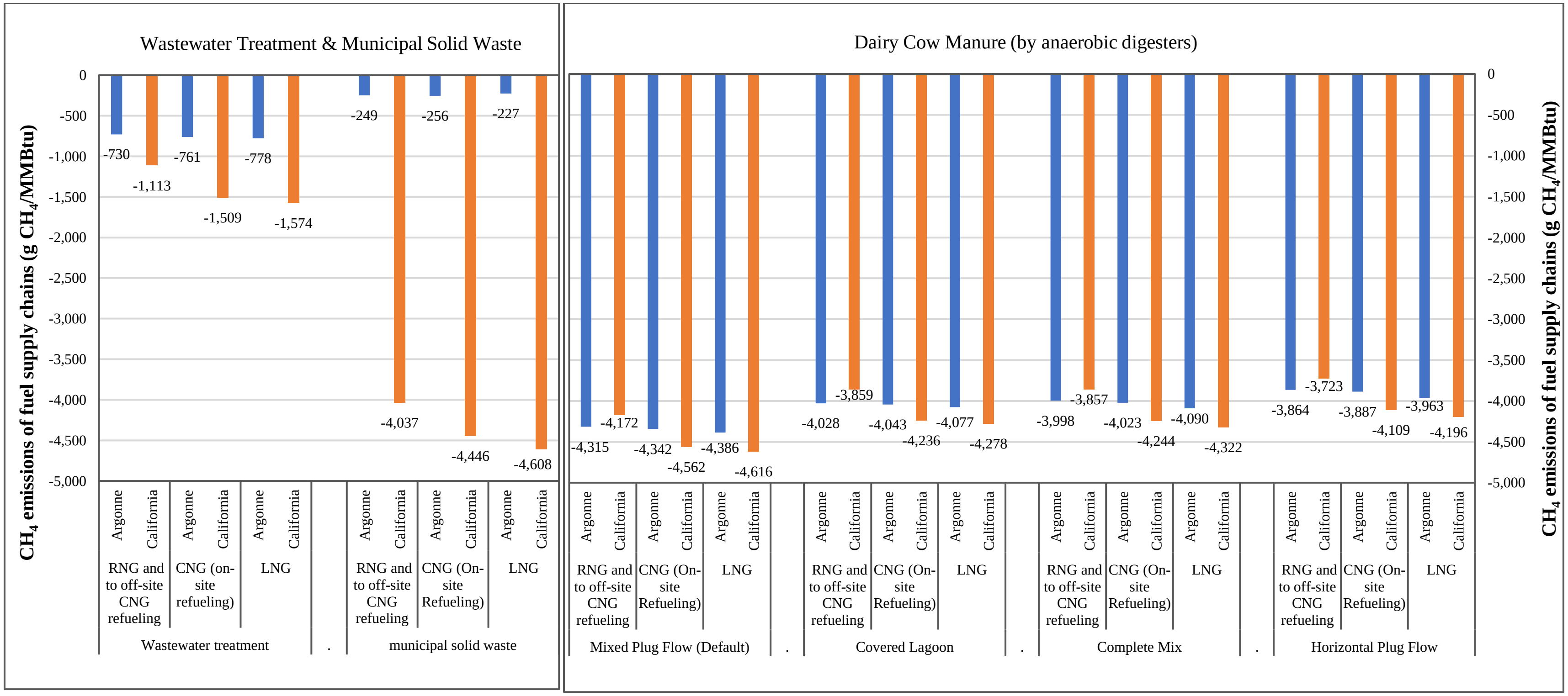


Figure 7. Total methane emissions of renewable CNG and LNG supply chains including emissions and avoided emissions from RNG production by multiple cleanup processes of biogas upgrading (ANL, 2020; CARB, 2019a).

Co-pollutant emissions of BBD supply chains

A common misconception of advanced biofuels such as BBD is that their combustion emits similar levels of co-pollutants (e.g., $PM_{2.5}$, PM_{10}, SOx, NOx, VOC) as petroleum fuels such as ULSD. While the combustion of BBD does result in tailpipe emissions of these co-pollutants, the actual emissions are substantially lower than from the combustion of ULSD. This is true for both biodiesel and renewable diesel to similar degrees (Brown, 2020). Figure 8 shows the potential reductions of greenhouse gas (GHG) and co-pollutant emissions that are achieved via the use of biodiesel, either as a 20% blend with ULSD (B20) or in unblended form (B100). Compared to the use of ULSD, B100 combustion in one study resulted in reductions of between 47% (particulate matter) and 100% (SO_2) to all major co-pollutants excepting NOx, which increased marginally (Caetano et al., 2019). Technologies such as fuel additives and selective catalytic reduction are also available that reduce NOx emissions from biodiesel (Hoekman, 2020; Jeevahan et al., 2017). Alternatively, renewable diesel's low tailpipe NOx emissions relative to both biodiesel and ULSD have led to the use of blends of renewable diesel and biodiesel in order to achieve reductions across all types of co-pollutants (Brown, 2020). Other studies have found that PM emissions, which have an especially pronounced negative impact on human health, are substantially reduced by the use of biodiesel or renewable diesel blends in both transportation and building applications (Brown, 2020; Ghafghazi et al., 2011; Kim et al., 2018).

