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Biogas Utilization in North Carolina: Opportunities and Impact Analysis

Report

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Contents

Figures

Number **Page**

Tables

Number **Page**

Acronyms and Abbreviations

$ or USD	U.S. dollar
$/mi	U.S. dollar per mile
$/y	U.S. dollars per year
ABC	American Biogas Council
AD	anaerobic digester
ANL	Argonne National Laboratory
bcf	billion cubic feet
bcf/y	billion cubic feet per year
Bgal/y	billion gallons per year
BIL	Bipartisan Infrastructure Law
bio-CNG	compressed biomethane
bio-electricity	electricity generated from biogas
BOE/y	barrels of oil equivalent per year
Btu	British thermal unit
Btu/GGE	British thermal units per gallon of gas equivalent
Btu/scf	British thermal units per standard cubic foot
CAFO	concentrated animal feeding operation
CAPEX	capital expenditure
CARB	California Air Resources Board
CEO	Chief Executive Officer
CH_4	methane
CHP	combined heat and power
CI	carbon intensity
CNG	compressed natural gas
CO_2	carbon dioxide
CPUC	California Public Utilities Commission
DA	day-ahead
DOE	U.S. Department of Energy
EBITDA	earnings before interest, taxes, depreciation, and amortization
ECU	East Carolina University
EIA	U.S. Energy Information Administration
EJ	Environmental Justice
EO	Executive Order
EPA	U.S. Environmental Protection Agency

EPC	Energy Policy Council
ER	emissions reduction
ft^3	cubic foot or feet
ft^3/d	cubic feet per day
ft^3/min	cubic feet per minute
ft^3/ton	cubic feet per ton
ft^3/y	cubic feet per year
g/mol	grams per mole
gal	gallon
gal/d	gallons per day
gCO_2e/MJ	grams of carbon dioxide equivalent per megajoule
GDP	gross domestic product
GED	general educational development
GGE	gallon of gasoline equivalent
GHG	greenhouse gas
GIS	geographic information systems
GMI	Global Methane Initiative
GWh/y	gigawatt hours per year
GWP	global warming potential of methane
IMPLAN	Impact Analysis for Planning
IRA	Inflation Reduction Act
KBFS	knockout pot, blower, and flare system
kg/m^3	kilograms per cubic meter
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
kWh/ft^3	kilowatt-hours per cubic foot
L/d	liters per day
L/kg	liters per kilogram
lb_c	pounds of carbon dioxide
lb_d	pounds of diesel
lb/d	pounds per day
lb/scf	pounds per standard cubic foot
lb/ton	pounds per short ton
LCFS	Low Carbon Fuel Standard
LCOE	levelized cost of energy

LF	landfill
LFG	landfill gas
LFMT	landfill microturbine
LFRE	landfill reciprocating engine
LFSE	landfill small reciprocating engine
LFTB	landfill combustion turbine
LMOP	Landfill Methane Outreach Program
m^3	cubic meter
m^3/d	cubic meter per day
m^3/gal	cubic meters per gallon
MACRS	Modified Accelerated Cost Recovery System
mi	mile
min	minute
mm	millimeter
MMBtu	million British thermal units
MMBtu/d	million British thermal units per day
MMBtu/y	million British thermal units per year
MMscfd	million standard cubic feet per day
$MMtCO_2e$	million metric tons of carbon dioxide equivalents
$MMtCO_2e$/y	million metric tons of carbon dioxide equivalents per year
MPa	megapascal
MSC	marginal supply curve
MT	microturbine
$MtCO_2e$	metric tons of carbon dioxide equivalents
$MtCO_2e$/y	metric tons of carbon dioxide equivalents per year
MW	megawatt
MWh	megawatt-hour
N_2	nitrogen
NCDEQ	North Carolina Department of Environmental Quality
NCDOR	North Carolina Department of Revenue
NCUC	North Carolina Utilities Commission
NG	natural gas
NIMBY	not in my back yard
NMAE	normalized mean absolute error
NPS	nominal pipe size
NPV	net present value

NREL	National Renewable Energy Laboratory
O_2	oxygen
ODM	organic dry matter
OPEX	operating expenditure
PADCED	Pennsylvania Department of Community and Economic Development
PADD	Petroleum Administration Defense District
PADEP	Pennsylvania Department of Environmental Protection
Pa-s	pascal-second
PP	purchase price
PURPA	Public Utility Regulatory Policies Act of 1978
QR	quick response
R^2	R squared
RE	reciprocating engine
REACH	Rural Empowerment Association for Community Help
REPS	Renewable Energy and Energy Efficiency Portfolio Standard
RFS	Renewable Fuel Standard
RIN	renewable identification number
RNG	renewable natural gas (biomethane)
RNG Coalition	The Coalition for Renewable Natural Gas
RPS	Renewable Portfolio Standard
scf	standard cubic foot
scf/d	standard cubic feet per day
scf/L	standard cubic feet per liter
scf/y	standard cubic feet per year
SF	swine farm
SFPN	swine farm physical network
SFVP	swine farm virtual pipeline
SFVP2X	swine farm virtual pipeline 2X case
SFVPBC	swine farm virtual pipeline base case
Tbtu	trillion British thermal units
Tbtu/y	trillion British thermal units per year
ton/scf	tons per standard cubic foot
USDA	U.S. Department of Agriculture
WWTP	wastewater treatment plant
WWTP1	WWTP assumed to have no pre-existing AD or flare system
WWTP2	WWTP assumed to have a pre-existing AD and flare system

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Executive Summary

As North Carolina strives to meet rapidly approaching greenhouse gas (GHG) emissions reduction targets, government officials are looking with increased urgency at developing in-state renewable energy or clean energy resources. In 2019, North Carolina Governor Roy Cooper issued Executive Order 80, which created ambitious GHG reduction goals and called for the creation of a Clean Energy Plan to put the state's energy use on a path to carbon neutrality. An additional aim of the Clean Energy Plan is to "… accelerate clean energy innovation, development, and deployment to create economic opportunities for both rural and urban areas of the state."[1] Governor Cooper's decarbonization goals were codified more recently in House Bill 951 (North Carolina General Assembly, 2021), which instructed the North Carolina Utilities Commission to "… take all reasonable steps" to achieve those goals.[2]

Biogas represents a significant, yet historically underutilized, renewable energy opportunity distinctively available to North Carolina. In fact, the state ranks third in the nation in terms of biogas potential, largely owing to its agricultural waste resources. Biogas consists of approximately 60% methane (CH_4) and 40% carbon dioxide (CO_2) as its primary components, both of which are released when organic material breaks down in oxygen-free or anaerobic environments. Biogas can be slightly upgraded by drying, and then fed into a microturbine or generator to generate electricity. Biogas can also be purified to create a nearly pure stream of CH_4 called renewable natural gas (RNG [i.e., biomethane]), which can be used in all of the ways in which natural gas can.

Because of the degradation of organic waste feedstocks, such as animal manure, wastewater treatment plants (WWTPs), and landfills, which produce biogas, harnessing organic waste to capture creates a pathway by which these fugitive CH_4 emissions can be turned into an energy resource. Harnessing biogas not only reduces fugitive CH_4 emissions generated by organic waste but could also offset GHG emissions from any fossil fuel it displaces.

Environmentally responsible use of the state's organic waste resources could create economic opportunities for North Carolina, particularly for rural areas where most of the state's agricultural organic waste resources are concentrated. In addition, depending on how biogas projects are implemented, biogas development could provide important benefits beyond climate and economic solutions, such as social, public health, and community benefits.

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1 For more information about the North Carolina Clean Energy Plan, see https://files.nc.gov/ncdeq/climate-change/clean-energy-plan/NC_Clean_Energy_Plan_OCT_2019_.pdf

2 For more information, see the Energy Solutions for North Carolina Act of 2015, S.L. 2021-165, § 1.

This report responds to recommendations made by the North Carolina Energy Policy Council (EPC) in 2018 to promote and develop the state's bioenergy resources and deployment.[3] The report is also expected to serve as a resource for the North Carolina Department of Environmental Quality's (NCDEQ's) efforts to incorporate biogas into the state's Clean Energy Plan.

This report represents the second phase (henceforth referred to as Phase II) of a two-phase effort funded by Duke Energy through North Carolina's Renewable Energy and Energy Efficiency Portfolio Standard (REPS) research funding and responds to the EPC's recommendations. This report also considers larger questions regarding the development of a biogas deployment strategy for North Carolina.

During Phase I, the team developed a detailed inventory of the biogas potential from several feedstock types available in the state including livestock waste, WWTPs, industrial food waste, landfill gas (LFG), and agricultural crop residue. All these feedstock types were assumed to be processed via anaerobic digestion.

The Phase I analysis focused on opportunities to develop and monetize swine manure as a biogas feedstock in North Carolina. Not only is swine manure the feedstock with the greatest biogas potential, but it is also geographically concentrated (arguably making it easier to aggregate and use) and has a very low carbon intensity. As part of the Phase I analysis, the team created a cost model to determine the costs for a variety of end uses of biogas developed from swine waste. From there, they developed a geospatial optimization tool which incorporates the cost models to form biogas feedstock clusters, thus minimizing RNG production costs.

Because the ultimate end use is dictated by external drivers, such as markets and policies at the federal and state level, the Phase I report (Parvathikar et al., 2021) discussed the costs of production in relation to information about markets available at the time when the report was written. Lastly, the Phase I report addressed associated environmental, economic, and community impacts and issues, as well as possible steps to overcome related barriers.[4]

The Phase II analysis extends to and expands upon technological options for the remainder of the state's biogas feedstock types, including LFG, WWTPs, dairy manure, crop residues, and poultry litter. Phase II is augmented by stakeholder outreach and evaluation of policy options to address what the state's objectives for the captured emissions should be, and the physical, economic, and political challenges to potential objectives.

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[3] Although the term "bioenergy" includes all energy derived from organic materials, regardless of production method or feedstock, in the EPC's recommendations in NCDEQ's *Energy Policy Council 2018 Biennial Report* (NCDEQ, 2018), bioenergy was discussed interchangeably with biogas and has been interpreted to refer only to North Carolina's biogas resources. Thus, this analysis focuses only on biogas, which is derived from the AD of organic materials, including but not limited to a variety of organic waste materials.

[4] These models are being independently published in peer-reviewed journals.

Regarding North Carolina's total saleable biogas potential, the results of the Phase II analysis were used to determine the following:

1. Based on calculated levelized costs of energy (LCOEs), approximately one quarter of the estimated total biogas potential from the sources analyzed can be used to produce saleable energy.
2. Despite recent analyses focusing on biogas-generated electricity (bio-electricity), the most cost-competitive pathway for biogas is for compressed biomethane (bio-CNG) projects collecting biogas at rates greater than or equal to 100 million British thermal units per day (MMBtu/d).

The key findings for consideration by North Carolina lawmakers include the following:

1. In a least-cost scenario, the construction of infrastructure for the biogas industry in North Carolina requires an estimated one-time capital investment of $318.2 million. The construction will result in a projected $295.4 million of added value as well as $17.3 million in state and local tax revenues. The annual operating cost under this scenario is expected to be $37.5 million, which will generate an estimated $29.0 million per year in added value to North Carolina's economy and will produce approximately $3.1 million in state and local tax revenues for every year of operation.

2. Federal- and state-level incentives could allow bio-CNG projects with collection rates as low as 45 MMBtu/d to become economically viable.

3. North Carolina policymakers could make use of the current focus and incentives, particularly at the federal level, for efforts to reduce CH_4 from any source.

    a. Existing projects demonstrate the feasibility of RNG production from LFG. Policymakers could consider more stringent policies for existing landfills, as well as stricter permit issuing in the future to harness the RNG potential of this source.

    b. Stringent environmental protections coupled with financial incentives for building and upgrading WWTP facilities could be considered as a means of protecting public health and harnessing the potential of biogas.

    c. Support from policymakers to capture and utilize biogas from livestock and agricultural production could help with developing relevant technology and achieving economic feasibility.

4. Most biogas sources are located among underserved communities. The voices of these communities and their concerns should be considered alongside the economic and climate impacts of any proposed project.

   a. Many community stakeholders are open to biogas technologies but are distrustful of industry to properly protect their interests and minimize harm.

   b. Community involvement in biogas projects ranging from education to partnerships could help lower barriers to success.

   c. Lawmakers should consult the NCDEQ's Environmental Justice Program and the U.S. Environmental Protection Agency (EPA) for guidance and considerations.

To properly incorporate stakeholder perspectives, the team suggests that North Carolina policymakers convene a commission or body to address the associated political, environmental, economic, technical, and equity concerns. One such approach could entail the establishment of something akin to a Biogas Development Commission. Members of the Commission should represent all major stakeholders and should explore options for end-use, including local treatment and mitigation, local production of heat and/or electricity, and for pipeline injection (either for electricity or as a transportation fuel), and any additional measures that will allow all organic waste categories to be addressed in a manner acceptable to all stakeholders.

The views and opinions expressed in this document belong to the authors of this report, and do not reflect the view, opinions, or legal positions of Duke Energy.

1. Introduction

According to the National Renewable Energy Laboratory (NREL), the state of North Carolina ranks third in the nation for biogas production potential (NREL, 2013). The American Biogas Council (ABC) estimates North Carolina's total annual biogas potential at 96.87 billion cubic feet (bcf), which ABC contends could yield up to 62 bcf of renewable natural gas (RNG [i.e., biomethane]) for energy, fuel, heat, and other uses (ABC, 2020). The findings from the present analysis confirm this volume.

Acknowledging the state's bioenergy potential (which, for the purposes of this report and underlying analysis, includes only biogas), the North Carolina Energy Policy Council (EPC)[5] sought in 2018 to establish an accurate inventory of the state's biogas resources. In addition, the EPC made other recommendations designed to promote and develop North Carolina's bioenergy resources and deployment. The list of actions recommended by the EPC included the following:

1. Developing a bioenergy resource inventory and economic impact analysis, establishing goals for the capture and refining of biogas into RNG for distribution, and developing goals for incorporating biogas-derived natural gas into North Carolina's transportation fuels program for the state's vehicle fleets and public transportation
2. Conducting an economic impact analysis, including analyses of environmental and community benefits and impacts, for the beneficial and optimum utilization of the state's bioenergy resources
3. Creating a bioenergy resource inventory for North Carolina based on input from industry, regulatory, and academic sources that are current and specific to the state
4. Completing and summarizing the results of this work in the *EPC 2020 Biennial Report* (NCDEQ, 2020).

In response to the EPC's list of recommendations, the Phase I report (Parvathikar et al., 2021) discussed the following items:

1. An inventory of the state's total biogas potential by feedstock
2. An estimate of the actual potential of the state's swine biogas resources, which represent the state's largest and most concentrated biogas feedstock

[5] In the *EPC 2018 Biennial Report* (NCDEQ, 2018), the point was made that policies that propelled the success of solar power generation in North Carolina may similarly advance bioenergy opportunities for our state. However, such a comparison has not yet been formally accomplished, nor have any such lessons learned been incorporated in prior State Energy Plans. In establishing the Renewable Energy and Energy Efficiency Portfolio Standard (REPS), the state set goals and requirements for the provision of renewable electricity, inclusive specifically of bioenergy resources, such as swine manure and poultry manure. However, no such goals have been established for the development of RNG from bioenergy resources. As noted in the *EPC 2018 Biennial Report*, "Although there are few other energy resources in North Carolina with this level of potential and comparative advantage to other states, North Carolina lacks a comprehensive and implementable plan by which to pursue biogas development."

3. A tool to optimize the cost of RNG production from swine waste and identify specific farms and farm networks that would result in the lowest cost of production
4. An estimate of the economic impact of swine biogas development on farm networks with the highest swine biogas feedstock potential
5. A description of the potential environmental and community benefits and impacts related to swine biogas development, including community perspectives
6. Suggestions for addressing barriers to biogas development.

The results of the Phase I analysis confirm that North Carolina has tremendous biogas potential of approximately 97 billion cubic feet per year (bcf/y), equivalent to 58 trillion British thermal units per year (TBtu/y). As discussed in the Phase I report, swine waste is the largest contributing feedstock, comprising approximately 29% of the state's biogas potential. Landfill gas (LFG) is also attractive in the near-term because landfills provide some of the largest single-source opportunities. Overall, the Phase I analysis found that biogas potential is concentrated in eastern North Carolina, particularly in counties with the highest pork production, which warrants a deeper analysis of the opportunities, options, and impacts of biogas capture from swine waste.

Addressing the challenges facing the development of the biogas industry requires a multi-pronged approach that encompasses technical, policy, and community engagement solutions. To be responsive to recommendations identified by the *EPC 2020 Biennial Report* (NCDEQ, 2020), the following topics are the focus of the Phase II analysis:

1. **Technoeconomic Assessment of Major Biogas Sources in North Carolina**—This section discusses the practical biogas potential that can be derived from a variety of feedstocks in North Carolina, including the methodology for the geospatial analysis that identifies feedstock locations with the potential to be integrated into an RNG or bio-CNG network. This analysis expands upon the one conducted during Phase I by including feedstock types in North Carolina other than swine waste, such as LFG, wastewater treatment plants (WWTPs), industrial food waste, crop residues, and poultry litter. Furthermore, the updated model places constraints on injection locations to generate a more realistic network scenario. The result is a comprehensive plan detailing North Carolina's realistic biogas-to-RNG or bio-CNG production potential by using networked hubs that can drive economies of scale and reduce network levelized costs of energy (LCOEs).[6]
2. **Economic Impact Analysis**—The economic impact analysis estimates the potential economic contributions that would be provided to the state of North Carolina as a result of the developing biogas industry.
3. **Policy Landscape Analysis**—This section outlines current policies and regulations at both the state and federal levels that benefit the production, development, and application of biogas

[6] Note that this report can only offer recommendations related to the extent of RNG development that the state might reasonably expect for biogas from North Carolina feedstocks based on current technology and market conditions in the absence of any further incentives or policy support. These recommendations could assist stakeholders with establishing goals for electricity and/or RNG production from biogas, including the use of renewable compressed natural gas as transportation fuel to power the state's vehicle fleets.

infrastructure. The analysis provides recommendations and identifies crucial considerations for North Carolina lawmakers as the state seeks to utilize its potential biogas resources.

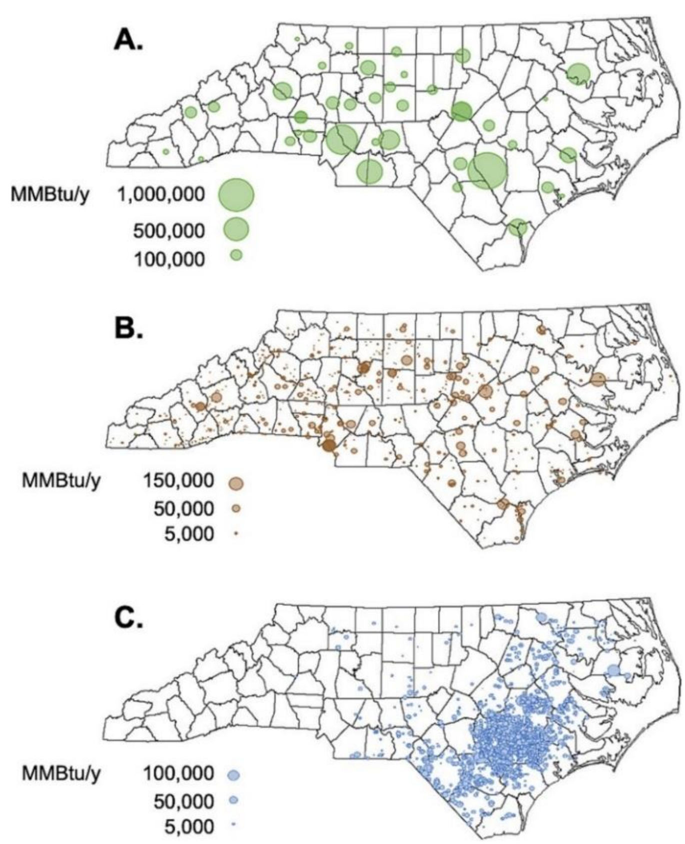
4. **Community Stakeholder Assessment**—The stakeholder engagement assessment discusses the views of different community stakeholders in eastern North Carolina regarding biogas infrastructure development and the perceived impact on the community. The assessment aims to maximize socioeconomic benefits while supporting biogas development in North Carolina.

2. Technoeconomic Assessment of Major Biogas Sources in North Carolina

This technoeconomic assessment aims to update existing costs estimates for biogas-to-energy projects using the currently available biogas feedstocks in North Carolina. The model explored options to produce each of the following forms of energy: RNG, bio-CNG, and biogas-generated electricity (bio-electricity). These new estimates were then benchmarked against current prices for natural gas, compressed natural gas (CNG), and electricity in regional markets across the United States.[7]

The cost to produce energy from biogas depends on factors such as the type and amount of organic waste as well as the technology needed to collect, process, and convert raw biogas into one of the three forms of energy being considered. To account for these factors, we estimated biogas-to-energy project costs at 11 landfills, 784 WWTPs, and 2,042 swine farms in North Carolina (**Figure 1**).

Figure 1. Locations of the Analyzed Feedstock Sources. (A) Landfills, (B) WWTPs, and (C) Swine Farms. *



* Dots marking locations are sized according to each facility's annual biogas production. Sizing is uniform across all three maps. Note that whereas landfills and WWTPs are distributed across North Carolina, most swine farms are concentrated in the eastern portion of the state.

Notes: MMBtu/y = million British thermal units per year; 1 million British thermal units (MMBtu) ≈ 1 gigajoule.

[7] This section has been published independently in a peer-reviewed journal. To access the full paper including supplemental information, visit https://www.sciencedirect.com/science/article/pii/S2213138823005507.

The three types of sites analyzed are the largest biogas point-sources in North Carolina, with biogas potentials ranging from as low as 13 cubic meters per day (m^3/d) to almost 400,000 m^3/d (Parvathikar et al., 2021). Additionally, the concentration of swine farms in the eastern portion of North Carolina (**Figure 1C**) allows us to explore the feasibility of achieving economies of scale by potentially networking the biogas output of multiple farms, either by pipeline or by using tanker trucks.

Previous assessments of biogas potential in the United States have gauged the viability of various technologies including the anaerobic digestion of food waste (Shen et al., 2015), biogas production and utilization at WWTPs (Dalke et al., 2021), the role that recent federal policy could play in increasing electricity generation from livestock farms (Erickson et al., 2023), and the national waste-to-energy potential (Murray et al., 2014; NREL, 2013; Skaggs et al., 2018). Of these, our analysis is most like that of Murray et al. (2014), who modeled aggregate marginal supply curves (MSCs) of RNG and bio-electricity production for the entire United States based on the biogas potential of the same organic waste sources that we consider here, along with livestock and crop waste.

Although our technoeconomic analysis involves a smaller, more geographically limited set of biogas sources, we updated and expanded upon the work of Murray et al. (2014) by using the range in type and scale of prospective biogas projects in North Carolina as a proxy for assessing the production potential and economic competitiveness of similar projects elsewhere in the US. We carried out this assessment in two ways. The first way was to assemble MSCs as a function of LCOE for producing bio-electricity, bio-CNG, and RNG in North Carolina and evaluate the MSCs in the context of the state's consumption of and prices for electricity, CNG, and natural gas. The findings from the comparison suggest that the amount of energy that technically could be produced from biogas sources for commercial sale in the United States is likely smaller and more costly than previous estimates.

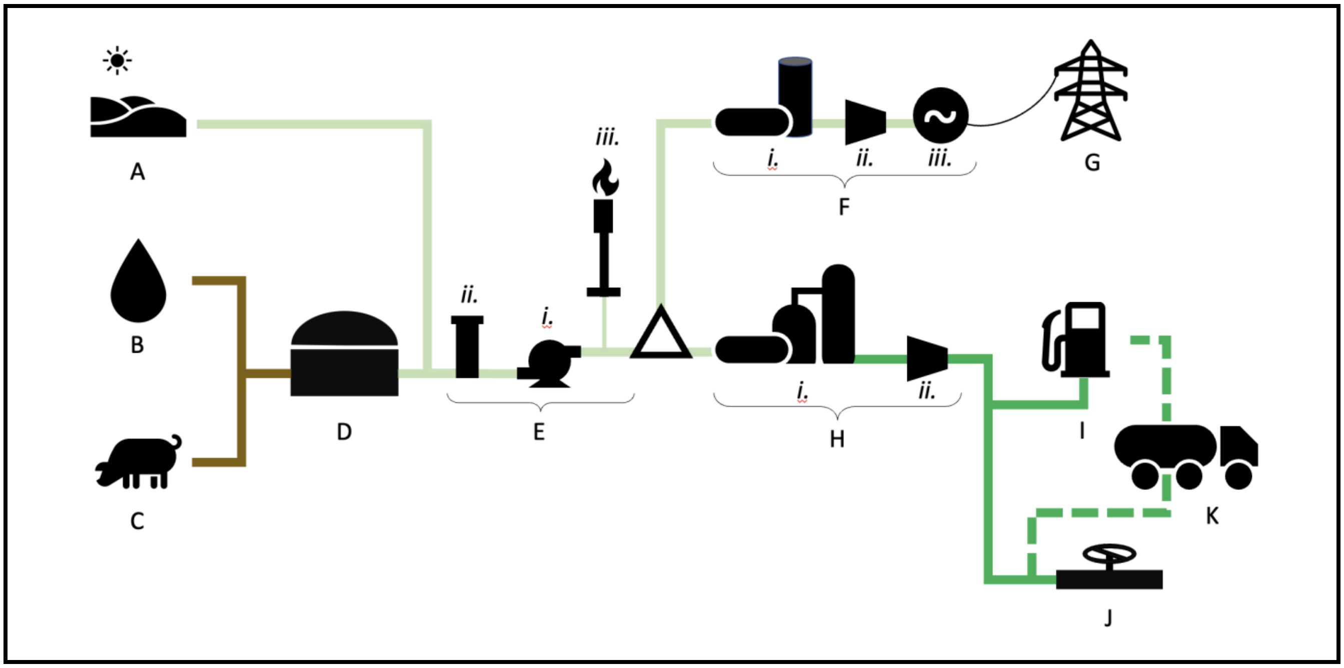
We then plotted our LCOEs estimates for individual bio-electricity, bio-CNG, and RNG projects as a function of the collectable biogas amounts and compare the LCOEs with recent prices for electricity, CNG, and natural gas in regional markets across the U.S. (e.g., New England, the Gulf Coast, the West Coast). The results of our comparison show that the greatest market potential for bio-CNG and RNG is as transportation fuel, a market that was just being established at the time of the study by Murray et al. (2014), and thus one they did not assess.

2.1 Methods and Data

2.1.1 Systems Overview

At landfills (**Figure 2A**), biogas is collected using wells that feed into gathering pipelines. At WWTPs (**Figure 2B**) and swine farms (**Figure 2C**), collection is accomplished using anaerobic digesters (ADs) (**Figure 2D**). We assumed that the ADs at WWTPs are one or more mixed digester tanks, while those at swine farms are covered, in-ground lagoons into which the swine waste is washed.

Figure 2. A Schematic of Biogas Collection and Energy Production Systems Analyzed in the Technoeconomic Assessment.



Notes:

Biogas Sources: A = landfill; B = wastewater; and C = swine farms.

Collection and primary processing system: D = anaerobic digester; E.i = blower; E.ii = knockout pot; and E.iii = flare stack.

Bio-electricity production system: F.i = secondary processing to remove water vapor, sulfur, and/or siloxane; F.ii = compressor; F.iii = electric generator; and G = electric grid.

Bio-CNG and RNG production system: H.i = advanced processing to also remove carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), and any volatile organic compounds; H.ii = compressor; I = CNG station; J = natural gas pipeline; and K = tanker truck.

At all three sources, a blower (**Figure 2E.i**) is used to convey biogas from the wells or ADs to a preliminary processing site. The biogas arrives mixed with liquid water, which is removed by passing the biogas through a knockout pot (**Figure 2E.ii**). At this point, any biogas that cannot be converted into energy (e.g., because of a system shut down for maintenance) is directed to a flare stack (**Figure 2E.iii**).

After dewatering, further processing of the biogas depends on the form of energy it will be turned into. To generate electricity, secondary processing of the biogas involves chilling to precipitate out any water remaining as vapor and treating to remove sulfur and/or siloxane (**Figure 2F.i**). The gas is then compressed (**Figure 2F.ii**) and pumped into an electric generator that burns the gas as fuel (**Figure 2F.iii**) and feeds the bio-electricity into the grid (**Figure 2G**).

Similarly to bio-electricity generation, converting biogas into CNG or RNG requires secondary processing (i.e., chilling and siloxane/sulfur removal); however, biogas that is being upgraded into either bio-CNG or RNG must undergo additional treatments prior to compression (**Figure 2H.ii**) to remove carbon dioxide (CO_2), nitrogen (N_2), oxygen (O_2), and any volatile organic compounds (**Figure 2H.i**). The compressed gas, which is now pipeline-quality methane (CH_4), is either directly used at a CNG station as a transportation fuel (bio-CNG) (**Figure 2I**) or injected into a natural gas pipeline (RNG) (**Figure 2J**) for sale to another party.

2.1.2 Systems Modeling

Similar to the approach used by Murray et al. (2014), we sized and costed the biogas collection systems for landfills (wells with gathering pipelines), WWTPs (mixing-tank ADs), and swine farms (covered, in-ground ADs) (**Figure 2A–C**, respectively) using empirical functions from other sources. Murray et al. (2014) relied on functions that were published by Cooley et al. (2013), ICF International (2013), Krich et al. (2005), and Prasodjo et al. (2013); in contrast, we used functions from more recent modeling tools, reports, and scientific studies. Functions for landfill wells and gathering pipelines are from the LFGcost-Web model (version 3.5), which is a Microsoft Excel spreadsheet tool created in 2023 by the U.S. Environmental Protection Agency (EPA) Landfill Methane Outreach Program (LMOP) (EPA, 2023c). The functions for WWTP ADs are those developed by El Ibrahimi et al. (2021) and Michailos et al. (2020) and El Ibrahimi, et al. (2021). The functions for swine farm ADs are from Parvathikar et al. (2021). For the sake of brevity, all the functions utilized in this assessment are provided in **Appendix A** of this report.

We modeled the remaining steps for transforming the collected wet biogas into bio-electricity (**Figure 2E–G**), bio-CNG (**Figure 2E, H, and I**), or RNG (**Figure 2E, H, and J**) and estimated the direct and avoided CH_4 emissions reductions using empirical functions from the LFGcost-Web model (EPA, 2021). Although the functions were sourced from a model for landfills, they represent components within the other types of biogas-to-energy projects that we analyzed. Again, for the sake of brevity, the functions are provided in **Section A.3.2, Appendix A**. We note that the LFGcost-Web CAPEX and OPEX functions for the different energy conversion technologies are suitable only for specific ranges of biogas production rates.[8] Consequently, we assumed that if the flux of biogas at a prospective project (e.g., a landfill) is outside the specified range of a given technology (e.g., a standard turbine generator), then that technology was not an option for the project.

2.1.3 Additional Modeling for Renewable Natural Gas Systems

In the LFGcost-Web model, RNG project costs were valid only if the prospective project site produced biogas at high rates of 40,750–244,660 m^3/d. Furthermore, the model considered only the case of connecting the single site to a nearby natural gas pipeline using a dedicated RNG pipeline. However, existing RNG projects have been structured in at least two other ways. One approach achieves economies of scale from smaller biogas sources by using a network of pipelines to gather the output and send it to a central RNG processing site. The central site, in turn, is connected by an RNG pipeline to a nearby natural gas pipeline. This method has operated on a small scale in the Optima-KV project, which is a network of five swine farms in Kenansville, NC, that inject approximately 80,000 million British thermal units per year (MMBtu/y) of RNG into an adjacent natural gas pipeline, where it is purchased by the electric utility Duke Energy (Cavanaugh & Associates, P.A., 2023). The other approach involves first converting biogas into CNG. At an onsite fueling station, the CNG is then loaded onto a tanker truck that transports the fuel to an RNG injection site, where it is slightly depressurized and pumped into

[8] The functions include those for sizing and costing four different types of generators: a small reciprocating engine (100 kW–1 MW), a microturbine (30–750 kW), a reciprocating engine (greater than 800 kW), or a turbine (greater than 3 MW).

the line for sale (**Figure 2K**). This type of "virtual pipeline" is being used by Smithfield's Ruckman Farm in Albany, MO, which is also selling its approximately 244,000 MMBtu/y production of RNG to Element Markets (EPA & AgSTAR, May 2023).

To assess these other ways of structuring an RNG project, we developed two additional modeling approaches. The more complex approach simulates the pipeline networking of multiple swine farms to a central RNG processing site. Similar models published by others indicate that such networking can be economically viable (Cavanaugh & Associates, P.A., 2023; Havrysh et al., 2019; Hengeveld et al., 2016; Hoo et al., 2018; IEA Bioenergy, 2018; Jaffe et al., 2016; O'Shea et al., 2017; and Prasodjo et al., 2013). Our model differs from previous approaches in that it successively adds swine farms, from largest to smallest biogas potential, to networks that grow with each farm addition. In the process, the economics of the networks at each stage in their evolution are computed. This approach offers two major advantages over previous methods because it allows us to determine (1) when during the growth of a network there are enough participating farms for the network to qualify for an RNG project, and (2) the point afterward at which the buildout achieves its lowest LCOE. Factored into this LCOE are the cost of:

- Each pipe segment in the network, based on its length and diameter, as determined from the pressure in the pipe segment
- Capture, primary processing, and compression of biogas at each farm in the network
- The central RNG processing and injection sites for the network.

A detailed explanation of how the model works is provided in **Section A.3, Appendix A**.

