Environmental Science & Technology

pubs.acs.org/est

Article

Comparative Life Cycle Evaluation of the Global Warming Potential (GWP) Impacts of Renewable Natural Gas Production Pathways

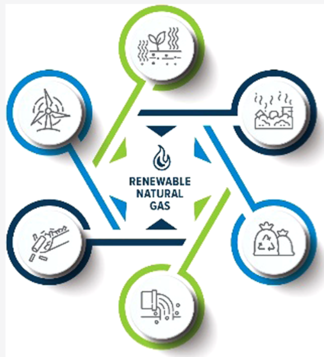
Srijana Rai, Danny Hage, James Littlefield, Gabrielle Yanai, and Timothy J. Skone*

Cite This: *Environ. Sci. Technol.* 2022, 56, 8581−8589

Read Online

ACCESS | Metrics & More | Article Recommendations | SI Supporting Information

ABSTRACT: Renewable natural gas (RNG) sources are being considered in future energy strategy discussions as potential replacements for fossil natural gas (FNG). While today's supply of RNG resources is insufficient to meet U.S. demands, there is significant interest in its viability to supplement and decarbonize the natural gas supply. However, the studies compare the life cycle global warming potential (GWP) of various RNG production pathways are lacking and focus mostly on a singular pathway. This effort is an attempt to close this gap and provide a comparison between the life cycle GWP of three major RNG pathways and the FNG pathway. The three RNG pathways evaluated are anaerobic digestion (AD), thermal gasification (TG), and power-to-gas (P2G) using various feedstocks. The functional unit is 1 MJ of compressed RNG ready for injection into the natural gas transmission network. The results show that RNG production is not always carbon neutral or negative. Depending on the pathway, the GWP impact of RNG production can range from −229 to 27 g CO_2e/MJ compressed RNG, with AD of animal manure and AD of municipal solid waste being the least and the most impactful pathways, respectively, compared to the 10.1 g CO_2e/MJ impact for compressed FNG.



KEYWORDS: *life cycle analysis, renewable natural gas, greenhouse gas, global warming potential, natural gas, anaerobic digestion, thermal gasification, power-to-gas*

INTRODUCTION

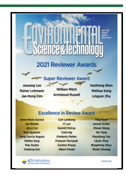
Renewable natural gas (RNG) sources are being considered in future energy strategy discussions as potential replacements for fossil natural gas (FNG). There is significant interest in the viability of RNG; however, there is a lack of resources that compare the life cycle global warming potential (GWP) of various RNG production pathways. In this paper, we model all major RNG pathways using a single, consistent framework.

This work is a life cycle assessment (LCA) of three RNG pathways with multiple feedstocks and technologies. The three pathways evaluated are anaerobic digestion (AD), thermal gasification (TG), and power-to-gas (P2G). AD generates biogas by breaking down organic matter in the absence of oxygen. Feedstocks in the AD pathway include animal manure, landfill gas, municipal solid waste, and wastewater sludge, within which the biogas from wastewater sludge can be upgraded to RNG using one of the three biogas upgrading technologies: methyl diethanolamine (MDEA) scrubbing, monoethanolamine (MEA) scrubbing, or high-pressure water scrubbing (HPWS). The TG pathway uses a wood waste feedstock and represents three gasification technologies: air, catalyst, and steam gasification, where a controlled amount of air, steam, or catalysts reacts with available carbon in the biomass in a gasifier at high temperatures to generate syngas, which is then cleaned, upgraded, and passed through methanation to produce RNG. The P2G pathway uses renewable electricity (wind power) to produce hydrogen (H_2) from water electrolysis, which is then reacted with CO_2 to produce RNG.

The combinations of pathways, feedstocks, and technologies result in a total of 10 different scenarios, whose system boundaries start at the AD unit for the AD scenarios, transport of feedstock for the TG scenarios, and electrolysis of water for the P2G scenarios. The boundary ends in all of the scenarios with the compression of produced RNG to the required pressure for injection into the natural gas transmission network. The RNG scenarios have a functional unit of 1 MJ of compressed RNG. We also compare the RNG scenarios to their corresponding business-as-usual (BAU) scenarios, which have a functional unit of 1 MJ of processed FNG before it enters the transmission network and waste management of the same amount of feedstock that is needed in its corresponding RNG scenario to produce 1 MJ of RNG. We model the pathways using two analytical approaches:

(1) Attributional LCA of RNG pathways compared to the corresponding BAU scenarios
(2) System expansion LCA of RNG pathways

Received: January 11, 2022
Revised: May 6, 2022
Accepted: May 10, 2022
Published: June 2, 2022



https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

As with any energy technology, including FNG, RNG is going to have similar potential risks in handling and may occasionally lead to extreme leak/escape events. While we recognize that these extreme events will lead to significantly higher emissions in a short period of time, this study models steady-state operations and does not represent any unexpected extreme events.

LITERATURE REVIEW

RNG presents interesting decarbonization opportunities as a substitute for FNG since RNG can be a direct drop-in replacement that is not coal or liquefied natural gas (LNG). The American Gas Foundation[1] reported that RNG deployment could achieve 101−235 million metric tons (MMT) of greenhouse gas (GHG) emission reductions by the year 2040.

Within RNG pathways, studies have already compared many of them at a high level. Fendt et al.[2] compared the three main pathways in terms of their respective development states, efficiencies, and economics. The authors determined that the thermochemical pathway (i.e., TG) had the highest efficiency at the time of publication, though all three concepts needed outside intervention to be competitive in the natural gas market. Di Salvo and Wei[3] presented a case study for the industrial sector in California, focusing on RNG from the TG and P2G pathways and its injection into the existing natural gas pipeline. Findings included that RNG produced via the TG and P2G pathways could displace about 17 and 6% of 2050 levels of industrial natural gas demand in California, respectively.

Other existing research in this field mainly focuses on certain specific pathways or certain stages of the supply chain. Li et al.,[4] Lee et al.,[5] and Mills et al.[6] performed LCA of different AD pathways using wastewater sludge. Patterson et al.[7] and Walker et al.[8] also analyzed AD but with food waste or wheat feed and dairy farm manure as feedstocks, respectively. Walker et al.[9] performed an LCA of a P2G pathway based in Ontario, Canada. These individual studies provided values to which the results from this report can be compared.

A more recent study, Lee et al.,[10] performed an LCA on anaerobic digestion of multiple wet waste feedstocks of which the wastewater sludge and swine manure feedstock pathways align with the pathways in this study. The boundaries of the two studies are in alignment except for the RNG compression stage, which is not included in Lee et al. They estimated the GWP impact of AD on wastewater sludge and swine manure to be 27 and −146 g CO_2e/MJ RNG, respectively.