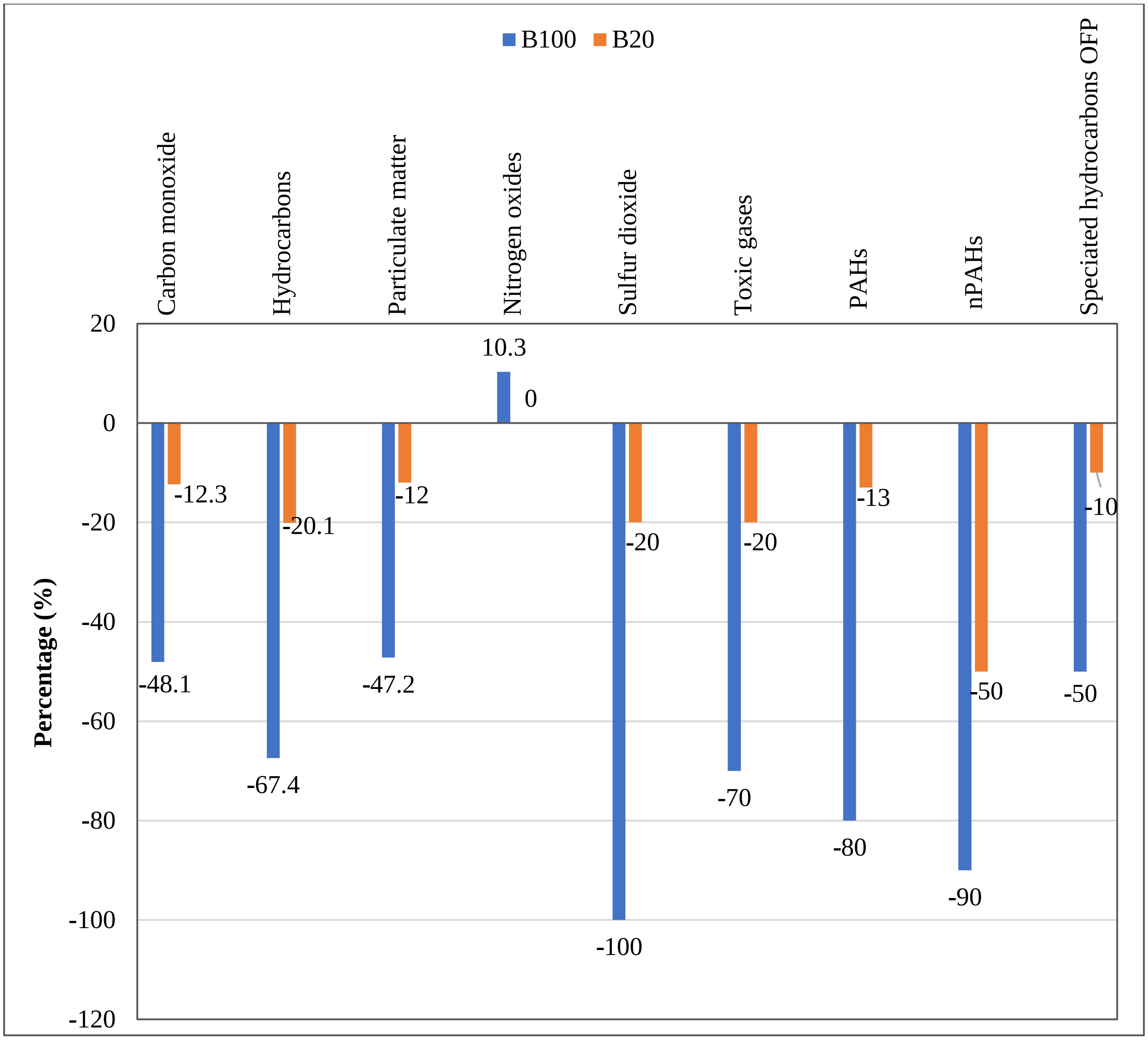


Figure 8. Average percentage variation of some pollutants emissions generated after switching from diesel to biodiesel (B20 and B100) in engines (Caetano et al., 2019). (Note: NOxPAHs = polycyclic aromatic hydrocarbons; nPAHs = nitrated polycyclic aromatic hydrocarbons; OFP = ozone-forming potential).

Tailpipe emissions only represent one source of BBD co-pollutants, of course, and other stages of the supply chain such as BBD production, transportation, and distribution also result in indirect emissions (e.g., from any fuel that is combusted as part of the movement of BBD from the point of production to the point of sale). Both the Argonne GREET model and CA-GREET3.0 model calculate life cycle co-pollutant emissions for BBD across the full supply chain. The two models' results contain some notable differences due to their respective assumptions about the form that the BBD supply chain takes. In the case of renewable diesel that is produced from forest residue feedstock, both GREET models report low emissions of PM_{10}, $PM_{2.5}$, and SOx during the conversion of the feedstock to renewable diesel (see Figure 9). Both models also report no emissions of SOx but higher emissions of PM_{10} and $PM_{2.5}$ during the vehicle operation stage (although, as noted above, less than is emitted when ULSD is combusted). Where the models disagree is on emissions of PM_{10}, $PM_{2.5}$, and SOx during the fuel stage, which includes transportation and distribution (T&D) of the renewable diesel from the point of production to the point of use, with the CA-GREET3.0 model reporting large emissions of all three relative to both its own calculation of emissions during the vehicle operation stage and the Argonne GREET model's calculation of emissions during the fuel T&D stage.