To model the virtual pipeline RNG approach, we added the cost of tanker truck transport to a nearby injection site to our estimated bio-CNG production costs.[9] We evaluated two cases for this scenario. In the base case, we set transport costs to the 2021 marginal cost of trucking in the southeastern United States of $1.16 per kilometer (Leslie & Murray, 2022) and added a 15% surcharge for unaccounted costs. The common distance we used in the base case was 18 kilometers (km), which is the average driving distance between every swine farm and the nearest terminus of a natural gas transmission pipeline (i.e., a City Gate where an interstate pipeline connects with a local utility's distribution lines), as measured using geographic information systems (GIS). Additionally, the median number of farms linked by shortest routes to a pipeline terminus is five, so every facility shipping to an injection site is assumed to pay one fifth of the injection site's one-time interconnection fee of $1.2 million plus an ongoing OPEX fee of $2.50 per million British thermal units (MMBtu) (same as in the LFGcost-Web model for RNG projects). In the "2X" case, trucking costs and distances are doubled (to $2.31 per kilometer and 36 km, respectively), and the interconnection cost of an injection site is split between two rather than among five users. Using these two sets of inputs, we calculated a total LCOE for every swine

[9] This approach differs from that of O'Shea et al. (2017), Sarker et al. (2019), and Ghafoori & Flynn (2007), who assumed that the biogas source material (e.g., crop waste to animal manure) is transferred by truck or pipeline from a feedstock source to one or more hubs where the material is turned into biogas and upgraded (either there or elsewhere) to bio-CNG or RNG before being transported by truck or pipeline to a demand center.

farm that could produce enough biogas to meet the modeling threshold for a CNG project. For further details, see **Section A.4, Appendix A**.

2.1.4 Financial Modeling

We evaluated the cost–benefit of each prospective biogas-to-energy project based on a project LCOE that we solved for by using the same equation (see Equation 1) that Murray et al. (2014) used:

$$LCOE = \frac{\sum_{t=0}^{P}\left[\frac{(CAPEX_t + OPEX_t)}{(1+r)^t}\right]}{\sum_{t=0}^{P}\left[\frac{E_t}{(1+r)^t}\right]} \quad \text{(Eq. 1)}$$

Where:

- P = The project duration in years
- t = The project year
- r = The project discount rate
- E = The annual amount of saleable energy produced by the project.

We chose Equation 1 over more sophisticated approaches to computing LCOEs because of its ease of use both in replicating the analysis results and in computing comparable LCOEs using different project durations and/or discount rates.

For this analysis, we set P (the project duration in years) to 15 years, the default project length in the LFGcost-Web model, and we fixed r (the project discount rate) at 8%. This latter value not only aligns with commonly cited discount rates for renewable energy projects (Steffen, 2020), but it also yields LCOEs that are within 5% of the LCOEs produced by using a net present value (NPV) optimization method for LCOE (EPA, 2021; Lazard, 2023) (**Section A.6, Appendix A**).[10]

2.1.5 Modeling Input

The single input to the biogas-to-energy modeling was each source's annual biogas production. For landfills, production amounts come from EPA's LMOP database (EPA, 2023c). The estimates for annual biogas production at swine farms and WWTPs are those reported by Parvathikar et al. (2021). The latter WWTP amounts are based on annual flows of treated wastewater given by the North Carolina Department of Environmental Quality's (NCDEQ's) permitting database (NCDEQ, 2022). Harvestable biogas from these flows was calculated assuming an average mass of organic dry matter (ODM) per unit

[10] Note that for landfill projects, annual energy output will change with time depending on when the landfill opened and when it is scheduled to close (see

Table A-2 [**Appendix B**]), so using a fixed amount of energy production as in Equation 1 will result in an LCOE that is up to 10% different from one calculated using the NPV optimization approach. For completeness, we included LCOEs computed both ways in the modeling results in **Appendix B**.

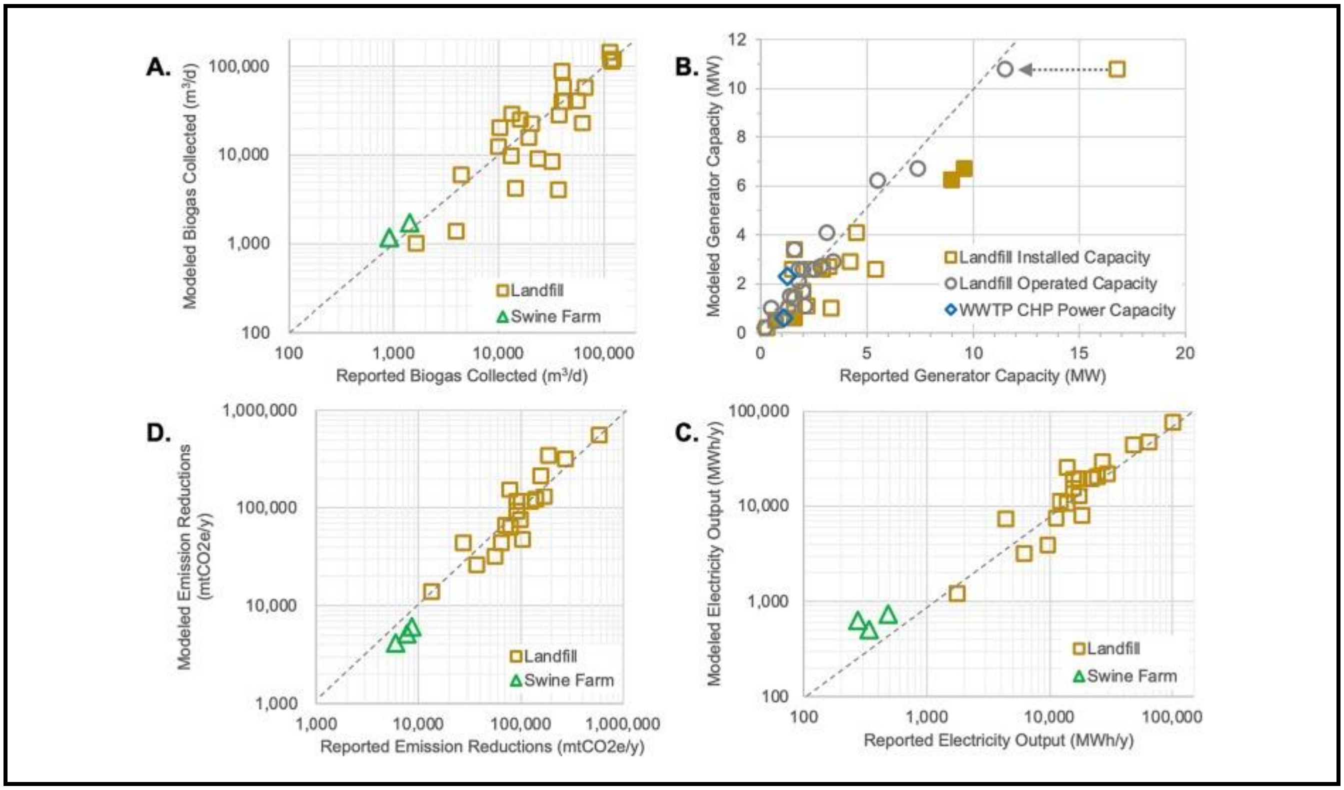
volume of wastewater of 0.94 kg/1,000 (NRC, 1996) and an average volume of biogas produced per unit mass of ODM of 500 liters per kilogram (L/kg) (Bachmann et al., 2015).[11]

2.2 Results

2.2.1 Modeling Validation

We first constrained the accuracy of our modeling systems using available data from landfills, WWTPs, and swine farms in the state with already operating biogas-to-energy projects (**Figure 3**). Of the 34 such sites, 27 were of the type modeled for this analysis, and all of them use biogas to generate electricity.[12] The extent of quantitative information reported for these projects varied by biogas source, and none included financial information.

Figure 3. Modeling Results for North Carolina Sites Already Converting Biogas into Electricity as Compared with Reported Values for (A) Biogas Collected, (B) Installed and Operated Electric Generator Capacity, (C) Annual Electricity Production, and (D) Emission Reductions.



Notes:

[11] A list of biogas potentials for all sources, along with additional information (e.g., waste accumulation rates at landfills, flow rates of water treated at WWTPs, and head and waste production at swine farms), is provided with the publication which can be accessed at https://www.sciencedirect.com/science/article/pii/S2213138823005507.

[12] The full list of sites with already-operating biogas-to-energy projects used in this analysis is included with the peer-reviewed publication which can be accessed at https://www.sciencedirect.com/science/article/pii/S2213138823005507.

Open squares in (B) represent correct predictions of generator type, while filled squares are predictions that differ from reported type. Dashed lines in plots delineate what would be a one-to-one relationship between modeled and reported values. Modeled values in all plots have a normalized mean absolute error of less than or equal to 35%.

CHP = combined heat and power; $MtCO_2e/y$ = metric tons of carbon dioxide equivalents per year; MW = megawatt; MWh = megawatt-hour; scf/d = standard cubic feet per day.

Reported and modeled amounts are compared in terms of biogas collected (**Figure 3A**), installed electric generator capacity (**Figure 3B**), annual electricity production (**Figure 3C**), and total emissions reductions (**Figure 3D**). The sites involved in the four comparisons are mostly landfills. There are three swine farms in three of the comparisons and two WWTPs in the fourth (i.e., the one for installed generator capacity). The comparison in the latter, however, is not direct because the WWTPs have combined heat and power (CHP) systems, systems not modeled here.

In all four comparisons, our modeling results exhibited a good one-to-one relationship with reported values. The systems modeling correctly predicted the type of generator for 84% of the projects (**Figure 3B**), while the normalized mean absolute errors (NMAE) of the predictions are 32% for biogas collected (**Figure 3A**), 33% (28% excluding outlier) for annual electricity production (**Figure 3C**), and 29% for annual emissions reductions (**Figure 3D**). For installed generator capacity, the NMAE was slightly larger at 35%, and the modeled capacities tended to increasingly underestimate installed capacities at landfills with higher biogas production rates (**Figure 3B**). The LMOP database, however, reported not only installed capacities for these landfills, but also the average capacity the generators were operated at over the course of a year (EPA, 2023c). When we plotted these operated capacities against the model results, which are based on the average annual amount of waste received by landfills, the alignment of the two data sets improved considerably (**Figure 3B**), dropping the NMAE for the predictions to 19%. This improvement in alignment suggests that the generators installed at the landfills have been oversized, presumably to handle projected future biogas production rates when annual waste deliveries become higher and/or the landfills approach being filled.

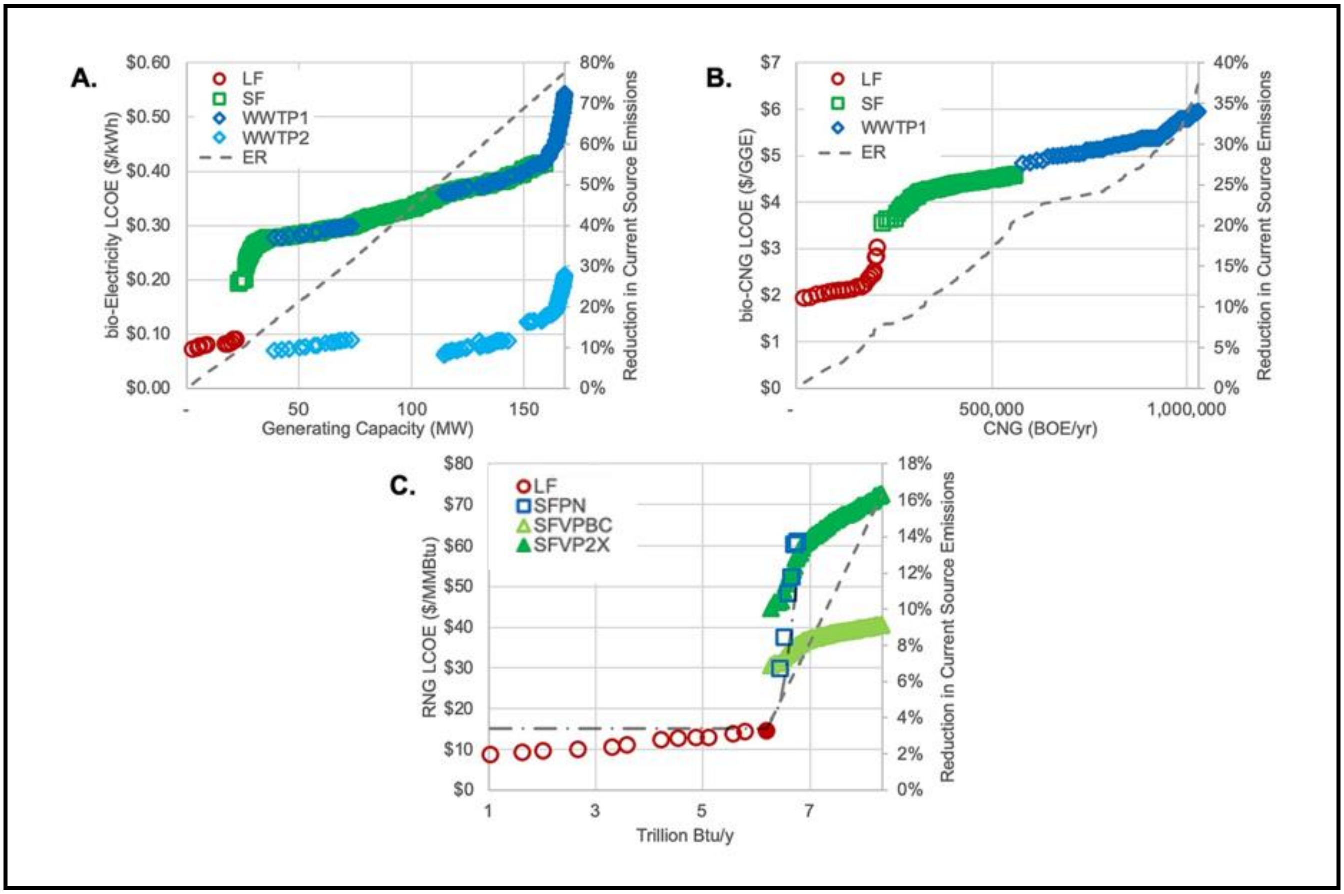
The comparisons in **Figure 3** suggest that at least when it comes to sizing project infrastructure, the systems modeling predictions are accurate to within 35% across project scales spanning three orders of magnitude.

2.2.2 Marginal Supply Curves

As previously mentioned, North Carolina ranked third for biogas potential in the U.S. in 2013, the last time such a survey was published by NREL. North Carolina is also a large energy-consuming state. In 2022, North Carolina was in the top 10 in population, state GDP, the manufacturing component of state GDP, and vehicle miles traveled (EIA, April 2023). North Carolina was also ranked 12th in the U.S. in total primary energy consumption, and in the top 10 for consumption of gasoline and electricity. At the same time, per capita use of natural gas is among the lowest in the United States. These contrasting attributes make North Carolina an attractive case study for evaluating the role that locally produced biogas might be able to play in increasing sustainable energy production in the United States.

Figure 4 shows MSCs for bio-electricity, bio-CNG, and RNG constructed from our modeling results. Apart from landfills in **Figure 4C**, only results for sites not known to already be producing energy are included in the MSCs. Because of uncertainty regarding which WWTPs already have ADs and flares, two sets of results are shown in **Figure 4A and 4B** for this source: (1) one set in which LCOEs include the CAPEX and OPEX costs for an AD and a flare system (WWTP1) and (2) one set in which the LCOEs do not (WWTP2). As mentioned previously, the production and cost functions from the LFGcost-Web model-imposed constraints on the minimum and, in all but one case (turbine generators), the maximum biogas flux needed to support a particular type of energy production. Consequently, the number of sites included in each plot differs. Additionally, because many sites qualified to produce bio-electricity with more than one type of generator (e.g., either a microturbine or a small reciprocating engine), only the project assessment with the generator that led to the lowest LCOE is plotted in the bio-electricity MSC.[13]

Figure 4. Modeled MSCs for (A) Bio-electricity, (B) Bio-CNG, and (C) RNG. Also Shown Are the Marginal Greenhouse Gas (GHG) Emissions Reductions (ERs).



Notes:

1 trillion British thermal units (Btu) ≈ 1 million gigajoules.

BOE/y = barrels of oil equivalent per year; GGE = gallon of gas equivalent; kWh = kilowatt-hour; LF = landfill; MW = megawatt.

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[13] All modeling results are tabulated in the supplemental information section of the peer-reviewed publication which can be accessed at https://www.sciencedirect.com/science/article/pii/S2213138823005507.

Labels: SF = swine farm; SFPN: swine farm physical network; SFVP = swine farm virtual pipeline; SFVPBC = swine farm virtual pipeline base case; SFVP2X = the swine farm virtual pipeline 2X case; WWTP1 = assumes no pre-existing AD and flare system; WWTP2 = assumes AD and flare system already in place.

Because the range of biogas fluxes that qualified for modeling bio-electricity production was the most expansive, the number of qualifying sites for this type of project was the greatest. The MSC (**Figure 4A**) includes 64% of all swine farms analyzed, 23% of all WWTPs, and 100% of all landfills not already producing energy. Of the sites that met the specifications for bio-electricity production, the cheapest sources are landfills and WWTP2. The landfills and most of the WTTP2 sites appear capable of producing electricity at less than or equal to 10¢ per kilowatt-hour (kWh). Bio-electricity production is more costly at swine farms and WWTP1. The LCOEs at these sites start at approximately 20¢/kWh and climb to more than 50¢/kWh. Production of electricity at all of the sites would reduce their current greenhouse gas (GHG) emissions by 77%. This calculation includes both the direct CH_4 emissions from the sources, as well as the emissions avoided by displacing output from existing fossil-fuel generators in the state; however, the cumulative power capacity of all 1,527 potential biogas-to-electricity projects, would sum to less than 170 megawatts (MW) and produce just 1% of the state's total annual electricity consumption in 2022 (1.8 million megawatt-hours [MWh] of potential electricity generation versus greater than 140 million MWhs of electricity consumption [EIA, October 2023a]).

The bio-CNG functions in our model required higher biogas fluxes, leading to fewer qualified projects for this type of energy production. The sites include 64% of the candidate landfills analyzed, 11% of the WWTPs, and just 6% of the swine farms. As a result, the total potential reduction in GHG emissions from all sources analyzed would reach only 33% (**Figure 4B**). The modeled production of bio-CNG exceeded one million barrels of oil equivalent per year (BOE/y) (**Figure 4B**). This quantity is slightly more than the amount of natural gas used for transportation in North Carolina in 2021 (EIA, April 2023), indicating that the state has more than enough biogas resources to meet recent vehicle demand for CNG. As with bio-electricity, we estimated that landfills and WWTP2 had the lowest production costs. LCOEs for these facilities were approximately $2 to $3 per gallon of gas equivalent (GGE).[14] Production at qualifying swine farms and WWTP1 would be more expensive. LCOEs at these sites started at approximately $3.50/GGE and increased to almost $6/GGE.

Direct production of RNG required the highest flux of biogas in our modeling. Of all the sources analyzed, only one not currently producing energy met this criterion (a landfill [solid red circle in **Figure 4C**]). Eleven other landfills already generating heat and/or electricity also met the criterion (open red circles in **Figure 4C**). In fact, one of these landfills (i.e., the South Wake Landfill in Apex, NC) is in the construction phase of switching from electricity to RNG production (Wake County, North Carolina, 2022).

RNG could also be produced among the sites that we analyzed if sources were connected via either physical or virtual pipelines. Again, because they are so densely concentrated in the eastern portion of North Carolina, we used only swine farms to assess these scenarios. Among the physical pipeline

[14] GGE is the volume of bio-CNG that has the energy content of a gallon of gasoline.

networks modeled, only six ended up collecting enough biogas annually to support direct RNG production (**Figure 4C**). The largest and most costly of these networks involved 46 swine farms, whereas the smallest and least costly had eight farms. Importantly, these were the network extents that yielded both the minimum biogas flux needed for direct RNG production *and* each network's lowest LCOE. As more farms were added to the networks, LCOEs increased. These additional iterations of the networks are included in **Section A.3, Appendix A**, but only the lowest cost versions of the networks are shown in the RNG MSC (**Figure 4C**). The LCOEs for these were between $30 and $61/MMBtu.

LCOE values for RNG production under the virtual pipeline scenario were comparable to those for the physical pipeline scenario. The LCOEs were calculated to be $31 to $41/MMBtu for the swine farm virtual pipeline base case, and $45 to $73/MMBtu for the swine farm virtual pipeline 2X case (**Figure 4C**). Shifting from a physical pipeline scenario to a virtual one increased cumulative production potential from 6.2 to 8.2 TBtu/y, or approximately 1% of the total natural gas consumption in North Carolina in 2022 (i.e., 735 TBtu [EIA, October 2023b]). Furthermore, potential reductions in total annual GHG emissions from all sources in the virtual pipeline scenario rose from 11% to 16%. This result occurred despite there being fewer swine farms involved in the virtual pipeline scenario than in the physical pipeline network scenario (124 versus 181). The reason is that the former scenario involved only farms with biogas fluxes high enough to qualify for bio-CNG production, whereas in the latter scenario, smaller farms proximal to the pipeline networks got incorporated into them as they grew.

2.2.3 Project Scale versus Cost Competitiveness

The MSCs in

Figure 5 reflect both the cumulative amount of bio-electricity, bio-CNG, and RNG producible from biogas in North Carolina, and the energy prices that in theory would attract investment in biogas-to-energy projects needed to achieve that potential. More difficult to establish from the MSCs, however, are the project scales and energy market(s) that would offer the greatest potential for economic viability, not just in North Carolina, but also elsewhere in the US.

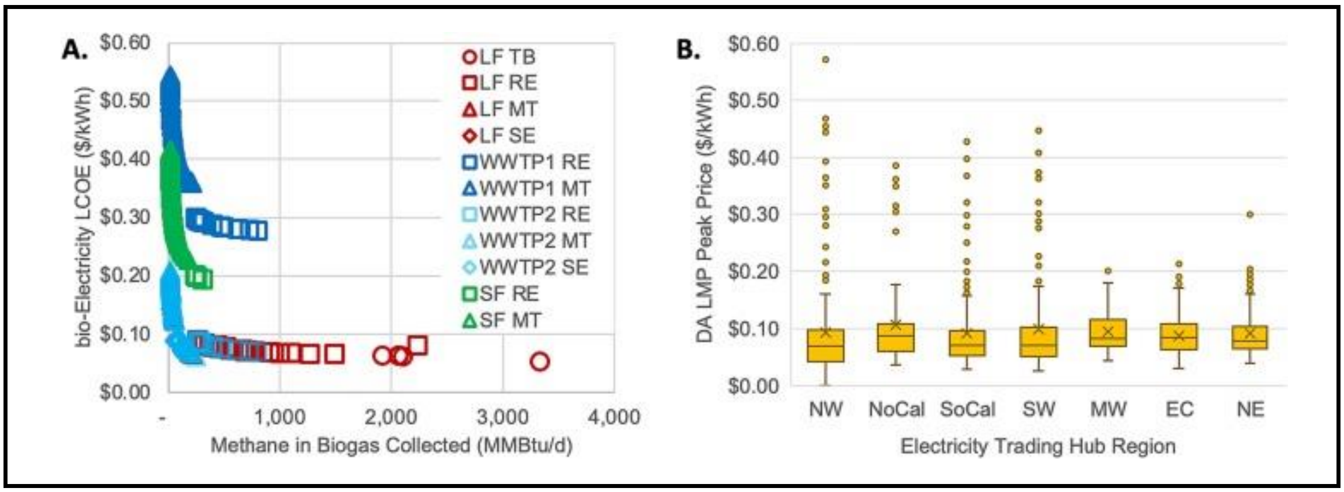
Figure 5 **through .**

Figure 7 compare project LCOEs as a function of CH_4 in the biogas collected to recent prices for substitutable energies in different regional U.S. markets and, where applicable, to major federal and state incentives for which the projects would be eligible.

In terms of bio-electricity, the most cost-competitive sites for the project development were landfills and WWTP2 with CH_4 fluxes of approximately 500 million British thermal units per day (MMBtu/d) or higher (i.e., fluxes large enough to fuel a reciprocating-engine or combustion-turbine generator). Estimated LCOEs at these sites were comparable to the 2022 median peak day-ahead (DA) locational marginal price for electricity at seven major electricity trading hubs located across the U.S. (midline in boxes,

Figure 5**B**). These prices, which are what utilities paid generators for electricity, are notably consistent among the trading hubs, indicating that on most days, DA wholesale prices for electricity are relatively uniform across the US. Furthermore, the prices are far below those needed to support bio-electricity generation at WWTP1 and at livestock farms with CH_4 fluxes equivalent to those of swine farms in North Carolina. Presently, at the federal level, while the Inflation Reduction Act (IRA) provides certain production tax credits and investment tax credits for electricity generation from biogas, these credits are only interpretations and formal guidance and rules from the U.S. Treasury Department are pending. At the state level, most have enacted Renewable Portfolio Standards (RPSs; i.e., policies that encourage or require suppliers to generate a minimum amount of electricity from renewable energy sources). Although the states with RPSs offer market incentives for renewable electricity, the type and maximum power capacity of generators that qualify for these incentives vary from state to state.

Figure 5. (A) Individual Bio-Electricity Project LCOE Estimates as a Function of CH_4 Collected. (B) Box Plot of Peak DA Locational Marginal Electricity Prices at Major Regional Electricity Trading Hubs During 2022. [a]



[a] EIA (November 2023).

Notes: kWh = kilowatt-hour.

Abbreviations: LF MT = landfill microturbine; LF RE = landfill reciprocating engine; LF SE = landfill small reciprocating engine; LF TB = landfill combustion turbine; SF RE = swine farm reciprocating engine; SF MT = swine farm microturbine; WWTP1 MT = wastewater treatment plant 1 microturbine; WWTP1 RE = wastewater treatment plant 1 reciprocating engine; WWTP2 MT = wastewater treatment plant 2 microturbine; WWTP2 RE = wastewater treatment plant 2 reciprocating engine; and WWTP2 SE = wastewater treatment plant 2 small reciprocating engine.

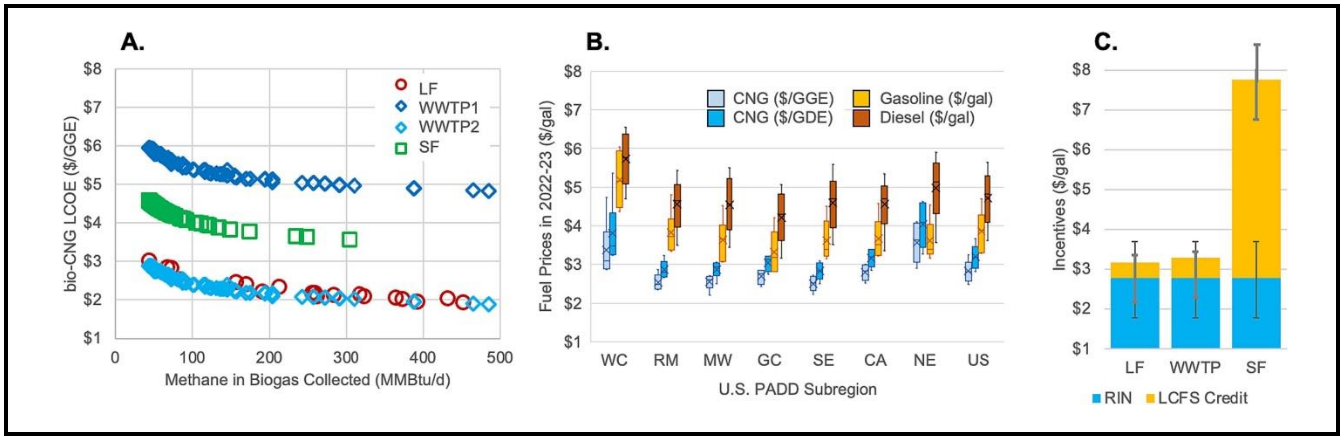
U.S. Trading Hub Regions: EC = PJM West; MW = Indiana Hub; NE = Mass Hub; NoCal = NP-15; NW = Mid-C; SoCal = SP-15; SW = Palo Verde.

Greater market opportunity currently exists for bio-CNG projects in the US. We found that such projects at landfills and WWTP2 would have LCOEs comparable to the recent price of CNG across all continental U.S. Petroleum Administration Defense Districts (PADDs) (

Figure 6**A and**

Figure 6**B**). This finding held regardless of whether the energy content of the CNG was expressed in terms of GGE or gallons of diesel equivalent. The higher LCOEs for bio-CNG produced at large livestock farms also appear cost-competitive with conventional CNG in at least two PADDs: the West Coast and New England.

Figure 6. (A) Individual Bio-CNG Project LCOE Estimates as a Function of CH_4 Collected. (B) Box Plot of CNG, Gasoline, and Diesel Prices in 2022 to Mid-2023 in Each of the Seven U.S. PADDs and for the United States on Average. (C) The 2022 to Mid-2023 Value of Major Incentives Available to Qualifying Bio-CNG Projects Expressed for Each Biogas Source in U.S. Dollars ($)/GGE: EPA Renewable Fuel Standard (RFS) Renewable Identification Number (RIN), and California Low Carbon Fuel Standard (LCFS) credit. [a]



[a] DOE (January 2022), DOE (April 2022), DOE (July 2022), DOE (October 2022), DOE (January 2023), DOE (April 2023).

Notes: 1 gallon (gal) = 3.8 liters.

Biogas Source Abbreviations: SF = swine farm; LF = landfill; WWTP = wastewater treatment plant; WWTP1 = wastewater treatment plant 1; WWTP2 = wastewater treatment plant 2.

U.S. PADD Regions: CA = Central Atlantic; GC = Gulf Coast; MW = Midwest; NE = New England; RM = Rocky Mountains; SE = Southeast; US = United States; WC = West Coast.

Note that the LCOEs for bio-CNG are comparable to current market prices before inclusion of two major incentive programs that the three types of bio-CNG projects analyzed here could apply to participate in.

The first major incentive program is the EPA's Renewable Fuel Standard (RFS) program. In this program, each gallon of bio-CNG produced from any of the three sources would, when sold, generate one D-3 Q-pathway[15] renewable identification number (RIN) (EPA, March 2023). Bio-CNG producers can then sell their RINs to "obligated parties" (refiners and distributors) that must purchase enough of them for the fuel they sell to federally register as having a minimum required fraction of biofuel. During

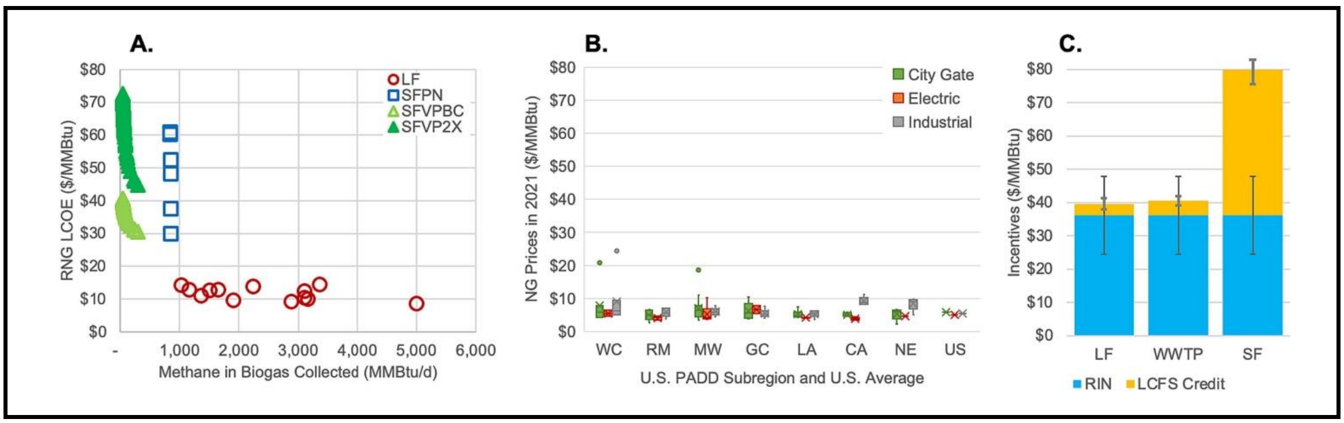
[15] The EPA's RFS program specifies a "D Code" for each fuel pathway for RIN generation. In D-3 Q, the D designates that it's a D code, the 3 specifies that it is cellulosic biofuel, and the Q describes the fuel type as bio-CNG, RNG, or bio-electricity. For more information on RFS D Codes, see https://www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel.

2022 through mid-2023, D-3 Q RINs were selling on average for $2.78 ± $0.90[16]/gallon (gal), an amount greater than the LCOEs for bio-CNG from landfills and large WWTP2s, and an amount that when combined with the recent prices for CNG would meet or exceed the LCOEs of bio-CNG projects at livestock farms with CH_4 capture rates exceeding 100 MMBtu/d (**Figures 6A and 6C**).

The second major incentive program that bio-CNG projects can apply for is the state of California's Low Carbon Fuel Standard (LCFS). Because projects located outside California typically inject their bio-CNG output as RNG into a natural gas pipeline, we also considered the program in the context of the current market opportunity for RNG, which is shown in **.**

Figure 7.

Figure 7. (A) Individual RNG Project LCOE Estimates as a Function of CH_4 Collected. [a] (B) Box Plot of Natural Gas Prices in 2022 to Mid-2023 in Each of the Seven U.S. PADDs and for the United States on Average. (C) The 2022 to Mid-2023 Value of Major Incentives Available to Qualifying RNG Projects Expressed for Each Biogas Source in U.S. Dollars ($) per MMBtu. [a]



[a] As discussed in text, swine farm pipeline networks that just meet the biogas flux needed to produce RNG are also the modeling point at which the networks achieve the lowest LCOE, which is why all these LCOEs are for the same level of CH_4 collected.

[b] EIA (October 2023c).

Notes:

Biogas Source Abbreviations: LF = landfill; SFPN = swine physical network; SFVPBC = swine farm virtual pipeline base case; SFVP2X = swine farm virtual pipeline 2X case.

U.S. PADD Regions: CA = Central Atlantic; GC = Gulf Coast; LA = Lower Atlantic; MW = Midwest; NE = New England; RM = Rocky Mountains; SE = Southeast; US = United States; WC = West Coast.