The three RNG production pathways examined here are also compared with the BAU pathway (i.e., traditional FNG). Previous works by the United States (U.S.) Department of Energy (DOE) National Energy Technology Laboratory (NETL) have evaluated FNG systems. Littlefield et al.[11] performed an LCA of the extraction and power generation of FNG, finding that the life cycle GHG emissions from the current U.S. natural gas supply chain are 19.9 g carbon dioxide equivalents (CO_2e)/MJ based on the 2016 data year. Rai et al.[12] used 2017 data to determine that the average U.S. natural gas system emits 14.1 CO_2e/MJ of delivered natural gas.

Our work builds and expands on the current state of literature by providing a robust analysis of multiple production pathways from start to finish of the supply chain, as well as standardizes the results to a single functional unit. In doing so, all of the major RNG production pathways and their results can be directly compared with each other and with the FNG business as usual, all within a consistent framework.

PATHWAYS AND BOUNDARIES

We model a waste-to-energy (WTE) RNG case and a BAU case to compare the production of RNG to the production of FNG and conventional waste treatment.

RNG Case. In the RNG case, we model three different pathways—AD, TG, and P2G—using a variety of feedstocks. The AD pathway begins with an anaerobic digestor unit, the TG pathway begins with feedstock transport, and the P2G pathway begins with electrolysis, and all pathways conclude with compression of the RNG product for injection into the natural gas transmission network. The RNG scenarios have a functional unit of 1 MJ of pipeline-ready RNG from various feedstocks. Upstream emissions associated with waste production are excluded from the RNG case boundary because waste is not being specifically produced for RNG production but rather would have already been produced in a BAU case. As we applied the cutoff approach for waste products and assumed their carbon content was 100% biogenic, no positive CO_2 emissions are accounted for in the RNG process releases and there are no negative CO_2 emissions associated with CO_2 uptake. Additionally, feedstock transport is excluded from the AD boundaries because it is assumed that the anaerobic digester is located on-site, where waste management would conventionally take place. More details on pathway-specific boundaries are discussed in the following sections.

Anaerobic Digestion. AD is the natural process of breaking down organic materials in the absence of oxygen, generating a biogas composed of methane (CH_4), carbon dioxide (CO_2), and small amounts of water vapor (H_2O) and other trace gases. The natural process of AD can be mimicked in a built system called an anaerobic digester.[13] We model AD using the following feedstocks as the organic material input:

Animal Manure (AM). The source of AM feedstock was calculated from Argonne National Laboratory's (ANL) Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model RNG database.[14] Of the operational facilities in the database producing AM-based pipeline-ready RNG, 25% of the animal population feeding the digester is dairy cow, while the remaining 75% is swine. The boundary for AD via AM begins with the AD process and ends with compression of RNG for pipeline injection.

Landfill Gas (LFG). In the LFG pathway, the landfill acts as an anaerobic digester, and LFG refers to the capture of gas released during the decomposition of waste in the landfill. While LFG is listed as an AD feedstock, it is technically the equivalent of the biogas output in the other AD pathways. The LFG pathway boundary begins with upgrading and cleaning of the LFG and ends with compression of RNG for pipeline injection.

Municipal Solid Waste (MSW) (Organic Portion). In the MSW pathway, the organic portion of waste conventionally going to landfill is diverted to an anaerobic digester. The breakdown of the contribution of organic materials to the U.S. average mixture of landfilled waste is 8.1% wood, 21.6% food, and 7.9% yard trimmings.[15] The MSW pathway boundary begins with AD and ends with compression of RNG for pipeline injection.

Wastewater Sludge (WWS). In the WWS pathway, the sludge output of the wastewater treatment process is the input to the RNG pathway. Although WWS has the highest moisture content of all of the AD feedstocks, no pretreatment is necessary to prepare it for the AD process. The WWS pathway boundary

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

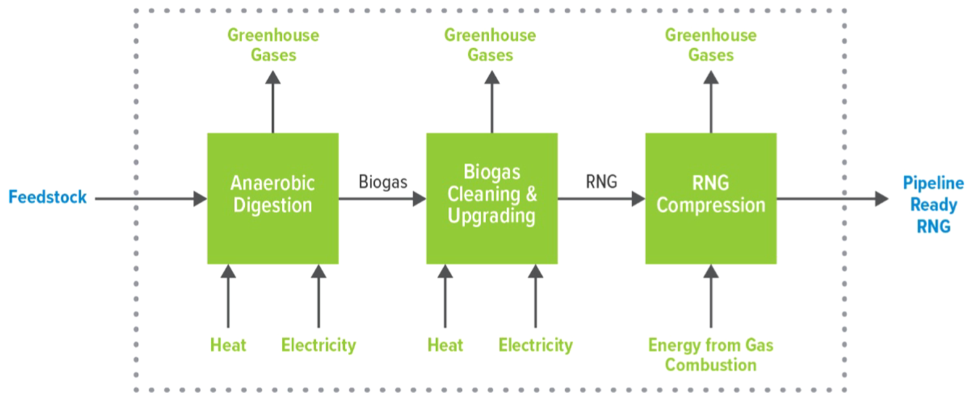


Figure 1. RNG case AD supply chain and boundary (upstream burdens of feedstock acquisition are not included in the boundary).

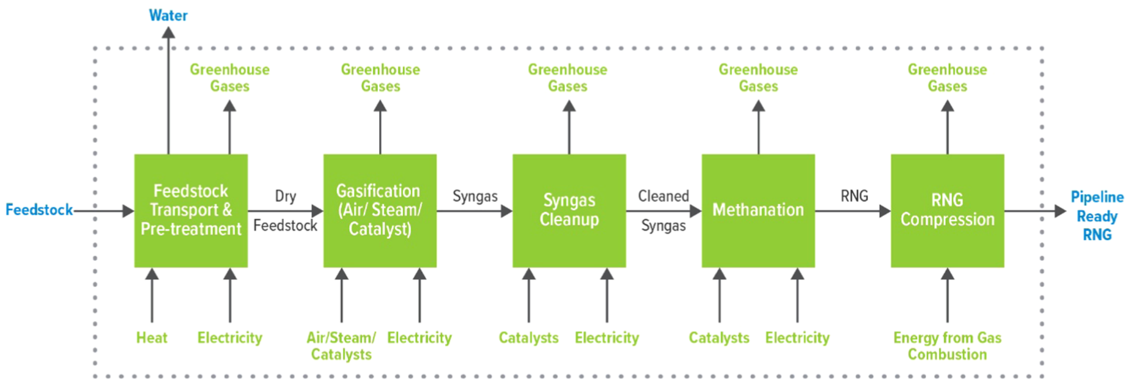


Figure 2. RNG case TG supply chain and boundary (upstream burdens of feedstock acquisition are not included in the boundary).

begins with AD and ends with compression of RNG for pipeline injection.