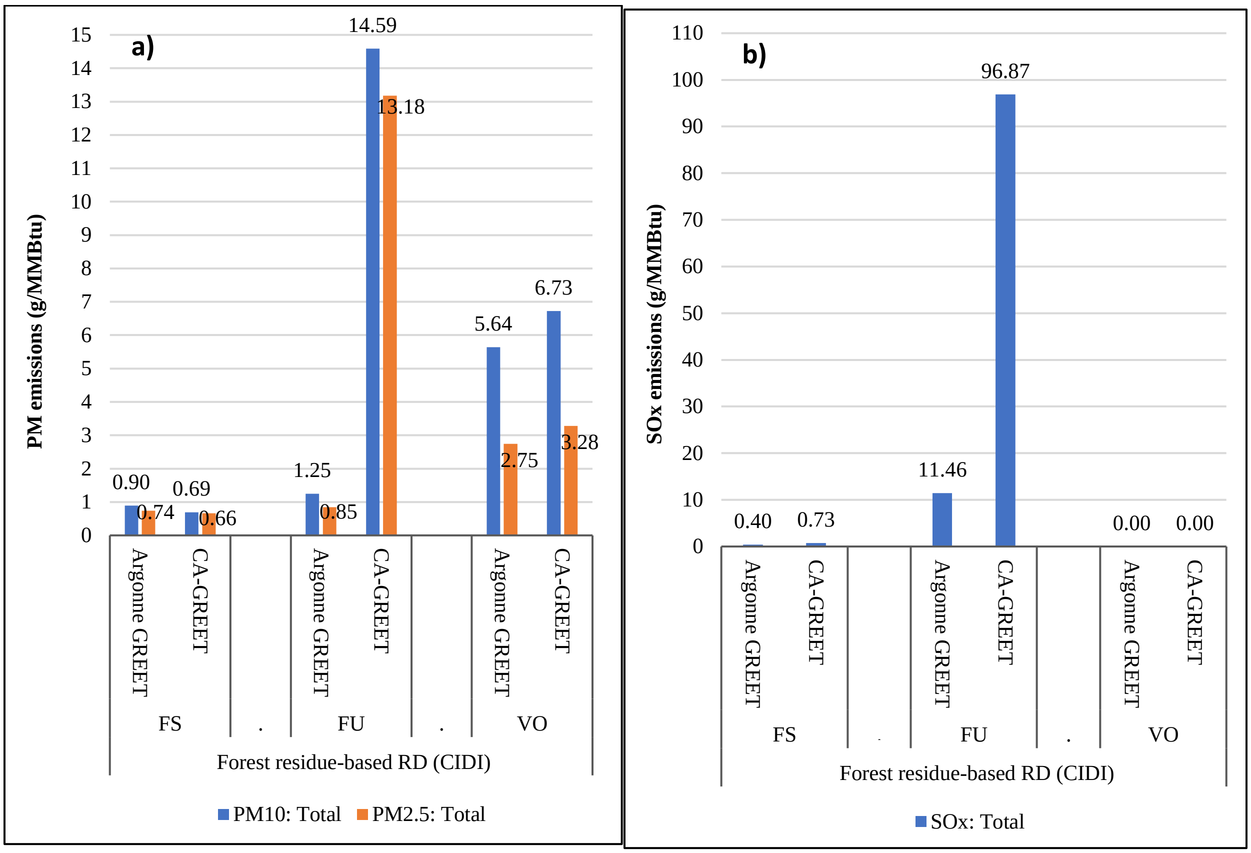


Figure 9. Comparison of lifecycle PM and SOx emissions of CA-GREET3.0 and Agronne GREET (ANL, 2020; CARB, 2019a). Note: FS = feedstock production stage; FU = fuel production stage; VO = vehicle operation stage; SI = spark ignition engine; CIDI = compression ignition direct injection engine; DME = dimethyl ether.

The discrepancy between the two GREET models is due to differences in assumptions about how the renewable diesel is moved to the end-user. BBD is commonly moved by either pipeline, rail, barge, ocean tanker, truck, or more commonly some combination of modes (Brown, 2020). This in turn affects the life cycle co-pollutant emissions (CARB, 2018b; Fan et al., 2018). As an example, total emissions of PM_{10}, $PM_{2.5}$, and SOx differ for each mode of transportation, although the type of fuel that is used in the vehicle moving the renewable diesel also matters (e.g., a tanker truck fueled with renewable diesel will result in lower indirect emissions of co-pollutants than a tanker truck fueled with ULSD). In the case of renewable diesel, the CA-

GREET3.0 model assumes that one shipment stage is performed by an ocean tanker on a 7,677-mile one-way trip, while the Argonne GREET model assumes that renewable diesel is not moved by ocean tanker but rather by barge (8%), rail (29%) and truck (63%). The CA-GREET3.0 model's assumption of the heavy use of bunker fuel, which is characterized by a high content of both particulate and sulfur, by the ocean tanker is the primary cause of the discrepancy between the two models on renewable diesel's life cycle co-pollutant emissions. While substantial volumes of renewable diesel are moved to California via ocean tanker due to the presence of a major renewable diesel production facility in Singapore (Brown, 2020), the CLCPA's emphasis on domestic and even in-state production (Anon, 2020b) makes the Argonne GREET model's results more relevant to New York State. Furthermore, it should be noted that the actual impacts of co-pollutant emissions are more sensitive to location than are GHG emissions: whereas the global warming potential of GHG emissions is the same regardless of where they occur, the human health impacts of co-pollutant emissions are much reduced if they occur in an unpopulated area (e.g., the middle of a large ocean). In addition, the emission levels of both GHG and co-pollutants are sensitive to the size of ocean tanker. Figure 10 presents the relationship between vessel size, CI score, and emissions factor (CARB, 2019a). Both factors are 8-9x greater for the smallest vessels as they are for the largest vessels. While the CA-GREET3.0 model does not report the relationship between vessel size and co-pollutant emissions, a similar relationship can be expected since both GHG and co-pollutant emissions are a function of fuel consumption.

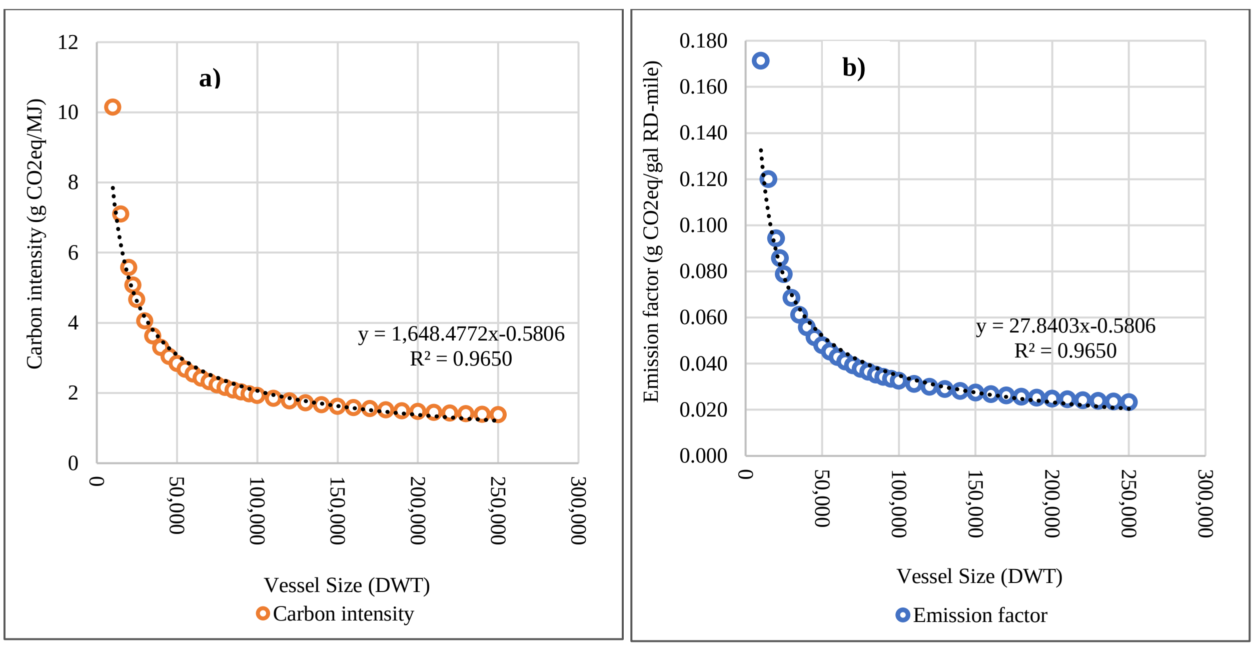


Figure 10. Impact of vessel size on CI values and emission factors association with the transport of renewable diesel by ocean tanker (CARB, 2019a). (Note: DWT = deadweight tonnage; RD = renewable diesel).