Across all seven PADDs, prices received for natural gas during 2022 to mid-2023, either at the City Gate or from electricity generators and industrial customers (i.e., lowest cost buyers that receive natural gas directly from transmission pipelines), were approximately half of the lowest RNG project LCOEs in our analysis (i.e., those involving large landfills [**.**

Figure 7**A and .**

[16] https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information

Figure 7**B**]). If the gas is purchased explicitly for use as transportation fuel, however, sellers of RNG or bio-CNG that qualify for the RFS would also receive the same RINs discussed previously, which when converted to gas units would equate to approximately $36 ± $12/MMBtu (**.**

Figure 7**C**). In addition, if the transportation fuel were being sold into California, then the sellers qualified for the LCFS would receive carbon credits that obligated parties in that state also would have to obtain in addition to RINs. The number of LCFS credits the sellers would receive depend on the carbon intensity (CI) of the seller's bio-CNG product relative to that of gasoline or diesel (93 and 94 grams of CO_2 equivalent per megajoule [gCO_2e/MJ], respectively), where CI is the life-cycle emissions of each fuel per unit of energy. Based on current CIs for active LCFS-approved projects producing bio-CNG from landfills, WWTPs, and swine farms, in combination with the value of LCFS credits sold during 2022 to mid-2023 ($85 ± $54/metric tons of carbon dioxide equivalents [$MtCO_2e$]), this additional incentive equates to $3.43 ± $1.64/MMBtu (or $0.39 ± $0.19/gal) for landfill bio-CNG, $4.40 ± $1.35/MMBtu (or $0.50 ± $0.15/gal) for WWTP bio-CNG, and $43.82 ± $4.51/MMBtu ($4.96 ± $0.51/gal) for swine farm bio-CNG (

Figure 6**C and .**

Figure 7**C**). The greater value of bio-CNG from swine farms is because of their substantially lower life-cycle emissions, which have resulted in current CIs for active swine farm projects in the LCFS of 402 ± 40 gCO_2e/MJ (versus 49 ± 29 gCO_2e/MJ for landfills and 38 ± 24 gCO_2e/MJ for WWTPs).

Thus, in the United States, the most valuable market for biogas-to-energy projects is currently the transportation fuel market, especially the market in California, where approved sellers can receive $40–$80 ± $13/MMBtu (or $3.17–$7.75 ± $1.41/gal,

Figure 6) on top of the going price for CNG. At such price levels, many to all of the prospective bio-CNG in North Carolina that we analyzed would be profitable, including large, high-LCOE WWTP1 projects.

2.3 Discussion

Although our technoeconomic analysis considered only three types of biogas sources, all of which were limited to North Carolina, the results have broader implications for the potential scale, markets, and cost competitiveness of biogas-to-energy projects in the United States. Estimates for the total annual energy resource potential in the nation's organic waste range from 431 TBtu/y (NREL, 2013) to 815 TBtu/y (Skaggs et al., 2018) and possibly higher (Murray et al., 2014). A recent report on biogas resources in North Carolina placed the state's potential at 45 TBtu/y (this amount excludes the energy in crop waste, which is not currently extracted using ADs) (Parvathikar et al., 2021). Of this amount, 62% (28 TBtu/y) is stored in landfills, WWTPs, and swine farms. Based on our modeling results, the fraction of energy from these same North Carolina sources producible from qualifying projects lies between 22% of their resource potential if the energy being generated is electricity (6.2 TBtu/y or 1,824 gigawatt hours per year [GWh/y]) and 29% (8.2 TBtu/y) if the energy is in the form of bio-CNG or RNG. This finding implies that approximately one quarter of the U.S. biogas resource potential in animal manure, wastewater, and landfills, as well as industrial, institutional, and commercial organic waste, is technically recoverable for commercial sale. This finding further implies that the amount of natural gas that could be displaced by biogas from these sources is likely less than 1% of the nation's natural gas consumption in 2022 (33,600 TBtu [EIA, October 2023b]), a percentage at least several times lower than previous estimates (Murray et al., 2014; NREL, 2013).

Relatedly, MSCs similar to those in **Figure 4A and 4C** were developed by Murray et al. (2014) using data at the time from all U.S. states. Their MSCs projected that much of the nation's biogas potential could be produced at an LCOE of $5–$6/MMBtu (1.7¢–2.0¢/kWh). In contrast, our LCOE estimates start at two or more times that level (**Figure 4A and 4C**). This discrepancy is partially the result of our having used a higher discount rate (8% versus 5%) and shorter project length (15 years versus 20 years) when calculating LCOEs (Equation 1). Inflation since Murray et al. (2014) published their study is also a factor; however, calculating LCOE as they did and adjusting for inflation reduced our estimated LCOEs by only between 17% and 24%. Our still higher LCOEs may be due to our having used a smaller sample size of prospective biogas-to-energy projects but, because the set is still large and diverse, we suspect that our updated LCOEs are more realistic.

Nonetheless, producing energy from biogas is sustainable, reduces GHG emissions, and, at a large enough scale, can also be profitable, particularly in markets with incentives for boosting renewable energy production and/or reducing emissions. Although many studies of biogas potential have focused on using the gas to generate electricity, our analysis makes clear that the far more attractive market for biogas-to-energy projects in the United States is transportation fuel. Wholesale electricity prices can certainly reach or exceed the bio-electricity LCOEs that we estimated (

Figure 5), particularly in the real-time market; however, to receive these prices, biogas generators must either have must-run status or be dispatchable and thus able to store accumulating biogas onsite until called upon. Furthermore, such peak prices tend to be relatively infrequent and short lived, so barring some form of regular payment, there might not be enough such events in a year for a bio-electricity project to break even.

In contrast, bio-CNG and RNG projects that succeed in selling their output as transportation fuel are more likely to generate a steadier, more predictable revenue stream, particularly if they can establish multiyear contracts for injecting their product into a natural gas pipeline. In addition, unlike for the bio-electricity results, there are at least two regional CNG markets in the United States where prices have recently exceeded the LCOE estimates for large biogas-to-energy prospects in North Carolina even before including available incentives (

Figure 6**A and**

Figure 6**B**). When the value of RFS RINs is factored in, with or even without the added value of LCFS credits, even smaller, more expensive-to-develop biogas-to-fuel projects become profitable (

Figure 6 **and.**

Figure 7). In fact, the incentives are so lucrative that they could attract existing bio-electricity projects to shift to producing bio-CNG. Possible examples include the South Wake Landfill in Apex, NC (Wake County North Carolina, 2022), which was discussed previously in this report, and the energy-intensive WWTPs currently selling bio-CNG into the LCFS program rather than using that energy to offset these facilities' own energy purchases (CARB, 2023).

Our analysis also suggests that, similar to in North Carolina, the national production potential of bio-CNG and RNG could meet or even exceed current demand for CNG in the United States. A major reason for this result is the relatively low number of CNG vehicles in the nation. At present, these vehicles constitute less than 0.1% of the U.S. vehicle fleet (175,000 CNG vehicles out of more than 278,000,000 total vehicles) (DOE, 2023; Tilford & Megna, 2023). In addition, given the auto industry's shift toward producing electric vehicles, current growth of the CNG market in the United States will likely depend on greater adoption of heavy-duty CNG and/or LNG trucks (Peters et al., 2021).

Even so, both near- and long-term demand for biofuels looks to remain strong. The EPA has set volume targets for renewable fuel consumption through 2025, and given the current value of RINs, their future value could well remain in the tens of dollars per MMBtu. Similarly, the California LCFS program has been extended through 2030, and though the value of LCFS credits for landfill and WWTP biofuels could decline as the net CI of the California's fuel mix drops towards zero, the much lower CI of bio-CNG and RNG from livestock manure should ensure that the value of LCFS credits for qualifying projects of this type will remain high. Demand for bio-CNG and RNG is now also coming from more recently established LCFS programs in the state of Oregon, the state of Washington, and the Canadian Province of British Columbia, and if proposed legislation in the states of Illinois, Michigan, Minnesota, New Mexico, New York, and Vermont is enacted, then these states will implement LCFS programs as well (Beta Analytic Testing Laboratory, 2023).

Longer term, there are at least three emerging markets for biogas: (1) the "clean" (i.e., non-fossil-fuel derived) hydrogen market, (2) the sustainable aviation fuel market, and (3) a recently proposed update to the RFS program. The U.S. market for clean hydrogen, which can be produced from biogas products among other sources (Marcoberardino et al., 2018), is still nascent, but is now being accelerated by billions of dollars in federal funding that will be directed toward developing regional clean hydrogen hubs, expanding the use of hydrogen in the industrial sector, and helping establish domestic hydrogen supply chains (IEA, May 2023; Kramer, 2022). The U.S. Department of Energy (DOE), along with other U.S. federal agencies, will also be issuing billions in federal funding to meet a shared goal of producing 3 billion gallons per year of domestic sustainable aviation fuel by 2030 and 100% of projected aviation jet fuel use (35 billion gallons per year [Bgal/y]) by 2050 (Oakleaf et al., 2022). Biogas products will be an important source for achieving such targets (Gupta et al., 2010). Finally, the EPA has proposed an update to the RFS program that would allow bio-electricity generated from biogas that is purchased for electric vehicle fleets to qualify for a new type of RIN—an eRIN (EIA, December 2022). The proposal is still under review, but if implemented, it would spur manufacturers of electric vehicles to secure new power purchase agreements from biogas-fueled generators for all the manufacturers' existing and new light-duty vehicles.

2.4 Conclusions

We have used more than 2,800 prospective biogas-to-energy projects in North Carolina with potential biogas yields spanning five orders of magnitude to explore the possible scale, market potential, and current cost competitiveness of bio-electricity, bio-CNG, and RNG projects in the United States. Among our principal findings is that the technical potential for producing saleable energy from biogas is approximately one quarter of the total resource potential estimated for all sources analyzed. Project LCOEs are also higher than previous estimates (Murray et al., 2014) and exceed current energy prices for electricity and natural gas in regional energy markets across the contiguous United States. Although many previous studies have focused on using biogas to produce electricity, we find that LCOEs for bio-CNG projects collecting biogas at rates of greater than or equal to 100 MMBtu/d are most cost-competitive with recent prices for conventional CNG. In addition, when key federal- and state-level incentives are factored in, smaller bio-CNG projects with collection rates of as low as 45 MMBtu/d become economically viable as well.

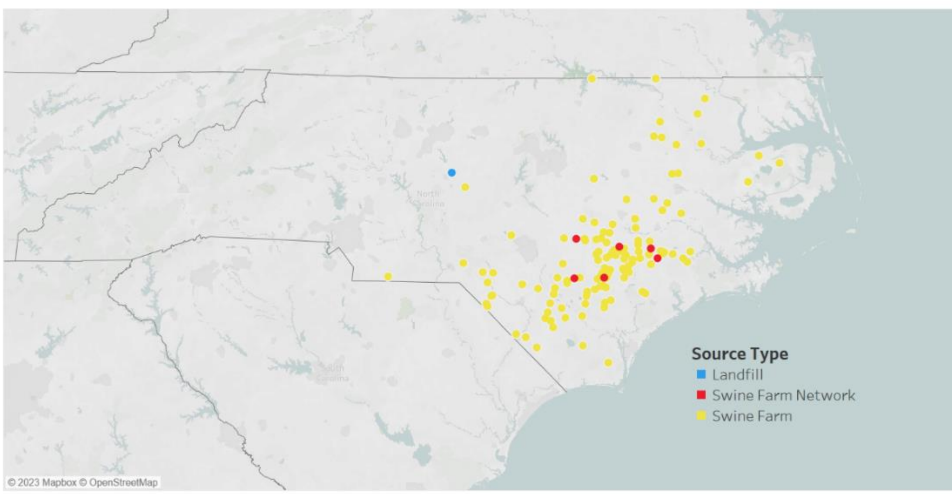
Despite the economic incentives for project development available through the evolving RFS and the expanding LCFS programs, adoption of biogas-based energy in the United States has been slow. Several areas of future research are needed to address this issue. One of the most critical topics for additional research is improving the technical and thus economic potential for extracting energy from biogas and thereby also increasing reductions in GHG emissions. The low commercial energy recovery (approximately 25%) and low emissions reductions (approximately 2% of total North Carolina GHG emissions in 2022 for bio-CNG/RNG up to 8.5% for bio-electricity (NCDEQ, January 2022) estimated in this study are the result of many of the prospective projects having biogas yields that were too low for producing saleable energy, particularly bio-CNG and RNG. Research is also needed on policies for permitting the addition of RNG injection sites along natural gas pipelines. Federal U.S. legislation, such as the Public Utility Regulatory Policies Act of 1978 (PURPA) and the Energy Policy Act of 1992, were critical in allowing renewable electricity generators access to the nation’s electric grids (Martinot et al., 2005). A similar set of policies is now needed for more biogas projects to access the natural gas pipeline system. Establishing uniform policies, however, is likely to be difficult because most gas lines where injection sites would be needed are regulated by state public utility commissions, which often have different priorities, policies, and permitting processes. Criteria for identifying the best locations for injection sites are also necessary to minimize infrastructure costs, optimize transportation routes biogas and biogas products, and avoid adversely impacting local communities in which biogas-to-energy projects might be established. The last issue is of particular importance for projects relying on manure from industrial livestock operations (Kelly-Reif & Wing, 2016). In North Carolina, for example, past pollution and health impacts to low-income Black and Latino communities surrounding large industrial swine farms have fueled opposition to producing energy from manure at these sites (Addison, 2022). There is a critical need for research into whether and how energy projects at swine farms could be developed to improve the local health, environment, and economy of adjacent communities if manure from such operations is going to be considered an acceptable source of sustainable energy.

3. Economic Impact Analysis

RTI International used Impact Analysis for Planning (IMPLAN) software to examine the economic impacts associated with the development of the biogas industry in North Carolina. This economic impact analysis follows earlier work completed under this project by our counterparts at Duke University which resulted in a series of alternative least cost network systems for delivering RNG produced in North Carolina to a gas pipeline system. RTI's Center for Applied Economics and Strategy was then asked to assess the expected economic impacts of the required investments in facilities and infrastructure for biogas recovery and RNG upgrading using the cost estimates developed in the technoeconomic analysis in **Section 2** of this report.

To simplify the analysis, the RTI team has chosen to model the contributions to the North Carolina economy from the implementation of the least-cost scenario of biogas infrastructure development. The least-cost scenario utilizes a combination of three feedstock sources: (1) the Great Oak Landfill in Randolph County, NC; (2) 125 swine farms in eastern North Carolina that would collect gas and use tanker truckers to transport it to an injection site; and (3) six networks of swine farms with interconnecting pipelines and access to a central RNG processing site (**Figure 8**).

Figure 8. Map of Site Locations by Source Type.



3.1 Total Investment and Operations Cost

The total capital investment needed for the optimal scenario is $318.2 million. These capital expenditures (CAPEXs) represent investment in the equipment and infrastructure needed to collect, process, and store biogas. CAPEXs are one-time costs for infrastructure that is expected to last 15 years. The $37.5 million in operating expenditure (OPEX) represents the ongoing costs associated with biogas collection processes. These costs will repeat each year of operation and are variable depending upon level of production, inflation, and other industry and/or market changes that influence the cost of goods and services, including labor and material costs.

3.2 Methodology

This economic impact model provides an estimate of the potential economic contributions provided to the state of North Carolina resulting from the development of the state's biogas industry. The model includes the following measures:

- Jobs are reported as an annual average and consist of all full-time, part-time, and temporary positions. Direct jobs are those created within the biogas industry. Indirect jobs are those supported by industry spending among local businesses. Induced jobs are supported by employees, both in the industry and employed at businesses with industry contracts, who spend their wages in the local economy.
- Labor income indicates how much additional personal income is created by biogas industry activities and is a component of value added (see next bullet point). Labor income represents multiple forms of employee compensation such as wages, benefits, and proprietor income.[17]
- Value added provides an indicator of the labor, capital, and tax income generated from production activities. Value added consists of a combination of labor income, proprietor income, and profits.
- State and local tax revenue is the sum of tax revenue that will be generated at the subcounty, county, and state levels. These taxes include items such as state income taxes, corporate business taxes, sales taxes, and special district fees.

The economic impacts associated with biogas industry development will occur in two stages: (1) construction and (2) facilities operations. Results are reported separately for construction impacts, which will occur for a single year, and operations impacts, which will be incurred each year that the facilities are in operation.

A detailed methodology to determine the economic impacts of the biogas industry in North Carolina is included in **Appendix B** of this report.

3.3 Construction Phase

Construction impacts from the $318.2 million CAPEX investment scenario are summarized in

Table *1*.

Table 1. Economic Activity Supported by Biogas Infrastructure Construction (2024 USD).

	Number of Jobs	Labor Income	Value Add	Local and State Tax Revenue
Direct	1,824	$109.3 million	$117.9 million	−$0.5 million
Indirect	824	$58.4 million	$96.9 million	$10.1 million

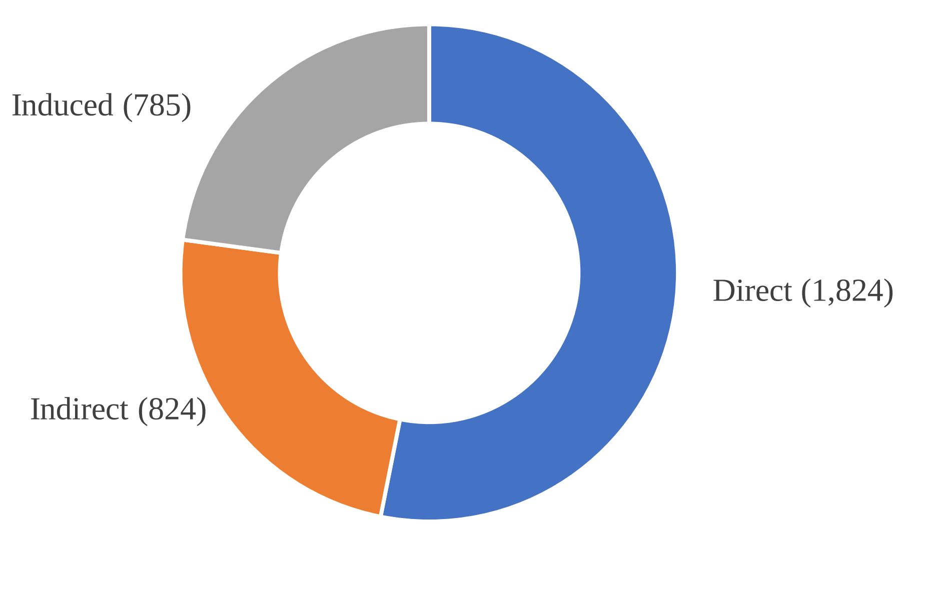
[17] Proprietor income consists of income from self-employed individuals and independent business owners.

	Number of Jobs	Labor Income	Value Add	Local and State Tax Revenue
Induced	785	$43.4 million	$80.6 million	$7.8 million
Total	**3,433**	**$211.1 million**	**$295.4 million**	**$17.4 million**

3.3.1 Construction Phase Jobs

During the one-year construction phase of biogas infrastructure, North Carolina would experience an increase of 1,824 direct jobs (**Figure 9**), most of which would be in the construction industry. For every direct job created by biogas infrastructure construction, another 0.9 jobs are supported in the economy. Jobs supported in the construction supply chain would include retail building supply stores, employment services, truck transportation, and architectural and engineering services. Additional jobs supported by worker spending would be in the restaurant, healthcare, and retail sectors of the economy.

Figure 9. Jobs Created from Biogas Infrastructure Construction.



3.3.2 Construction Phase Labor Income

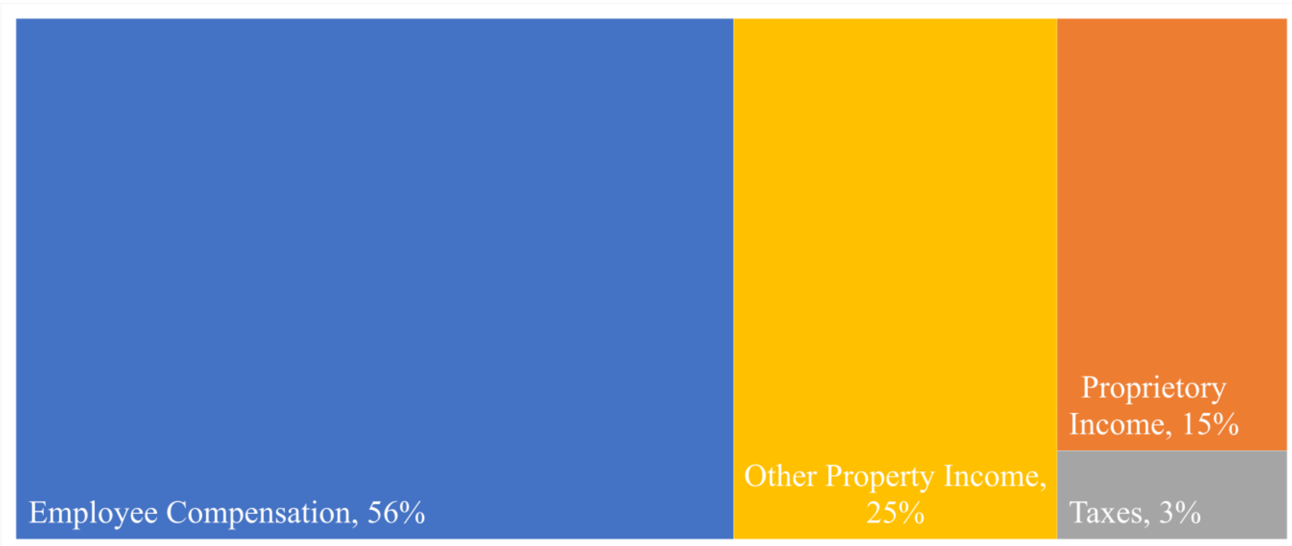
Construction activities would support $211 million of labor income, which is the largest component of value added (**Figure 10**).

3.3.3 Construction Phase Value Added

More than $295 million in total value across North Carolina would be generated by biogas infrastructure construction. Value added is a measure of the size of specific industries and the economy. Value added, which is also referred to as contribution to gross domestic product (GDP), provides an indicator of the labor, capital, and tax income generated from production activities and consists of the following:

- Labor income (employee income + proprietor income)
- Taxes on production and imports (taxes to operate a business and imports)
- Other property income (dividends, corporate profits, interest earned on bank deposits, and reduction in value of fixed assets).

Figure 10. Components of Value Added from Biogas Infrastructure Construction.

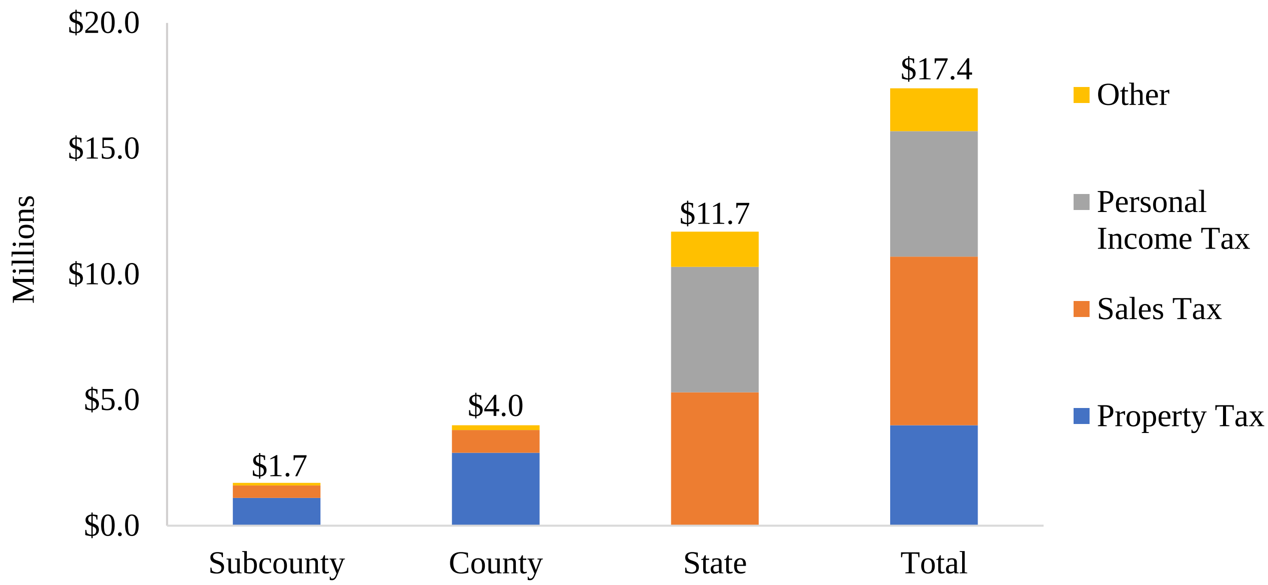


3.3.4 Construction Phase Tax Revenue

Of the projected $17.4 million in state and local tax revenue from the construction of biogas infrastructure (

Table *1*), more than half is collected at the state level (**Figure 11**). The majority of the $11.7 million in estimated state tax revenue is comprised of personal income tax ($5.0 million) and sales tax ($5.3 million). At the county level, the $4 million in tax revenue is derived largely from property tax ($2.9 million) and county sales tax ($0.9 million). Finally, an expected $1.7 million of tax revenue is raised by subcounty assessments, including property tax ($1.1 million) and local sales tax ($0.5 million).

Figure 11. State, County, and Local Tax Revenues from Biogas Infrastructure Construction (2024 USD).



3.4 Operation Phase

Operation of strategic biogas resources would support jobs, labor income, and economic activity across North Carolina. These impacts would occur each year biogas facilities are operational; however, projected annual operation impacts are only reported for 2025 (**Table 2)**.

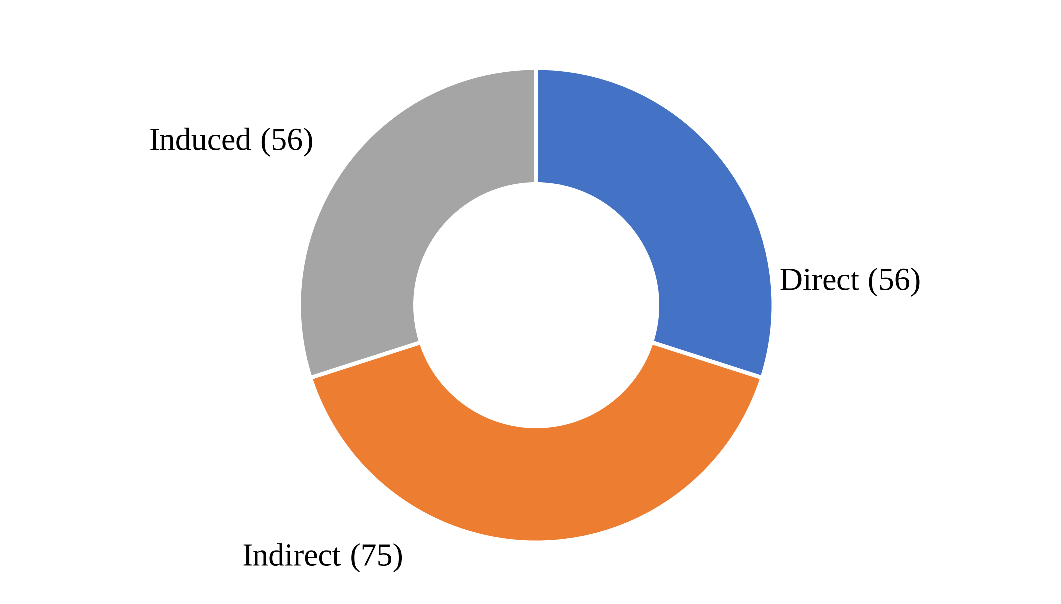
Table 2. Annual Economic Activity Supported by Biogas Infrastructure Operation (2025).

	Number of Jobs	Labor Income	Value Add	Local and State Tax Revenue
Direct	56	$6.2 million	$14.0 million	$1.8 million
Indirect	75	$5.7 million	$9.3 million	$0.9 million
Induced	56	$3.1 million	$5.7 million	$0.4 million
Total	**187**	**$15.0 million**	**$29.0 million**	**$3.1 million**

3.4.1 Operation Phase Jobs

During the operation of the biogas facilities identified in this report, North Carolina would experience an increase of 56 direct jobs (**Figure 5**), most of which would be in the chemical manufacturing and natural gas distribution industries. For every direct job created by biogas facility operations, another 2.3 jobs are supported in the economy. Jobs supported in the biogas industry supply chain would be clustered in the employment services, management services, truck transportation, and equipment wholesaler industries. Additional jobs supported by worker spending would be in the restaurant, healthcare, and retail sectors of the economy.

Figure 12. Jobs Created from Biogas Infrastructure Construction (2025).



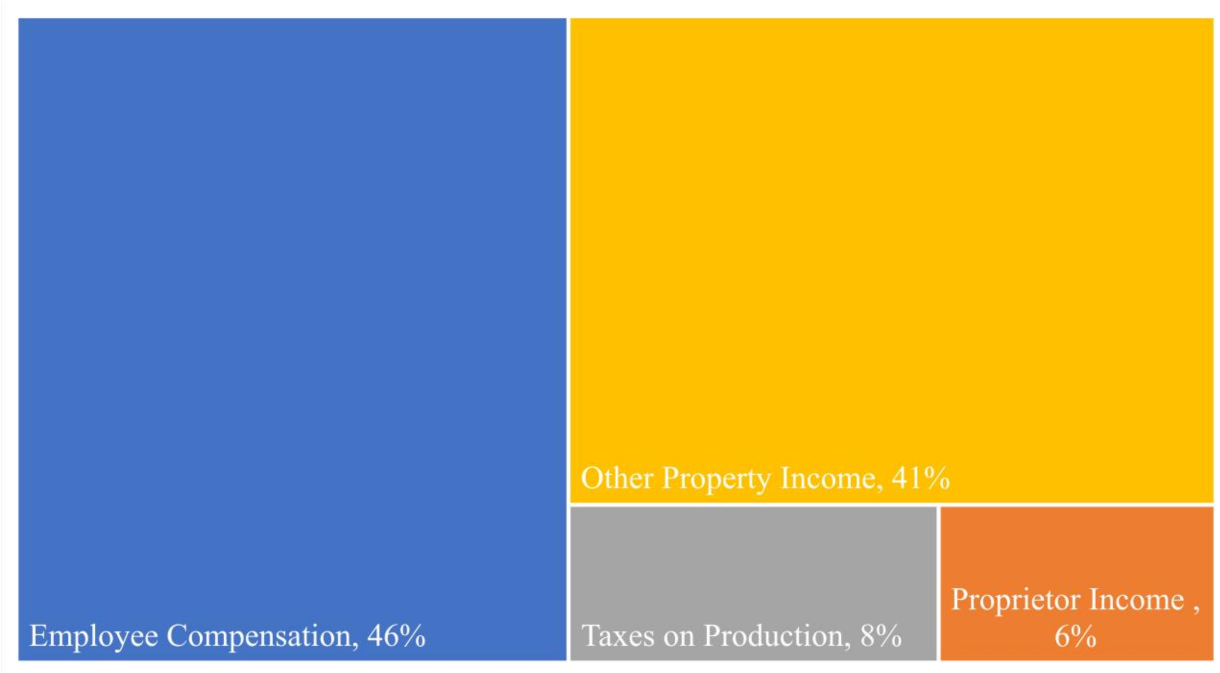
3.4.2 Operation Phase Labor Income

In 2025, biogas operations could support $15 million in labor income which is the largest component of value added (**Figure 13**).

3.4.3 Operation Phase Value Added

More than $29 million in total value across North Carolina would be generated by biogas facilities per year of operation. **Figure 13** lists the components and relative size of value added for biogas facility operations.

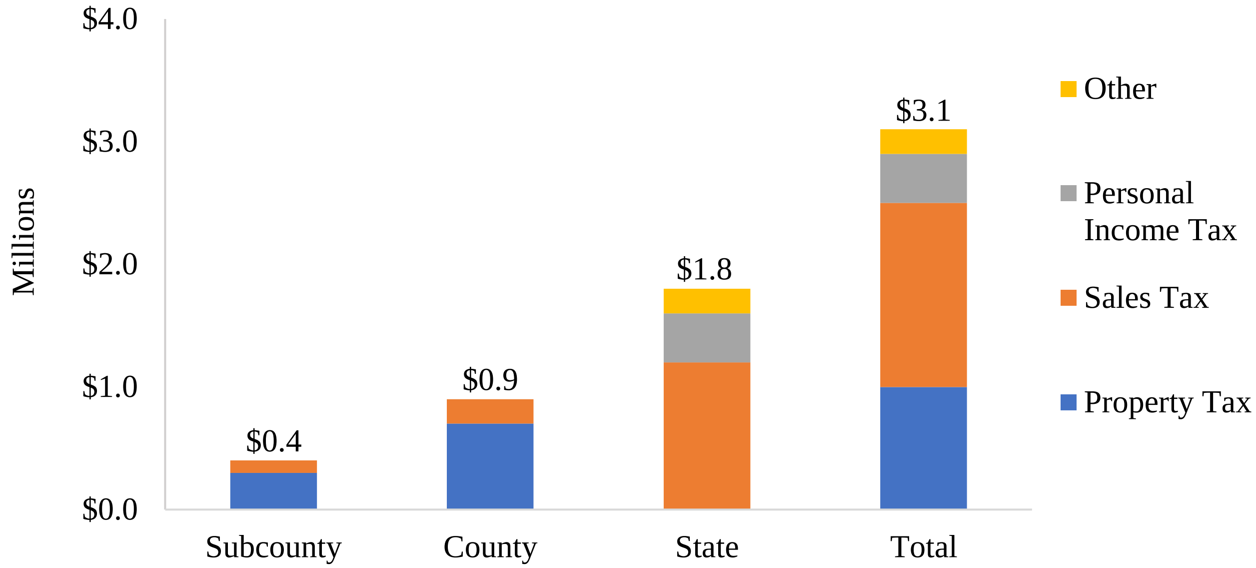
Figure 13. Components of Value Added from Biogas Infrastructure Operation.



3.4.4 Operation Phase Tax Revenue

Of the projected $3.1 million in annual state and local tax revenue from the operation of biogas infrastructure (**Table *2***), more than half is collected at the state level (**Figure 14**). The majority of the $1.8 million in estimated state tax revenue is comprised of personal income tax ($0.4 million) and sales tax ($1.2 million). At the county level, the $0.9 million in tax revenue is derived largely from property tax ($0.7 million) and county sales tax ($0.2 million). Finally, an expected $0.4 million of tax revenue is raised by subcounty assessments, including property tax ($0.3 million) and local sales tax ($0.1 million).

Figure 14. State, County, and Subcounty Tax Revenue from Biogas Infrastructure Operation (2025).