The biogas obtained from the AD process is cleaned and upgraded at a co-located facility to remove CO_2, H_2O, and other trace gases to produce an ∼99% CH_4 content RNG product. The RNG is then compressed to make it pipeline-ready. We model three biogas cleaning and upgrading technologies:[16]

(1) HPWS: This is a two-stage process with a high-pressure reactor column in the first stage. In this stage, cold water flows downward, while biogas flows upward under high pressure. The soluble gases like CO_2 dissolve in water, leaving mostly CH_4 to exit this column. The second stage consists of a depressurization column, where CO_2 is degassed by releasing the pressure from the solution.

(2) Amine scrubbing using MDEA: This is a two-stage process with an adsorption and a desorption tower. In the first stage, an amine scrubbing solvent reacts chemically with the CO_2 in the biogas and adsorbs and retains it in a solution and the CH_4 portion of the biogas passes through this tower untouched, thus creating a concentrated stream of bio-CH_4. In the second stage, the solution containing the amine solvent and the adsorbed CO_2 is heated to its boiling point, which reverses the chemical reaction, and the CO_2 is discharged into the atmosphere and the regenerated amine solution is cooled and reused. MDEA is a common chemical used as a scrubbing solvent.

(3) Amine scrubbing using MEA−This is the same process as item (2) above, except MEA is the amine in the scrubbing solvent instead of MDEA.

We model HPWS technology as the default cleaning and upgrading technology for biogas from AM, LFG, MSW, and WWS feedstocks; the additional two technologies mentioned above are also modeled for the WWS feedstock.[17−20] The AD pathway also produces a digestate as a co-product that can displace the production and application of fertilizer to land. However, since our system boundary does not include upstream burdens associated with acquiring feedstock, we exclude the digestate to prevent double-counting of avoided emissions from upstream agriculture processes related to RNG production. Figure 1 shows the supply chain and the boundary for the AD pathway.

Thermal Gasification. TG uses wood waste—which is traditionally landfilled—as the feedstock, which is pretreated to dry and resize the biomass before feeding it into the gasification unit.[21]

Gasification is a thermochemical process through which biomass is converted to syngas, which is composed of CO_2, CH_4, H_2, carbon monoxide (CO), nitrogen (N_2), H_2O, higher hydrocarbons, and other impurities. During the gasification process, a controlled amount of air, steam, or catalysts reacts with available carbon in the biomass in a gasifier at high temperatures.[22] We model three gasification methods—air, steam, and catalyst—and use data from the literature to estimate the input and output energy, product, and GHG flows.

The resultant syngas from the gasification goes through multiple screening, scrubbing, heating, and cooling cycles and reacts with catalysts that remove all impurities, H_2O, and heavy hydrocarbons. We model a simplified process wherein we account for all energy, product, and GHG flows associated with syngas cleanup. This process is based on the specifications defined by the Gas Technology Institute (GTI) in their report on RNG.[21]

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

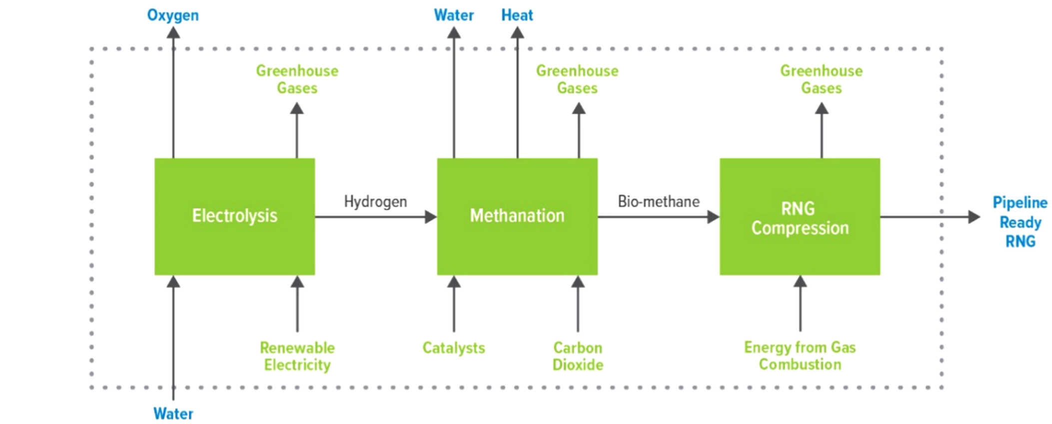


Figure 3. RNG case P2G supply chain and boundary.

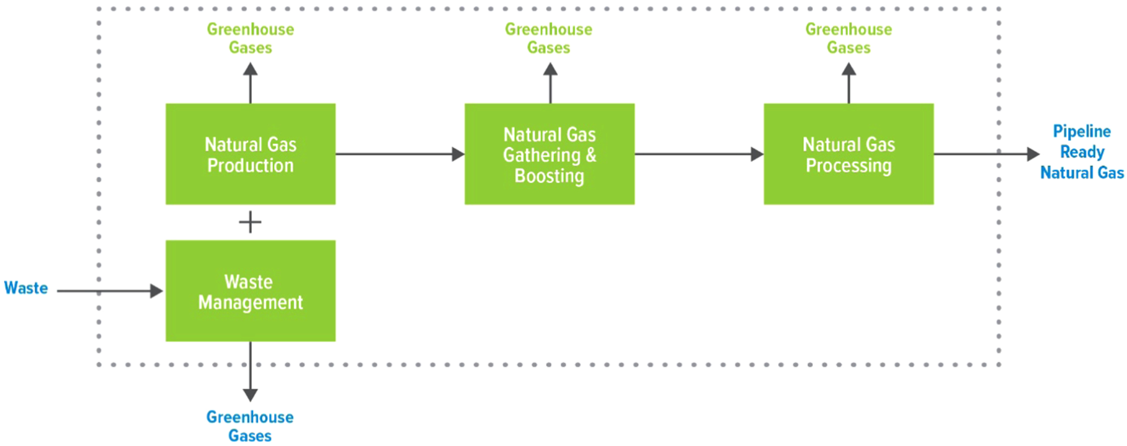


Figure 4. BAU case supply chain and boundary (upstream burdens of waste acquisition are not included in the boundary).

The resultant clean syngas goes through a methanation reactor, where the H_2, CO_2, and CO in the clean syngas react to form bio-CH_4 or RNG, which is then compressed in preparation for pipeline injection. Figure 2 shows the supply chain and the boundary for the TG pathway.

Power-to-Gas. The P2G pathway uses renewable electricity to produce H_2 from water electrolysis, which is then reacted with CO_2 in the methanation step to yield RNG, which is compressed for pipeline injection. Figure 3 shows the supply chain and the boundary for the P2G pathway.