The CA-GREET3.0 and Argonne GREET models also calculate life cycle co-pollutant emissions for each stage of the forest residue to renewable diesel production pathway, and the results clearly show their sensitivity to how the T&D stage is conducted. The conversion of forest residue to renewable diesel via thermochemical processing (e.g., biomass pyrolysis) yields a liquid intermediate that is then upgraded to the final fuel. This upgrading can be performed either on-site or off-site, with the latter being done at a conventional petroleum refinery. Nor is the scale of the production system uniform, and the CA-GREET3.0 model reflects this by modeling both large integrated facilities and smaller distributed facilities. Disparities in the results between the two models again illustrate the importance of assessing co-pollutant emissions on a location-specific basis (see Table 5). The main differences are attributed to T&D of the renewable diesel rather than its production, with the CA-GREET3.0 model reporting much higher co-pollutant emissions from the T&D stage than are reported by the Argonne GREET model. T&D stage emissions can either be inconsequential (Argonne GREET) or 1-2 orders of magnitude greater than co-pollutant emissions across the rest of the supply chain (CA-GREET3.0), depending on how the renewable diesel is moved to the end-user.

Table 5. Co-pollutant emissions of forest residue based renewable diesel supply chain (pyrolysis, upgrading, and T&D) in Argonne GREET and CA-GREET3.0 models (ANL, 2020; CARB, 2019a).

Model (integrated system)	Co-pollutants (total emissions: grams/mmBtu of fuel throughput)	Pyrolysis and upgrading	Pyrolysis and upgrading: non-combustion emissions (SMR)	RD refining at conventional petroleum refinery	Sum of fuel conversion stage (no T&D included)	Fuel supply chain	T&D of fuel
Argonne GREET	VOC	2.99	0.32	N/A	3.31	4.56	1.25
	CO	9.46	0.42	N/A	9.87	10.44	0.57
	NOx	13.11	0.54	N/A	13.65	16.30	2.65
	PM10	0.77	0.40	N/A	1.16	1.25	0.08
	PM2.5	0.39	0.38	N/A	0.77	0.85	0.07
	SOx	11.42	0.01	N/A	11.43	11.46	0.04
CA-GREET	VOC	3.12	0.61	N/A	3.73	9.47	5.74
	CO	9.60	3.03	N/A	12.63	23.27	10.63
	NOx	14.08	4.89	N/A	18.98	132.45	113.47
	PM10	1.01	3.81	N/A	4.82	14.58	9.76
	PM2.5	0.48	3.81	N/A	4.29	13.27	8.97
	SOx	14.90	0.00	N/A	14.90	92.91	78.01

Model (distributed system)	Co-pollutant emissions (grams/MMBtu of fuel throughput)	Pyrolysis	Pyrolysis and upgrading: non-combustion emissions (SMR)	RD refining at conventional petroleum refinery	Sum of fuel conversion stage (no T&D included)	Fuel supply chain	T&D fuel
	VOC	2.44	0.54	1.92	4.90	10.82	5.93

CA-GREET	CO	7.50	2.67	3.69	13.86	25.07	11.22
	NOx	11.34	4.31	5.50	21.15	137.62	116.47
	PM10	0.94	3.36	0.45	4.74	14.59	9.84
	PM2.5	0.44	3.36	0.33	4.13	13.18	9.05
	SOx	13.56	0.00	5.20	18.76	96.87	78.11

(Note: T&D fuel = fuel supply chain column – sum of fuel conversion stage column).

This difference between the two GREET models applies to other low-carbon fuels in addition to renewable diesel. The CA-GREET3.0 model also reports much higher co-pollutant emissions than the Argonne GREET model during the fuel movement stage for LNG and ULSD in addition to renewable diesel (see Figure 11). This discrepancy again reflects the CA-GREET3.0 model's analysis of the California fuels market with its heavy reliance on ocean tankers. Otherwise the models' results are similar, with the exception of some co-pollutant emissions during the production of LNG.

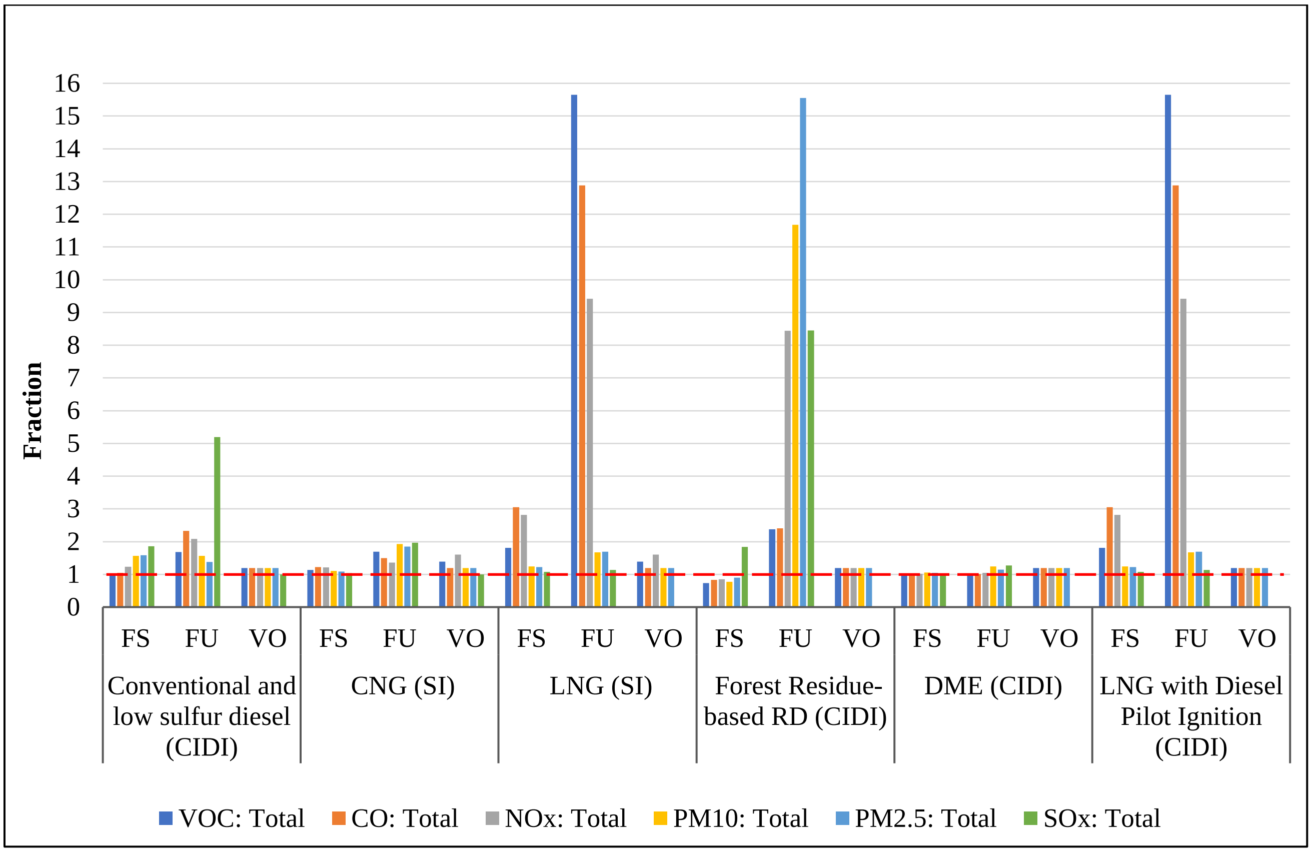


Figure 11. CA-GREET3.0 model's reported emissions divided by Argonne GREET model's reported emissions for low-carbon fuels used in heavy-duty trucks (CARB, 2019b) (Horizontal red dotted line indicates parity between the two models' results).