4. Policy Landscape Analysis

4.1 Introduction

Policymakers in North Carolina set goals to reduce the state's GHG emissions including North Carolina Governor Roy Cooper's Executive Order (EO) No. 80 which includes a statewide emission reduction target of 40% below 2005 levels by 2025. EO No. 80 also includes the establishment of the North Carolina Climate Change Interagency Council (NCDEQ, 2018).

Furthermore, in EO No. 246, the state updated its goals by striving to reduce GHG emissions 50% below 2005 levels by 2030, with a net-zero target by 2050. Additionally, EO No. 246 established Environmental Justice (EJ) priorities and processes. Finally, the state legislature passed, and Governor Cooper signed, House Bill 951 (North Carolina General Assembly, 2021) into law in October 2021, committing to a 70% reduction of carbon emissions in the electric sector by 2030, as well as carbon neutrality by 2050. The resulting Carbon Plan, which was adopted by the North Carolina Utilities Commission (NCUC), outlines the pathway for achieving these goals which includes utilizing North Carolina's extensive biogas resources.

This policy landscape analysis provides an overview of the current federal and state policies and regulations that benefit the production, development, and application of biogas-to-energy projects. By analyzing key initiatives, incentives, and challenges experienced by government entities, industry stakeholders, and concerned citizens, this analysis outlines the opportunities, barriers, and considerations for North Carolina policymakers as the state seeks to utilize its potential biogas resources.

The analysis briefly considers current federal policies related to biogas products, and then focuses on the state policy landscape which details policies designed to advance biogas-to-energy projects organized by source: LFG, WWTPs, and livestock. For each feedstock, the study discusses successful policies enacted in other states that are relevant to North Carolina's biogas opportunities and could be used as models by North Carolina policymakers. From there, we conduct a broad assessment of stakeholders in North Carolina, focusing on those located in rural and farming communities. This section of the report concludes with policy options for North Carolina officials that aim to either develop biogas-to-energy infrastructure or improve the state's management of organic waste, including advantages and disadvantages of each pathway and recommendations for implementation.

Tapping into the biogas resources in North Carolina requires policymakers to make several fundamental choices, including whether the policy pathway seeks to promote economic development, decrease emissions, or build consensus among local stakeholders or to use a combination of all three. Prioritization is essential to the development of impactful policy; therefore, this report can be used to weigh the cost–benefit balance and determine the appropriate path forward for biogas infrastructure development in North Carolina.

4.2 Federal Policy Landscape

In the 117th U.S. Congress (2021–2023), the federal government made historic investments to incentivize states (as well as municipalities, non-government, and private entities) to pursue carbon-reduction technologies, including biogas products such as bio-CNG, RNG, and bio-electricity. Using the federal funding, tax incentives, and policy options now available, these stakeholders are poised to make significant investments in the biogas industry.

4.2.1 Inflation Reduction Act

The Inflation Reduction Act (IRA), which was signed into law on August 16, 2022, provides historic funding for programs and incentives related to clean energy and limiting carbon emissions. Those incentives include programs that directly or indirectly relate to biogas products including bio-CNG, RNG, and bio-electricity. Many incentives are designed to support efforts to reduce, capture, or avoid emissions from carbon pollution and CH_4, and may be applicable in processes that support the development and use of biogas-to-energy technologies. Other examples of programs that are relevant for biogas technology development include programs funded within the U.S. Department of Agriculture (USDA) that support the use of anaerobic digesters geared toward agricultural producers for generating and collecting biogas from agricultural waste products.

For more information on federal programs that are applicable to biogas infrastructure development, interested parties may consult resources provided by The White House (2023), DOE (n.d.-b), EPA (2023), and USDA (n.d.-a).

4.2.2 Bipartisan Infrastructure Law

The Bipartisan Infrastructure Law (BIL), which was signed into law on November 15, 2021, represents the largest investment in federal infrastructure in U.S. history. Although most of the programs are focused broadly on infrastructure, some include specific mentions about and support for LFG and wastewater treatment facilities. Specifically, WWTPs and sewage systems are not built to withstand the increasing frequency and severity of new weather patterns caused by the warming climate; therefore, substantial funding was earmarked to replace or upgrade the existing infrastructure, providing an opportunity to include biogas infrastructure given the necessary policy is in place.

For more information, interested parties may consult resources provided by The White House (2022) and EPA (2023, November 17).

4.2.3 Additional Federal Programs and Resources

Additional resources and information about federal programs are available as follows:

- USDA’s Rural Development Energy Programs (USDA, n.d.-b)
- The EPA AgSTAR Program’s Biogas Toolkit (EPA, July 19, 2023) is a comprehensive resource for “biogas project stakeholders” that encompasses information from other EPA programs, including the LMOP and the Global Methane Initiative (GMI).

- EPA's LMOP focus on RNG (EPA, August 3, 2023)
- DOE's Alternative Fuels Data Center Natural Gas Laws and Incentives (DOE, n.d.-c).

4.2.4 Justice40 and Environmental Justice

A critical component of the federal government's energy and infrastructure programs is EJ, especially in underserved communities. President Joseph Biden Jr.'s EO No. 14008 established several tools and federal policies designed to support EJ communities, including The White House Environment Justice Interagency Council and The White House Environmental Justice Advisory Council (The White House, n.d.). EO No. 14008 also established the Justice40 Initiative and Climate and Economic Justice Screening Tool to help direct federal support and resources to EJ and underserved communities. Information provided by The White House and the EPA may provide guidance for interested parties seeking federal support for biogas projects in North Carolina (EPA, n.d.-a; EPA, 2023, November 21).

4.3 State Policy Landscape

States continue to pursue diverse strategies to support biogas-to-energy development, both directly and indirectly, via policies to abate carbon emissions or to provide resources for alternative fuels. According to the Argonne National Laboratory's (ANL's) Renewable Natural Gas Database, there were 230 operational bio-CNG and RNG projects, 108 under construction, and 80 in various stages of planning as of January 2022 (ANL, 2022; EPA, 2023d).

The role of state policies in pursuing incentives for biogas-to-energy projects is unique and critically important. The policy options available to develop biogas infrastructure are further unique, given the varying feedstock source options, the infrastructure required to process and transport the finished product, and the financial support needed to bring biogas products to market at scale. Because bio-CNG and RNG remain relatively new in their technology, adoption, and use, there are limited existing pathways to connect these biogas sources to traditional natural gas infrastructure and/or markets. States that elect to pursue the development and use of biogas products may enact policies that directly connect the biogas sources to those markets (i.e., physical or virtual pipeline networks) as well as indirect policies that encourage the private sector to pursue these goals (i.e., financial incentives or broad carbon reduction policies).

Additionally, although not easily captured in this section, given the rapidly changing landscape of federal government programs and guidance, state policies may be developed to complement existing federal policies and incentives or to fill gaps needed to support state-specific industries or goals.

4.3.1 General State Policy Options

Many state biogas policy options are technology or source neutral, and do not call for the development of biogas products from a particular point source or feedstock type. Most policies offer financial incentives such as direct payments, tax exemptions, or cost recovery policies for biogas projects and/or equipment (Holst, 2022). As such, this section of the report will list key state-based policy options for consideration in North Carolina.

Greenhouse Gas Reduction Policies

1. Iowa's 1983 Alternate Energy Production Law was the first state policy created to adopt an RPS (Tipton, n.d.). An RPS is a mandate to increase production from renewable energy sources (NREL, n.d.) and are intended to increase the use of alternative fuels, such as RNG and bio-CNG. According to the U.S. Energy Information Administration (EIA, February 2022), the District of Columbia and 31 states (including North Carolina) have adopted RPS or clean energy standards as of the end of 2021 (CESA, n.d.).

Alternative Fuels Procurement Policies

1. Pennsylvania's Alternative Fuel Incentive Grants, which are administered by the Pennsylvania Department of Environmental Protection (PADEP), creates a market for bio-CNG and RNG by providing nearly $3 million for school districts, municipalities, non-profit organizations, and businesses to switch to cleaner transportation fuel (PADEP, n.d.).

2. California's Biomethane Procurement Program requires the California Public Utilities Commission (CPUC) to adopt biogas-derived CH_4 targets for utilities in an effort to meet California's climate reduction goals (CPUC, 2022).

Regulatory Policies

1. Washington State's Clean Fuel Standard requires a reduction in the CI of transportation fuels (Washington State Department of Ecology, n.d.).

2. California's LCFS, which was implemented in 2011, uses a credit trading system to incentivize the deployment of low carbon, renewable fuels in place of traditional diesel in the transportation sector, including using LFG to produce bio-CNG (CARB, n.d.-c).

Financial/Tax Incentives

1. Pennsylvania's Alternative and Clean Energy Program, which is administered by the PADEP and the Pennsylvania Department of Community and Economic Development (PADCED), provides loans and grants for manufacturers of alternative and/or clean energy generation equipment or components (PADCED, n.d.).

Additional Policy Considerations

Raising sufficient private capital or having the required demand for full-scale bio-CNG and RNG projects is difficult, but state-level incentives can help close the gap. Four major costs capture the key concerns with bio-CNG and RNG development: gas compression and treatment, pipeline development, interconnection fees, and OPEX costs (EPA, 2023d). To offset some of these costs, drive market demand, and encourage investment in biogas infrastructure development, many states have implemented

RPSs, renewable gas procurement targets, and LCFS. Renewable energy credits and tax credits may be made available to further incentivize production and adoption of biogas products (Psihoules et al., 2021).

States may be able to indirectly drive down the cost of RNG infrastructure through natural gas pipeline incentives. Widespread acceptance and implementation of natural gas pipelines can prove crucial for the adoption of RNG by providing some of the base infrastructure for RNG production and potentially reducing pipeline development costs. Furthermore, policies that drive market demand for renewable gas combined with the reduced RNG pipeline infrastructure and interconnection costs could incentivize natural gas utilities to incorporate RNG into their pipelines. As RNG grows in popularity and more natural gas utilities welcome RNG into their pipelines, the implementation of this alternative energy source can reach full acceptance and bankability (EPA, 2023d).

<u>State Comparison: California's RNG Market</u>

California has made considerable investments in RNG on its path towards a low-carbon future through comprehensive state incentives and programs. In 2011, California implemented its LCFS program, which uses a credit trading system to incentivize the deployment of low-carbon, renewable fuels in place of traditional diesel in the transportation sector (CARB, n.d.-b). As the largest diesel fuel consumer in the United States, with 3.2 billion gallons consumed in 2019, California's decision to fully adopt an LCFS drastically altered the market for RNG and other low-carbon fuels (Macpherson & Martin, 2022). Since 2011, California's low-carbon fuel market has continued to grow as the number of LCFS credits traded between 2018 and 2020 grew 63% and the average price per credit increased 24% in the same period (Macpherson & Martin, 2022).

Along with a pioneering LCFS, California also incorporates RPSs and renewable gas procurement targets into state law to facilitate widespread integration of RNG. California's RPS has the ambitious goal of eliminating carbon-emitting sources from state-electricity generation by 2045. The state's three largest investor-owned utilities helped California make progress toward their zero-carbon electricity goal in 2017 when they served 36% of their load with renewable energy sources (CPUC, n.d.). Additionally, California is the only state with a biogas-derived CH_4 procurement target for utilities. With the help of the CPUC, California developed a groundbreaking program that aims to reduce CH_4 and other short-lived climate pollutants 40% from 2013 levels by 2030 (CPUC, 2022).

4.3.2 Landfill Gas

Decomposing organic matter in landfills across the United States produces mass amounts of CH_4 each year, but proactive landfill management can mitigate some negative impacts of these emissions and provide significant opportunity for RNG production. Biogas produced in landfills naturally occurs underground as waste is collected from residential, commercial, and industrial sources, emitting CH_4 and CO_2. The waste product of this simple microbial process is better known as LFG and accounts for approximately 16% of annual CH_4 emissions in the United States (EPA, 2023a). To bridge the gap between CH_4 emissions and alternative fuel generation, entities have increasingly leaned on established

LFG collection and treatment procedures. Vertical and horizontal extraction wells bore deep into the compacted landfill waste to draw the CH_4 produced in the anaerobic conditions (EPA, 2016). The captured CH_4 gas can then be sent to flare, combusted for on-site electricity generation, or further purified into bio-CNG or RNG, with quality analogous to traditional fossil fuel standards. This basic framework for LFG capture and refinement can be widely applied to landfill sites around the United States, and the EPA's LFG Energy Project Development Handbook provides a concise summary of steps and eligibility requirements for such projects (EPA, 2016).

<u>State LFG Policies</u>

1. Pursuant to the California Global Warming Solutions Act, the California Air Resources Board (CARB) approved the Landfill Methane Regulation, which requires municipal solid waste landfills to reduce CH_4 and other air pollutant emissions through emissions monitoring and capturing fugitive CH_4 (CARB, n.d.-a).

2. Oregon's Environmental Quality Commission approved LFG emissions rules to track, report, collect, and control GHG emissions from landfills (ORDEQ, n.d.). The rules require many landfills in Oregon to obtain an Air Contaminant Discharge Permit to submit data regarding the landfill characteristics and potentially monitor, collect, and/or control LFG emissions.

3. Maryland's Department of the Environment adopted the Control of Methane Emissions from Municipal Solid Waste Landfills (Maryland Register, June 2, 2023). The rule requires municipal solid waste landfills of a specific size that accepted waste after November 1987 to meet requirements for CH_4 control devices, including open flares (SCS Engineers, 2023).

<u>State Comparison: Pennsylvania's LFG</u>

Pennsylvania is second only to Texas in natural gas reserves and historically has relied heavily on fossil fuels for state energy needs. Favorable state policy conditions and recent investment have paved the way for RNG to diversify Pennsylvania's energy supply (EIA, November 2022). Pennsylvania has a broad base of landfill CH_4 projects, with 37 currently active in the state and 8 more in the planning stages (PADEP, 2011). Of the existing projects, the most common biogas application is combustion for bio-electricity generation, but upgrading to RNG for direct use in natural gas pipelines is also common. The prominence of these projects helps utilities stay in compliance with Pennsylvania's Alternative Energy Portfolio Standard, which requires 8% of utility-supplied electricity to come from RNG and other "Tier I" sources (DSIRE, 2023). By 2021, biomass, which includes municipal solid waste, LFG, and wood and forest by-products, made up 20% of Pennsylvania's renewable energy generation and helped meet the Alternative Energy Portfolio Standard target (EIA, November 2022). With proven success and a consistent demand signal, Archea Energy developed Project Assai, which is the highest capacity RNG facility in the world, located at the Keystone Sanitary Landfill in Dunmore, PA (Foelber, 2022). Capable of producing 12,000 MMBtu/d, Archea Energy estimates that Project Assai will generate $40 million in earnings before interest, taxes, depreciation, and amortization (EBITDA) in 2022 alone, which is more than half of the company's EBITDA in 2021.

4.3.3 Wastewater Treatment Plants

Biogas derived from WWTPs requires capturing, processing, and refining CH_4 produced by the facilities' remediating stormwater and sewer systems. During the process of treating the water for return to public use, large pools and lagoons are used that emit substantial amounts of GHGs. Biogas-to-energy projects from WWTP-derived biogas requires capping the pools to capture the gaseous by-product and directing it towards an on-site scrubber for processing (Burmahl, 2022).

Nationally, only 1,200 of more than 16,000 WWTPs in the United States have ADs, falling well short of the biogas production potential (DOE, n.d.-a). The EPA estimates that 100 gal of wastewater can produce 1 cubic foot (ft^3) of digester gas (EPA & Combined Heat and Power Partnership, 2011). Fully realizing this potential, a study prepared by several water organizations asserts that bio-electricity produced solely by biogas from WWTPs could meet up to 12% of the United States' electricity demand (NACWA, WERF, & WEF, 2013).

<u>State Comparison: Iowa WWTP</u>

Iowa recently started a hybrid WWTP and agricultural by-product system, in which human and animal-derived waste products are commingled and processed for the town of Waterloo, IA, and the adjacent Tyson poultry operation. This facility had already been capturing and burning, or flaring, the CH_4; however, this project will now consider piping a potential 1.2 million ft^3 of biogas into California's pipeline network (Bioenergy Insight, 2023; Kuiper, 2023).

4.3.4 Livestock

Cattle, pork, and poultry are the most common sources of livestock waste. The manure and other solid waste matter produced by these animals are collected, often in pools or lagoons. In open-air lagoons, the waste is left to biodegrade naturally with limited processing, resulting in fugitive CH_4 released into the air. Accordingly, industrial-scale commercial cattle operations along with other livestock are said to be responsible for 40% of global CH_4 emissions (Booker & Weber, 2022).

By creating an airtight seal on these lagoons, the conditions for an anaerobic environment are formed. The result is an AD with the ability to capture CH_4, preventing its release into the atmosphere. The CH_4 is then easily secured and captured, and the remaining matter leftover after the production lifecycle (known as "digestate") can also be used in a variety of applications, such as fertilizer or bioplastics (EPA & AgSTAR, 2023). The process can eliminate 90% of pathogens in the digestate, as well as concentrate nutrients beneficial for use as fertilizer (Steward et al., 2021).

<u>State Comparison: Colorado Dairy Farms</u>

Colorado municipalities have realized the potential and started capitalizing on their potential power generation from communities' agricultural by-products. The NREL assessed that one dairy farm with a herd of 13,000 head of dairy cattle could provide 1.1–1.9 MW of electricity back to the grid, even after using enough of their own RNG for pasteurization, chilling processes, and transportation of the milk via 14 CNG-fueled trucks per day (Steward et al., 2021). Colorado also lays claim to the largest biogas AD plant in the world (Sevcenko, 2016).

4.4 Stakeholder Engagement

A key piece of any policy lever must also consider public opinion and participation. Adequate development of RNG will require additional infrastructure and likely have significant impact (both positives and negatives) on the community surrounding sites that can be used for RNG.

As part of this process, researchers at East Carolina University (ECU) in Greenville, NC, interviewed the following three key groups with a focus on swine farms in eastern North Carolina, given the opportunity for RNG development from livestock:

1. Communities (mostly minority) that are near swine farms in eastern North Carolina
2. Concentrated animal feeding operation (CAFO) operators and owners in North Carolina
3. General community members in North Carolina.

For this analysis, research was conducted via focus group interviews, individual interviews, mailed surveys, and online surveys. Participants were asked about their personal experiences with neighboring swine farms; their views on the potential of RNG production from swine farms, landfills, and wastewater treatment facilities; and the types of biogas facilities that they would prefer. **Section 4.5.1, Survey Conclusions** summarizes those findings. A complete detailed analysis of the findings is discussed in **Section 5, Community Stakeholders**, and the methodology is provided in **Appendix C** of this report.

4.4.1 Survey Conclusions

Although stakeholder groups differed in their concerns about polluting industries, there were some patterns across stakeholder groups. In general, respondents shared the following:

1. An openness to the potential of biogas technologies to reduce harmful gases
2. A distrust in the industry to be transparent, inclusive, and innovative in responding to pollution in creative and safe ways
3. A concern that partial or incomplete investment in biogas technologies could only fuel future polluting industries.

With an open dialogue among different stakeholders, there is potential for positive change through the implementation of biogas technologies. Although the overwhelming majority of the research participants prioritized CAFOs as the site to focus on biogas capture, they saw the benefits in biogas capture at landfills and wastewater treatment facilities.

As biogas capture and other “green” technologies emerge and become implemented, success will be greater if:

- Affected communities are educated about the technologies

- Feedback from affected communities is sought and included in policies and practices
- Partners from affected communities are brought in as team members.
- Industry is mindful to focus on community-building and not just profits.

4.5 Policy Opportunities for North Carolina

North Carolina exemplifies unique and extensive opportunity to develop the technology, application, and marketplace for biogas products because of its existing biogas feedstock resources. With a steadily growing population, extensive swine and cow farms, substantial resources recently made available by the federal government, and recently updated state power sector regulations that call for a carbon neutral electric sector by 2050, policy changes could allow biogas-to-energy projects to play a substantial role in the clean energy transition (Cline, 2022; USDA & NCDA&CS, 2022; North Carolina General Assembly, 2017).

According to the EIA, nuclear and natural gas were the dominant sources of electricity generation in North Carolina in April 2023. Successful adoption and implementation of polices that support biogas-to-energy infrastructure development could provide substantial benefits, including decreased GHG emissions, improved public health, job creation, and other local community benefits, all while utilizing an existing, renewable resource.

4.5.1 *Existing Policies in North Carolina That Support Renewable Natural Gas*

North Carolina has a mix of existing clean energy and energy efficiency policies already available (DSIRE, n.d.). North Carolina's adoption of the Renewable Energy and Energy Efficiency Portfolio Standard (REPS), which was adopted in 2007, requires the state's investor-owned utilities to produce 12.5% of their energy needs from renewable sources or energy efficiency measures, which specifically include waste from swine (NCCETC, 2022; NCUC, n.d.).

In 2017, North Carolina Governor Cooper also signed House Bill 589 (North Carolina General Assembly, 2017), the "Competitive Energy Solutions for NC" Act. Among the many provisions geared toward supporting renewable energy development, procurement, and use, House Bill 589 contained provisions allowing for small power producers of RNG. House Bill 589 allows for small power producers, including those of RNG and biogas, to negotiate for fixed-terms contracts with public utilities.

As previously mentioned, North Carolina's Carbon Plan represents a critical piece of the clean energy future of the state. House Bill 951 (North Carolina General Assembly, 2021), which passed with overwhelming support in the state legislature, sets ambitious goals for reducing carbon emissions from electricity generation. NCUC issued its first Carbon Plan order on December 30, 2022, with a requirement that the plan must be reviewed every 2 years. This review process, which is currently underway, will allow important consideration—and reconsideration—of what has worked, what needs to be improved, and additional circumstances vital to achieving the original decarbonization goals of

House Bill 951. Working closely with the power sector and communities, this forum could prove fertile ground for RNG adoption and goal setting in the years ahead.

Finally, North Carolina has also adopted several requirements for the use of alternative fuels and fuel-efficiency requirements, as well as state government procurement requirements for alternative fuel vehicles (DOE, n.d.-d). These laws provide a basis for the potential use of, and market for, RNG as a transportation fuel.

4.5.2 *Landfill Gas*

According to the NCDEQ, there are more than 400 permitted solid waste facilities across the state (NCDEQ, n.d.-d). Separate data compiled by the EPA indicate that only 24 North Carolina municipal solid waste facilities have existing LFG projects (EPA, 2023b).

Sampson County, North Carolina is home to the state's single largest landfill and, according to the EPA, is the second largest CH_4-producing landfill in the country, emitting approximately 824,568 $MtCO_2e$ (Sorg, January 2023; EPA, n.d.-b). Most of this CH_4 is currently flared, but the company in charge of this landfill is considering capturing at least some of the biogas and upgrading it for use in natural gas pipelines (Sorg, June 2023). GFL Industries and OPAL Fuels, which are partners in this proposal, estimate that half of the emissions released at the landfill are CH_4, and the project would be able to capture more than 97% of that CH_4 (Wagner, 2023). This proposal and others like it could be analyzed through multiple lenses, including their impacts on emissions, economic opportunity, the community, and cost, among others (Sorg, June 2023).

In 2022, Duke Energy also announced further investments in two LFG projects in Caldwell and Person Counties to be used for RNG (Duke Energy, 2022).

Recommendations:

North Carolina policymakers could make use of the current focus and incentives, particularly at the federal level, for efforts to reduce CH_4 from any source, including landfills. Although LFG provides some level of current RNG production, that level is far below its potential in the state. Following policies enacted in other states, policymakers and regulators may consider more stringent efforts to reduce CH_4 emissions at current landfills, and certainly for issuing future permits, to require more aggressive capture and therefore potential use of the resource. Existing projects in North Carolina and other states demonstrate the opportunity and use of RNG from LFG.

4.5.3 Wastewater Treatment Plants

As North Carolina's population continues to grow, the ability to source biogas from WWTPs will increase proportionally. Although state policies may play a limited role in where new WWTPs are located, state oversight is critical to ensure that environmental and public health safety standards are met (NCDEQ, n.d.-b). Coupled with North Carolina's projected economic growth, these new WWTP sites present the opportunity to design new infrastructure to protect the environment and take advantage of potential RNG resources, but likely only with the necessary support from state policymakers (McConnell, 2023).

On their own, WWTPs are energy intensive to run. As WWTPs process waste and upgrade biogas, municipalities can use the biogas products as their own energy resource. When completed in 2024, the city of Raleigh's Bio-Energy Recovery Project, which is located at the Neuse River Resource Recovery Facility, is estimated to provide enough fuel for 70 of the buses in its fleet per year (City of Raleigh, North Carolina, 2023).

Recommendations:
North Carolina policymakers should continue their oversight role of WWTPs via the NCDEQ. As the state's population grows, new infrastructure will be needed in addition to upgrading and repairing existing infrastructure to meet projected demand. Stringent environmental protections combined with financial incentives for building and upgrading WWTP facilities could be considered a means of protecting public health and harnessing the potential of biogas, very similar to what Raleigh, NC, and Longmont, CO, are doing (Sevcenko, 2016; City of Raleigh, North Carolina, 2023). Existing federal credits from the EPA, in addition to new federal resources provided by the BIL, will help offset initial costs, and additional savings from utilizing the biogas products, either for the electricity or transportation needs of the municipality, could provide further economic and emissions reduction benefits.

4.5.4 *Livestock*

Biogas in North Carolina presents significant potential and viability. North Carolina's swine industry produces nearly two-thirds of the state's 24.3 million tons of manure, according to 2020 data from the ABC. Many CAFOs are concentrated in disadvantaged, marginalized, and often minority-heavy counties such as Duplin, Sampson, and Robeson. Many of these CAFOs operate lagoon systems, with limited remediation to address their GHG emissions or any other environmental concerns to which the adjacent communities are exposed. Installing AD systems and capturing the ensuing biogas can not only mitigate detrimental human and environmental health effects, but also produce energy from the biogas, a potential additional source of income to communities.

The primary challenge when trying to utilize biogas resources is the prohibitive transportation costs. Colorado meets its biogas operations with established success because of the state's relative ease in tying into the natural gas pipelines in the western half of the United States, thereby allowing Colorado to take advantage of California's generous LCFS subsidies as an example. North Carolina's current limitations of natural gas pipelines, or outright absence in the relatively isolated locations where biogas sources are typically found, would mean incurring the investment in the physical infrastructure or the development of a "virtual" pipeline of trucks to transport the biogas or biogas product to the nearest upgrading facility or pipeline injection station. Additional information regarding the economic viability of a virtual pipeline can be found in **Section 2, Technoeconomic Assessment of Major Biogas Sources in North Carolina** of this report.

Recommendations:

Livestock and agricultural production emit substantial amounts of GHGs, but also represent large opportunities for the capture and use of biogas. As more focus is given to these emissions, including critical resources from the federal government, technologies and best practices will rise to economic scale and become prevalent. The EPA data indicate there are already 10 ADs in operation in North Carolina. Commitment and support from state policymakers could encourage the construction of additional ADs to not only bring the technologies to scale, but also to help improve the economics of biogas-to-energy projects moving forward.

4.5.5 Environmental Justice Considerations

Although the production, development, and use of biogas infrastructure holds the potential for meaningful economic and climate benefits, consideration of any policy or project should adequately take EJ voices and concerns into account. The NCDEQ's Environmental Justice Program is a critical tool in this process (NCDEQ, n.d.-a). In fact, the EPA has released relevant guidance and considerations specifically for biogas projects (EPA, n.d.-a). This is especially relevant for North Carolina policymakers since most of the state's biogas feedstock resources are in EJ and underserved communities. Additionally, federal focus and resources, particularly through the Justice40 Initiative, should conceivably allow for more clarity in a complicated process of siting and permitting RNG. The voices of these communities and their concerns should be considered alongside the economic and climate impacts of any proposed project.

4.5.6 List of Policy Considerations

In addition to the recommendations discussed throughout this policy landscape analysis, the following are additional specific policy actions that could be considered:

1. The North Carolina Governor and/or General Assembly could establish a Commission to study additional questions and policies related to the development and use of biogas infrastructure, with a requirement that the Commission issue a report within a specified period that includes a list of policy options. This Commission could be established by the Governor via an EO or adopted by the legislature as a Blue Ribbon Commission (North Carolina Office of the Governor, n.d.; The North Carolina General Assembly, 2013).
2. The North Carolina General Assembly could require NCUC to study biogas-to-energy projects as a pathway to achieving the goals of the Carbon Plan.
3. As the NCDEQ and North Carolina Climate Change Interagency Council engage in permitting review processes through the Permitting Transformation Program, the General Assembly could require specific consideration of requiring a study to identify any barriers or hurdles that may exist to siting and permitting biogas-to-energy projects (NCDEQ, n.d.-c).
4. The NCDEQ could consider new or updated CH_4 capture requirements in permitting processes for landfills, WWTPs, and/or livestock facilities.
5. The General Assembly could explore additional funding avenues for compliance with CH_4 capture regulations.

6. The NCDEQ's Environmental Justice Program could consider the findings of this report, including the analysis provided by ECU, to further engage EJ communities in areas where biogas project development is under consideration.
7. Along with the NCDEQ Environmental Justice Program, the Governor could host a series of roundtable meetings with utilities, developers of biogas projects, communities, and agencies to identify areas of common ground or obtain consensus on biogas development by source.
8. The North Carolina Climate Change Interagency Council could study and report on the feasibility of biogas-to-energy projects as a means of complying with EO No. 80 and coordinating among relevant state agencies and stakeholders.
9. The NCDEQ State Energy Office and the North Carolina Department of Commerce could jointly study the economic impacts and opportunities of biogas infrastructure development by source and list the barriers of each.
10. The NCDEQ could review its Diesel Bus and Vehicles Program and identify potential complementary funding opportunities within the federal government for procurement of bio-CNG-ready transit and school buses and the feasibility of using bio-CNG as a transportation fuel, given North Carolina's potential for bio-CNG infrastructure.
11. Working alongside the findings of this report, the NCDEQ, the North Carolina Department of Transportation, and the North Carolina Department of Administration should study the feasibility of bio-CNG as a transportation fuel source for the purposes of complying with North Carolina statute 143-215.107C (North Carolina General Assembly, 2020), which requires state-owned alternative fuel vehicles and sets forth the fleet percentage.
12. The North Carolina Department of Revenue (NCDOR) should review and issue new guidance (if necessary) for the use of bio-CNG as a transportation fuel for the purposes of the state motor fuel tax and alternative fuels tax.
13. The NCDOR should review and issue guidance (if necessary) to determine whether bio-CNG, RNG, and bio-electricity comply with the definition of "clean energy" for the purposes of state renewable energy and fuel tax credits (NCDOR, n.d.).
14. The North Carolina General Assembly, working with NCDOR, could review and update (if necessary) the tax credits associated with CH_4 emissions reductions programs for large emitters, including ensuring that landfills, WWTPs, and CAFOs qualify.

4.6 Conclusion

The current marketplace for biogas products is dynamic, and policymakers must give careful and thorough consideration to this developing renewable energy source's future within the United States. Biogas is a burgeoning market, valued at more than $8 billion in 2022 and with predicted growth of 44% to more than $72.13 billion by 2030 (Business Research Insights, 2023). The United States already enjoys comparative success in the biogas market and does so while operating projects on only a fraction of the 7.9 billion tons of biogas produced annually (NREL, 2013). However, the federal funding made available by the BIL in 2021 and the IRA in 2022 provides notable opportunities and incentives to pursue biogas as a resource with the benefits previously discussed. In North Carolina, policymakers could consider these options and pursue further research and development regarding reducing emissions from RNG projects and direct use to effectively balance tradeoffs between emissions reductions, economic development, and community concerns.

5. Community Stakeholder Assessment

5.1 Introduction

A team of sociologists from ECU collected data on the views of different community stakeholders in eastern North Carolina regarding biogas capture technologies and their perceived impacts. The research methods included focus groups, individual interviews, and surveys. Participants were asked about their personal experiences with neighboring swine farms; their views on the potential of RNG production from swine farms, landfills, and WWTPs; and the types of biogas facilities that they would prefer.

The key stakeholder groups studied by ECU's research team included the following: (1) communities (mostly minority) that are near swine farms in eastern North Carolina, (2) CAFO operators and owners in North Carolina, and (3) general community members in North Carolina. Attempts were made to collect data from community leaders (e.g., members of the Chamber of Commerce); however, recruitment efforts yielded no results.

This report describes each method in detail (**Section 5.3**) and reports findings from our analysis of each stakeholder group (**Section 5.4**).

5.2 Summary of Findings at a Glance, by Stakeholder Group

This section of the report summarizes the findings, which have been grouped as follows: Communities (mostly minority) that are near swine farms in eastern North Carolina (**Section 5.2.1**), CAFO operators and owners in North Carolina (**Section 5.2.2**), and general community members in eastern North Carolina (**Section 5.2.3**).

5.2.1 Communities (Mostly Minority) That Are Near Swine Farms in Eastern North Carolina

The findings from respondents in this group are presented as follows:

- The community members are deeply concerned about the health and wellness of affected communities, mostly because of swine waste but also CH_4 in general.
- They note that these communities are often disempowered to make a change.
- The community members are concerned that the politics of the state will prevent effective new technologies from being implemented in marginalized communities.
- On average, the community members who responded are not pro-biogas.
    - The members do not want these technologies installed in their own "back yards," neither on swine farms nor landfills.
    - They still have concerns about the environmental impacts of swine farms, and they argue that biogas capture does not fix the underlying problem with swine waste.
    - The community members are concerned that installing biogas technologies will only enable polluting industries to expand.
- If biogas capture technologies are to be pursued, then they believe that the technologies should be installed on swine farms first and then at landfills and WWTPs.

- The community members want more transparency, accountability, and community buy-in on local policies and procedures (e.g., permits), as well as a voice in industrial decisions that impact the community.

5.2.2 Concentrated Animal Feeding Operation Operators and Owners in North Carolina

The findings from respondents in this group are presented as follows:

- They are aware of and sensitive to environmental issues related to swine farming.
- As a group, they are open to new biogas capture technologies—they can see the benefits in terms of environmental impacts.
- The owners and operators are skeptical about the feasibility of installation and implementation.
- They are critical of industrial practices and policies that undermine environmental progress in the name of protecting corporate profits.
- Ultimately, the owners and operators are concerned about their own costs. If the bulk of the costs is incurred by industry or the government, then these industry stakeholders would support and even welcome biogas capture.