RNG Compression. The RNG produced from all pathways must be compressed to a sufficiently high pressure for injection into the existing natural gas transmission network. The U.S. Environmental Protection Agency (EPA) suggests an inlet pressure of 50−1000 pound-force per square inch gauge (psig) depending on the pipeline and the interconnect location.[23] We use a conservative approach and model compression of RNG to 1000 psig using a reciprocating compressor. We model the compression by deriving a reduced-order relationship from NETL's unit process for fluid compression.[24] Using this equation, we calculated an energy requirement of 1.03×10^{-4} kg of natural gas to compress 1 MJ RNG to 1000 psig. Section S3 shows the equation used to estimate the energy requirement and discusses the method for generating that equation.

Business-as-Usual Case. The BAU case has a functional unit of 1 MJ of processed FNG and the amount of waste managed via conventional methods for each RNG feedstock that would otherwise be needed to produce 1 MJ of RNG. For example, if "*x*" kg of animal manure is needed to produce 1 MJ of compressed RNG, then the BAU represents 1 MJ of FNG and waste management of "*x*" kg of animal manure. Since we evaluate pathways with different feedstocks, there is a BAU scenario corresponding to each feedstock for each pathway. Figure 4 shows the generic supply chain and the boundary for the BAU case.

Fossil Natural Gas. We use the 2017 U.S. average GHG profile for FNG from NETL's ONE Future Phase 2 report[12] to model the BAU cases. The production, gathering and boosting, and processing stages of the natural gas supply chain are included, and the results are scaled to represent 1 MJ of processed FNG before it enters the transmission network. The resultant GWP impact for FNG is 10.1 g CO_2e/MJ of compressed gas.

Conventional Waste Management. We evaluate the GHG profile for the conventional waste management of each feedstock in the RNG WTE pathways and add it to the FNG GHG profile (detailed calculations are presented in Section S2); the resulting aggregate GHG impacts are the BAU values against which we compare the RNG production GHG profiles. Our methods for accounting for conventional waste management are as follows:

Animal Manure (AM). We assume the same split in feedstock as described in the Anaerobic Digestion section above for the BAU waste management case. Dairy cow manure and swine have conventionally been managed via one or more of the following techniques: flush systems, deep pit, liquid/slurry, anaerobic

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

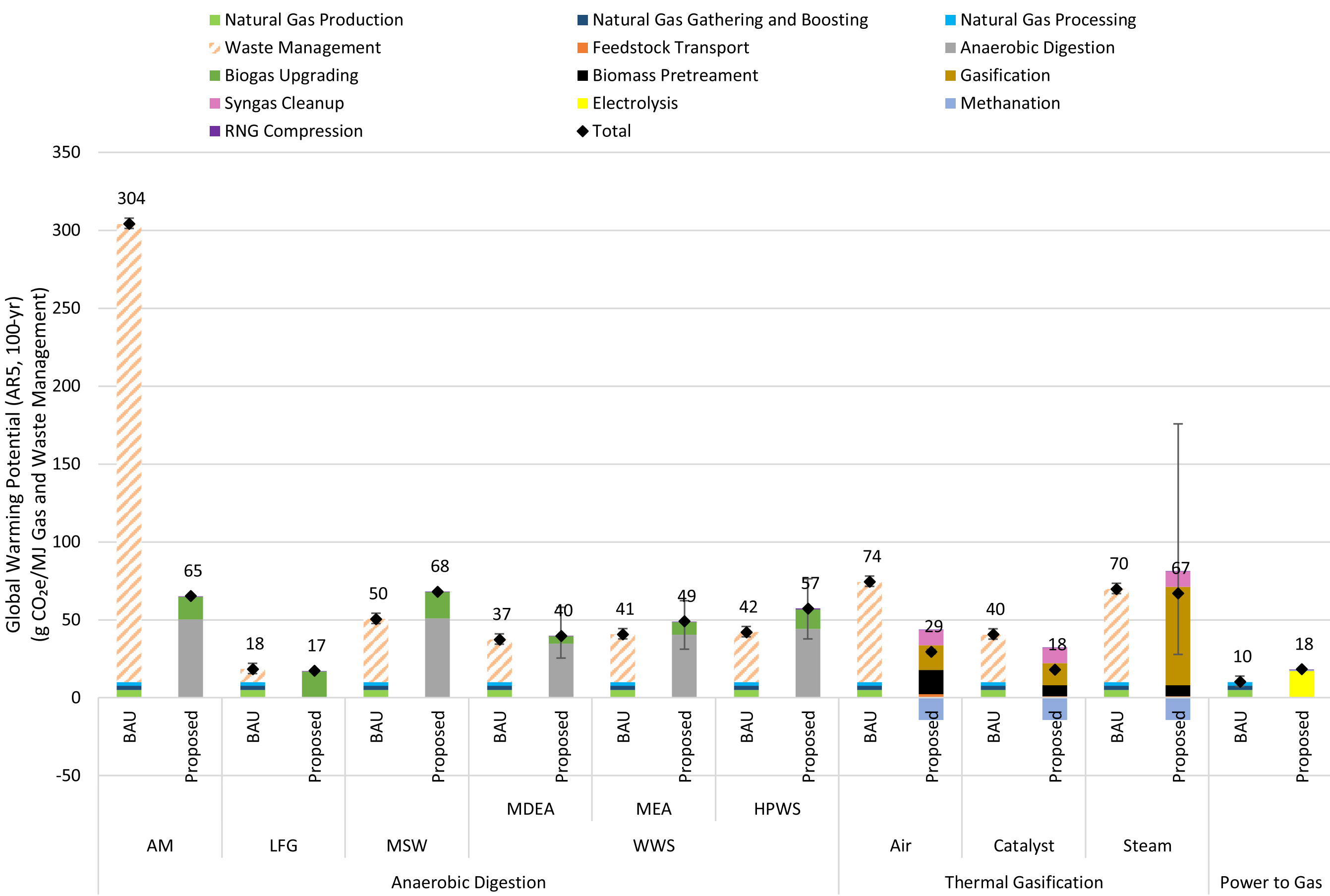


Figure 5. BAU and RNG cases' GWP impacts, when using a parasitic RNG flow to meet internal heat requirements.

lagoon, solid storage, daily spread, or scrape/slurry systems.[25] We use dairy cow- and swine-specific U.S. GHG Inventory emissions data to estimate a GHG emission rate of 0.12 g of CO_2e per g of AM for conventional management of feedstock in the BAU case.

Landfill Gas (LFG), Municipal Solid Waste (MSW), and Wood Wastes. Landfills that emit more than 25 000 metric tons of CO_2e per year are required to report their emission and activity data to the U.S. EPA's Greenhouse Gas Reporting Program (GHGRP). We use this reported data to evaluate an average GHG emission rate of 0.27 g CO_2e/g of landfill waste for the conventional management of these feedstocks in the BAU case.[26] This emission rate is applicable to the LFG, MSW, and wood waste BAU cases since all of these feedstocks would have been conventionally managed in a landfill.