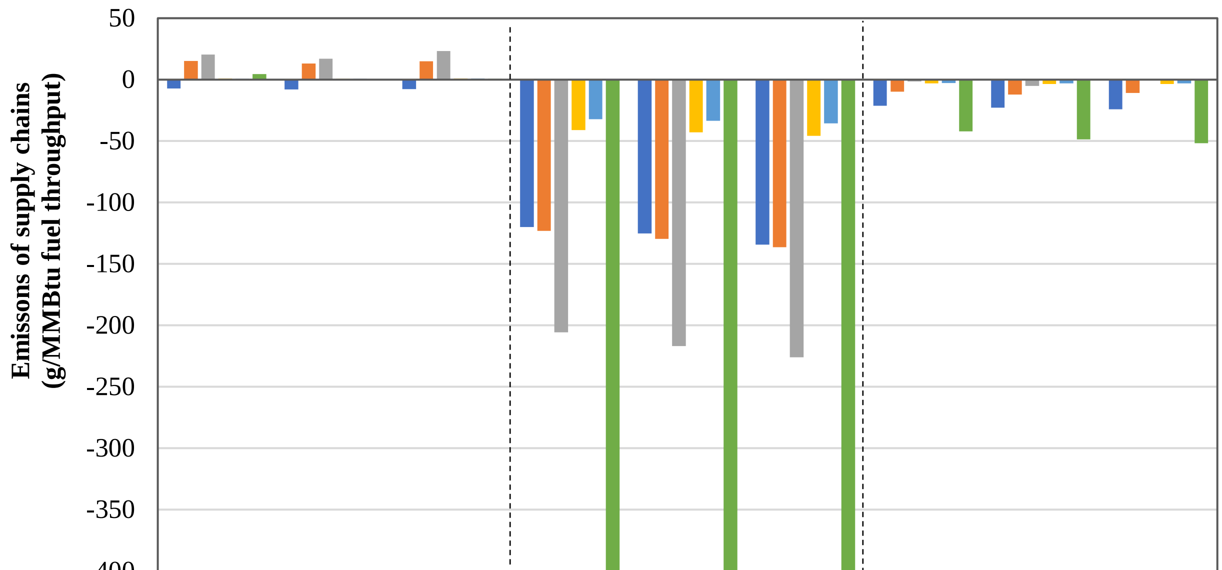
Comparisons of the two models' life cycle co-pollutant emissions for renewable diesel with those of different types of petroleum diesel show how the supply chain affects the magnitude of the biofuel's human health benefits. The forest residue-based renewable diesel supply chain has lower emissions across five different co-pollutants relative to three different types of petroleum diesel when the former is not shipped via ocean tanker, as represented by the Argonne GREET model (see Table 6). In many cases the reductions are by 50% or more (VOC, NOx, $PM_{2.5}$, and SOx). The renewable diesel supply chain has higher life cycle emissions of all five co-pollutants when the fuel is primarily moved via ocean tanker, on the other hand, as represented by the CA-GREET3.0 model. A domestic and/or shorter supply chain therefore has an important impact on renewable diesel's co-pollutant emissions relative to petroleum diesel. Similarly, a supply chain that relied on pipeline transport or ocean vessels operating in emission control areas (such as the Eastern U.S. seaboard) would also affect the supply chain's co-pollutant emissions.

Table 6. Co-pollutant emissions for forest residue-based renewable diesel and different types of petroleum diesel over the supply chain.

	Model (integrated system)				
	Argonne GREET	CA-GREET	Argonne GREET	Argonne GREET	CA-GREET
Co-pollutant emissions (grams/MMBtu of fuel throughput)	Forest residue-based renewable diesel	Forest residue-based renewable diesel	Conventional diesel	Low-sulfur diesel	Ultra-low sulfur diesel
VOC	4.56	9.47	7.53	7.53	10.26
CO	10.44	23.27	12.41	12.42	18.71
NOx	16.30	132.45	23.58	23.59	35.81
PM_{10}	1.25	14.58	1.51	1.51	2.40
$PM_{2.5}$	0.85	13.27	1.27	1.27	1.90
SOx	11.46	92.91	7.51	7.51	23.16

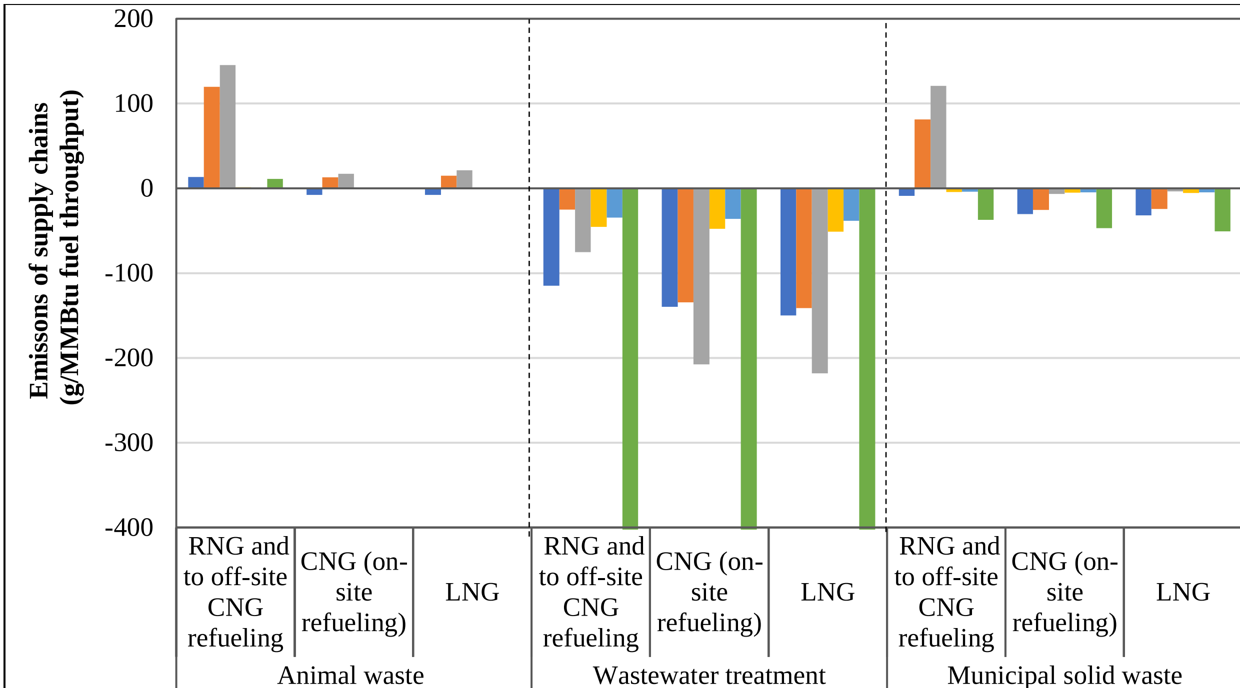
Co-pollutant emissions of renewable natural gas supply chains via anaerobic digestion and biogas upgrading