5.2.3 General Community Members in Eastern North Carolina

The findings from respondents in this group are presented as follows:

- The general community members support the swine industry as important for economic success in eastern North Carolina.
- They are concerned about the environmental impacts of the swine industry.
- The general community members are ambivalent about the impacts of biogas capture technologies regardless of location (swine farms versus landfills or WWTPs), possibly because of a lack of knowledge.
- The general community members are optimistic about the financial benefits of biogas capture.

5.3 Research Methodology

This section of the report discusses the following ways in which data were collected: focus groups (**Section 5.3.1**), ethnographic field observations (**Section 5.3.2**), surveys (**Section 5.3.3**), and one-on-one interviews with CAFO operators (**Section 5.3.4**).

5.3.1 Focus Groups

The research team followed a standard focus group protocol by designing a semi-structured discussion script, delineating the impacts that the introduction of biogas-to-energy projects on industrial swine farms could have on nearby communities. The goal of small focus group discussions was to capture all biogas themes and impacts and their rankings (from more significant to less significant and from larger in scope to a lesser in scope) prevailing in communities residing in a vicinity of industrial swine farms, and to a lesser degree, near landfills and WWTPs. Focus group methodology suggests that in a relatively homogeneous population, between three and six focus groups are likely to identify 90% of the themes

(Nyumba et al., 2018). In our case, by the fourth and fifth focus groups, no new biogas themes were introduced, while their ranking coalesced in a relatively stable hierarchy of biogas impacts evaluation. Thus, it could be claimed that while our research cannot be considered representative of the opinions of all community members, it is sufficient to generate methodologically valid data for outlining the structure of communal views on biogas-to-energy projects.

<u>Focus Groups Sample</u>

This report is based on the data collected in six focus groups conducted by a team of faculty from ECU's Sociology Department in North Carolina's Duplin and Sampson Counties in February through June 2023. Each focus group varied in size from 8 to 12 participants who were living in the vicinity of industrial swine farms and/or landfills and who volunteered to share their concerns and opinions about proposed development of biogas facilities in the area. A total of 55 focus groups participants were recruited by announcements in local churches and other civic venues and were conducted in local church halls.

3 out of 4 participants were women, and 9 out of 10 were African Americans. Half had completed high school as their highest level of education, 7 had associate degrees, and 13 were college graduates. The ages of the participants varied from 24 to 84, with a median age of 63 years old (half were younger than 63 and half were older than 63). Of the focus group participants, 17 were retirees, 10 were employed as sales and administrative assistants in various offices, 6 were working as teachers and substitute teachers, 5 were working as machinery technicians or drivers, and 1 was a nurse. In terms of education and social class, most of the participants could be considered to be in the lower middle class.

Of the participants who live near the swine farms, 20 live less than 1 mile from a swine farm, 7 of whom reported living half a mile or closer. 5 participants live less than 2 miles from a swine farm and the remaining participants live 3 miles or farther. Of the 55 participants, 51 were from Duplin County and 4 were from Sampson County in North Carolina.

Participants were given grocery store gift cards to thank them for their time. Moderated focus group discussions lasted from 1 hour and 15 minutes to nearly 2 hours, depending on the length and number of responses.

<u>Measures</u>

Discussions in the focus groups were structured by dividing the questions into the following four topics or blocks in order to elicit opinions and provide in-depth understanding of participants' views on the following items:

1. Positive, as well as negative, economic, social, and environmental impacts of industrial swine farming

2. Positive, as well as negative, economic, social, and environmental impacts of biogas-to-energy projects on industrial swine farms

3. Preferences or ranking of different technological types of biogas utilization that could be developed on local swine farms (i.e., on-site bio-electricity production, "virtual pipelines" where biogas is transported to a central location using tanker trucks, and physical biogas pipelines where biogas is transported from swine farms to central locations via low-pressure pipelines networks)

4. Preferences or ranking of different sources of biogas feedstocks available for development in local areas (i.e., collection of biogas from swine farms, landfills, or WWTPs).

Discussions of each of the previously mentioned four topics were based on a card ranking activity conducted by the participants. During this activity, each card listed a particular issue characterizing that particular topic. The four topics and their issue cards are presented in **Table 3**.

Table 3. Topics and Their Issue Cards for the Focus Group Discussions.

<table>
<tr><th colspan="2">Topic One: Impacts of Industrial Hog Farming</th></tr>
<tr><td>Positive Impacts</td><td>Negative Impacts</td></tr>
<tr><td>• Creates jobs in local communities
• Supports local organizations through sponsorships and scholarships
• Local hog farms make available low-priced good quality pork to local communities
• Pays taxes that benefit local communities</td><td>• Hog manure decomposing in lagoons releases greenhouse gases that contribute to global warming and climate change
• Water polluted in creeks, rivers, ponds; water blooming
• Hogs in farms are raised inhumanely, animals are suffering
• Negative impact on property values, people leaving
• Rodents, flies, mosquitoes
• Hog manure smell
• Trucks hauling hogs & feed; roads damaged (potholes, ripped asphalt)</td></tr>
<tr><th colspan="2">Topic Two: Impacts of Biogas Development on Industrial Hog Farms</th></tr>
<tr><td>Positive Impacts</td><td>Negative Impacts</td></tr>
<tr><td>• Reduce greenhouse gas emissions from hog farms to slow down global warming and climate change
• Reduce air pollution
• Create jobs
• Create revenue for local farmers
• Drive greater economic development for the area
• Bolster local taxes</td><td>• Polluting gas collection facilities
• Does not fully solve North Carolina's hog waste problem
• Could lead to expansion of the hog farming
• Gas pipes stretching across the country
• Too few jobs created; job creation may be temporary
• More heavy trucks; roads damaged (potholes, ripped asphalt).</td></tr>
<tr><th colspan="2">Topic Three: Technological Types of Biogas Production Preferences</th></tr>
<tr><td colspan="2">• I don't want to see biogas facilities built and operated in or near my community.
• I don't care which type of biogas facility is built and operated in or near my community.
• I would prefer that biogas is collected and used for electricity generation on the farm only (Option 1).
• I would prefer that biogas is collected from hog farms by trucks and trucked to a centralized gas collection facility (Option 2).
• I would prefer that biogas is piped from hog farms by underground pipes to a centralized gas collection facility (Option 3).</td></tr>
<tr><th colspan="2">Topic Four: Preferences for Local Sources of Biogas Production</th></tr>
</table>

- I don't want to see biogas facilities built and operated in or near my community
- I don't care which source of biogas facility is built and operated in or near my community
- I would prefer biogas being collected from hog farms
- I would prefer biogas being collected from landfills
- I would prefer biogas being collected from sewage/wastewater treatment plants

Issues listed on the cards were derived by operationalizing the goals of the research project titled Biogas Utilization in North Carolina: Opportunities and Benefits into measurable observations. When constructing the cards, the research team also drew upon extensive scholarly literature on economic, social, and environmental impacts of industrial swine production, as well as our own experience with conducting such research in North Carolina, as well as internationally (in eastern Europe).

<u>Focus Group Procedures</u>

The focus group discussions began with the moderator distributing four cards listing swine farming benefits to communities and asking the participants to rank them from what they would consider to be the most significant to the least significant. Once card sorting was finished, the moderator asked each individual participant one by one about their first choice in a stack of cards and the reasons for that preference while also soliciting comments from the entire group. Then the moderator moved to the second choice in the stack of cards and asked the participants to explain that preference and so on with the third card and the fourth card. Upon covering all four cards, the moderator inquired whether there any other benefits that participants could point to that were not covered and whether there were any other comments. The discussion of swine farming benefits concluded with the collection of ranked stacks of four cards each. The card preferences were later entered in Microsoft Excel for statistical analysis. Then the focus group moved to the second topic, which focused on ranking seven cards that listed the negative impacts of swine farming on local communities from most significant to the least significant. Once all the participants had completed their ranking choices, they discussed them in the manner previously described.

The discussion of the second topic (i.e., the impacts of biogas infrastructure development on industrial swine farms) began with a moderator giving a short presentation about three types of biogas technologies available for use on swine farms, landfills, and WWTPs. For this purpose, two handouts were distributed to the participants. The presentation focused on a description of potential impacts in and near the swine farm once it had equipment installed for biogas projects and was operational. These potential impacts then were operationalized in two sets of six cards each: one listing the positive impacts from biogas technology and the other listing the negative impacts from biogas technology. The focus group participants ranked and then discussed the cards that listed the positive and negative impacts from biogas technology by using the similar process as was used for the discussion of swine farming impacts previously described. The focus group concluded by ranking and discussing the biogas products (the third topic) and biogas sources (the fourth topic). The overall focus group protocol is discussed in **Section C.3, Appendix C**.

5.3.2 Ethnographic Field Observations

Ethnographic field observations of the focus group meetings were used as another method to collect data on the stakeholders' views. The methodology behind ethnographic field observations aims to capture a wealth of data about the situational context, interactional style, content of communication, and even physical space in which interactions occur. Ethnographers observe and record as many details as possible when collecting data in a social setting. Ethnographers take "field notes" after leaving each site, providing a "thick description" that is thorough enough that a person who was not in the setting can read the field notes and understand what occurred during the observation period (Geertz, 1973). In this study, we recorded field notes after each focus group and a team member also attended a town hall meeting to record field notes. Analyses of these data are included in **Section 5.4, Findings** of this report.

5.3.3 Surveys

Data were collected through two different survey instruments: a survey of swine CAFOs and a general survey of "swine country" residents' perceptions of biogas development.

Survey One: Survey of Swine Concentrated Animal Feeding Operations

This survey was developed in consultation with ECU's Center for Survey Research. The research team was given a current listing of all swine farms in North Carolina that hold permits from NCDEQ's Division of Water Resources. The list included permit information for 2,277 swine operations. The listing did not provide telephone numbers; therefore, the decision was made to mail a pen and paper questionnaire through the U.S. Postal Service. Based on recent mail surveys conducted by ECU's Center for Survey Research, we anticipated a response rate of between 8% and 10%.

Eliminating duplicate listings (N = 153) and incomplete mailing addresses (N = 108) yielded 2,016 permitted swine operations with a valid mailing address. Surveys were mailed to all 2,016 swine operations via First Class Mail. A pre-survey postcard was distributed the week of April 21, 2023. This postcard briefly described the project and alerted recipients that a survey would be arriving soon. A week later, the survey booklet was sent on April 28, 2023. This booklet included a cover letter describing the project that clearly communicated the voluntary and confidential nature of the process. A business reply envelope was also included for participants to use for returning the completed survey. Two subsequent follow-up postcards were sent as reminders approximately 1 and 2 weeks after the questionnaire was mailed. The mailings also included a quick response (QR) code that participants could use to take the survey online via their telephones. In all, 65 surveys were returned, comprising a response rate of approximately 3.2%. Surveys were entered into an SPSS data file, and results were analyzed using the SPSS statistical analysis software.

Concentrated Animal Feeding Operation Operator Sample

Demographics: CAFO operators in the sample ranged in age from 49 to 91 with a median age of 65 years. Nearly all respondents identified as men (96%), and all respondents were White. Approximately three out of four CAFO operators indicated their political affiliation as Republican (77%); 21% identified themselves as Independent and 2% as Democrat. In terms of education, approximately one third (31%) of the CAFO operators reported that they had received a high school diploma or general educational development (GED) diploma; another 40% reported having completed an associate's degree or trade or technical school beyond high school. Approximately one in five (19%) of the CAFO operators reported completing a 4-year degree, and 10% of the remaining participants reported having some post-graduate professional school or training. The income for CAFO operators is notably above statewide norms, with more than half (54%) reporting household incomes of at least $120,000; only 5% of the remaining participants reported having incomes below $60,000.

Farming Role and Background: One in five participants (19%) indicated they were the site manager; the remaining 81% reported that they were owners. Approximately 7 in 10 participants (71%) reported that they grew up in families where farming was the primary source of income, and 64% said that they started swine farming on land they already owned. As a group, the participants said that they have been in the swine farming business for a long time. The mean year they began any form of farming for a living was 1983. Three-quarters of the participants said that they began farming 33 or more years ago prior to 1991; only 25% of the participants reported that they began farming after 1991.

Similarly, the participants said that they are also long-term swine farmers, with the mean year they began farming at the large scale being 1988. Approximately half of the participants (50%) reported that they built their first swine facility prior to 1989, and only 25% reported getting into the large-scale swine business since 1995. Alternatively stated, the typical operator responding to our survey has been in the swine business for 40 years, suggesting that they are nearing retirement. Nearly half of the participants (46%) reported having "feeder to finish" operations, which comprise the last two of the three-stage production process that take recently weaned pigs through delivery to a processor. Other stages in the process are comparably represented with the exception of "farrow to feeder" operations, which are unrepresented our sample.

Farm Characteristics: Farm size varied widely, from a minimum of 24 acres for the smallest farm to 2,000 acres for the largest farm. The mean farm size was 339 acres with a median of 175 acres, indicating that the mean size is pulled up by a smaller number of very large farms. The median size of 175 acres indicates that half of all farms were smaller than that. The portion of these farms devoted to raising swine ranged from just 3 acres to as many as 350 acres. A median of 30 acres, or approximately 17% of total farm acreage, is devoted to swine farming, suggests that many of these farms may also produce various types of row crops.

Another way to gauge the size of swine operations is the number of hogs on site at a given time. Again, the farms represented here range dramatically in size from zero hogs to 33,000. Yet, the median herd size was 3,810 with a mean of 5,713. On average, the swine operations represented here had a mean of 6.0 barns and 2.73 waste lagoons. Thus, the median of four barns indicates that half of these operations had four or fewer barns and no more than two waste lagoons. The means are skewed upward by a small number of swine operations with more than 10 barns (12.5%). Similarly, approximately three-quarters (77%) of operations have just one or two waste lagoons.

Finances: The participants estimated the annual gross income of their overall farm operations. The annual gross income reported by the participants was as high as $3 million with a median gross income of $200,000. The median value indicates that half of the swine operations had annual gross revenues below $200,000 and half above it. The mean gross income of $546,316 indicates that the overall results have been skewed upward by a small number of very big operations. Finally, the participants estimated the percentage of their total farm revenue that came from their swine operations. Median values will provide a more typical portrait of the swine operations represented here. Hogs contributed from 0% to 100% of overall farm income. The median of 75% indicates that half of all farms derived approximately three-quarters of their total income from the swine operation. In other words, the swine operations were the primary money maker for a majority of these farms.

Farming Contracts: The participants were asked a set of questions about whether they were raising hogs under contract and most of the participants (82.7%) reported that they were, in which case they were asked the details of those contracts. Most of those contracts (79.1%) were directly with Smithfield Foods. A smaller portion of the participants (16.3%) were contracted with Prestage Farms Inc., 2.3% had contracts with Murphy/Brown LLC, and the final 2.3% had contracts with Carolina Swine Integrators. Out of the 65 respondents, 43 indicated that they had previously held a contract with a different integrator than the one they were currently with. Half (48.8%) of those 43 participants had previously held a contract with Murphy/Brown, and 15.0% had previously held a contract with Carroll's Food Inc. Smaller numbers of the participants (between 2.6 % and 7%) indicated that they had previously held a contract with another integrator or had never contracted. Finally, the participants were asked how they initially came into contact with the first integrator with which they contracted. The two most common methods were through fellow farmers (34.1%) or through direct recruitment by a company representative (30.1%). Other notable pathways for obtaining a contract were through family members (15.2%) and friends (18.9%). In general, this set of questions revealed that the overwhelming majority of large-scale swine operators in this region are raising hogs under direct contract with Smithfield Foods. Although a few other, smaller options exist, Smithfield Foods (and by extension, the WH Group) appears to be the primary swine operator in eastern North Carolina.

Measures: The entire mailed survey is presented in **Section C.1, Appendix C**. An electronic version was also made available to the farmers, through a link or a QR code.

Survey Two: General Survey of "Swine Country" Residents' Perceptions of Biogas Development

The research team once again partnered with ECU's Center for Survey Research to conduct a survey of residents living in seven North Carolina counties that represent the heart of swine country (i.e., Bladen, Duplin, Greene, Pender, Robeson, Sampson, and Wayne). The participants were asked a series of questions designed to elicit their thoughts regarding the potential for biogas development in their communities, as well as their perceptions of positive or negative impacts of potential biogas capture technologies within their communities. Responses were gathered through randomized telephone samples conducted by Bovitz and Clint (formerly Lucid). Responses were received from 212 residents between May 8–12, 2023.

Community Sample: To ensure an accurate sampling of swine country residents, the sample was weighted for several demographics, such as gender, race/ethnicity, education level, and age to provide percentages reflective of the latest state population estimates for the seven-county region. **Table 4** presents estimates of demographic characteristics of the study region, characteristics of the unweighted sample, and the weighted sample, which is used for analyses of data.

Table 4. Community Survey Population and Survey Sample Characteristics.

	Population 2022 Census Data	Unweighted Survey Sample	Weighted Survey Sample
Total Population Sample Size	453,425	212	212
Gender			
Female	49.0	71.2	49.0
Male	51.0	28.3	51.0
Race/Ethnicity			
Black or African American	25.1	34.4	25.0
White	47.6	55.1	48.0
Hispanic or Latino/Latina	13.3	3.3	13.0
Native American	9.9	7.5	10.0
Other	4.1	1.4	4.0
Education			
High school or less	51.4	38.7	51.0
Some college	32.3	41.9	32.0
4-y college degree	11.3	15.1	12.0
Post-graduate degree	4.9	4.2	5.0
Age			
18–24 years	11.5	18.5	12.0
25–35 years	16.1	19.9	16.0
36–45 years	15.4	21.3	15.0
46–54 years	16.5	14.2	16.0
55–64 years	17.7	14.7	18.0
65 years and older	22.6	11.4	23.0

Comparing the population, sample, and weighted sample demographics, we see that the survey predominantly sampled female respondents over male participants. Additionally, the survey disproportionately sampled Black and White respondents over Hispanic, Native American, or other participants. Regarding education, the survey disproportionately sampled individuals who had attended or graduated from college over those who had not. Regarding age, the survey disproportionately sampled younger individuals over older participants. However, once properly weighted, the weighted survey sample accurately reflected the population demographics. Therefore, to ensure that the findings best represent the surveyed population, we conducted the following analysis on the weighted survey sample.

Respondent connections to the swine industry: Several questions explored what connections, if any, the participants had to the swine industry. The participants were asked to estimate how close their residence was to a large-scale swine farm. Approximately 1 in 10 (11.3%) said they were "less than a mile" from a swine farm, 23.7% said that there was one within "a couple of miles," 39.6% said there was one "more than 5 miles" away, and 25.5% said they "were not sure" about the distance. Approximately three in five participants (61.2%) reported that they did not personally know someone who owns or works for a large-scale swine farm. Among the 38.8% who do, they reported those contacts as friends (62.4%), family (26.6%), neighbors (8.6%), others (2.4%).

Taken as a whole, these data suggest that many of the residents of these seven counties live close to a large-scale swine farm, but only a few live in immediate proximity to one. Furthermore, slightly less than half of the residents have a personal connection to a large-scale swine farm, and the overwhelming majority of those connections are either friends or family members.

Measures***:*** The entire survey instrument is included in **Section C.2, Appendix C**.

5.3.4 One-on-One Interviews with Concentrated Animal Feeding Operation Operators

All CAFO operators were invited to speak confidentially in the form of a one-on-one interview with a member of the research team if they wanted. Two participants agreed to participate in the one-on-one interview, explaining that the survey did not capture all their interests, experiences, and concerns. A member of the research team contacted each respondent and scheduled a time to meet virtually via Microsoft Teams or Zoom. The team member used a semi-structured interview guide in these interviews and had a set of questions to ask each participant based on the survey instrument itself; however, the one-on-one interview was still flexible and allowed each participant to steer the conversation into areas that the individual believed needed to be addressed. Each in-depth interview lasted longer than 1 hour. The interviews were recorded, transcribed using OtterAI, and coded for patterns using a grounded method of qualitative analysis.

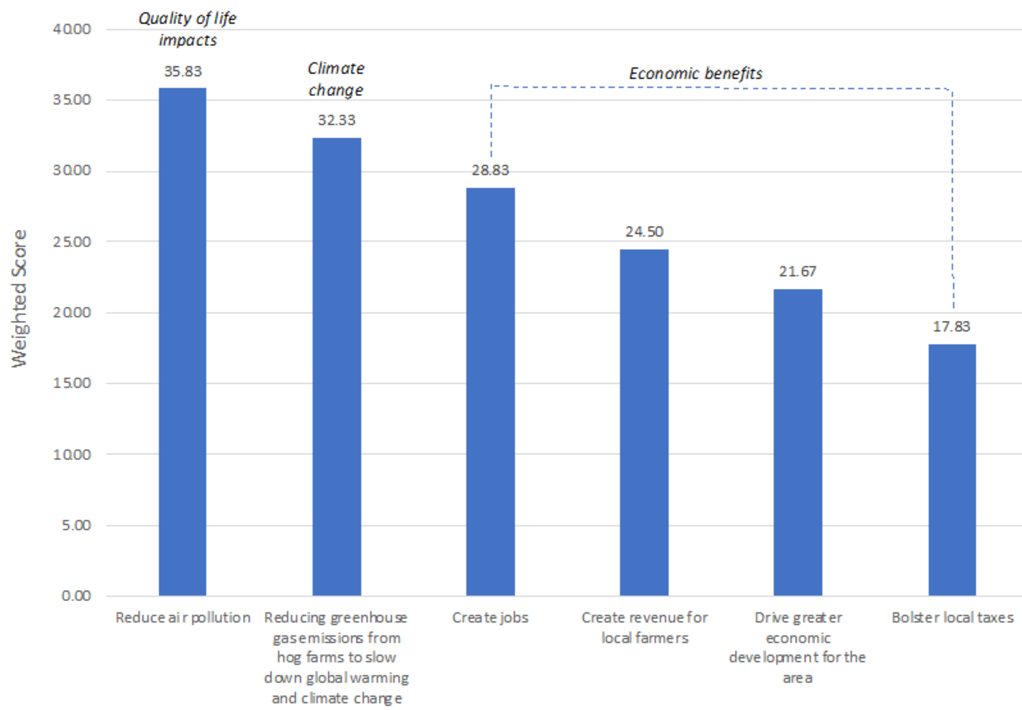
5.4 Findings

The findings from the study are reported in depth by stakeholder group with the goal of capturing all the data collected by each of the research methods as well as understanding the motivations of each stakeholder group in context. **Section 5.5, Analysis and Conclusions**, reports on overall patterns in the findings.

5.4.1 Findings from Communities (Mostly Minority) That Are Near Swine Farms in Eastern North Carolina

Overall Attitudes: Among this group of largely African American respondents living near swine farms, the participants were open and receptive to biogas technologies once they learned more about them. As the data in **Figure 15** show, the participants agreed that biogas technologies were beneficial in numerous ways.

Figure 15. Biogas Positives Weighted Scores (#1 = 1, most significant to #6 = 0.17, least significant). (N = 51).

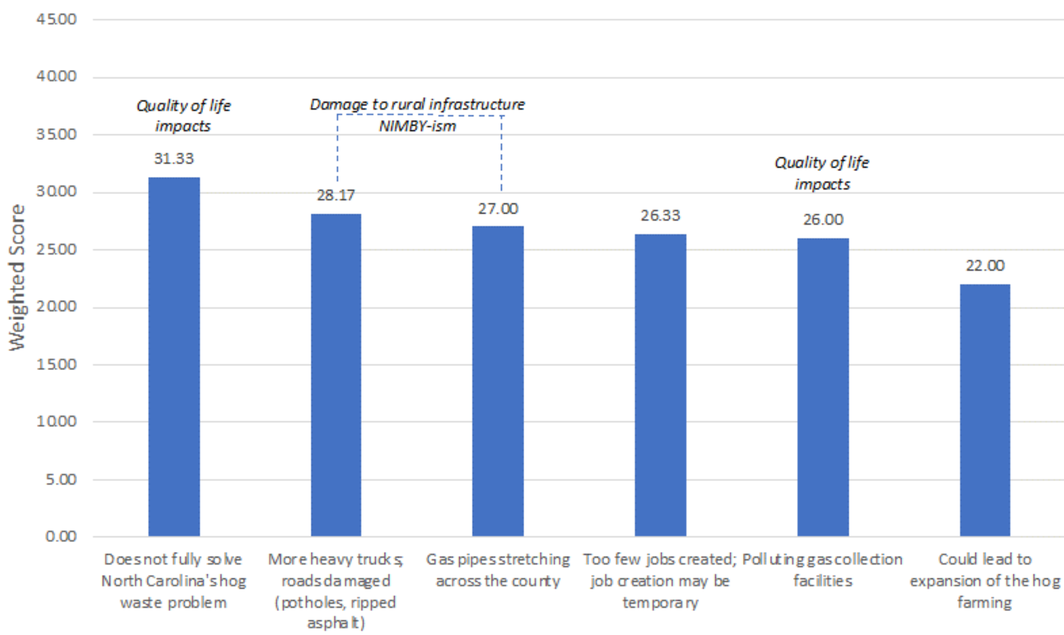


The large majority of participants believed that biogas technologies would reduce air pollution and slow down global warming. Most of the participants said that they believed that biogas technologies would create jobs; however, despite their general positive reception toward biogas, most participants were skeptical about the ability of biogas technologies to fix underlying problems. As the data in **Figure 16** show, participants believed that the swine waste problem would not be affected by biogas technologies; instead, they said that biogas capture technologies might actually make the problem worse because it might incentivize the expansion of swine farming. In one focus group in Sampson County, NC, the participants argued that the same problem would happen if biogas technologies were installed at landfills. One participant explained,

> *"Sampson County ranks second in the nation in methane emissions: 824,568 metric tons of carbon dioxide equivalents, according to the 2021 EPA figures. Of the estimated 1,321 municipal solid waste landfills in the United States, only a facility in West Palm Beach [Florida] emits more, at 1.01 million metric tons of CO2 equivalents."*

Some participants in this focus group rejected the value of biogas technologies altogether. As one participant remarked, *"I'm not so sure there's any actual capture that benefits the community because you're creating more methane … I see all of this stuff as greenwashing."*

Figure 16. Biogas Negatives Weighted Scores (#1 = 1, most significant to #6 = 0.17, least significant). (N = 51).



Note: NIMBY = not in my back yard.

<u>Prioritize Improvements to the Swine Industry</u>: Although support for biogas technologies was low, when asked to rank sites for installing biogas technologies (**Note:** One focus group refused to sort cards or to rank sites), the most commonly preferred source for biogas was swine farms, followed by landfills, and WWTPs. Participants prioritized swine farms because they are more numerous than the other two categories and because the participants said they are more affected by them daily.

The focus group interviews provided an opportunity to gain an understanding of the various impacts that swine farming and the biogas industry have or could have on local communities. For example, during discussions with the local residents, a distinct hierarchy of impacts emerged. Specifically, industrial swine farming had the most extensive impact on the quality of life of the residents, whereas the next two issues—economic development and GHG reduction from swine farms—were less important.

<u>Not in My Back Yard</u>: Participants had protracted and heated discussions; most of the respondents in the focus groups preferred an option of "I don't want to see biogas facilities built and operated in or near my community." Such an opinion (referred to as "not in my back yard" [NIMBY]) prevailed, despite participants agreeing on biogas industry benefits that are not insignificant, especially when compared to the status quo. For example, the overwhelming majority of focus group participants ranked "Reducing greenhouse gas emissions from swine farms to slow down global warming and climate change" as the second most important benefit of the biogas industry, after the most important, "Reducing air pollution."

However, in the hierarchy of swine farming impacts on local communities, the issue of GHGs was deemed to be of the lowest importance.

Similarly, although limited and mostly indirect economic benefits of biogas development were considered more important than biogas capture to reduce global warming, they were also not the ultimate concern and preoccupation of the participants. Instead, the community members were interested primarily in improving the quality of life in local communities which, in their view, largely would not be assisted by biogas industry development. More specifically, although biogas conversion projects would limit air pollution by having manure lagoons covered by synthetic cover to capture CH_4, it would do little to mitigate the most pressing issue for local communities—reducing the impacts of large-scale discharges of swine manure slurry in surrounding areas.

The acknowledgement and then discounting or dismissing the biogas benefits via the position of "I don't want to see biogas facilities built and operated in or near my community" can only in part be accounted for by their paucity. Two additional and complementary NIMBY discourses were used by community representatives in their biogas rejection explanations. The first was reflective of a bitter sense of being disregarded and disempowered by industrial swine farming interests and their allies and of deep mistrust and skepticism that the swine industry and its supporters in the pro-business North Carolina legislature would in good faith consider accommodating local communities' interests in biogas development. What one participant referred to as "*they*" only "*take the land and give us nothing … because the hog industry lobbies those in the government, and the government ignores local communities … we don't stand a chance if they decide to build chicken or hog farms.*"

Also derived from the skepticism and mistrust was the second, biogas NIMBY discourse; however, the NIMBY-ism was reflective, not as much of narrow and selfish views of the biogas opponents, but more about the vulnerability and disempowerment of communities of color subjected to large-scale toxic emissions and noxious odors from swine farms. More specifically, if the industrialization of swine farms could not be forestalled because of the powerlessness of local communities, then the second preferred option was either to:

- Restrict biogas collection and conversion to bio-electricity to the swine farms that have minimal potential to impact local communities, or
- Use biogas collection on geographically further removed landfills.

In the words of one of the participants,

> *"I think it [biogas conversion] can be helpful. I just don't want to see it next door to me. … I'm gonna stay in Roseboro on my land where I'm at. I just don't want it around me."*

Such views were especially prominent during a discussion of biogas-to-energy projects that involved physical pipeline networks connecting swine farms to a centralized gas collection facility. This type of biogas infrastructure is currently under construction in Sampson and Duplin Counties as a part of a $500-million investment project by Smithfield Foods, which is the nation's largest pork producer, and

Dominion Energy. The project is titled Align RNG. The project involves collecting and processing biogas from swine waste from 19 nearby farms and piping biogas via 30 miles of pipelines to what will be a newly constructed natural gas processing plant in Turkey, NC. The new plant is slated to be operational sometime in 2023. The second project, which involves connecting 35 farms in Duplin County, NC, is scheduled to be completed in 2026.

The Align RNG project in Sampson and Duplin Counties elicited especially strong criticisms and objections from the focus group participants because it required easements from 75 property owners to lay the pipes. The overwhelming majority of the participants considered the property easement clause as a menacing sign of further disempowering and disregarding the interest of local communities. Thus, the biogas NIMBY view was agitated primarily by the deep mistrust of the state authorities that were "in the pocket of the swine industry" and have a long history of dismissing or disregarding the interests of the local communities.

5.4.2 Findings from Concentrated Animal Feeding Operation Operators

Moderate Biogas Experience and Knowledge: Only 3.5% of the survey participants were currently using biogas capture technology on their farms. In terms of self-rated expertise regarding biogas capture technology, on a scale of 1 to 7, with 1 being "Completely Unaware" and 7 being "Expert", the participants' responses trended toward the middle with a mean of 3.8 and a median of 4 (which means "Aware"). Most of the participants (75.5%) indicated one of the three middle categories (3 to 5) and not a single respondent rated themselves as a 7 (an "Expert").

Business Concerns: The swine operators were asked a series of questions to determine their level of concern about potential issues in developing biogas capture.
Table *5* presents an overview of the concerns that surfaced because of the questions. The operators' two greatest concerns both involved the potential costs of biogas development on their swine operations. Nearly seven out of eight participants (83.3%) rated additional expenses from constructing new waste lagoons as a major concern, and 81.0% rated the prospect of taking on additional debt to pay for biogas technology as a major concern. The other major concerns of swine operators were complying with new environmental regulations and oversight (66.7%) and having to build and maintain new machinery (52.5%). Swine operators were least concerned by the prospect of the construction of pipelines connected to their farms and increased traffic from the transport of biogas, with only 20.0% and 15.4%, respectively, seeing them as relatively minor concerns.

Table 5. Potential Concerns About Biogas Capture, with 0 = No Concern, 1 = Minor Concern, and 2 = Major Concern (N = 65).

Potential Concerns	Percentages (%)			Mean (Standard Deviation)
	No Concern	Minor Concern	Major Concern	
Taking on the expense of constructing an additional or new lagoon	4.8	11.9	83.3	1.76 (0.52)

Taking on additional debt to pay for this technology	7.1	11.9	81.0	1.72 (0.57)
Having to comply with new environmental regulations or oversight	4.8	28.6	66.7	1.62 (0.60)
Having to build and maintain new machinery on your farm	2.5	45.0	52.5	1.50 (0.58)
Increased maintenance time and/or costs	2.6	48.7	48.7	1.45 (0.58)
The amount of disruption involved in adopting the new technology	14.3	52.4	52.4	1.20 (0.67)
Entering into a contractual relationship with an energy company	19.5	56.1	56.1	1.02 (0.63)
The construction of pipelines connected to your farm for the transport of biogas	25.0	55.0	55.0	1.00 (0.68)
Increased amount of traffic from the transport of biogas	20.5	64.1	64.1	0.95 (0.59)

The participants who were interviewed underscored their concerns about cost. One participant noted that industrial leaders have undermined the development and implementation of environmentally progressive technologies by refusing to support the costs. As one participant, a longtime swine farmer, said:

> *"The CEO [Chief Executive Officer] of Smithfield Foods, said, you know, 'We're not interested in doing things that make no profit, if there's no profit in it, we as a corporation, and that's business sense. You know, that's the way it works. We're not interested in investing in technologies that have not been proven.'*
>
> *And all the technologies like osmosis and reverse osmosis [are] what we're headed toward, hopefully. And with that simple solution, and I've been to dairies, the wastes that come out of the cow that morning, you can drink the water that afternoon. I've done it. I've drank the water. We had that same technology. Twenty-five years ago in Greenville, North Carolina, and the hog farm there. I actually drank the water that came out of the hot pit 2 hours earlier. [It's] okay, as drinking water. They never adopted the technology. Why? I don't know. It seems like to me it would, they would want to be popular in an environmentally friendly, but I know it's very, very expensive, and they're about profit, and they're not bad expenses, but that's a corporate thing."*

Based on the results of the study, most swine farmers are unwilling and unable to shoulder the financial burden of new technologies and would need industry to support the cost.