Wastewater Sludge (WWS). The sludge from wastewater treatment plants can either be applied to land, incinerated, or landfilled. In the U.S., 50% of the available sludge is not beneficially utilized, and the remaining 50% is applied to land.[27] For the BAU scenario, we assume sludge to be applied to land and estimate a GHG emission rate of 0.009 g CO_2e/g of untreated liquid sludge.[28]

DATA AND METHODOLOGY

In this work, we use publicly available literature and data sources to model flows and processes. Section S1 and Table S1 show the estimated values of all parameters and their sources.

We construct a process-based life cycle model for the RNG pathways defined in the sections above and compare their GWP impacts to the BAU scenarios for the same unit of feedstock used and energy generated. We used the open source openLCA software for modeling and constructed a unit process for each block of the pathways, as shown in Figures 1−44. We use a 100-year GWP of 1, 36, and 298 for CO_2, CH_4, and N_2O, respectively, as developed by the Intergovernmental Panel on Climate Change (IPCC) in its fifth assessment report (AR5).[29]

In this work, we use data points from various literature sources and model a range of values in openLCA to represent this variability. We use the average value of the literature data as the expected model value for flows that are informed by two data points. For the flows informed by three data points, we assign a triangular probability distribution function and use the central data point as the expected model value, while the two end data points are used to establish the bounds of variability. For flows informed by four or more data points, we again use a triangular approach, where the end data points are used to establish the bounds of variability, while the average of the central points is calculated and used as the expected model value.

We also model two subscenarios for each feedstock and pathway, one where the process of RNG generation uses a parasitic flow of the RNG product to satisfy internal heat requirements and the other where the process of RNG generation uses purchased FNG to meet internal heat requirements. These subscenarios differ not just due to the emission profile of FNG or parasitic RNG flow but also because it changes the feedstock requirement for the production of 1 MJ RNG.

The BAU scenario accounts for a functional unit of 1 MJ of processed FNG before it enters the transmission network and waste management of the same amount of feedstock that is

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

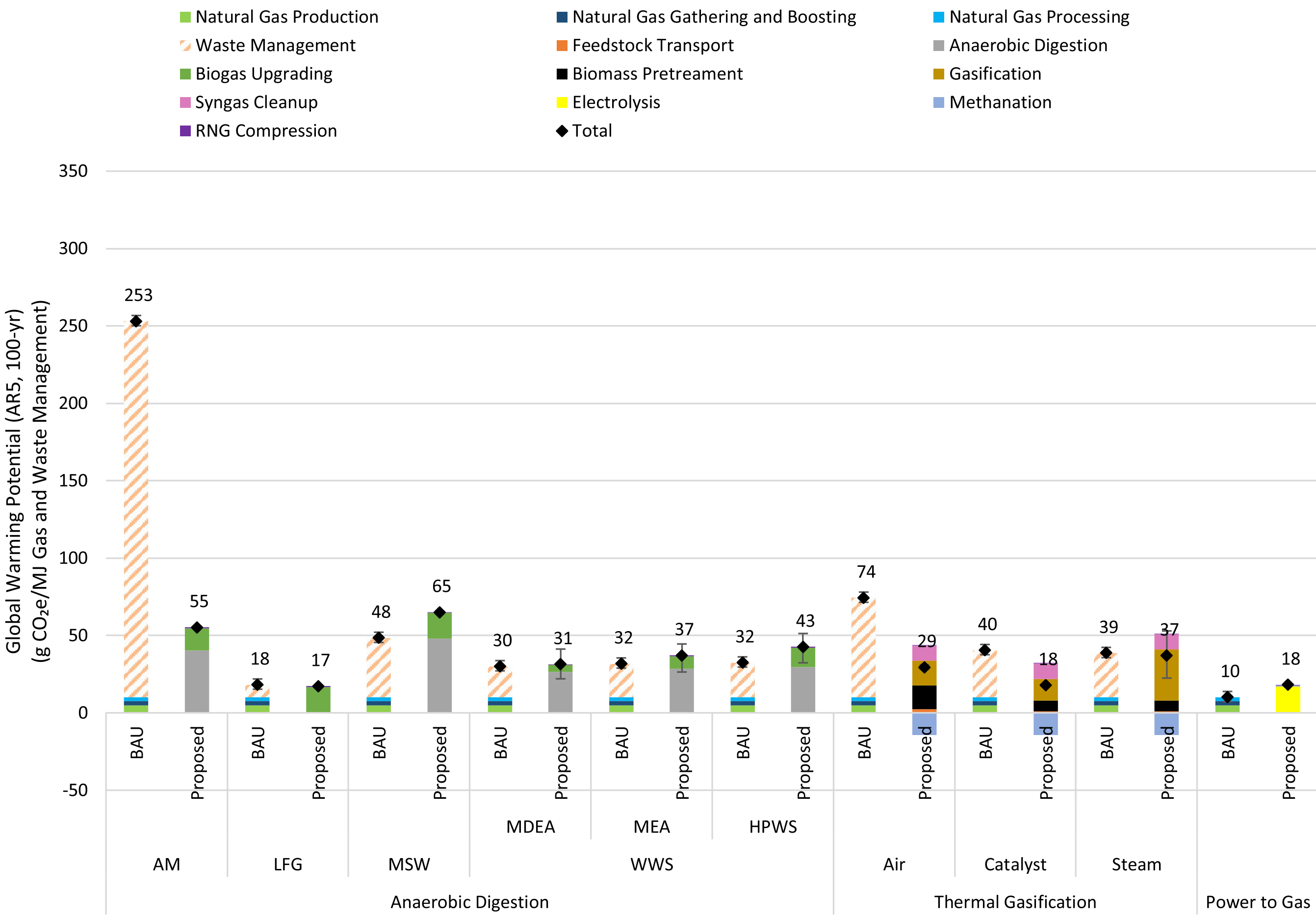


Figure 6. BAU and RNG cases' GWP impacts, when using purchased FNG to meet internal heat requirements.

needed in its corresponding RNG scenario to produce 1 MJ of RNG. The FNG profile is modeled using the NETL life cycle natural gas model[11] and by scaling the results to represent 1 MJ of processed FNG before it enters the transmission network. The data from the sources listed in Table S1 are used to perform an attributional LCA for waste management of the different types of feedstocks. Table S2 lists the amount of feedstock required to generate 1 MJ of RNG for the two subscenarios, one where parasitic RNG is used and the other where purchased FNG is used to supply the internal heat requirements. Note that more feedstock is needed in the parasitic RNG scenarios compared to FNG to account for the RNG that is being used for internal heat purposes. Section S2 also shows the data behind the estimated GWP impacts of conventional waste management of different feedstocks.