The RNG supply chain generally achieves low-to-negative emissions of co-pollutants, although the emissions outcome is a function of the AD system's feedstock, how it would be handled were it not converted to RNG, and how the RNG is ultimately consumed. Both the Argonne GREET model (see Figure 12) and CA-GREET3.0 model (see Figure 13) agree that the production of RNG at wastewater treatment facilities results in very large reductions to emissions across co-pollutant categories. How the RNG is consumed has a minor effect by comparison, with LNG achieving slightly larger reductions than CNG across feedstock categories due to its reduced conversion efficiency. Both models also show reductions to co-pollutant emissions when MSW is converted to RNG, albeit to a lesser extent than for wastewater treatment and not as uniformly, with the CA-GREET3.0 model reporting slight increases to carbon monoxide and NOx emissions when the RNG is compressed and moved to an off-site location for refueling. Finally, both models report slight emissions increases to some co-pollutants and slight reductions to others when animal waste is converted to RNG regardless of how the fuel is consumed.



	Animal waste: RNG and to off-site CNG refueling	Animal waste: CNG (on-site refueling)	Animal waste: LNG	Wastewater treatment: RNG and to off-site CNG refueling	Wastewater treatment: CNG (on-site refueling)	Wastewater treatment: LNG	municipal solid waste: RNG and to off-site CNG refueling	municipal solid waste: CNG (on-site refueling)	municipal solid waste: LNG
VOC	-7	-8	-8	-120	-125	-134	-21	-23	-24
CO	15	13	15	-123	-130	-136	-10	-12	-11
NOx	20	17	23	-206	-217	-226	-1	-5	0
PM10	1	1	1	-41	-43	-46	-3	-3	-4
PM2.5	1	1	1	-32	-33	-36	-3	-3	-3
SOx	4	0	1	-1,127	-1,178	-1,268	-42	-49	-52

Figure 12. Total co-pollutant emissions of renewable CNG and LNG supply chains with animal waste, wastewater treatment sludge, and MSW from the Argonne GREET model (ANL, 2020).



	Animal waste: RNG and to off-site CNG refueling	Animal waste: CNG (on-site refueling)	Animal waste: LNG	Wastewater treatment: RNG and to off-site CNG refueling	Wastewater treatment: CNG (on-site refueling)	Wastewater treatment: LNG	Municipal solid waste: RNG and to off-site CNG refueling	Municipal solid waste: CNG (on-site refueling)	Municipal solid waste: LNG
VOC	13	-8	-8	-115	-140	-150	-9	-30	-32
CO	120	13	15	-25	-134	-141	81	-25	-24
NOx	145	17	21	-75	-208	-218	121	-7	-4
PM10	1	1	1	-46	-48	-51	-4	-5	-5
PM2.5	1	1	1	-35	-36	-38	-4	-5	-5
SOx	11	0	0	-1,332	-1,381	-1,487	-37	-47	-51

Figure 13. Total co-pollutant emissions of renewable CNG and LNG supply chains with animal waste, wastewater treatment sludge, and MSW from the CA-GREET3.0 model (CARB, 2019a).

Comparisons between the co-pollutant emissions of RNG and fossil fuels are complex due to the broad range of RNG applications (e.g., CNG vehicles, LNG vehicles, building heat, etc.) and ability to displace multiple types of fossil fuels (gasoline, ULSD, natural gas, etc.). In general, though, RNG's tailpipe emissions of co-pollutants are similar to those of natural gas and lower than those of petroleum fuels. A study of different alternative fuels in urban buses reports that CNG buses fueled with RNG achieved the same tailpipe emissions of NOx and PM as CNG buses fueled with natural gas (Union of Concerned Scientists and Greenlighting Institute, 2017). Both RNG and natural gas in CNG buses are reported to achieve reductions to both NOx and PM emissions of 90% relative to buses fueled with ULSD. Other studies have found emissions control technologies to be capable of greatly reducing those NOx and PM emissions that do occur from lean combustion in older-model CNG vehicles (Yoon et al., 2013).

Conclusions

This review of the scientific literature reports the GHG and co-pollutant emission profiles for the biomass-based diesel (BBD) and renewable natural gas (RNG) pathways when produced from waste, residue, and coproduct feedstocks. It finds that both BBD and RNG achieve moderate-to-large reductions to life cycle carbon intensities compared to fossil fuels, with the largest reductions being reported from the use of waste feedstocks and/or feedstocks that are currently a large source of methane emissions (e.g., animal manure). Waste and some coproduct-derived BBD fuels are already able to achieve deep reductions to carbon intensity that are similar to the CLCPA's 85% deep decarbonization threshold for 2050. RNG's carbon intensity is often reported to be negative on the grounds that the CO_2 that is emitted during its combustion has a small fraction of the total global warming potential of the methane that is captured and converted during anaerobic digestion. While not all forms of BBD and RNG reach these thresholds, those that do therefore have the potential to make strategic contributions to New York State's deep decarbonization targets.

A second important finding of this review is that anaerobic digestion (AD) systems do not generate large fugitive methane emissions even when accounted for across the entire RNG supply chain. Methane leakage rates do vary widely across AD and biogas upgrading systems, with older technologies accounting for the highest leakage rates. Leakage rates for newer upgrading technologies such as amine scrubbing are reported to be up to 99% lower than for the older technologies. Notably, however, the net methane emissions of AD and biogas upgrading systems that utilize feedstocks such as food waste and animal manure are negative regardless of which upgrading technology is employed, as the magnitude of avoided methane emissions greatly exceeds any methane leakage that does occur. The methane emission reductions achieved by AD and biogas upgrading systems are larger still when the product RNG displaces natural gas that has been moved through infrastructure with its own high methane leakage rate.