<u>Open to New Technologies</u>: The swine operators were asked a series of questions to determine their perceptions of the potential benefits associated with developing biogas capture on their farms. **Table 6** presents an overview of the perceived benefits that were mentioned during this questioning. The participants' perceptions of the potential positive outcomes of biogas infrastructure development were mildly positive, indicating that overall, they believed somewhat in the validity of these positive outcomes. Furthermore, the operators' ratings of these outcomes largely labeled them as either "minor" or "major" benefits. Only a small percentage of participants (between 5.7% and 15.4%) rated any of the 10 potential outcomes as "no benefit" with the rest evenly split between "minor benefit" and "major benefit."

The five outcomes that participants viewed as having the most potential were as follows:

- Making it easier to comply with any future environmental regulations (50.9% rating it a "Major Benefit")
- Reducing the potential negative impacts of your farm on your neighbors (50.9% rating it a "Major Benefit")
- Improving the public perception of your farm (49.1% rating it a "Major Benefit")
- Reducing the potential negative impacts of your farm on the environment (48.1% rating it a "Major Benefit")
- Reducing your potential liability in any future nuisance lawsuits (48.1% rating it a "Major Benefit").

Table 6. Perceived Potential Benefits of Adopting Biogas Capture Technology on Your Farm, with 0 = No Benefit, 1 = Minor Benefit, and 2 = Major Benefit (N = 65).

Potential Outcomes	Percentages (%)			Mean (Standard Deviation)
	No Benefit	Minor Benefit	Major Benefit	
Being better prepared for any future shifts to renewable energy	5.7	47.2	47.2	1.42 (0.60)
Reducing overhead by producing your own electricity	5.7	47.2	47.2	1.42 (0.60)
Improving the public perception of your farm	11.3	39.6	49.1	1.38 (0.68)
Making it easier to comply with any future environmental regulations	15.1	34.0	50.9	1.36 (0.74)
Reducing the potential negative impacts of your farm on your neighbors	15.1	34.0	50.9	1.36 (0.74)
Reducing your potential liability in any future nuisance lawsuits	13.5	38.5	48.1	1.35 (0.71)
Reducing the smell from your waste lagoons	7.5	50.9	41.5	1.34 (0.62)
Reducing the potential negative impacts of your farm on the environment	15.4	36.5	48.1	1.33 (0.73)
Reducing your potential liability in any future environmental lawsuits	15.1	39.6	45.3	1.30 (0.72)
A profitable addition to your business	13.5	48.1	38.5	1.25 (0.68)

As these data show, the swine farmers interviewed were open to the positives of biogas technologies and saw the potential benefits of implementing them.

Skeptical About Feasibility: The swine operators were asked a series of questions to determine their views on the feasibility of adding biogas capture technology to their own farming operations. **Table 7** presents the results for several survey questions which indicate somewhat lukewarm views regarding the feasibility of adopting biogas capture technology on their farming operations and a relative reluctance to take on any additional debt to implement said technology.

When asked to rate their own views toward biogas capture as a potential addition to their swine operation (with 1 being “Very Unfavorable” and 7 being “Very Favorable”) the mean response was 4.43, only slightly above the middle option. When asked to rate the economic feasibility of incorporating biogas capture on their swine operations (with 1 being “Near Impossible” and 7 being “Very Feasible”) the mean response was 3.58, only slightly below the middle option.

When asked about the size of a possible loan that the participants would be willing to take out to implement biogas capture technology on their swine operations, most of the respondents (67.3%) indicated that they would not be willing to take on any additional debt. Smaller numbers indicated a willingness to take on a loan under $250,000 (16.3%) or between $250,000 and $500,000 (12.2%).

Table 7. Feasibility of Biogas on Their Farm (N = 65).

Questions	Mean (Standard Deviation)
One a scale of 1 to 7, with 1 being “Very Unfavorable” and 7 being “Very Favorable,” how would you describe your views toward biogas capture as a potential addition to your hog operation?	4.43 (1.66)
One a scale of 1 to 7, with 1 being “Near Impossible” and 7 being “Very Feasible,” how would you rate the economic feasibility of incorporating biogas capture as a potential addition to your hog operation.	3.58 (1.73)
Questions	**Percentage of “Yes” Responses**
If it was necessary to take out a loan to implement biogas capture and renewable energy development on your farm, how large of a loan would you be willing to take out to cover the costs? I would be willing to take out a loan for …	
No additional debt	67.3
Under $250,000	16.3
Between $250,000 and $500,000	12.2
Between $500,000 and $750,000	2.0
Above $750,000	2.0

Importantly, one-third of this sample of swine farm operators were willing to incur more debt to implement new biogas technologies.

5.4.3 Findings from the Broader Community in Eastern North Carolina

Support for the Swine Industry in Eastern North Carolina: Participants were asked a set of questions to determine their perceptions of swine farming and its impacts on communities in eastern North Carolina. The participants were given seven statements characterizing perceptions of potential impacts of swine farming and were asked how much they agreed or disagreed with each statement. Responses used a Likert-style scale ranging 1 to 7, with 1 = "Strongly Agree," 2 = "Agree," 3 = "Somewhat Agree," 4 = "Neither Agree, nor Disagree," 5 = "Somewhat Disagree," 6 = "Disagree," and 7 = "Strongly Disagree." For the purposes of presentation, the three "Agree" categories (i.e., scales 1 through 3) and the three "Disagree" categories (i.e., scales 5 through 7) have been collapsed into two categories: "Agree" and "Disagree," leaving a third category of "Neither Agree, nor Disagree."

Most of the participants (77.8%) agreed with the statement, "Hog farming has very positive impacts on the economy where I live." Even more participants (86.0%) agreed that "Hog farming is an important source of jobs for the region." A slight majority of the participants (59.9%) agreed that "Hog farming makes a substantial contribution to the tax base." Importantly, for all three of those statements, less than 10% of the participants actually disagreed with each statement (the remainder of the participants had responded as "Neither Agreed, nor Disagreed").

<u>Concerns About the Swine Farming Industry</u>: For the three statements regarding the negative impacts of swine farming, just under half of the participants (44.6%) agreed that "Odor from hog farms diminishes quality of life in my community." Just over half of the participants (51.3%) agreed that "Hog farming has a strong negative effect on water quality in streams and rivers." Finally, just under half of the participants (42.7%) agreed with the statement, "Waste from hog farms has contaminated drinking water wells in our region." For all three of these statements, a higher percentage of the participants disagreed with them than they had with the three statements regarding the economic benefits of swine farming.

Taken as a whole, it seems that the community members view swine farming as an economic boon that carries with it specific negative impacts on the environment and residents' quality of life. Most of the participants agreed with the three statements regarding swine farming having positive economic benefits. Concomitantly, a preponderance of the participants agreed with the three statements regarding swine farming having negative impacts on the region. Finally, a slight majority of the participants (58.8%) agreed that "Overall, the positive impacts of hog farming outweigh the negative impacts," indicating that residents in the area tend to think that the positive economic benefits of swine farming are more important than the negative consequences it may have for the environment and residents' quality of life.

<u>Ambivalence About Biogas Development in Eastern North Carolina</u>: The participants were then asked a set of questions to obtain their perceptions of biogas development and its impacts on communities in eastern North Carolina. The preponderance of the participants (47.7%) "Neither Agreed, nor Disagreed" that "Biogas jobs would only be temporary during the construction phase." Additionally, approximately the same number of participants said they "Agree" (23.8%) or "Disagree" (28.5%) with the statement, demonstrating a truly divided response. The preponderance of the participants (44.1%) "Neither Agreed, nor Disagreed" that "Economic development from biogas will mostly benefit big power companies." Additionally, in response to the statement, "Local farmers and businesses will not benefit much from biogas development," the participants were almost evenly divided (i.e., "Agree" [30.4%], "Disagree" [32.8%], and "Neither Agree, nor Disagree" [36.8%]). Although the majority of participants remained

neutral, there were a higher percentage of participants who agreed with the statement, "Biogas capture will not reduce hog waste pollution of streams and rivers" than disagreed with it (i.e., "Agree" [35.8%], "Neither Agree, nor Disagree" [44.4%], and "Disagree" [19.8%]). The participants produced a similar leaning towards agreeing over disagreeing despite the majority remaining neutral for the statement, "Biogas development does nothing to reduce the amount of hog waste produced."

The participants tended to view the economic potential of biogas capture more favorably. Most of the participants (67.6%) said that they "Agree" with the statement, "Biogas capture will benefit local farmers by creating a new source of income," with less than one-third (28.2%) responding with "Neither Agree, nor Disagree," and only 4.2% responding with "Disagree." Similarly, most of the participants (74.8%) said that they "Agree" with the statement, "Biogas capture will create new jobs in eastern North Carolina," with less than one-third (22.1%) responding that they "Neither Agree, nor Disagree," and only 3.1% saying they "Disagree." In response to the statement, "Biogas development will lead to even more growth of the hog industry," the responses were almost evenly split, with 45.6% saying they "Agree" and 46.7% saying they "Neither Agreed, nor Disagree"; only 7.7% of the participants said they "Disagree." Regarding the statement, "Biogas development will provide increased tax revenue for local governments," 64.8% of the participants said they "Agree" and 30.5% said they "Neither Agree, nor Disagree"; only 4.7% of the participants said they "Disagree." Comparable results were obtained for the statement, "Biogas development will spur greater economic development benefitting local businesses," with 54.7% of the participants saying they "Agree" and 41.2% saying they "Neither Agree nor Disagree"; only 4.1% of the participants said they "Disagree."

The participants also tended to not disagree with the two remaining statements describing the potential benefits of biogas capture technology. Regarding the statement, "Biogas development will reduce the smell of waste lagoon odors," 46.8% of the participants said they "Agree," with a comparable number (44.3%) of the respondents saying they "Neither Agree nor Disagree"; only 8.9% of the participants said they "Disagree." The participants had similar views of the statement, "Biogas production will improve climate sustainability by capturing greenhouse gases," with 55.3% of respondents saying they "Agree" and 40.6% of them saying they "Neither Agree nor Disagree;" only 4.1% of them said they "Disagree."

The responses to the questions about biogas infrastructure development were much more ambivalent than the responses to the questions regarding the swine industry. Although the participants seemed to agree with the idea that biogas would lead to economic development, they were rather divided regarding statements about who would benefit from biogas capture. Regarding the environmental benefits of biogas capture, participant responses indicated that they did not believe this technology would do much to reduce waste and water pollution; however, they did believe that it might help with controlling odor issues and reducing the production of GHGs. These findings could be because the participants were not directly impacted by biogas capture technology on a daily basis.

<u>Prioritize Biogas Development on Swine Farms</u>: In the final set of questions (**Table 8**), respondents were asked about their overall views and preferences regarding biogas infrastructure development. The participants were first asked, "Overall, would you say the potential benefits of biogas development

outweigh the potential negatives?" Most of the participants (71%) said they "Agree" with that statement, indicating an overall favorable view of the potential of biogas capture. However, the participants were almost evenly divided on their preference for how biogas should be developed. They were asked, "If biogas were developed in eastern North Carolina, what type of facilities would be preferred?" In response, 51% of the participants indicated a preference for "One or two large facilities to process gas from many hog farms," and 49% responded "Smaller facilities built on each individual hog farm."

Table 8. Biogas Development Preferences.

Question			**Percentage of "Yes" Responses**
Overall, would you say the potential benefits of biogas development outweigh the potential negatives?			71.0
Question			**Percent Preferring**
If biogas were developed in eastern North Carolina, what type of facilities would be preferred?			
One or two large facilities to process gas from many hog farms			51.0
Smaller facilities built on each individual hog farm			49.0
Question	**Number of Top Rankings (N = 195)**	**Percentage (%) of Top Rankings**	**Mean Rank Scores (Lower Score Indicates More Highly Ranked)**
If biogas capture could be implemented at only one type of facility, which should be top priority?			
Large-scale hog farms	79	40	1.87
Wastewater treatment plants	63	32	2.06
Municipal landfills	54	28	2.07

The final question in this set asked the participants which type of facility would they consider their top priority for implementing biogas capture technology among three options: large-scale swine farms, WWTPs, and municipal landfills. The participants were able to sort the three options into their order of preference. The order was then coded as "1" for their top priority, "2" for their second priority, and "3" for their third priority. Of the responses from the participants, the top priority was large-scale swine farms (40%), followed by WWTPs (32%), and municipal landfills (28%).

5.5 Analysis and Conclusions

Although stakeholder groups differed in their concerns about polluting industries, there were some patterns across the groups. In general, the groups shared:

1. An openness to the potential of biogas technologies to reduce harmful gases
2. A distrust of corporations to be transparent, inclusive, and innovative in responding to pollution in creative and safe ways.
3. A concern that partial or incomplete investment in biogas technologies could only fuel future polluting industries.

It is interesting and important to note that the different stakeholder groups—particularly the CAFO operators and the communities living nearby CAFOs—would coalesce around these issues.

5.5.1 Analysis

As is often the case, the qualitative data analysis of the focus groups that was conducted enables us to develop conceptual models for understanding patterns. In this study, our researcher team developed the focus group data thusly. Specifically, the four focus group topics and their sequencing in discussions were derived from what could be called the hierarchical-nested analytical framework that we designed for the survey. This analytical approach allows us to plot attitudes on one issue alongside attitudes about another issue to determine how these attitudes relate to one another.

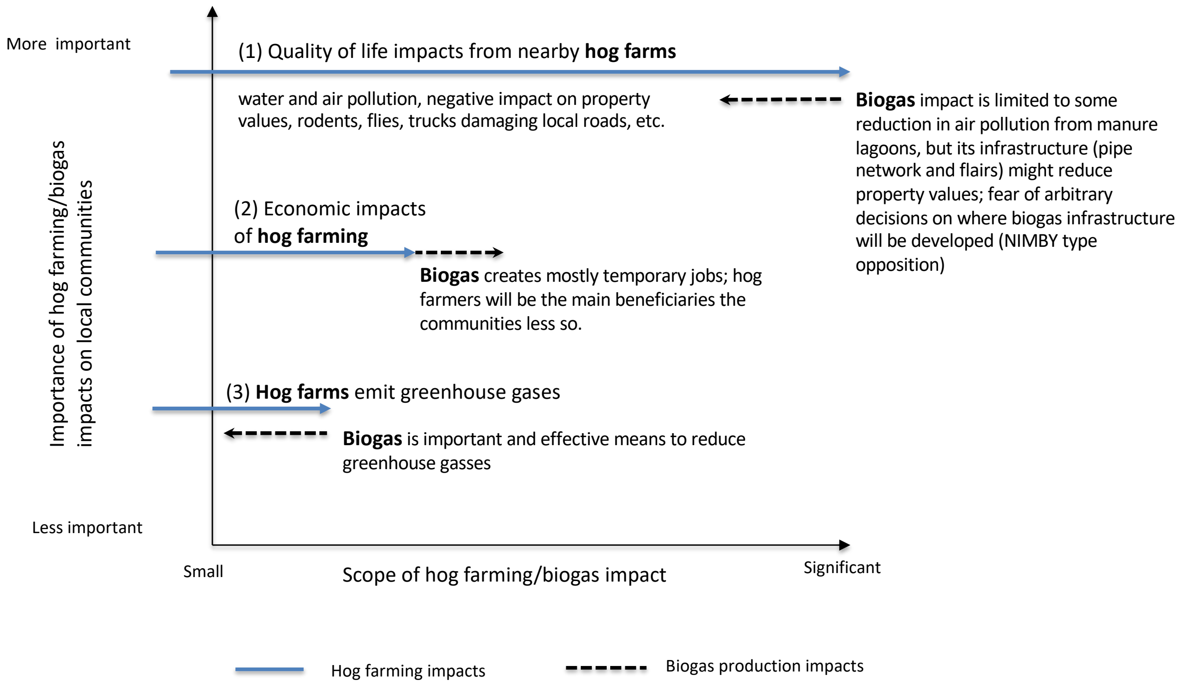
For example, if the swine industry is viewed primarily in economic terms as providing jobs, taxes, etc., then a biogas facility would probably be viewed more favorably as well because it brings more economic development. If the major problem with the swine industry is considered to be air pollution, then a biogas facility will also be probably viewed more favorably because it promises to reduce air pollution. If the major problem with the swine industry is thought to be water pollution from swine manure runoff, then a biogas facility would probably be considered of less importance because it does not reduce manure discharge in sprayfields in surrounding areas. If the major concern in a community is restricting further expansion of CAFOs, then a biogas facility would probably be seen more negatively because by making swine farms more environmentally sustainable, it could potentially encourage CAFO expansion, not only for production of hogs but also for production of poultry or cattle.

Differentiating Views of the Biogas Stakeholders in Rural North Carolina: The proposed hierarchical-nested scheme in **Error! Not a valid bookmark self-reference.** could apply to an analysis, as well as a comparison, of biogas views held by constituencies invested in or affected by biogas infrastructure development in rural North Carolina.

In comparison with communal views represented in **Figure 17**, the hierarchy and scope of biogas impacts for biogas supporters were flipped, ranking in order of importance from (1) climate change, to (2) economic impacts, and to (3) quality of life/local impacts. For constituents who hold a firm anti-biogas stance, the hierarchy of impacts was from (1) quality of life/local impacts, to (2) climate change, and to (3) economic impacts of the biogas industry. **Figure 18** depicts the inherent differences in the hierarchies held by pro- versus anti-biogas stakeholders.

The announcement of the “Align RNG” project by Dominion Energy and Smithfield Foods in 2018 generated fierce controversies and debates between its pro- and anti-biogas advocates. These controversies can in part be explained by differences in their nested hierarchies of importance and the scope of projected biogas impacts shown in **Figure 18**.

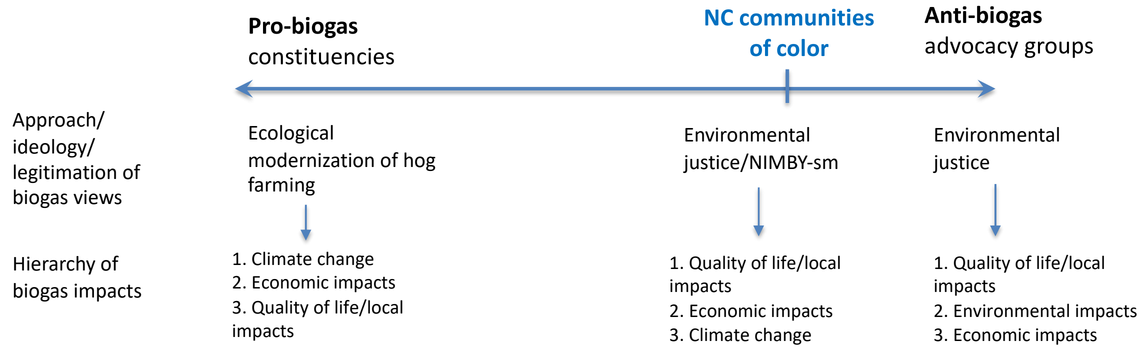
Figure 17. Hierarchical-Nested Structure of Minority Communal Views on Biogas Production on Local Swine Farms.



The views of biogas supporters and its opponents require a separate and more detailed analysis based on focus group data collected from representatives of those two specific groups. Instead, in this report we limit the discussion to brief descriptions of the approaches, ideology, and legitimation that pro-biogas and anti-biogas advocates employ in their public campaigns to promote and justify or to thwart and delegitimize the new swine production industrialization initiative in rural North Carolina.

Why does climate change mitigation via biogas capture on swine farms rank at the top of pro-biogas advocacy concerns? In part, this issue is related to the crucial role that federal and state authorities play in biogas development by facilitating alliances of corporate swine producers with energy companies via mandates that set GHG emission reduction and renewal energy production targets and by providing incentives for biogas industry development, such as favoring the industry regulations, subsidies, and tax reductions. Incentives and mandates are needed because when compared with natural gas, biogas products can be up to eight times more expensive (Oglesby, 2021). Biogas infrastructure development is promoted by its advocates as eco-efficient innovation, or as a type of ecological modernization strategy involving the introduction of environmentally friendly biogas capture technologies that would also help to increase the profitability of swine farms and, to a lesser degree, energy companies, thus contributing to rural economic development.

Figure 18. Views of Pro-biogas and Anti-biogas Constituencies in Rural North Carolina.



However, as noted by Jänicke (2008), profitability is only one of the considerations for undertaking ecological modernization strategies. Even more important is the role of the strategies in reducing business risks involved in pollution. It is especially the case for CAFO operators and owners who were and continue to be embroiled in decades-long on-and-off public controversies and litigation over the detrimental impacts that local communities have experienced because of factory farming. Therefore, in the public statements by the corporate interests promoting biogas-to-energy technologies, there is an overwhelming emphasis on what is claimed to be substantial benefits in mitigating global climate change that biogas capture and its utilization for clean energy production would provide, and its commercial potential is listed as a downstream effect of ecologically modernized hog production.

Following the hierarchical nested analytical model, the anti-biogas advocates agenda of the North Carolina Riverkeepers Waterkeepers Alliance, the North Carolina Environmental Justice Network, and the Rural Empowerment Association for Community Help (REACH) is derived from their principled opposition to the lagoon and sprayfield model upon which the industrial swine farming in North Carolina is based. From this point of view, the technologically antiquated and environmentally destructive lagoon and sprayfield system is the cause of the sickness and pollution caused by large-scale toxic emissions and noxious odors from swine farms, as well as poor conditions that compromise the welfare of the animals. Thus, the mitigation of the communal and environmental impacts requires not a modification of what anti-biogas advocates call a “archaic” lagoon and sprayfield system via covering of lagoons for biogas production, but its replacement with environmentally superior manure disposal technologies currently available (Muhlbauer et al., 2008; NCCN, 2021). An anaerobic lagoon is preferred because it is the simplest and the cheapest, at a cost of $500,000 for its installation. However, the anaerobic lagoon classified as “passive” biogas production system is characterized by the lowest degree of manure treatment involved. In comparison, “active” biogas systems, such low rate complete mix, plug low, and mixed flow digesters and especially high-rate fixed film, suspended media, and sequencing batch digesters, offer extensive manure treatment, thus allowing significant reduction of toxic emissions and noxious odors from swine farms (Hamilton, 2017).

Furthermore, anti-biogas advocates are not denying the importance of capturing CH_4 from swine farms, or some reduction of air pollution via covered lagoons. Instead, anti-biogas advocates are arguing that constructing additional anaerobic lagoons on the farms while keeping the existing uncovered lagoons in place for effluent storage and spraying on the nearby fields will only exacerbate the negative impacts experienced by communities, the environment, and farm animals. More specifically, covered lagoons not only capture CH_4, but they also catalyze and manufacture CH_4 in abundant quantities. It is only in conditions of the absence of O_2 that microbes decomposing manure generate CH_4 (i.e., lagoons that are left uncovered produce CH_4 in much lower quantities). Furthermore, because lagoon and sprayfield-based systems of swine waste management are plagued by leakages and spillages, it is highly likely that biogas-capture infrastructure would experience similar pitfalls and leak CH_4 into the atmosphere at multiple points throughout the process of digestion, transportation, and storage. Finally, anti-biogas advocates claim that the biogas industry could increase water pollution because covered lagoons increase the concentration of ammonia in liquid slurry that will continue to be sprayed to surrounding fields.

In summary, if biogas supporters strive to limit the debates to comparisons of the advantages and disadvantages of the biogas capture on the swine farms (e.g., more or less CH_4 released; more or less air pollution; more or less ammonia in the water), then the anti-biogas advocates strive to change the subject and debate the advantages and disadvantages of lagoon and sprayfield system itself; Tnti-biogas advocates propose dismantling the lagoon and sprayfield systems altogether and replacing them with swine manure treatment based on “superior technology standards” (i.e., ideally approximating standards and technologies used in human waste treatment) (NCCN, 2021).

Because of these differences, a divide emerged between anti-biogas advocates and the larger community stakeholders surrounding the question of what to do regarding biogas development in the region. Although the anti-biogas advocates took hardline opposition to biogas, the community representatives’ opposition was of a “soft line” (i.e., biogas in principle could be developed as long as it was developed and was NIMBY. The NIMBY position, in our view, can be only partly explained by political disempowering of local communities, including because of the new “ag-gag” and “right-to-farm” laws limiting nuisance lawsuits.

A comparison with the surge in grassroots activism that led to a moratorium on new swine farm development in North Carolina in 1997, making it permanent in 2007, could be instructive. The moratorium was instituted and made permanent at the time when the swine industry was in crisis mostly because of the devastating impacts that repeated hurricane floodings caused, thus producing large-scale runoffs from lagoons and affecting wide areas in the eastern North Carolina. In comparison, the swine industry is currently not in an acute crisis; therefore, it is not imperative for the swine industry to embrace biogas infrastructure development as a measure to improve public opinion of the industry or to mitigate the consequences of a particularly harmful event. Instead, the introduction of biogas is driven by a combination of the government incentives and regulations, as well as its commercial potential and opportunity to increase legitimacy as ecological modernizers, thus making it easier to deflect its critics.

5.5.2 Conclusions

With an open dialogue among different stakeholders, we can see the potential for positive changes through the implementation of biogas technologies. Although the overwhelming majority of the research team's sample prioritized CAFOs as the site on which to focus biogas capture, the participants realized the benefits in biogas capture at landfills and wastewater treatment facilities.

As biogas capture and other "green" technologies emerge and become implemented, success will be greater if:

- Affected communities are educated about the technologies
- Feedback from affected communities is sought and included in policies and practices
- Partners from affected communities are brought in as team members
- Industry is mindful to focus on community-building and not just profits.

6. Conclusions

This study analyzed biogas-to-energy project costs at 11 landfills, 784 WWTPs, and 2,042 swine farms in North Carolina for with bio-electricity, bio-CNG, and RNG as the possible products. The biogas feedstock sites studied in this report were estimated to have a collective biogas potential of 28 TBtu/y; the updated technoeconomic model used in this study determined that it would be technically feasible to convert approximately 25% of this potential (or 7 TBtu/y) into saleable energy.

Unlike previous studies that focused largely on bio-electricity production, this model explored bio-CNG production as well and found that bio-CNG projects that collect biogas at rates greater than or equal to 100 MMBtu/d are cost-competitive with recent CNG prices. When accounting for key federal- and state-level incentives, bio-CNG projects with collection rates as low as 45 MMBtu/d become economically viable as well.

The stakeholder assessment conducted for this report found that, overall, North Carolina CAFO owners and operators recognized the potential benefits of implementing biogas-to-energy infrastructure; the technology's potential to make complying with future environmental regulations easier as well as its potential to reduce harmful impacts to neighbors were each categorized as "major benefits" by more than half of the participants. Despite this, the stakeholder assessment determined that the majority of CAFO owners (greater than 67%) are not willing to take out a loan to implement biogas-to-energy on their farm. The survey concluded that these industry stakeholders are concerned about the costs and risks associated with this investment but would support and even welcome biogas infrastructure on their farms if government or industry partners were to incur some of the financial burden. This finding highlights the influence that policymakers in North Carolina have on the development of the state's biogas-to-energy portfolio.

This report provides guidelines and considerations for North Carolina policymakers looking to improve the state's management of organic waste in an equitable and environmentally sound manner. Despite the potential of biogas-to-energy projects to produce meaningful economic and environmental benefits, policymakers need to weigh the concerns from the historically underserved and environmental justice communities. Although critical for all policy considerations, environmental justice is a particularly relevant concern when discussing biogas projects because the majority of the state's biogas feedstock resources are located in underserved communities and, historically, the operation of these factory farms, landfills, and WWTPs has been detrimental to the quality of life for the local residents.

Effective policy is going to require trade-offs between climate concerns, economic development opportunities, and community welfare. North Carolina policymakers should consider the options presented in this report and pursue further research to gain a better understanding of the impacts that this technology and the manner in which it is deployed would have on their constituents.

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Appendix A. Methodology to Determine the Production Cost of Biogas and Biogas Products

A.1 North Carolina Landfills, Wastewater Treatment Plants, and Swine Farms Analyzed

A.1.1 Sites, Locations, and Operational Data

The biogas sourced analyzed in this study were organized based on the type of source (i.e., landfill, WWTP, and swine farm). Names of and identification (ID) numbers for the facilities that fall under each source are listed, along with data regarding facility location, operation type and size, and annual biogas production or potential.[18]

A.1.2 Estimates of Annual Biogas Potential

Biogas potentials for landfills are those reported in the U.S. Environmental Protection Agency's (EPA's) Landfill Methane Outreach Program (LMOP) database (EPA, 2023c).

WWTP potentials are estimated from the annual flow of wastewater handled by the facilities. The reported biogas potential from wastewater was obtained from the EPA (EPA & Combined Heat and Power Partnership, 2011).

Swine farm biogas potentials are directly from Parvathikar et al. (2021) and, as there, are reported in English units. The potentials were calculated from the amount of annual waste, density, and potential yield based on average values reported in the literature (see **Table A-1**) (Hamilton, 2016; Cucchiella et al., 2019; Koelsch, 2007; Chastain et al., 2003; Sims & Maguire, 2004; Kime et al., 2005; Sharara, 2019; Linville et al., 2015; Scarlat et al., 2018; Arora, 2007; Jurgutis et al., 2020; Jones et al., 2015; Kulesza & Gatiboni, 2021; Lorimor et al., 2004; Kephart, 2009).

Table A-1. Manure Production Rates, "As-Excreted," Including Urine and Feces, Biogas Potential, and Biogas Heating Value by Livestock Operation. [a]

Operation	Activity	Manure Production (Ton $Head^{-1}$ y^{-1})	Moisture Content (Percentage [%])	Biogas Potential from Wet Manure (ft^3 Ton^{-1} Wet)	Biogas Potential Yield (ft^3 $Head^{-1}$ y^{-1})	Biogas Heating Value (Million Btu $Head^{-1}$ y^{-1})
Swine	Gilt	0.49 ± 0.1	89	26 ± 2.1	400 ± 80	0.24 ± 0.05
	Boar/stud	1.5 ± 0	91		1,200 ± 100	0.74 ± 0.06
	Farrow to wean (per sow)	6.1 ± 1.9	89		5,000 ± 1,600	2.9 ± 0.9
	Farrow to feeder (per sow)	6.3 ± 1.4	89		5,100 ± 1,200	3.0 ± 0.7
	Farrow to finish (per sow)	19.7 ± 1.3	90		16,000 ± 1,700	9.6 ± 1.0
	Feeder to finish (per pig)	2.3 ± 0.3	90		1,900 ± 260	1.1 ± 0.2
	Wean to feeder (per pig)	0.9 ± 0.1	89		720 ± 110	0.43 ± 0.06

[18] **Section 2** of this report is independently published in a peer-reviewed journal. The lists of biogas sources and their data are provided with the publication which can be accessed at https://www.sciencedirect.com/science/article/pii/S2213138823005507.

Operation	Activity	Manure Production (Ton Head^{-1} y^{-1})	Moisture Content (Percentage [%])	Biogas Potential from Wet Manure (ft^3 Ton^{-1} Wet)	Biogas Potential Yield (ft^3 Head^{-1} y^{-1})	Biogas Heating Value (Million Btu Head^{-1} y^{-1})
	Wean to finish (per pig)	1.9 ± 0.1	89		1,500 ± 160	0.9 ± 0.9
Cattle	Beef brood cow	14.2 ± 3.1	88	29 ± 4.9	13,000 ± 3,500	7.6 ± 2.0
	Beef stocker calf	8.9 ± 1.8	92		8,300 ± 2,200	5.0 ± 1.3
	Beef feeder	10.6 ± 2.0	92		9,900 ± 2,500	5.9 ± 1.5
	Dairy heifer	9.9 ± 1.7	88		8,800 ± 2,200	5.3 ± 1.2
	Dairy cow	14.2 ± 1.3	88		22,000 ± 4,700	13 ± 2.7
	Dairy calf	3.3 ± 0.4	88		2,900 ± 600	1.8 ± 0.4
	Dry cow	14.2 ± 1.3	88		13,000 ± 2,500	7.6 ±1.4
Poultry	Broiler	0.037 ± 0.006	74	140 ± 65	140 ± 70	0.08 ± 0.04
	Layer	0.042 ± 0.020	75		160 ± 100	0.09 ± 0.06
	Pullet	0.013	75		50 ± 20	0.03 ± 0.01
	Turkey	0.13 ± 0.015	75		480 ± 230	0.30 ± 0.13

[a] Source: Parvathikar et al. (2021).

Note: Btu = British thermal units; ft^3 = standard cubic foot; y = year.

A.2 Assumptions and Empirical Functions Used in Systems Modeling

The empirical functions and fixed values used to model the infrastructure requirements and cost of the biogas-to-energy projects in the report are tabulated as discussed in this section of **Appendix A**.

A.2.1 Biogas Collection and Primary Processing

A.2.1.1 Landfills

The design assumptions for biogas collection and primary processing at landfills are listed in

Table A-2, and the infrastructure cost functions are provided in **Table A-3**. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021) and, as there, are reported in English units as well as 2013 U.S. dollars (USD). Note that the costs include installation and operation costs for a knockout pot, blower, and flare system (KBFS) (as mentioned in **Table A-3** note [a], the cost functions are also included in cost estimates for potential WWTP and swine farm projects). Because we assumed that a KBFS would also be installed at every WWTP and swine farm project, the same cost functions are also used in estimating the costs at these two other types of project sites.

Table A-2. Landfill Project Design Assumptions. [a]

Design Assumptions	Quantities
Q_t, landfill gas generation rate at time, t (ft^3/y)	$Q_t = (1 \div (C_4 \div 100)) \times L_0 \times R \times [e^{-kc} - e^{-kt}]$
C_4, methane content of landfill gas (percentage)	Given in EPA's LMOP database
L_0, potential CH_4 generation capacity of waste (ft^3/ton)	3,204
R, average annual waste acceptance rate during active life (tons)	Given in EPA's LMOP database
k, CH_4 generation rate constant (1/y)	0.04
c, time since landfill closure (y)	Given in EPA's LMOP database, zero if landfill is still open
t, time since the initial waste placement (y)	Given in EPA's LMOP database
Average depth of landfill waste (ft)	65
Number of wells per acre	100
Number of flares per system	1
Electricity usage by blowers (kWh/ft^3)	0.002

[a] EPA (2021).

Note: CH_4 = methane; ft = feet; ft^3/ton = cubic feet per ton; ft^3/y = cubic feet per year; kWh/ft^3 = kilowatt-hours per cubic feet; y = year or years.