■ RESULTS

Our results are expressed in terms of CO_2e per MJ of natural gas ready for pipeline transport and include attributional boundaries that account for the cradle-to-gate burdens of RNG with comparisons to conventional (BAU) natural gas pathways and system expansion boundaries that include displacement of conventional waste management methods.

Attributional LCA of RNG Pathways. The cradle-to-gate GWP impact of various RNG pathways when using a parasitic RNG flow to meet the internal heat requirements was in the range of 17.1−68.1 g CO_2e/MJ compressed RNG compared to 17.2−65.1 g CO_2e/MJ compressed RNG when using purchased FNG. In both cases, the pathway with the smallest impact is LFG, and the pathway with the largest impact is AD of MSW. We can better understand the relative GHG impacts from RNG by comparing them to corresponding BAU scenarios. Figures 5 and 6 show the GWP impact of all of the RNG pathways along with their corresponding BAU scenarios, using parasitic RNG flow and purchased FNG in the RNG cases, respectively (Section S5 shows the numerical data behind these figures). The TG pathway generates excess electricity in the methanation step, which is included in the attributional LCA boundary through system expansion. The error bars in these figures show the variability in the data from the literature that is used to calculate the parameters in the model. However, there is not enough data to understand the variability behind the BAU scenarios; hence, the BAU bars in the figures do not have error bars to represent this variability.

AD of AM is the most beneficial method of generating RNG as compared to its BAU scenario. This is mainly because in BAU scenarios, AM emits a significant amount of CH_4 during traditional management techniques; therefore, capturing this CH_4 to produce RNG reduces the GWP impacts by 79 and 78% for the pathway with parasitic RNG flow and purchased FNG, respectively.

This analysis also shows that not all pathways are beneficial in terms of GHG emissions as compared to BAU. The AD pathway with MSW and WWS as feedstock has a higher GWP impact when these feedstocks are used to generate RNG as compared to BAU. And although the P2G pathway does not have a

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

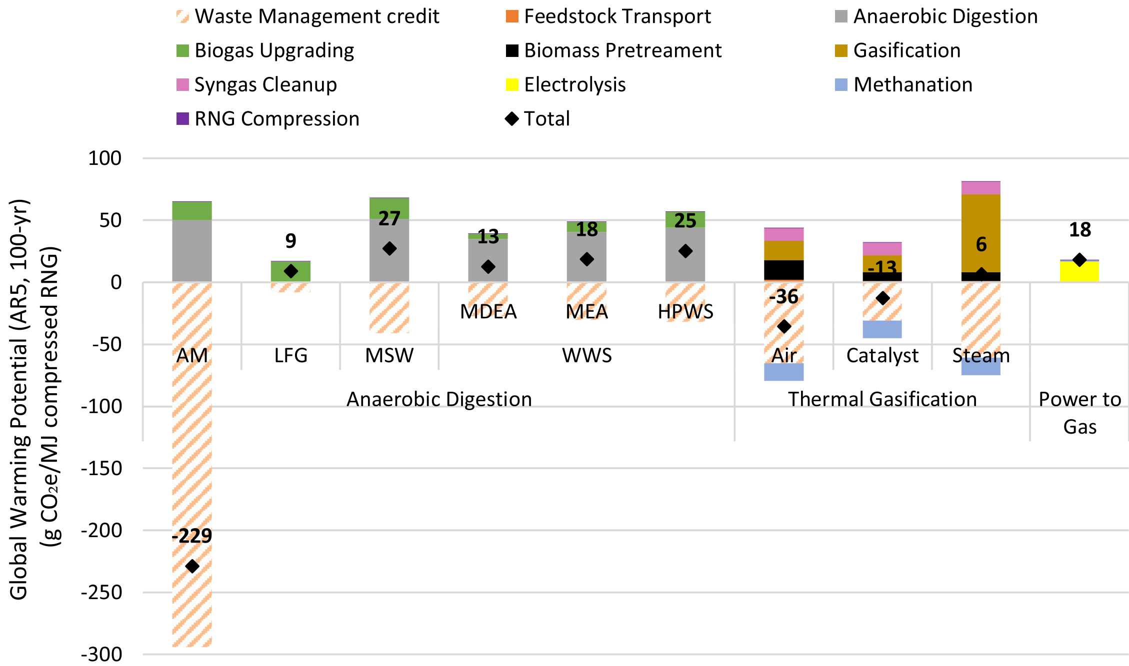


Figure 7. System expansion LCA GWP impacts of all RNG pathways using a parasitic RNG flow to meet internal heat requirements.

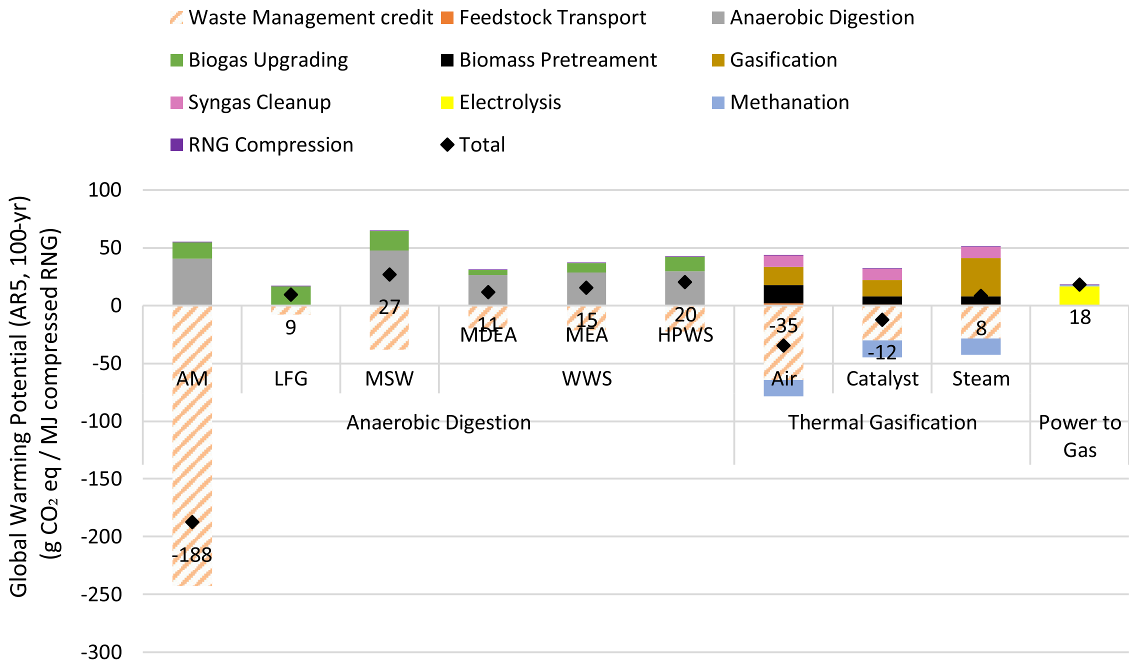


Figure 8. System expansion LCA GWP impacts of all RNG pathways using purchased FNG to meet internal heat requirements.

corresponding waste management scenario since it is only using renewable electricity to generate RNG and not a waste feedstock, it is still more impactful than producing FNG.