Finally, both BBD and RNG are reported to result in large reductions to most co-pollutant emissions both at the tailpipe and across their full supply chains. BBD achieves almost uniformly deep reductions to emissions across different co-pollutants, although this result on a life cycle basis is sensitive to the mode by which the fuel is shipped to the consumer. RNG also achieves large reductions to tailpipe co-pollutant emissions relative to ULSD when used in vehicles (especially those CNG/LNG vehicles with emissions control technology), although reductions at the other stages of the supply chain depend on the choice of feedstock and the location of the AD and biogas upgrading system. The largest reductions across the supply chain are reported for AD and biogas upgrading systems at wastewater treatment facilities while the smallest reductions are reported for systems that utilize animal manure. This discrepancy is not as impactful on human health as it may appear given that the location of wastewater treatment facilities near population centers increases the negative effects on human health of their co-pollutant emissions compared to sources of emissions such as dairy operations that are located in rural areas.

This report identifies three areas that require further research and/or analysis. First, the use of food-waste in AD systems has received comparatively little attention from the GREET models due to a lack of landfill diversion policies mandating its separate processing. This has in turn limited its use in the types of AD systems covered by the models. Additional research is needed to analyze the emissions, particularly of co-pollutants, from food waste AD systems. Second, New York State's unique use of a 20-year GWP for methane emissions prevents easy comparison with the GREET models with their use of a 100-year GWP value. Additional analysis is needed to quantify the carbon intensities of different AD systems and natural gas infrastructure types as reported by the GREET models using a 20-year GWP. Third, the small volume of renewable diesel demand in the Northeast U.S. has resulted in a lack of analysis on the region's renewable diesel supply chain. Given the differences between California's existing renewable diesel supply chain and the Northeast's prospective supply chain, additional study of the latter is warranted.

Both BBD and RNG have the potential to make meaningful contributions to New York's climate and human health targets under the CLCPA. First, though, it will be important for the state's policymakers to accurately identify and incentivize the conditions in which the two classes of biofuels achieve the largest reductions to GHG and co-pollutant emissions. The use of waste/residue feedstocks, development of domestic supply chains, and prioritization of biogenic methane capture and destruction will ultimately enable BBD and RNG to achieve their maximum climate and human health benefits as New York decarbonizes.

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References

Alvarez, R.A., Zavala-Araiza, D., Lyon, D.R., Allen, D.T., Barkley, Z.R., Brandt, A.R., Davis, K.J., Herndon, S.C., Jacob, D.J., Karion, A., Kort, E.A., Lamb, B.K., Lauvaux, T., Maasakkers, J.D., Marchese, A.J., Omara, M., Pacala, S.W., Peischl, J., Robinson, A.L., Shepson, P.B., Sweeney, C., Townsend-Small, A., Wofsy, S.C., Hamburg, S.P., 2018. Assessment of methane emissions from the U.S. oil and gas supply chain. Science (80-) 361, 186–188. https://doi.org/10.1126/SCIENCE.AAR7204/SUPPL_FILE/PAP.PDF

ANL, 2020. Argonne GREET Model (GREET1_2020) [WWW Document]. URL https://greet.es.anl.gov/ (accessed 9.4.21).

Anon, 2021. Minutes of the Climate Action Council Meeting Held on July 22, 2021. Albany.

Anon, 2020a. Pathways to Deep Decarbonization in New York State. San Francisco.

Anon, 2020b. Pathways to Deep Decarbonization in New York State Appendix A: Methods and Data. San Francisco.

Brown, T., 2020. Biomass-based diesel: a market and performance analysis [WWW Document]. Fuels Inst. URL https://www.fuelsinstitute.org/Research/Reports/Biomass-Based-Diesel-A-Market-and-Performance-Anal (accessed 11.7.21).

Caetano, N.S., Ribeiro, V., Ribeiro, L., Baptista, A., Monteiro, J., 2019. Biodiesel production systems: operation, process control and troubleshooting, in: Tabatabaei, M., Aghbashlo, M. (Eds.), Biodiesel : From Production to Combustion. Springer, Cham, pp. 27–56. https://doi.org/10.1007/978-3-030-00985-4_3

Cai, H., Ou, L., Wang, M., Davis, R., Dutta, A., Harris, K., Wiatrowski, M.R., Tan, E., Bartling, A., Bruno, K., Hartley, D., Lin, Y., Roni, M., Thompson, D.N., Snowden-Swan, L., Zhu, Y., 2021. Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2020 State-of-Technology Cases. Argonne, IL (United States). https://doi.org/10.2172/1807565

California Air Resources Board, 2021. LCFS Pathway Certified Carbon Intensities [WWW Document]. Fuel Pathw Table.

CARB, 2021. LCFS pathway certified carbon intensities: current fuel pathways [WWW Document]. URL https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities (accessed 9.9.21).

CARB, 2020. Low Carbon Fuel Standard tier 2 pathway application staff summary: Element Markets Renewable Energy, LLC Valley View Farms Greencastle, Missouri Swine Manure Biomethane.

CARB, 2019a. CA-GREET3.0 model [WWW Document]. URL https://ww2.arb.ca.gov/resources/documents/lcfs-life-cycle-analysis-models-and-documentation (accessed 10.4.21).

CARB, 2019b. LCFS life cycle analysis models and documentation: CA-GREET3.0 Model and Tier 1 simplified carbon intensity calculators [WWW Document]. URL https://ww2.arb.ca.gov/resources/documents/lcfs-life-cycle-analysis-models-and-documentation (accessed 10.2.21).

CARB, 2018a. CA-GREET3.0 lookup table pathways: technical support documentation.

CARB, 2018b. CA-GREET3.0 supplemental document and tables of changes.

CARB, 2015. LCFS land use change assessment: Detailed analysis for indirect land use change.

Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., O'Connor, D., Duffield, J., 2018. Life cycle energy and greenhouse gas emission effects of biodiesel in the United States with induced land use change impacts. Bioresour Technol 251, 249–258. https://doi.org/10.1016/j.biortech.2017.12.031

Climate Leadership and Community Protection Act, 2019.

Dalke, R., Demro, D., Khalid, Y., Wu, H., Urgun-Demirtas, M., 2021. Current status of anaerobic digestion of food waste in the United States. Renew Sustain Energy Rev 151, 111554. https://doi.org/10.1016/J.RSER.2021.111554

EPA, 2020. Lifecycle greenhouse gas results [WWW Document]. URL https://www.epa.gov/fuels-registration-reporting-and-compliance-help/lifecycle-greenhouse-gas-results (accessed 5.22.20).

ERCE, 2021. IPCC Sixth Assessment Report Global Warming Potentials [WWW Document].