Table A-3. Landfill Project Cost Assumptions. [a]

Cost Assumptions and Functions	Costs (2013 USD)	Cost Units
Drilling and pipe crew mobilization	$20,000	per system
Installed cost of vertical gas extraction wells	$4,675	per well
Installed cost of wellheads and pipe gathering systems	$17,000	per well
Installed cost of knockout pot, blower, and flare system [b]	$(x)^{0.61} \times \$4,600$	\$, x = ft^3/min
Engineering, permitting, and surveying	$700	per well
Annual OPEX for collection (excluding energy)	$2,600	per well
Annual OPEX for flare (excluding electricity) [b]	$5,100	per flare
Price for electricity to power blower [b]	$0.067	per kilowatt-hour (kWh)

[a] EPA (2021).

[b] These cost functions are also included in cost estimates for potential WWTP and swine farm projects.

Note: ft^3 = standard cubic feet of biogas; ft^3/min = standard cubic feet per minute; kWh = kilowatt-hour; min = minute; OPEX = operating expenditures.

A.2.1.2 WWTPs

Design assumptions for biogas collection and primary processing at WWTPs are listed in

Table A-4, and infrastructure cost functions are provided in **Table A-5**. The design assumptions come from different sources: Bachmann et al. (2015), El Ibrahimi et al. (2021), and NRC (1996). The cost functions beyond those for the KBFS are from Michailos et al. (2020) and El Ibrahimi et al. (2021). In keeping with the other tables, assumptions are expressed in English units.

Table A-4. WWTP Project Design Assumptions.

Design Assumptions	Quantities
Organic dry matter (kg per 1,000 gal of water) [a]	0.94
Biogas produced (L/kg of organic dry matter) [b]	500
Biogas flow rate (L/d)	4,700,000
L to scf conversion (scf/L)	28.3168
CH_4 content in biogas (percent volume)	65
Btu content in biogas (Btu/scf)	590
Sludge flow rate (10^6 gal/d)	0.1
Hydraulic retention time (d)	21
V_w, working volume of AD in 10^6 gal	2.1
Gallon to m^3 conversion (m^3/gal)	0.00378541
V_T, total AD volume needed	$1.25 \times V_w$
V_0, base standard volume of an AD tank in m^3 [c]	4,000
N, number of AD tanks	$[V_T \div V_0]$

[a] NRC (1996).

[b] Bachmann et al. (2015).

[c] El Ibrahimi et al. (2021).

Note: AD = anaerobic digester; Btu/scf = British thermal units per standard cubic foot; d = day; gal = gallon; gal/d = gallons per day; kg = kilogram; L = liter; L/d = liters per day; L/kg = liters per kilogram; m^3 = cubic meter; m^3/gal = cubic meters per gallon; scf/L = standard cubic feet per liter.

Table A-5. WWTP Cost Assumptions. [a]

Cost Assumptions and Functions	Costs (2013 USD)	Cost Units
Installed cost of knockout pot, blower, and flare system [b]	$(x)^{0.61} \times \$4,600$	\$, x = ft^3/min
Annual OPEX for flare (excluding electricity) [b]	$5,100	per flare
Price for electricity to power blower [b]	$0.067	per kWh
PP for AD tanks [c]	$N \times 2,121 \times V_0^{0.067}$	$
I_n, installation	39% × PP	$
I_s, instrumentation	26% × PP	$
P, piping	31% × PP	$
E, electrical	10% × PP	$
D_c, Total Direct Costs [d]	$PP + I_n + I_s + P + E$	$
I_c, Indirect Costs	$21.9\% \times D_C$	$
S_c, start-up costs	$5\% \times (D_c + I_c)$	$
Annual OPEX	7% × PP	$/y

[a] Some assumptions rely on variables defined in

Table A-4.

[b] EPA (2021).

[c] El Ibrahimi et al. (2021).

[d] Michailos et al. (2020).

Note: $/y = U.S. dollars per year; AD = anaerobic digester; ft^3 = standard cubic feet of biogas; ft^3/min = standard cubic feet per minute; kWh = kilowatt-hour; OPEX = operating expenditure; PP = purchase price.

A.2.1.3. Swine Farms

Design assumptions and sizing functions for biogas collection and primary processing at swine farms are listed in **Table A-6**, and infrastructure cost functions are provided in **Table A-7**. These design assumptions, sizing functions, and infrastructure cost functions all come from Parvathikar et al. (2021), and, as there, are reported in English units and 2013 USD.

Table A-6. Swine Farm Project Design Assumptions. [a]

Design Assumptions	Quantity
Biogas collection by covered in-ground lagoon (ft^3/d)	0.3335 × wet manure (lb/d)

[a] Parvathikar et al. (2021).

Note: ft^3/d= standard cubic feet of biogas per day; lb/d = pounds per day.

Table A-7. Swine Farm Project Cost Assumptions.

Cost Assumptions and Functions	Costs (2013 USD)	Cost Units
Installed cost of knockout, blower, and flare system [a]	$(x)^{0.61}$ × $4,600	$, x = ft^3/min
Annual OPEX for flare (excluding electricity) [a]	$5,100	per flare
Price for electricity to power blower [a]	$0.067	per kWh
Installed lagoon cost [b]	2.7 × wet manure $(lb/d)^{1.03}$	$
Annual OPEX [b]	4.86 × wet manure $(lb/d)^{0.66}$	$/y

[a] EPA (2021).

[b] Parvathikar et al. (2021).

Note: $/y = U.S. dollars per year; ft^3 = standard cubic feet of biogas; ft^3/min = standard cubic feet per minute; kWh = kilowatt-hour; lb/d = pounds per day; OPEX = operating expenditure.

A.2.2 Secondary Processing and Energy Generation

A.2.2.1 Electricity Generation

This section discusses the design assumptions used to model bio-electricity generation using various technologies including turbines (A.2.2.1.1), reciprocating engines (A.2.2.1.2), small reciprocating engines (A.2.2.1.3), and microturbines (A.2.2.1.4).

<u>Turbines</u>: Design assumptions for secondary processing and electricity generation using a turbine generator are listed in **Table A-8**, and infrastructure cost functions are provided in **a EPA** (2021).

Note: Btu/ft3 = British thermal units per standard cubic foot; Btu/kWh = British thermal units per kilowatt-hour; h/y = hours per year.

Table A-9. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021), and, as there, are reported in English units. Note that the modeling criteria for this type of project is that the calculated capacity for the generator be greater than 3 megawatts (MW).

Table A-8. Turbine Electricity Project Design Assumptions. [a]

Design Assumptions	Quantities
Gross capacity factor	93%
System operating schedule (h/y)	8,146.8
Fuel use rate (Btu/kWh generated)	13,000
Parasitic loss efficiency	88%
Biogas heat content (Btu/ft^3)	506

[a] EPA (2021).

Note: Btu/ft^3 = British thermal units per standard cubic foot; Btu/kWh = British thermal units per kilowatt-hour; h/y = hours per year.

Table A-9. Turbine Electricity Project Cost Assumptions. [a]

Cost Assumptions and Functions	Costs (2008 USD)	Cost Units
Installed cost of gas compression/treatment, turbine/generator, site work, and housings	$\$2,340(x) - 0.103(x^2)$	$, x = kW capacity [$1,015/kW for ($2,340 − 0.103 × kW capacity) < 1,015]
Installed cost of electrical interconnection equipment	$250,000	per system
Annual OPEX of compression/treatment and turbine/generator (excluding energy)	$0.0144	per kWh generated

[a] EPA (2021).

Note: kW = kilowatt; kWh = kilowatt-hour; OPEX = operation expenses.

Reciprocating Engine: Design assumptions for secondary processing and electricity generation using a reciprocating engine generator are listed in **Table A-10**, and infrastructure cost functions are provided in **Table A-11**. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021) and, as there, are reported in English units. Note that the modeling criteria for this type of project is that the calculated capacity for the generator be greater than or equal to 800 kilowatts (kW).

Table A-10. Reciprocating Engine Electricity Project Design Assumptions. [a]

Design Assumptions	Quantities
Gross capacity factor	93%
System operating schedule (h/y)	8,146.8
Fuel use rate (Btu/kWh generated)	11,250
Parasitic loss efficiency	93%
Landfill gas heat content (Btu/ft^3)	506

[a] EPA (2021).

Note: Btu/ft^3 = British thermal units per standard cubic foot; Btu/kWh = British thermal units per kilowatt-hour; h/y = hours per year.

Table A-11. Reciprocating Engine Electricity Project Cost Assumptions. [a]

Cost Assumptions and Functions	Costs (2013 USD)	Cost Units
Installed cost of gas compression/treatment, engine/generator, site work, and housings	\$1,300(x) + \$1,100,000	\$, x = kW capacity
Installed cost of electrical interconnection equipment	\$250,000	per system
Annual OPEX of compression/treatment and engine/generator (excluding energy)	\$0.025	per kWh generated

[a] EPA (2021).

Note: kW = kilowatt; kWh = kilowatt-hour; OPEX = operation expenses.

Small Reciprocating Engine: Design assumptions for secondary processing and electricity generation using a small reciprocating engine generator are listed in **Table A-12**, and infrastructure cost functions are provided in **Note:** ft3/kWh = standard cubic feet of biogas per kilowatt-hour; h/y = hours per year.

Table A-13. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021) and, as there, are reported in English units. Note that the modeling criteria for this type of project is that the calculated capacity for the generator be between 100 kW to 1 MW.

Table A-12. Small Reciprocating Engine Electricity Project Design Assumptions. [a]

Design Assumptions	Quantities
Gross capacity factor	93%
System operating schedule (h/y)	8146.8
Fuel use rate (ft^3/kWh generated)	36
Parasitic loss efficiency	92%

[a] EPA (2021).

Note: ft^3/kWh = standard cubic feet of biogas per kilowatt-hour; h/y = hours per year.

Table A-13. Small Reciprocating Engine Electricity Project Cost Assumptions. [a]

Cost Assumptions and Functions	Cost (2008 USD)	Cost Units
Installed cost of gas compression/treatment, engine/generator, site work, housings, and electrical interconnection equipment	\$2,300	per kW capacity
Annual OPEX of compression/treatment and engine/generator (excluding energy)	\$0.024	per kWh generated

[a] EPA (2021).

Note: kW = kilowatt; kWh = kilowatt-hour; OPEX = operation and maintenance.

Microturbine: Design assumptions for secondary processing and electricity generation using a microturbine generator are listed in **Table A-14**, and infrastructure cost functions are provided in **a EPA** (2021).

Note: Btu/ft3 = British thermal units per standard cubic foot; h/y = hours per year.

Table A-15. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021) and, as there, are reported in English units. Note that the modeling criteria for this type of project is that the calculated capacity for the generator to be between 30 kW to 750 kW.

Table A-14. Landfill Project Design Assumptions. [a]

Design Assumptions	Quantities
Gross capacity factor	93%
System operating schedule (h/y)	8,146.8
Fuel use rate (Btu/kWh generated)	14,000
Parasitic loss efficiency	83%
Landfill gas heat content (Btu/ft^3)	506

[a] EPA (2021).

Note: Btu/ft^3 = British thermal units per standard cubic foot; h/y = hours per year.

Table A-15. Landfill Project Cost Assumptions. [a]

Cost Assumptions and Functions	Costs (2006 USD)	Cost Units
Installed cost of gas compression/treatment, microturbine/generator, site work, housings, and electrical interconnection equipment	$19,278 × (x)0.6207	$, x = kW capacity
Annual OPEX of compression/treatment and microturbine/generator (excluding energy)	0.0736 − 0.0094ln(x)	$/kWh generated, x = kW capacity

[a] EPA (2021).

Note: kW = kilowatt; kWh = kilowatt-hour; OPEX = operation expenses.

A.2.2.2 Compressed Natural Gas

Design assumptions for additional processing and bio-CNG production are listed in **Table A-16**, and infrastructure cost functions are provided in **a EPA** (2021).

Note: Btu/GGE = British thermal units per gallon of gas equivalent; CH4 = methane; h/y = hours per year; kW = kilowatt; kWh = kilowatt-hour; LFG = landfill gas.

Table A-17. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021) and, as there, are reported in English units. Note that the modeling criteria for this type of project is that biogas flow rates must be 50 standard cubic feet per minute (ft^3/min) to 600 ft^3/min.

Table A-16. Landfill Project Design Assumptions. [a]

Design Assumptions	Quantities
Project landfill gas design flow rate (ft^3/min)	18.33579578
Gross capacity factor	93%
System operating schedule (h/y)	8,146.8
Conversion efficiency of LFG CH_4 to CNG	65%
Fuel use rate (Btu/GGE)	111,200

[a] EPA (2021).

Note: Btu/GGE = British thermal units per gallon of gas equivalent; CH_4 = methane; h/y = hours per year; kW = kilowatt; kWh = kilowatt-hour; LFG = landfill gas.

Table A-17. Landfill Project Cost Assumptions. [a]

Cost Assumptions and Functions	Costs (2013 USD)	Cost Units
Installed cost of on-site CNG conversion and fueling station equipment	$95,000 × (x)0.6	$, x = ft^3/min
Annual OPEX for media and equipment replacement and parasitic load	$1.00	per GGE

[a] EPA (2021).

Note: ft^3 = scf of biogas; GGE = gasoline gallon equivalent; OPEX = operation expenses.

A.2.2.3 Renewable Natural Gas

Landfills: Design assumptions for additional processing of biogas to produce RNG (renewable natural gas; [i.e., biomethane]) production are listed in **Table A-18**, and infrastructure cost functions are provided in **Table A-19**. These design assumptions and infrastructure cost functions all come directly from the LFGcost-Web model (EPA, 2021) and, as there, are reported in English units. Note that the modeling criteria for this type of project is that biogas flow rates must be between 1,000 ft^3/min and 6,000 ft^3/min.

Table A-18. Landfill RNG Project Design Assumptions. [a]

Design Assumptions	Quantities
Project landfill gas design flow rate (ft^3/min)	18.33579578
Electricity usage (kWh/ft^3)	0.009
Gross capacity factor	93%
System operating schedule (h/y)	8,146.8
Distance between landfill and end-use (mi)	1
RNG technology CH_4 capture rate	90%
Fuel use rate (Btu/GGE)	111,200

[a] EPA (2021).

Note: Btu/GGE = British thermal units per gallon of gas equivalent; CH_4 = methane; h/y = hours per year; kWh/ft^3 = kilowatt-hours per standard cubic foot; LFG = landfill gas; mi = mile.

Table A-19. Landfill RNG Project Cost Assumptions. [a]

Cost Assumptions and Functions	Cost (2019 US Dollars [$])	Cost Units
Installed cost of gas processing equipment (blowers, compressors, piping controls, gas separators, and dryers for pipeline quality gas)	$6,000,000 × $e^{0.0003x}$	$, x = ft^3/min
Installed cost of pipeline interconnection equipment	$400,000	$
Installed cost of pipeline to convey gas to project site (less than 1 mi)	$600,000	$
Installed cost of pipeline to convey gas to project site (1 mi or more)	$1,000,000	$ per mile of pipeline
Annual operation and maintenance of compressor and separators/dryers (excluding electricity)	250 × x + 148,000	$, x = ft^3

[a] EPA (2021).

Note: ft^3 = scf of biogas; mi = mile.

A.2.2.4 Emissions Reductions

Emissions Destroyed: Emissions destroyed by biogas-to-energy projects are assumed to be the total annual amount of methane (CH_4) collected annually and either destroyed by the project flare or used by the energy project. The assumptions that were used in calculating emissions destroyed are listed in

Table A-20.

Table A-20. Emission Destroyed Assumptions. [a]

Cost Assumptions and Functions	Quantities
CH_4 collected and used or destroyed (scf/y)	*Q* (computed for each potential biogas-to-energy project)
CH_4 pounds per standard cubic foot (lb/scf)	0.0423
Pounds per short ton (lb/ton)	200
Metric tons per short ton (Mt/ton)	0.9072
100 y global warming potential of CH_4 (GWP)	25
Metric tons per million metric tons (Mt/MMt)	10^6
CH_4 destroyed (MMtCO$_2$e/y)	MMtCO$_2$e = Q × lb/scf × ton/scf × ton/Mt × GWP × Mt/MMt

[a] EPA (2021).

Note: MMtCO$_2$e = million metric tons of carbon dioxide equivalents; MMtCO$_2$e/y = million metric tons of carbon dioxide equivalents per year; scf/y = standard cubic feet per year; ton/scf = tons per standard cubic foot; y = year.

Emissions Avoided: Emissions avoided are those from the combustion of fossil fuels displaced by biogas-derived CH_4. Depending on the type of energy produced (i.e., RNG, CNG, or electricity), different assumptions are used in calculating avoided emissions. Assumptions are listed in **Table A-21**, **Table A-22**, and **Table A-23**.

RNG Emissions Avoided

Table A-21. RNG Emissions Avoided Assumptions. [a]

Cost Assumptions and Functions	Quantities
CH_4 produced by the project (scf/y)	*Q* (computed for each potential biogas-to-energy project)
Energy per standard cubic foot of CH_4 (Btu/scf)	1,012 (E_m)
Energy per cubic foot of natural gas (Btu/scf)	1,050 (E_g)
Pounds of CO_2 per standard cubic foot of natural gas (lb_c/scf)	0.12037
Pounds per short ton (lb/ton)	200
Metric tons per short ton (Mt/ton)	0.9072
Metric tons per million metric tons (Mt/MMt)	10^6
RNG avoided emissions (MMtCO$_2$e/y)	$Q \times E_m \times E_g \times lb_c$/scf × ton/lb × Mt/ton × MMt/Mt

[a] EPA (2021).

Note: CO_2 = carbon dioxide; $MMtCO_2e$ = million metric tons of CO_2 equivalents; $MMtCO_2e/y$ = million metric tons of carbon dioxide equivalents per year; scf/y = standard cubic feet per year; ton/lb = tons per pound.

CNG Emissions Avoided

Table A-22. CNG Emissions Avoided Assumptions. [a]

Cost Assumptions and Functions	Quantities
CH_4 produced by the project (scf/y)	*Q* (computed for each potential biogas-to-energy project)
Energy per standard cubic foot of CH_4 (Btu/scf)	1,012 (E_m)
Energy per pound of diesel ($MMBtu/lb_d$)	0.02
British thermal units to million British thermal units conversion factor (MMBtu/Btu)	$1/10^6$
Pounds of CO_2 per cubic foot of diesel (lb_c/scf)	161
Pounds per short ton (lb/ton)	200
Metric tons per short ton (Mt/ton)	0.9072
Metric tons per million metric tons (Mt/MMt)	10^6
CNG avoided emissions ($MMtCO_2e/y$)	$Q \times E_m \times MMBtu/Btu \times lb_d/MMBtu \times lb_c/scf \times ton/lb \times Mt/ton \times MMt/Mt$

[a] EPA (2021).

Note: CO_2 = carbon dioxide; $MMtCO_2e/y$ = million metric tons of CO_2 equivalents per year; scf/y = standard cubic feet per year; ton/lb = tons per pound.

Electricity Emissions Avoided

Table A-23. Electricity Emissions Avoided Assumptions. [a]

Cost Assumptions and Functions	Quantities
Grid-specific CO_2 per electricity produced (lb/kWh)	0.42 (SERC Reliability Corporation/East [*C*])
Net electricity produced (kWh/y)	E_N (computed for each potential biogas-to-energy project)
Pounds per short ton (lb/ton)	200
Metric tons per short ton (Mt/ton)	0.9072
Metric tons per million metric tons (Mt/MMt)	10^6
RNG avoided emissions ($MMtCO_2e/y$)	$C \times E_N \times MMBtu/Btu \times ton/lb \times Mt/ton \times MMt/Mt$

[a] EPA (2021).

Note: CO_2 = carbon dioxide; $MMtCO_2e/y$ = million metric tons of CO_2 equivalents per year; scf/y = standard cubic feet per year; ton/lb = tons per pound.

A.3 Swine Farm Biogas Pipeline Network Modeling

A.3.1 Network Modeling

Because of the spatial density of swine farms in the eastern portion of North Carolina, we analyzed whether economies of scale can be achieved using gathering pipelines to collect biogas from multiple farms to be processed at a central site into RNG that is then injected into a nearby natural gas pipeline. A similar analysis was conducted by Prasodjo et al. (2013); the findings of which helped provide the impetus for the Optima-KV project, which is a network of five swine farms in Kenansville, NC, that inject approximately 80,000 million British thermal units per year (MMBtu/y) of RNG into an adjacent natural gas pipeline where it is purchased by Duke Energy, which is the electric utility (Cavanaugh & Associates, P.A., 2023).

The basic approach used by Prasodjo et al. (2013) was to first identify clusters of farms that collectively produced an annual amount of biogas that met or exceeded an arbitrarily specified threshold. The farms in a cluster were then networked together by connecting each farm to the neighboring farm within the cluster that was the least-cost distance away. The least-cost distance was determined by using a shortest-path algorithm across a gridded cost surface developed for pipeline mapping in which cells in the grid are weighted according to key attributes of the terrain they encompass (e.g., slope, land use). Additionally, the farm within the cluster closest to a natural gas pipeline was designated as the hub for centralized processing of the biogas into RNG. A high-pressure pipeline was then mapped along the least-cost path from this hub farm to the natural gas pipeline. Finally, an optimization program was used to determine the most cost-effective scales for the farm and pipeline infrastructure (e.g., minimum suitable pipe diameters) needed to build the network. Pipe sizing was based on an approach developed for piping supercritical carbon dioxide (CO_2). Sizing of other infrastructure, along with all of its costing, was based on empirical functions fit to vendor quotes.

In this analysis, we take a different approach to both mapping the pipeline network and sizing and costing required infrastructure. The approach does not require pre-clustering of farms, develops more compact pipeline networks, and uses a more appropriate scheme for sizing and costing biogas pipelines. The approach is carried out iteratively and is explained in the schematic illustration shown in **Figure A-1**. The first iteration starts with the swine farm with the highest annual biogas production rate (Farm A in **Figure A-1**). A biogas pipeline route is mapped from this farm to the nearest natural gas pipeline (0 in **Figure A-1**) along a least-cost path (1 in **Figure A-1**), which was determined by using the same Dijkstra shortest path algorithm and cost surface as Prasodjo et al. (2013). More details about mapping the pipeline network and sizing and costing required infrastructure are presented in **Section A.3.2, Appendix A**.

Subsequent mapping iterations then plot out biogas pipeline routes from swine farms with successively smaller annual biogas yields (Farms B, C, D, and E in **Figure A-1**). In each of these iterations, the new biogas pipeline route can either connect anywhere along a previously established biogas pipeline route (2, 4, and 5 in **Figure A-1**) or elsewhere along a natural gas pipeline (3 in **Figure A-1**), whichever option is the least-cost distance from the new farm being added to the mix. The former type of connection leads to a build out of an existing pipeline network, while the latter seeds the start of a new one. All pipeline routes, along with the order in which they are mapped, are saved (e.g.,

Figure A-3).

Figure A-1. Schematic Illustration of How the Swine Farm Biogas Pipeline Network Model Builds the Network.

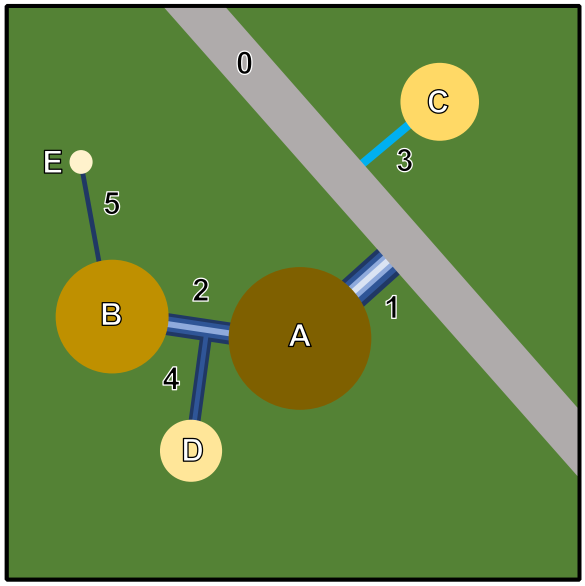
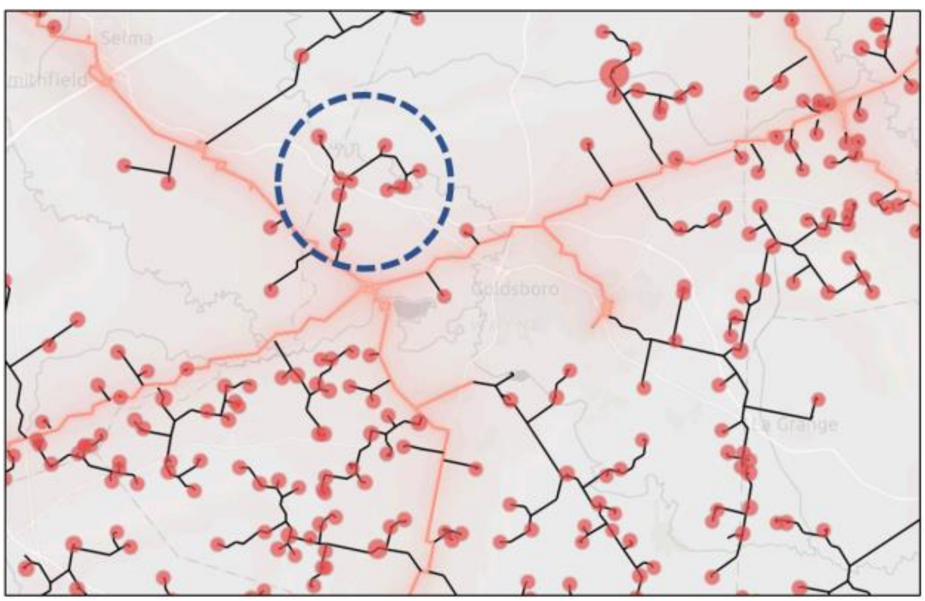


Figure A-2. An Example of Built-out Swine Farm Networks.



Notes:

Red circles are swine farm locations with the circle size representing biogas production potential.

Light red, blurred lines are existing natural gas pipelines.

Black lines are biogas pipelines.

Individual swine farm networks consist of all black lines linking a set of swine farms to a natural gas pipeline, such as the network inside the dashed circle.

Once a pipeline route has been established for every swine farm, the process loops back through the mapping iterations to size and cost the infrastructure needed to build the resulting networks at each stage of their evolution. Revisiting the first iteration for this network, the farm with the largest annual biogas yield (A in **Figure A-1**) is assumed to be the site where an RNG processing facility will be installed for the network that this farm is a part of. The processing facility, along with the RNG pipeline leading from the farm to the injection site at the nearby gas pipeline (1 in **Figure A-1**), are sized and costed based on the biogas production rate at just this farm. The functions used to determine these costs are those previously mentioned. The result is saved, and the process moves on to subsequent mapping iterations.

In each of these later iterations, a new farm joins the network (e.g., B follows A in **Figure A-1**), so its annual biogas production is added to that from the farm or farms connected to the network in the previous mapping iteration. To accommodate this increase in total biogas to be converted into saleable RNG, the size and cost of the network's RNG processing facility (at A in **Figure A-1**) and natural gas interconnection pipeline (1 in **Figure A-1**) are increased accordingly. The biogas produced at the farm hosting the RNG processing facility (A in **Figure A-1**) is fully treated by that facility, whereas the biogas from the other farms in the network (B, D, and E in **Figure A-1**) must be cleaned and dried before being sent through gathering pipelines to the facility. Consequently, farms added to a network are modeled as installing on site both a KBFS and a skid-mounted filter and a dehydration and compressor unit that pre-treats the biogas and pumps it into the gathering pipeline leading from the farm.

A.3.2 Biogas Pipeline Pressure, Sizing, and Cost Modeling

The addition of more biogas with each mapping iteration requires that the sizes and costs of gathering pipelines from the previous iteration must also be recalculated because the pipe segments are networked. The recalculation is conducted by using an approach modeled after Hengeveld et al. (2016). The first step in the process is to move from the farms toward the network outlet, summing the biogas fluxes where pipe segments in the network join. This sum yields the flux leaving the pipe junction through the downstream segment and ultimately sums to the same flux at the network outlet as that is used to resize the RNG processing facility and interconnection pipeline.

The second step in the process reverses course. Starting from the network outlet where a biogas pressure is assumed, the pressure in each pipe segment upstream of the outlet is solved for and used to select the appropriate pipe diameter for the segment. To avoid pulling biogas out of a farm AD faster than it is being produced while also avoiding excessive pressure buildup in the AD, biogas piping from the AD is typically operated at low pressure (Hengeveld et al., 2014; O'Shea et al., 2017; Hengeveld et al., 2016). We assume that the pressure at the outlet of the biogas gathering pipeline network (A in **Figure A-1**) is atmospheric and that the increase in biogas pressure from the downstream to the upstream end of each pipe segment in the network (e.g., A to B along 2 in **Figure A-1**) remains less than 10%. Gas flow at such a low pressure drop behaves similar to an incompressible fluid, allowing the Darcy-Weisbach equation and length of each pipeline segment to be used to select an appropriate diameter for the pipe segment.

The selection process is carried out by looping through a sequence of available nominal pipe size (NPS or inside) diameters, starting from the smallest (0.32 cm or 0.125 in) and increasing toward the largest (91 cm or 36.0 in). In an iteration of the loop, the pipe diameter is used in the Darcy-Weisbach equation to estimate the velocity at which the biogas would be moving through the pipe segment, u. Equation A-1 is presented as follows:

$$u = \frac{4Q}{\left(\pi D_j^2\right)} \qquad \text{(Eq. A-1)}$$

Where:

Q = Flux of biogas through the pipe segment
D = Pipe diameter
j = Position of the diameter in the pre-defined sequence of NPSs.

The biogas velocity is then used to calculate the biogas flow's Reynolds number by using Equation A-2, which is presented as follows:

$$Re = \frac{\rho u D_j}{\mu} \qquad \text{(Eq. A-2)}$$

Where:

ρ = Density of the biogas (assumed to be 1.298 kilograms per cubic meter [kg/m^3])
μ = Dynamic viscosity of the biogas (assumed to be 0.0000121 pascal-seconds [Pa-s]).

Next, Re is used to solve for the friction factor by using Equation A-3, which is presented as follows:

$$f_d = \begin{cases} 64/Re & \text{if } Re < 3{,}000\text{, else} \\ \left\{-2\log_{10} 2.51/\left[Re\sqrt{f_d} + \varepsilon/(3.71D_j)\right]\right\}^{-0.5} \end{cases} \qquad \text{(Eq. A-3)}$$

Like Hengeveld et al. (2014), we use an absolute roughness, ε, of 0.1 mm. Note that the lower half of Equation A-3 is a recursive formula, so f_d must be solved iteratively (i.e., it is solved using a loop within the main loop). Then, f_d is used in Equation A-4 to solve for the pressure at the upstream end of the pipe segment. Equation A-4 is presented as follows:

$$p_{upstream} = \frac{f_d L \rho u^2}{\left(2D_j\right)} + p_{downstream} \qquad \text{(Eq. A-4)}$$

Where:

$p_{downstream}$ = Pressure at the downstream end of the pipe segment, which at the outlet of a biogas pipeline network is assumed to be atmospheric
$p_{upstream}$ = Pressure at the upstream end of the segment
L = Pipe segment length in meters.

If at this point the pressure drop between the pipe segment inlet and outlet exceeds 10% of the inlet pressure, then the loop moves to the next largest NPS diameter (i.e., D_{j+1}), and the process is repeated. Otherwise, D_j is selected as the pipe segment diameter, and the loop ends for that pipe segment. The algorithm then moves on to the next pipe segment upstream in the network. The process continues until all diameters have been determined for every segment in a network.

Finally, the diameter and length of each pipe segment are input to the cost functions provided by Hengeveld et al. (2016) to solve for the total capital expenditure (CAPEX) and operating expenditure (OPEX) of the gathering pipeline network, including the cost for the electricity to run the compressors at each farm that feeds into the network. In the supplementary information to their publication, Hengeveld et al. (2016) provide a table of pipeline installation costs for different pipe diameters. Fitting a linear regression through this data gives a CAPEX function as calculated by using Equation A-5 as follows:

$$I_{pipe} = 23{,}454 \times D \qquad \text{(Eq. A-5)}$$

Where:

I_{pipe} = Investment cost of the pipe segment

D = In this instance, the variable is the pipe diameter in inches. The R squared (R^2) for the fit is 0.996.

To move the biogas through the network to the first farm where the centralized processing site is located, a compressor is installed at every other farm in the network. Electricity consumption by the compressors at these farms is solved for by using a variation of the equation for isentropic compressor power (Green & Southard, 2019) as provided by Hengeveld et al. (2016). Equation A-6 is presented as follows:

$$P = \left(\frac{1+n_c}{n_c}\right)\frac{\rho}{n_i n_m 3600}\frac{ZRT}{m}\frac{Nk}{(k-1)}\left[\left(\frac{p_{inlet}}{p_n}\right)^{\frac{k-1}{Nk}} - 1\right]Q_m \qquad \text{(Eq. A-6)}$$

$$N = \sqrt{\frac{p_{farm}}{p_n}}$$

The variables in Equation A-6, along with their values used in solving the equation, are listed in **.**

Table A-24. Variables and Assumed Values Used in Equation A-6. [a].

Table A-24. Variables and Assumed Values Used in Equation A-6. [a]

Symbols	Terms	Values
Z	Compressibility factor	0.9977
R	Gas constant (joules per mole kelvin [J/mol-K])	8.3145
T	Suction temperature (kelvin [K])	288.15
k	Specific heat ratio	1.304

Symbols	Terms	Values
M	Molar mass (grams per mole [g/mol])	28.97
η_i	Isentropic efficiency	0.6
η_m	Mechanical efficiency	0.99
η_c	Cooling efficiency	0.07
η_e	Electrical efficiency	0.9
P	Suction pressure (megapascal [MPa])	0.101325
ρ	Biogas density (kg/m^3)	1.298
Q_m	Mass flux of biogas (kilograms [kg])	ρQ
Q	Volumetric flux of biogas from the farm (cubic meters [m^3])	

[a] Values are from Hengeveld et al. (2016)

Hengeveld et al. (2016) calculate the CAPEX of each compressor using the following equation (Equation A-7):

$$I_{compressor} = 11{,}257 + 0.1469Q \quad \text{(Eq. A-7)}$$

Hengeveld et al. (2016) calculate the OPEX for each compressor using the following equation (Equation A-8):

$$OPEX_{compressor} = 0.05 * I_{compressor} \quad \text{(Eq. A-8)}$$

Once all of these costs have been solved for, they are summed, along with the capture and primary processing costs at each farm in the network, to determine a total network CAPEX and OPEX.