Along with understanding the total GWP potential of the scenarios, it is also important that we understand the breakdown of the impacts of various GHGs in the proposed scenarios. The detailed breakdown of the GHGs is shown in Section S4.

System Expansion LCA of RNG Pathways. To evaluate the GHG impacts of the RNG pathways from a system expansion approach, the GWP impact of the waste management in the BAU scenarios is subtracted from the total GWP impact from the corresponding RNG scenario. The impact of 1 MJ of processed FNG is not subtracted in the system expansion approach because the production of RNG does not displace the same unit of FNG directly, although it does displace the unit of waste directly that would otherwise have to be treated and/or managed. Figures 7 and 8 show the results for the system expansion LCA of all of the RNG pathways with parasitic RNG flow and purchased FNG, respectively. AD of AM is the least impactful pathway, with a net GWP impact of −229 and −188 g CO_2e/MJ compressed RNG for scenarios using parasitic RNG flow and purchased FNG, respectively.

In contrast to the attributional perspective, the system expansion perspective has higher impacts for AD of AM, AD of WWS, and TG scenarios using purchased FNG to meet internal heat requirements as compared to the respective

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

scenarios using parasitic RNG. This is because less feedstock is now required to produce RNG, thus reducing the waste management credit for these scenarios.

This study does not include the upstream of the CO_2 source for the P2G scenario. However, if we were to assume that the CO_2 comes from a nearby saline aquifer and use the GWP impact of 14.78 kg CO_2e/kg CO_2 sequestered,[30] then the GWP impact of the P2G pathway would increase by ~5%. This number would vary depending on the source of CO_2.

DISCUSSION

This LCA shows that the process of RNG production in itself is not always carbon neutral or carbon negative. The GWP impact of RNG production is highly dependent on the production pathway and feedstock.

The system expansion approach shows that RNG production via AD of AM and TG of wood wastes via air and catalyst gasification technologies leads to net negative GHG emissions ranging from −229 to −13 g CO_2e/MJ of compressed RNG when using a parasitic RNG flow, as compared to a GWP impact of 10.1 g CO_2e/MJ of compressed FNG (production through processing stages).[11]

The LFG pathway and TG of wood wastes via steam gasification have net positive GHG emissions ranging from 6.2 to 9.0 g CO_2e/MJ of compressed RNG when using a parasitic RNG flow. However, these pathways are still preferable as they have a smaller GWP impact as compared to the 10.1 g CO_2e/MJ impact for compressed FNG.[11] The AD MSW, AD WWS, and P2G pathways have higher GWP impacts than the production of FNG.

The AD of wastewater sludge and animal manure pathway results are comparable to the results from Lee et al.,[10] and the difference between the manure feedstock pathway can be attributed to the difference between the source of manure. This study assumes a 75−25% mix of swine and dairy cow manure, while Lee et al. represent 100% swine manure.

With this paper, we hope to provide a thorough GWP impact analysis for multiple waste-to-RNG pathways that can be utilized by communities to evaluate the best waste management approach based on their waste/feedstock availability and generate a renewable fuel in the process. The attributional results of this analysis were intended to express relative differences between various waste product feedstock systems for producing RNG and should not necessarily be used as an unmodified data source in other LCAs, as additional flows (e.g., biogenic CO_2 emissions) may be needed. The system expansion results may be used directly (i.e., without additional flows), but the LCA practitioner will need to consider whether the BAUs as modeled here also apply to their systems. Investment decisions about particular feedstock pathways for RNG production should also consider techno-economic aspects, which were not considered in this study.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.2c00093.

> Additional modeling parameters, conventional waste management data, equation for RNG compression, speciated emissions for the pathways, and more detailed inventories of life cycle GWP impacts than provided in the manuscript (PDF)

AUTHOR INFORMATION

Corresponding Author

Timothy J. Skone − *National Energy Technology Laboratory, U.S. Department of Energy, Pittsburgh, Pennsylvania 15236, United States*; Email: timothy.skone@netl.doe.gov

Authors

Srijana Rai − *National Energy Technology Laboratory Support Contractor, U.S. Department of Energy, Pittsburgh, Pennsylvania 15236, United States*; orcid.org/0000-0003-0546-4237

Danny Hage − *National Energy Technology Laboratory Support Contractor, U.S. Department of Energy, Pittsburgh, Pennsylvania 15236, United States*

James Littlefield − *National Energy Technology Laboratory Support Contractor, U.S. Department of Energy, Pittsburgh, Pennsylvania 15236, United States*

Gabrielle Yanai − *National Energy Technology Laboratory Support Contractor, U.S. Department of Energy, Pittsburgh, Pennsylvania 15236, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.est.2c00093

Author Contributions

The manuscript was written through contributions of all authors. All authors have approved the final version of the manuscript.

Notes

This project was funded by the Department of Energy, National Energy Technology Laboratory, an agency of the United States Government, through a support contract. Neither the United States Government nor any agency thereof, nor any of its employees, nor the support contractor, nor any of their employees, makes any warranty, express or implied, assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof. All images in this paper were created by NETL, unless otherwise noted.

The authors declare no competing financial interest.

S.R. is now an employee of GTI Energy, and J.L. is now an employee of Aramco Americas.

ACKNOWLEDGMENTS

The authors would like to thank Donald J. Remson, Matthew B. Jamieson, H. Scott Matthews, and Michelle Krynock for their overall guidance and review of the draft versions of this paper.

ABBREVIATIONS

AD anaerobic digestion
AM animal manure
ANL Argonne National Laboratory
AR5 fifth assessment report
BAU business-as-usual
CH_4 methane

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589

CO carbon monoxide
CO_2 carbon dioxide
CO_2e carbon dioxide equivalent
DOE Department of Energy
EPA Environmental Protection Agency
FNG fossil natural gas
g gram
GHG greenhouse gas
GHGRP Greenhouse Gas Reporting Program
GREET greenhouse gases, regulated emissions, and energy use in technologies
GTI Gas Technology Institute
GWP global warming potential
H_2 hydrogen
H_2O water vapor
HPWS high-pressure water scrubbing
IPCC Intergovernmental Panel on Climate Change
kg kilogram
LCA life cycle assessment
LFG landfill gas
LNG liquefied natural gas
MDEA methyldiethanolamine
MEA monoethanolamine
MJ megajoule
MMT million metric tons
MSW municipal solid waste
N_2 nitrogen
NETL National Energy Technology Laboratory
P2G power-to-gas
psig per square inch gauge
RNG renewable natural gas
TG thermal gasification

REFERENCES

(1) American Gas Foundation. Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment, 2019. https://gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf (accessed December 15, 2020).