Fan, Y. Van, Perry, S., Klemeš, J.J., Lee, C.T., 2018. A review on air emissions assessment: Transportation. J Clean Prod 194, 673–684. https://doi.org/10.1016/J.JCLEPRO.2018.05.151

Flatt, C., 2021. Washington Joins Oregon, California, British Columbia In Passing Low-Carbon Fuel Standard. Northwest News Netw.

Fulcrum Bioenergy, 2021. Our Process [WWW Document]. Technology.

Ghafghazi, Saeed, Sowlati, Taraneh, Sokhansanj, Shahab, Bi, X., Melin, Staffan, Ghafghazi, S, Sowlati, T, Sokhansanj, S, Bi, : X, Melin, S, 2011. Life cycle assessment of base–load heat sources for district heating system options. Int J Life Cycle Assess 16, 212–223. https://doi.org/10.1007/s11367-011-0259-9

Hoekman, S.K., 2020. Review of nitrous oxide (N2O) emissions from motor vehicles. SAE Int J Fuels Lubr 13, 79–98. https://doi.org/10.4271/04-13-01-0005

Howarth, R.W., 2020. Methane emissions from fossil fuels: exploring recent changes in greenhouse-gas reporting requirements for the State of New York. J Integr Environ Sci 17, 69–81. https://doi.org/10.1080/1943815X.2020.1789666

Howarth, R.W., Robert Howarth, C.W., 2014. A bridge to nowhere: methane emissions and the greenhouse gas footprint of natural gas. Energy Sci Eng 2, 47–60. https://doi.org/10.1002/ESE3.35

Howarth, R.W., Santoro, R., Ingraffea, A., 2011. Methane and the greenhouse-gas footprint of natural gas from shale formations. Clim Change 106, 679. https://doi.org/10.1007/s10584-011-0061-5

Jeevahan, J., Mageshwaran, G., Joseph, G.B., Raj, R.B.D., Kannan, R.T., 2017. Various strategies for reducing Nox emissions of biodiesel fuel used in conventional diesel engines: a review. http://dx.doi.org/10.1080/00986445.2017.1353500 204, 1202–1223. https://doi.org/10.1080/00986445.2017.1353500

Kim, D.S., Hanifzadeh, M., Kumar, A., 2018. Trend of biodiesel feedstock and its impact on biodiesel emission characteristics. Environ Prog Sustain Energy 37, 7–19. https://doi.org/10.1002/EP.12800

Kraemer, T., Gamble, S., 2014. Integrating anaerobic digestion with composting. ByoCycle.

Lackey, J., Champagne, P., Peppley, B., 2017. Use of wastewater treatment plant biogas for the operation of Solid Oxide Fuel Cells (SOFCs). J Environ Manage 203, 753–759. https://doi.org/10.1016/J.JENVMAN.2016.09.006

LCSL, 2021. State Renewable Portfolio Standards and Goals [WWW Document]. URL https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx (accessed 12.24.21).

Lee, U., Bhatt, A., Hawkins, T.R., Tao, L., Benavides, P.T., Wang, M., 2021. Life cycle analysis of renewable natural gas and lactic acid production from waste feedstocks. J Clean Prod

311, 127653. https://doi.org/10.1016/J.JCLEPRO.2021.127653

Lee, U., Han, J., Urgun Demirtas, M., Wang, M., Tao, L., 2016. Lifecycle analysis of renewable natural gas and hydrocarbon fuels from wastewater treatment plants' sludge. Argonne. https://doi.org/10.2172/1327830

Lee, U., Han, J., Wang, M., 2017. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. J Clean Prod 166, 335–342. https://doi.org/10.1016/J.JCLEPRO.2017.08.016

NYSERDA, 2019. New York State oil and gas sector methane emissions inventory: final report (report number 19-36) [WWW Document]. URL https://www.nyserda.ny.gov/About/Publications/EA-Reports-and-Studies/Greenhouse-Gas-Emissions (accessed 10.5.21).

Odeh, N., Abu-Ebid, M., 2016a. Methodology to Assess Methane Leakage from AD Plants. Harwell.

Odeh, N., Abu-Ebid, M., 2016b. Methodology to assess methane leakage from AD Plants_Part I: Report on proposed categorisation of AD plants and literature review of methane monitoring technologies.

Pfluger, A., Coontz, J., Zhiteneva, V., Gulliver, T., Cherry, L., Cavanaugh, L., Figueroa, L., 2019. Anaerobic digestion and biogas beneficial use at municipal wastewater treatment facilities in Colorado: A case study examining barriers to widespread implementation. J Clean Prod 206, 97–107. https://doi.org/10.1016/J.JCLEPRO.2018.09.161

Pirnie, M., 2007. Anaerobic digester gas-to-electricity for the municipal wastewater sector in New York. Albany.

Popp, J., Harangi-Rákos, M., Gabnai, Z., Balogh, P., Antal, G., Bai, A., 2016. Biofuels and Their Co-Products as Livestock Feed: Global Economic and Environmental Implications. Molecules 21. https://doi.org/10.3390/MOLECULES21030285

Saadabadi, S.A., Thallam Thattai, A., Fan, L., Lindeboom, R.E.F., Spanjers, H., Aravind, P. V., 2019. Solid Oxide Fuel Cells fuelled with biogas: Potential and constraints. Renew Energy 134, 194–214. https://doi.org/10.1016/J.RENENE.2018.11.028

Scheutz, C., Fredenslund, A.M., 2019. Total methane emission rates and losses from 23 biogas plants. Waste Manag 97, 38–46. https://doi.org/10.1016/J.WASMAN.2019.07.029

Taheripour, F., Tyner, W.E., 2020. US biofuel production and policy: Implications for land use changes in Malaysia and Indonesia. Biotechnol Biofuels 13, 1–17. https://doi.org/10.1186/S13068-020-1650-1/FIGURES/6

Tepper, N., 2017. Could Garbage Fuel Airplanes? Fulcrum BioEnergy wants to divert trash from landfills and create cheap green energy [WWW Document]. Smithson Mag. URL https://www.smithsonianmag.com/innovation/could-garbage-fuel-airplanes-180962261/ (accessed 12.31.21).

Union of Concerned Scientists, Greenlighting Institute, 2017. Delivering Opportunity Appendix C: Methodology for Heavy-Duty Vehicle Emissions Analysis.

Withey, P., Johnston, C., Guo, J., 2019. Quantifying the global warming potential of carbon dioxide emissions from bioenergy with carbon capture and storage. Renew Sustain Energy Rev 115.

Yoon, S., Collins, J., Thiruvengadam, A., Gautam, M., Herner, J., Ayala, A., 2013. Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies. J Air Waste Manage Assoc 63, 926–933. https://doi.org/10.1080/10962247.2013.800170