Finally, these steps (i.e., sizing and costing new infrastructure plus resizing and re-costing existing infrastructure) are repeated for every farm added to a network over the course of successive mapping iterations (e.g., D, B, and then E in **Figure A-1**). The results are then saved and will be used afterward to determine the point in the buildout of the network at which the greatest economies of scale are achieved.

A.4 Inputs for Virtual Pipeline Scenarios

The pro forma assumptions used in calculating the increase in the levelized cost of energy (LCOE) for CNG projects if the CNG could be trucked from the fueling station to a nearby natural gas pipeline injection site are listed in **Table A-25** for both the base case and 2X case.

Table A-25. Virtual Pipeline pro forma Assumptions.

Assumed Constants	Base Case	2X Case
Tanker truck capacity	3,000	3,000
Transport cost ($/mi)	$1.86	$3.72
Transport cost with a 15% markup	$2.14	$4.28
Median transport distance (mi)	11.2	22.4

Assumed Constants	Base Case	2X Case
Roundtrip distance (mi)	22.4	44.8
CNG GGE per MMBtu	7.74	7.74
Median number of sources per injection site	5	2
CAPEX per injection site	$1,200,000.00	$2,400,000.00
Added CAPEX per source	$240,000.00	$1,200,000.00
Pipeline injection fee ($/MMBtu)	$2.50	$5.00
Discount rate	8%	16%
Project lifetime (y)	15	15

Note: $/mi = U.S. dollar per mile; $/MMBtu = U.S. dollar per million British thermal units; GGE = gasoline gallon equivalent; mi = mile; MMBtu = million British thermal units; y = year.

The median distance used in the base case was determined by mapping the shortest road route between every swine farm and the terminus of a natural gas transmission line or City Gate by using the ArcGIS route analysis workflow.[19] The transport cost used comes from the American Transportation Research Institute's 2022 update to its analysis of trucking operational costs (Leslie & Murray, 2022). The figure $1.86 per mile (mi) is the sum of the following component costs as listed in the American Transportation Research Institute's report (**Table A-26**).

Table A-26. Average Marginal Cost per Mile in the Southeastern United States, 2021.

Component Costs	Cost (USD per mi)
Fuel costs	$0.326
Truck/trailer lease or purchase payments	$0.276
Repair and maintenance	$0.174
Insurance	$0.122
Permits and licenses	$0.020
Tires	$0.055
Tolls	$0.037
Driver wages	$0.580
Driver benefits	$0.117
Total	**$1.707**

Note: We assume that project operators would simply hire truckers to carry out this transport and not invest in a tanker themselves.

[19] More information about the ArcGIS route analysis workflow is available on Esri's website at https://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/route-finding-in-arcmap.htm

A.5 Operating Biogas-to-Energy Projects in North Carolina

As explained in the report, we tested the accuracy of our approach to modeling biogas-to-energy projects by simulating project attributes for 20 landfills, 2 WWTPs, and 3 swine farms where biogas is already being used to produce electricity.[20]

A.6 LCOE Input and Method Comparison

When a discount rate of 8% is used in the simple LCOE calculation (Equation 1 in the report), results are close to those achieved by using project pro forma financial assumptions given in both the LFGcost-Web model (EPA, 2021) and in Lazard's LCOE analysis (Lazard, 2023). These latter assumptions are given in **Table A-27**.

Table A-27. The pro forma Assumptions Used in LFGcost-Web Model (EPA, 2021) versus in Lazard's LCOE Analysis (2023).

Parameters	LFGcost-Web (EPA) Assumptions	Lazard's Assumptions
Project operational lifetime (years)	15	20
Project loan period	10	20
Project loan rate	6%	8%
General inflation rate	2.5%	0%
Equipment inflation rate	2%	2.25%
Electricity price	$0.078	Not applicable
Electricity price inflation rate	1.5%	Not applicable
Tax rate	35%	40%
Equity rate	8%	12%
Debt fraction	80%	60%
Depreciation schedule	5-year Modified Accelerated Cost Recovery System (MACRS)	5-year MACRS

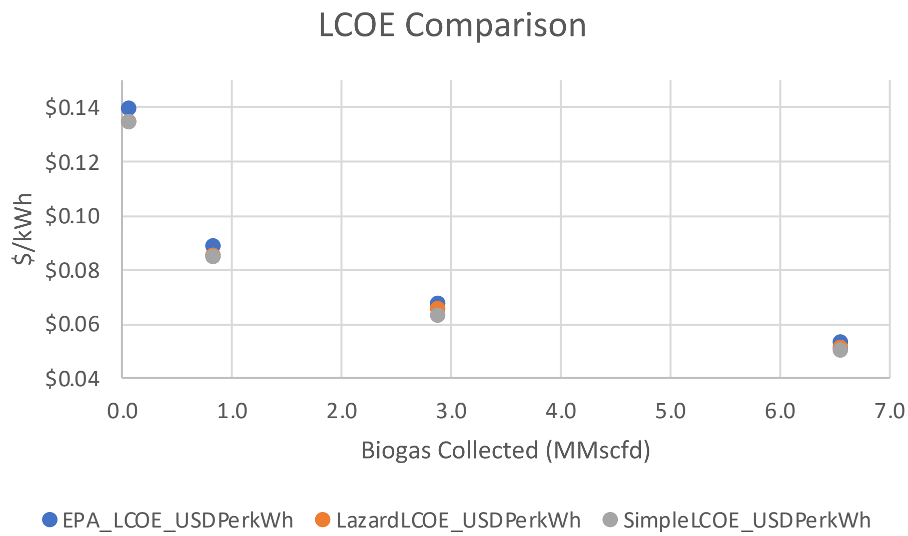
The assumptions, along with the project CAPEX, OPEX, and lifetime, are used to solve for the project LCOE by iterating to a value that yields the specified equity rate.

Figure A-3 plots the LCOEs determined by using this method with both the LFGcost-Web model and Lazard's pro forma assumptions applied to the scale and cost of electric generators modeled to handle increasing fluxes of biogas (i.e., from microturbine to turbine). Note that in this example, only the costs for gathering, processing, and compressing the biogas have been ignored, which is why the LCOEs are lower than those shown in

[20] A complete set of the modeling system results for each type of biogas-to-energy project for every facility including modeled estimates of energy production, CAPEX and OPEX costs, and emissions reductions (direct and avoided) are provided with the publication which can be accessed at https://www.sciencedirect.com/science/article/pii/S2213138823005507.

Figure 5. Included in the plot are the LCOEs calculated using Equation 1 in the report for the study's assumed project lifetime of 15 years and discount rate of 8%. The difference between all three sets of LCOE is less than or equal to 5%.

Figure A-3. LCOE Comparison.



Notes:

LCOEs are for the cost of different scale electric generators modeled to handle corresponding biogas fluxes on the *x*-axis.

EPA and Lazard's LCOEs are for the associated pro forma assumptions listed in Table A-27.

Simple LCOE is based on the same 15-year project lifetime as the EPA pro forma assumption and an 8% discount rate.

The difference between the LCOEs is less than or equal to 5%.

$/kWh = U.S. dollar per kilowatt-hour; MMscfd = million standard cubic feet per day.

Appendix B. Methodology to Determine the Economic Impact of the Biogas Industry in North Carolina

For capital and operational investments, the RTI International Team used guidance from the Coalition for Renewable Gas's 2022 analysis titled Economic Analysis of the U.S. Renewable Natural Gas Industry. Specifically, we used the guidance to determine the specific Impact Analysis for Planning (IMPLAN) industry sectors and composition of spending that should be used (RNG Coalition, 2022). Unlike this analysis, the activities modeled here would not have any waste collection, wholesale, or retail activities, so those industries are excluded from the analysis. In addition, we included IMPLAN industry 417, truck transportation to account for the virtual pipeline scenario in which gas will be collected from farms and transported by tanker truck to a central pipeline. **Table B-1** presents total construction and operational spending by IMPLAN industry, the percentages of spending, and the total amount.

Table B-1. Economic Activity by Industry and Spending.

Category	Activity	IMPLAN Industry Description (IMPLAN reference number)	Percentage (%) of Total Spending	Total Amount (in Millions)
Construction			**100**	**$318.2**
	Capture and upgrading	Non-residential construction (56)	83	$264.2
	Extraction and upgrading	Drilling oil and gas wells (35)	17	$54.0
Operations			**100**	**$37.5**
	Capture and upgrading	Other miscellaneous chemical product manufacturing (185)	59	$22.3
	Administration	Office administrative services (470)	2	$0.6
	Transmission	Natural gas distribution (48)	38	$14.2
	Transmission	Truck transportation (417)	1	$0.3

Model assumptions include the following:

- All constructions activities will occur in calendar year 2024. Although biogas infrastructure investments will likely occur over a much longer period of time, examining this investment in a single year provides some indication of the total impact related to biogas investment.
- Operations will start in 2025 and will continue each year afterward. In this report, the impacts for a single year are reported, but these impacts will continue to occur each year that biogas is captured, upgraded, and transported.

To calculate the impacts, RTI International generated an input–output model using IMPLAN economic software. The framework and methodological basis for the IMPLAN model were derived from the U.S. Department of Commerce's Benchmark Input–Output Accounts, which provide detailed information about the flows of the goods and services that make up the production processes of industries.[21] These relationships can be used to determine how regional economies may respond to specific economic events. IMPLAN uses these data to calculate economic multipliers and to estimate and break down the total impact into the following three separate effects:

1. Direct effects: The investing company's total spending on operating expenses, payroll, and capital investments.

2. Indirect effects: The supply chain businesses' spending at local businesses.

3. Induced effects: The direct and indirect effects of spending by employees of the company and its suppliers.

The summation of these different types of economic effects is typically considerably larger than direct expenditures.

[21] Additional information about the IMPLAN model and assumptions is provided in the IMPLAN Report Toolkit, which is available here: https://support.implan.com/hc/en-us/articles/360044985833-IMPLAN-Report-Toolkit

Appendix C. Methodology to Determine Community Stakeholder Views on Biogas Capture Technologies and Their Perceived Impacts

C.1 Mailed Survey of Hog Farmers

We invite you to participate in a research study called ***Hog Farming and the Potential for Biogas Production in Eastern North Carolina*** conducted by a team of researchers at East Carolina University® (ECU). Your address was selected from a list of permitted hog farms in the region. Please complete and return this survey. We want to know what farmers, like you, think about the potential for biogas development in our region. Your answers will help us get a better sense of the potential and challenges for implementing biogas capture technology on farms like yours.

We ask that the survey be completed by an adult knowledgeable about the hog farm's operations. The survey should take about 10 minutes to complete. It is anonymous. Please do not sign your name to the survey. The survey does not ask you to give your name or any other information that would identify you. We ask that you complete the survey and return it no later than two weeks after receiving it.

Your participation in this research is voluntary. You do not have to answer every question. We do not expect you to consult farm records when answering. Your best estimate is plenty. If you have questions about the survey, please call Dr. Bob Edwards at 252-328-4863. Or call the ECU Office of Research Integrity and Compliance (ORIC) at 252-744-2914 for any questions about your rights as a research participant.

Section One: Questions Regarding Biogas Capture, Specific Concerns and Benefits

This section asks questions related to your general experience, knowledge, and views regarding biogas capture on hog farms.

Biogas capture technology involves using some type of anerobic digester (such as a covered waste lagoon) to capture gases produced by the anerobic breakdown of hog waste. Those gases can then be processed into renewable natural gas, which can be used as an energy source, either on-site or elsewhere. A number of hog operations in North Carolina have already adopted this technology for use on their own farms.

1. Are you currently utilizing any biogas capture technology on your farm?

   0 Yes　　　0 No

2. If you answered "yes" to the previous question, please check each of the following boxes for the type of biogas capture technology you are currently using on your farm. *(Multiple Choice)*

   0 Covered lagoon digestion system
   0 Complete mix digester
   0 Plug flow digester
   0 Fixed film digester
   0 Suspended media digester
   0 Sequencing batch digester
   0 Other: ______________________

3. On a scale of 1 to 7, with 1 being "completely unaware" and 7 being "expert," how would you rate your knowledge about Biogas Capture? *(Circle the appropriate number)*

Completely Unaware			Aware			Expert
1	2	3	4	5	6	7

Biogas capture, like any business venture, offers opportunities and benefits as well as is associated with concerns and costs to hog farmers. We first would like to ask about your opinion about potential benefits of biogas development and then about potential concerns you may have.

4. Consider the prospect of implementing biogas capture technology on your farm. For each of the following potential benefits associated with biogas production, please rate how beneficial you think it would be for you and your business. *(Please rank the following as either a Major Benefit, Minor Benefit, or Not a Benefit.)*

A profitable addition to your business 0 Major Benefit 0 Minor Benefit 0 Not a Benefit	Improving the public perception of your farm 0 Major Benefit 0 Minor Benefit 0 Not a Benefit
Making it easier for you to comply with any future environmental regulations 0 Major Benefit 0 Minor Benefit 0 Not a Benefit	Being better prepared for any future shifts to renewable energy 0 Major Benefit 0 Minor Benefit 0 Not a Benefit
Reducing operational overhead by producing your own electricity 0 Major Benefit 0 Minor Benefit 0 Not a Benefit	Reducing your potential liability in any future nuisance lawsuits 0 Major Benefit 0 Minor Benefit 0 Not a Benefit
Reducing the smell from your waste lagoons 0 Major Benefit 0 Minor Benefit 0 Not a Benefit	Reducing your potential liability in any future environmental lawsuits 0 Major Benefit 0 Minor Benefit 0 Not a Benefit
Reducing the potential negative impacts of your farm on the environment 0 Major Benefit 0 Minor Benefit 0 Not a Benefit	Other ______________________________ ______________________________ ______________________________ ______________________________
Reducing the potential negative impacts of your farm on your neighbors 0 Major Benefit 0 Minor Benefit 0 Not a Benefit	

5. Again, consider the prospect of implementing biogas capture technology on your farm. For each of the following potential concerns associated with biogas capture, please rate how big of a concern it would be for you and your farm. *(Please rank the following as either a Major Concern, Minor Concern, or Not a Concern.)*

Taking on additional loans to pay for this technology 0 Major Concern 0 Minor Concern 0 Not a Concern	Increased maintenance time and/or costs 0 Major Concern 0 Minor Concern 0 Not a Concern
The amount of disruption involved in adopting the new technology 0 Major Concern 0 Minor Concern 0 Not a Concern	Having to build and maintain new machinery on your farm 0 Major Concern 0 Minor Concern 0 Not a Concern
Taking on the expense of constructing an additional or new waste lagoon 0 Major Concern 0 Minor Concern 0 Not a Concern	Increased amount of traffic from the transport of biogas 0 Major Concern 0 Minor Concern 0 Not a Concern
Having to comply with new environmental regulations or oversight 0 Major Concern 0 Minor Concern 0 Not a Concern	The construction of pipelines connected to your farm for the transport of biogas 0 Major Concern 0 Minor Concern 0 Not a Concern
Entering into a contractual relationship with an energy company 0 Major Concern 0 Minor Concern 0 Not a Concern	Other ______________________ ______________________ ______________________ ______________________

6. Taking into consideration what you indicated as being the benefits and concerns of having biogas production on your hog farm, on a scale of 1 to 7, with 1 being "very unfavorable" and 7 being "very favorable," how would you describe your views toward Biogas Capture as a potential addition to your hog operation?

Very Unfavorable						Very Favorable
1	2	3	4	5	6	7

7. Again, taking into consideration what you indicated as being the benefits and concerns of having biogas production on your hog farm, on a scale of 1 to 7, with 1 being "near impossible" and 7 being "very feasible," how would you rate the economic feasibility of incorporating Biogas Capture as a potential addition to your hog operation?

Very Unfavorable						Very Favorable
1	2	3	4	5	6	7

8. If it was necessary for you to take out a loan to implement biogas capture and renewable energy development on your farm, how large of a loan would you be willing to take on to cover those costs? *(Multiple Choice)*

0 I would not be willing to take on any additional debt

0 I would be willing to take on a loan under $250,000

0 I would be willing to take on a loan between $250,000 and $500,000

0 I would be willing to take on a loan between $500,000 and $750,000

0 I would be willing to take on a loan above $750,000

9. Please share with us other concerns you have about implementing Biogas capture technology on your farm.

____
____
____
____
____
____
____
____

Section Two: Farm Background

This section contains general questions about your farm.

10. Which of the following best describes your position with the hog farm? *(Multiple Choice)*

0 Site manager   0 Office manager

0 Owner   0 Other: ____________________

11. In what year did you start farming as your primary source of income? __________

12. Did you start farming on land that you or your family already owned?

0 Yes   0 No

13. Was farming your family's primary source of income growing up?

0 Yes   0 No

14. In what year did you build your first large-scale hog facility? __________

15. Which type of hog farm or farms do you have? *(Check all that apply)*

0 Farrow to wean
0 Farrow to feeder
0 Farrow to finish
0 Wean to feeder
0 Wean to finish
0 Feeder to finish
0 Other: ____________________

16. Are you currently raising hogs under contract with a specific integrator?

0 Yes 0 No

17. If you answered "yes" to the previous question, who are you currently under contract with? *(Multiple choice)*

0 Smithfield Foods
0 Prestage
0 Murphy/Brown
0 Carrolls
0 Other: ____________________

18. If you have ever previously had a contract with a different integrator than the one you are currently under contract with, please indicate which ones you have previously had a contract with. *(Check all that apply)*

0 Smithfield Foods
0 Prestage
0 Murphy/Brown
0 Carrolls
0 Other: ____________________

19. When you started raising hogs under contract, how did you come into contact with the first integrator you contracted with? *(Multiple choice, check all that apply)*

0 Family
0 Friends
0 Fellow farmers
0 Community members
0 Direct recruitment by a company representative
0 Other: ____________________

20. Approximately how large is your farm? ________ acres.

21. Approximately how much of your acreage is taken up by the hog operation? ________ acres.

22. About how many hogs do you have on-site at any given time? __________

23. How many hog barns do you have? ____________

24. How many waste lagoons do you have? ____________

25. Approximately what is the gross annual income from your farming operation?

    $ ____________ dollar amount

26. Approximately what percentage of that income comes from hog farming?

    _______ percent.

27. For each of the following options, please rate how concerned you are about this issue for your hog operation. *(Please rank the following as either a Major Concern, Minor Concern, or Not a Concern)*

Competition from within the United States 0 Major Concern 0 Minor Concern 0 Not a Concern	Increasing costs of running your operation 0 Major Concern 0 Minor Concern 0 Not a Concern
Competition from overseas 0 Major Concern 0 Minor Concern 0 Not a Concern	Environmental regulations from state and federal agencies 0 Major Concern 0 Minor Concern 0 Not a Concern
Market fluctuations in the price of pork 0 Major Concern 0 Minor Concern 0 Not a Concern	The potential negative impacts of your farm on the environment 0 Major Concern 0 Minor Concern 0 Not a Concern
The amount of debt you carry on your farm 0 Major Concern 0 Minor Concern 0 Not a Concern	What will happen to your farm when you retire 0 Major Concern 0 Minor Concern 0 Not a Concern
Compliance and regulations required by your integrator 0 Major Concern 0 Minor Concern 0 Not a Concern	Other ____________________ ____________________ ____________________ ____________________
The amount of recordkeeping required 0 Major Concern 0 Minor Concern 0 Not a Concern	
The potential negative impacts of your farm on your neighbors 0 Major Concern 0 Minor Concern 0 Not a Concern	

Section Three: Demographics and Background

Could you tell us a little bit about yourself? Your answers to the next set of questions will be used for statistical purposes only.

28. What is your year of birth? __________

29. What is your race or ethnicity? Please select all that apply. *(Multiple Choice)*

0 White
0 Black or African American
0 Hispanic or Latino
0 Asian or Asian American
0 Some other race or ethnicity *(please specify)* ______________________

30. What is the highest level of school that you have completed or the highest degree you have received? *(Multiple Choice)*

0 None, or grade 1-8
0 High school incomplete (Grades 9-11)
0 High school graduate (Grade 12 or GED)
0 Technical, trade or vocational degree AFTER high school
0 Some college, associate degree, no 4-year college
0 College graduate (B.S., B.A. or other 4-year degree)
0 Post-graduate training or professional schooling after college

31. Do you describe your gender as? *(Multiple Choice)*

0 Male 0 Female 0 Other *(Please specify)* ________________

32. In what county is your hog operation located? *(Multiple Choice)*

0 Bladen County
0 Duplin County
0 Robeson County
0 Sampson County
0 Wayne County
0 Other: ____________________

33. Which of the following best describes your yearly household income before taxes? *(Multiple Choice)*

0 Less than $20,000
0 $20,000 to $39,999
0 $40,000 to $59,999
0 $60,000 to $79,999
0 $80,000 to $99,999
0 $100,000 to $119,999
0 $120,000 to $139,999
0 $140,000 to $159,999
0 $160,000 or more

34. When it comes to politics, do you usually think of yourself as: *(Multiple Choice)*

0 Very Republican
0 Republican
0 Moderate Republican
0 Independent/Something Else
0 Moderate Democrat
0 Democrat
0 Very Democrat

35. Our research team is very interested in sitting down and talking to some large-scale hog farmers in order to better understand some of the reasons and motivations behind your views of biogas production. If you would be willing to be interviewed, please send a message to Kristen Myers at: 252-328-6092 or myerskr19@ecu.edu.

C.2 Qualtrics Survey of Local Community Members

Default Question Block

We invite you to participate in a research study called Understanding the Potential for Biogas Production in Eastern North Carolina conducted by a team of researchers at East Carolina University (ECU). Biogas is a source of renewable energy produced from methane gas emitted from facilities like hog farms, sewerage treatment plants, and landfills. Biogas is being developed in eastern North Carolina because of its economic potential as a new industry and because it slows climate change by converting harmful gases into renewable energy. Please complete and submit this survey. We want to know what you think about the potential for biogas development in our region. Your answers will help us get a better sense of the potential and challenges for implementing biogas capture technologies.

The survey should take about 10 minutes to complete. It is anonymous.
The survey does not ask you to give your name or any other information that would identify you. Your participation in this research is voluntary. You do not have to answer every question.

If you have questions about the survey, please call Dr. Bob Edwards at 252-328-4863. Or call the ECU Office of Research Integrity and Compliance (ORIC) at 252-744-2914 for any questions about your rights as a research participant.

Block 1

This is a large-scale hog farm in North Carolina:

About how far would you say it is from where you live to the closest large-scale hog farm?

- ◯ Less than a mile
- ◯ A couple of miles
- ◯ More than 5 miles
- ◯ I'm not sure

Do you personally know someone who owns or works for a large scale hog farm?

- ◯ No
- ◯ Yes

If yes, which of the following best describes your relationship to this person?

- ◯ They are a friend
- ◯ They are a family member
- ◯ They are a neighbor
- ◯ Other (please describe): ____________

Hog farming has many impacts on communities in eastern North Carolina. Please indicate how much you agree or disagree with the following statements.

	Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly Disagree
Hog farming has a very positive impact on the economy where I live.	○	○	○	○	○	○	○
Hog farming has a strong negative effect on water quality in streams and rivers.	○	○	○	○	○	○	○
Hog farming makes a substantial contribution to the tax base.	○	○	○	○	○	○	○
Odor from hog farms diminishes quality of life in my community.	○	○	○	○	○	○	○
Hog farming is an important source of jobs for the region.	○	○	○	○	○	○	○
Waste from hog farms has contaminated drinking water wells in our region.	○	○	○	○	○	○	○
Overall, the positive impacts of hog farming clearly outweigh the negative impacts.	○	○	○	○	○	○	○

Block 2

This section asks questions related to your general knowledge and views regarding biogas capture on hog farms.

About 10 million hogs in eastern North Carolina and they produce billions of gallons of waste each year. This is both a waste disposal challenge and a renewable energy opportunity called "biogas." Biogas technology enables swine waste to be turned into a renewable source of natural gas. The state of North Carolina is now mandating energy companies like Duke Power or Dominion Energy to develop renewable sources of energy. Biogas is an important part of that project.

How would you rate your knowledge about biogas capture and renewable energy development? Click the number on the line that best describes your knowledge.

	1	2	3	4	5	6	7
1 is "totally unaware" and 7 is "expert"							

Like any new business venture, renewable energy development offers opportunities and benefits, but also costs and concerns. In eastern North Carolina some are strong promoters of biogas development while some others are strong critics. The following statements describe a variety of positive and negative claims made about biogas development in eastern North Carolina. Please indicate how much you agree or disagree with each claim.

	Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly Disagree
Biogas jobs would only be temporary during the construction phase.	○	○	○	○	○	○	○
Economic development from Biogas will mostly	○	○	○	○	○	○	○

	Strongly agree	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree	Strongly Disagree
benefit big power companies.							
Local farmers and businesses will not benefit much from biogas development.	○	○	○	○	○	○	○
Biogas capture will not reduce hog waste pollution of streams and rivers.	○	○	○	○	○	○	○
Biogas development does nothing to reduce the amount of hog waste produced.	○	○	○	○	○	○	○
Biogas development will lead to even more growth of the hog industry.	○	○	○	○	○	○	○
Biogas development will reduce the smell of waste lagoon odors.	○	○	○	○	○	○	○
Biogas capture will benefit local farmers by creating a new source of income.	○	○	○	○	○	○	○
Biogas capture will create new jobs in eastern NC.	○	○	○	○	○	○	○
Biogas production will improve climate sustainability by capturing greenhouse gases.	○	○	○	○	○	○	○
Biogas development will provide increased tax revenue for local governments.	○	○	○	○	○	○	○
Biogas development will spur greater economic development benefitting local businesses.	○	○	○	○	○	○	○

If Biogas were developed in eastern North Carolina what is your preference for building facilities to process gas?

- ○ One or two large facilities should be built that process gas from many hog farms.
- ○ Smaller facilities should be built on each individual hog farm.

Block 3

Biogas capture can be applied to various industries where methane gas is produced, such as wastewater treatment plants and landfills. The next questions ask your opinions about biogas capture in those facilities.

This is a wastewater treatment plant in Clinton, North Carolina.

This is a landfill in Robeson County, North Carolina.

If you could only implement biogas capture in one type of facility at a time, what order would you go in? With your cursor or finger (if using a touch screen), drag the top priority to be first and drag the lowest priority as last.

Wastewater treatment plants

Landfills

Large-scale hog farms

Why did you rank the facilities in that order?

Overall, would you say that the potential benefits of biogas development outweigh the potential negative?

- No
- Yes
- It depends (please explain)

Block 4

Your answers to the next set of questions will be used for statistical purposes only.

What is the year of your birth?

What is your race or ethnicity? Please select all that apply.

- ☐ White
- ☐ Black or African American
- ☐ Native American
- ☐ Asian or Asian American
- ☐ Other

What is the highest level of school that you have completed or the highest degree you have received?

- ○ None, or grade 1-8
- ○ Some high school (Grades 9-11)
- ○ High school graduate (Grade 12 or GED)
- ○ Technical, trade or vocational degree AFTER high school
- ○ Some college, associate degree, no 4-year college
- ○ College graduate (B.S., B.A. or other 4-year degree)
- ○ Post-graduate training or professional schooling after college

What is your gender?

- ◯ Man
- ◯ Woman
- ◯ Other (please describe) ________

Are you a member of the Chamber of Commerce in your community?

- ◯ No
- ◯ Yes

Which of the following best describes your yearly household income before taxes?

- ◯ Less than $20,000
- ◯ $20,000 to $39,999
- ◯ $40,000 to $59,999
- ◯ $60,000 to $79,999
- ◯ $80,000 to $99,999
- ◯ $100,000 to $119,999
- ◯ $120,000 or more

When it comes to politics, do you usually think of yourself as:

- ◯ Very Republican
- ◯ Republican
- ◯ Moderate Republican
- ◯ Independent/something else
- ◯ Moderate Democrat
- ◯ Democrat
- ◯ Very Democrat

C.3 Focus Group Survey for Non-Hog Farmers

In addition to the following questions, within each block, we conducted a card sort. We prepared three decks of cards, one for each block, listing benefits and costs on cards and asking to rank them from most important to less/least important and then ask to explain why they make such a choice. We concluded the block by discussing the net benefits – costs or benefits. Then we used a chalkboard or flipchart to ask what was the first choice of each participant and why. This interactive approach yielded more discussion.

Block 1: Costs/benefits of the hog industry in their community, a discussion of the overall net benefits having a hog-based local economy.

1. How are you situated vis-à-vis the hog farms? How far away are you? Are they industrialized farms? Or small farms?

2. Do you know personally know hog operators or workers at the hog farms? What kind of relationship do you have with them, if any?

3. What are the impacts of the farms on the community from your perspective? (We should try to be neutral and ask about positive as well as negative and conclude in terms of net costs/benefits to them and their communities; also, putting it into context – are there other alternatives to the farms in their areas?)
    a. Probe: Do farms provide jobs, income to the residents, pay taxes? How important is hog farming to the economy of the area? Ask them to rank the benefits of hog farming from most important to less/least important.

    b. Probe: Do people have any concerns and/or complaints regarding the impact that hog farms are having on their community? ammonia smell, contamination of drinking water, trucks on the roads hauling feed (resulting in road damage), "blooming" pollution, flies, mice, and rats feeding on manure. What about disposal of dead animals? What about outbreaks of swine flu? etc. Asking to rank concerns from most important to the less/least important and ask why they give more importance/less importance to them. What concerns have increased and what concerns have diminished in say last 10 years?

    c. Discussion of the overall net costs and benefits of having hog farm based local economy.

4. Regarding complaints/concerns, have you talked to anyone? Who?
    a. Probe: To your neighbors, local authorities, NC Department of Agriculture, candidates running for offices, etc.? How do you feel about the responses that you received? Have they heard or got involved in local grass roots organizations such Environmental Justice Community Action Network or others that are involved in

educating and organizing around hog farming and its environmental hazards? What do you think about them?

b. In your opinion, what specific measures could help to address your concerns: i.e., changes in zoning, expansion in green barriers, reducing emissions, etc.

Block 2: Cost/benefits of the development of a biogas industry in their area, including for whom, with a discussion of the overall net benefits for the local economy.

With billions of gallons of manure produced by hogs in NC per year, waste is a massive problem (refer to section on concerns/complaints). Biogas, a waste management system, is becoming an increasingly popular and commercially profitable way to deal with manure disposal: manure lagoons are sealed in oxygen-free tents or covers, bacteria is introduced to break down organic waste—methane is collected from hog waste and convert it into natural gas for electricity.

5. Have you heard about biogas? (If not):

The development of "swine waste to energy" industry has its proponents as well as critics. Proponents claim that among the benefits would be reduction in air pollution, conversion of manure pollution into new revenue source benefiting local farmers, creating jobs, bolstering local tax bases, and driving greater economic development. Then there is energy and climate sustainability aspect of the biogas industry.

6. How important are these benefits for you?

7. NC is now mandating energy companies transition to renewal sources of energy and biogas is an important part of this. Opponents claim that biogas will create only temporary jobs during its construction process, and it is mostly a distraction that doesn't actually address North Carolina's growing hog waste problem. Yes, air quality will be improved, but what about water pollution which could potentially increase as toxic ammonia will not be escaping into air, but becomes trapped in liquified manure? The problem is that if there is too much hog waste in the first place, and we should focus on reducing the waste, i.e., diminishing demand for industrialized hog farming, promoting alternatives to industrial hog faming instead of creating incentives for its expansion, since it is now marketed as a "renewable" energy source. Please rank these costs from the most important to the less/least important and explain your ranking.

<u>Block 3</u>: Costs and benefits of various types of biogas infrastructure

8. There are costs and benefits of this type of industrial infrastructure on communities. (gas pipes stretching over tens of miles, gas collection facilities, trucks collecting/serving the infrastructure, etc.). Some models do integrate the gas collection into existing gas pipes, but this has not been determined yet. (?) Are you concerned with pipes crisscrossing your area or not? If this were to be implemented in your area, would you prefer that it be a centralized operation, such as a plant where the waste from several farms is processed? Or decentralized, such as locating such operations on individual farms?

9. Some of the benefits of this process for local communities are…. # of potential jobs it might for trained specialists.

10. Sampson and Duplin counties have high concentrations of hog farms, and Duke Energy is interested in building biogas facilities there.

11. If this were to be implemented in your area, would you prefer that it be a centralized operation, such as a plant where the waste from several farms is processed? Or decentralized, such as locating such operations on individual farms?

12. To what extent are you concerned about environmental sustainability? What particular issues concern you?
    a. Probe: carbon emissions, animal welfare, etc.
    b. Probe: is the local community concerned about environmental sustainability? Which issues, if any? What actions are people taking? Are organizations such as the Sierra Club involved?
    c. Probe: are local government representatives expressing concern or implementing environmental sustainability initiatives? What in particular?

13. Do you think you would be interested in a biogas facility in your area? Why or why not?
    I would support development of biogas industry in my area if …
    I would oppose development of biogas industry in my area if…

Appendix D—Additional Resources

EPA (U.S. Environmental Protection Agency). (July 2020). *An overview of renewable natural gas from biogas*. EPA 456-R-20-001. Retrieved from https://www.epa.gov/sites/production/files/2020-07/documents/lmop_rng_document.pdf

ICF. (December 2019). *Renewable sources of natural gas: Supply and emissions reduction assessment*. Prepared for the American Gas Foundation. Retrieved from https://www.gasfoundation.org/wp-content/uploads/2019/12/AGF-2019-RNG-Study-Full-Report-FINAL-12-18-19.pdf

IEA (International Energy Agency). (March 2020). *Outlook for biogas and biomethane: Prospects for organic growth.* World Energy Outlook special report. Retrieved from https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

USDA (U.S. Department of Agriculture), EPA (U.S. Environmental Protection Agency), & DOE (U.S. Department of Energy). (August 2014). *Biogas opportunities roadmap: Voluntary actions to reduce methane emissions and increase energy independence*. Retrieved from https://www.usda.gov/energy/maps/resources/BiogasRoadmap/$file/Biogas_Opportunities_Roadmap_8-1-14.pdf