(2) Fendt, S.; Buttler, A.; Gaderer, M.; Spliethoff, H. Comparison of synthetic natural gas production pathways for the storage of renewable energy. *WIREs Energy Environ.* **2016**, *5*, 327−350.

(3) Di Salvo, M.; Wei, M. Synthesis of natural gas from thermochemical and power-to-gas pathways for industrial sector decarbonization in California. *Energy* **2019**, *182*, 1250−1264.

(4) Li, H.; Jin, C.; Zhang, Z.; O'Hara, I.; Mundree, S. Environmental and economic life cycle assessment of energy recovery from sewage sludge through different anaerobic digestion pathways. *Energy* **2017**, *126*, 649−657.

(5) Lee, U.; Han, J.; Demirtas, M. U.; Wang, M. Lifecycle Analysis of Renewable Natural Gas and Hydrocarbons Fuels from Wastewater Treatment Plants' Sludge, 2016. https://greet.es.anl.gov/publication-sludge-2016 (accessed December 15, 2020).

(6) Mills, N.; Pearce, P.; Farrow, J.; Thorpe, R. B.; Kirkby, N. F. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. *Waste Manage.* **2014**, *34*, 185−195.

(7) Patterson, T.; Esteves, S.; Dinsdale, R.; Guwy, A.; Maddy, J. Life cycle assessment of biohydrogen and biomethane production and utilisation as a vehicle fuel. *Bioresour. Technol.* **2013**, *131*, 235−245.

(8) Walker, S. B.; Sun, D.; Kidon, D.; Siddiqui, A.; Kuner, A.; Fowler, M.; Simakov, D. S. A. Upgrading biogas produced at diary farms into renewable natural gas by methanation. *Int. J. Energy Res.* **2018**, *42*, 1714−1728.

(9) Walker, S. B.; Lanen, D. V.; Mukherjee, U.; Fowler, M. Greenhouse gas emissions reductions from applications of Power-to-Gas in power generation. *Sustainable Energy Technol. Assess.* **2017**, *20*, 25−32.

(10) Lee, U.; Bhatt, A.; Hawkins, T. R.; Tao, L.; Benavides, P. T.; Wang, M. Life cycle analysis of renewable natural gas and lactic acid production from waste feedstocks. *J. Cleaner Prod.* **2021**, *311*, No. 127653.

(11) Littlefield, J.; Roman-White, S.; Augustine, D.; Pegallapati, A.; Zaimes, G. G.; Rai, S.; Cooney, G.; Skone, T. J. *Life Cycle Analysis of Natural Gas Extraction and Power Generation*; National Energy Technology Laboratory, 2020.

(12) Rai, S.; Littlefield, J.; Roman-White, S.; Zaimes, G. G.; Cooney, G.; Skone, T. J. *Industry Partnerships & Their Role in Reducing Natural Gas Supply Chain Greenhouse Gas Emissions − Phase 2.*; U.S. Department of Energy, National Energy Technology Laboratory, 2021.

(13) U.S. Environmental Protection Agency. Basic Information about Anaerobic Digestion (AD) [Overviews and Factsheets], 2015. https://www.epa.gov/anaerobic-digestion/basic-information-about-anaerobic-digestion-ad (accessed December 15, 2020).

(14) Mintz, M.; Voss, P. *Database of Renewable Natural Gas (RNG) Projects: 2019 Update*; Argonne National Laboratory (ANL), 2019.

(15) ANL. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model, 2020. https://greet.es.anl.gov/ (accessed December 15, 2020).

(16) Greene, P. Basics of Biogas Upgrading, 2018. https://www.biocycle.net/basics-biogas-upgrading/ (accessed December 15, 2020).

(17) Bauer, F.; Persson, T.; Hulteberg, C.; Tamm, D. Biogas upgrading − technology overview, comparison and perspectives for the future. *Biofuels, Bioprod. Biorefin.* **2013**, *7*, 499−511.

(18) Petersson, A.; Wellinger, A. *Biogas Upgrading Technologies − Developments and Innovations*; International Energy Agency, 2020.

(19) Starr, K.; Gabarrell, X.; Villalba, G.; Talens, L.; Lombardi, L. Life cycle assessment of biogas upgrading technologies. *Waste Manage.* **2012**, *32*, 991−999.

(20) Gamba, S.; Pellegrini, L.; Lange, S. Energy Analysis of Different Municipal Sewage Sludge-Derived Biogas Upgrading Techniques. *Chem. Eng. Trans.* **2014**, *37*, 829−834.

(21) GTI. Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes, 2019. https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf (accessed December 15, 2020).

(22) Doherty, W.; Reynolds, A.; Kennedy, D. Aspen Plus Simulation of Biomass Gasification in a Steam Blown Dual Fluidised Bed. In *Materials and Processes for Energy: Communicating Current Research and Technological Developments*, Méndez-Vilas, A., Ed.; Formatex Research Centre, 2013.

(23) *An Overview of Renewable Natural Gas from Biogas*; U.S. Environmental Protection Agency, 2020.

(24) *NETL Life Cycle Inventory Data − Unit Process: Compressor, Single-Stage Reciprocating, Operation*; U.S. Department of Energy, National Energy Technology Laboratory, 2012.

(25) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990−2018, Annex 3.11*; U.S. Environmental Protection Agency, 2020.

(26) *Greenhouse Gas Reporting Program (GHGRP) Envirofacts − Subpart HH: Municipal Solid Waste Landfills [Data & Tools]*; U.S. Environmental Protection Agency, 2017.

(27) Seiple, T. E.; Coleman, A. M.; Skaggs, R. L. Municipal wastewater sludge as a sustainable bioresource in the United States. *J. Environ. Manage.* **2017**, *197*, 673−680. England

(28) Pradel, M.; Reverdy, A. L. Assessing GHG Emissions From Sludge Treatment and Disposal Routes: The Method Behind GESTABoues Tool. ORBIT2012, Global Assessment for Organic Resources and Waste Management, 2012. https://hal.archives-ouvertes.fr/hal-00781673/document (accessed December 15, 2020).

(29) *Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, United Kingdom, 2013.

(30) *Gate-to-Grave Life Cycle Analysis Model of Saline Aquifer Sequestration of Carbon Dioxide*; U.S. Department of Energy. National Energy Technology Laboratory, 2013.

https://doi.org/10.1021/acs.est.2c00093
Environ. Sci. Technol. 2022, 56, 8581−8589