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Biogas Utilization in North Carolina: Opportunities and Impact Analysis

Report

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Acronyms and Abbreviations

ABC	American Biogas Council
AD	anaerobic digestion
bcf	billion cubic feet
bcf/yr	billion cubic feet per year
Btu	British thermal unit
Btu/scf	British thermal units per standard cubic foot
Btu/yr	British thermal units per year
CAFO	concentrated animal feeding operation
CAPEX	capital expenditure
CARB	California Air Resources Board
CEPCI	Chemical Engineering Plant Cost Index
CH_4	methane
CI	carbon intensity
CNG	compressed natural gas
CO_2	carbon dioxide
c-RNG	compressed renewable natural gas
DAF	dissolved air flotation
dtpy	dry tons per year
dt/acre/year	dry tons per acre per year
E. coli	*Escherichia coli*
EPA	U.S. Environmental Protection Agency
EPC	Energy Policy Council
FOGS	fats, oils, and grease
ft^3	cubic feet
gCO_2e/MJ	grams of CO_2 equivalent per megajoule
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies (model)
H_2S	hydrogen sulfide
IMPLAN	Impact Analysis for Planning
$lb\ d^{-1}$	pounds per day
LCOE	levelized cost of energy
LDC	local natural gas distribution company
LFG	landfill gas

m^3	cubic meter
$m^3\ h^{-1}$	cubic meters per hour
$MTCO_2e$	metric tons of carbon dioxide equivalents
MWh	megawatt-hour
NAICS	North American Industry Classification System
NC-RETS	North Carolina Renewable Energy Tracking System
NH_3	ammonia
NO	nitric oxide
NO_x	nitrogen oxides
NREL	National Renewable Energy Laboratory
OPEX	operating expense
PSA	pressure swing adsorption
psi	pounds per square inch
PURPA	Public Utility Regulatory Policies Act
R^2	R squared
REC	renewable energy certificate
REPS	Renewable Energy and Energy Efficiency Portfolio Standard
RFS	Renewable Fuel Standard
RNG	renewable natural gas
RVO	renewable volume obligation
scf d^{-1}	standard cubic foot per day
SO_2	sulfur dioxide
STEPS	Sustainable Transportation Energy Pathways
tpy	tons per year
USD	U.S. dollar
WWTP	wastewater treatment plant

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Executive Summary

As North Carolina strives to meet rapidly approaching greenhouse gas (GHG) emission reduction targets, government officials are looking with increased urgency at developing in-state renewable energy or clean energy resources. In 2019, 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 H. 951, 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), 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 it 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.

This report responds to recommendations made by the North Carolina Energy Policy Council (EPC) in 2018 to promote and develop North Carolina's bioenergy resources and deployment.[3]

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 Energy Solutions for North Carolina Act of 2015, S.L. 2021-165, § 1

3 Although the term "bioenergy" includes all energy derived from organic materials, regardless of production method or feedstock, in the EPC's recommendations in the North Carolina Department of Environmental Quality's (NCDEQ's) *Energy Policy Council 2018 Biennial Report* (NCDEQ, 2018), bioenergy was discussed interchangeably with biogas and has been

The report is also expected to serve as a resource for the North Carolina Department of Environmental Quality's efforts to incorporate biogas into the state's Clean Energy Plan.

This report represents the first phase (henceforth referred to as Phase I) of a two-phase effort funded by Duke Energy through North Carolina's Renewable Energy Portfolio Standard (REPS) research dollars and responds to the EPC's recommendations. The 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, all of which were assumed to be processed via anaerobic digestion (AD). These feedstocks include livestock waste, WWTPs, industrial food waste, landfill gas (LFG), and agricultural crop residue. Because swine manure represents the largest feedstock category, is geographically concentrated (arguably making it easier to aggregate and use) and has a very low carbon intensity, the team's efforts in Phase 1 focused on an in-depth analysis of opportunities to develop and monetize this feedstock. The analysis discusses strategies for utilizing and treating organic waste based on available technologies and the costs of these technologies, in a manner that, in the aggregate, is less natively impactful to the environment. Whether it should be developed and monetized as opposed to treated with a goal for minimization is beyond the scope of this report.

The in-depth analysis included development of a model to determine the costs for several end uses of biogas which the state might expect to produce from swine manure, including local (on-site) electricity production, local RNG production, and RNG production for injection into existing natural gas pipelines for centralized electricity production or transportation fuels. The team then developed a geospatial optimization tool that incorporates these cost models to identify techno-economically viable uses of biogas from swine waste and optimal farm clusters to minimize RNG production costs. Since the ultimate end use is dictated by external drivers such as markets and policies at the federal and state level, the analysis discusses the costs of production in relation to information about currently available markets. Lastly, the report discusses associated environmental, economic, and community impacts and issues, as well as possible steps to overcome related barriers.[4]

Regarding North Carolina's total biogas potential, the analysis determined the following:

1. If all biogas resources were capable of being developed without technological or cost limitations, then the team estimates that North Carolina has the potential to produce approximately 97 billion cubic feet per year (bcf/yr) of biogas. That amount of biogas is the equivalent of approximately 58 trillion British thermal units per year (Btu/yr) in total

interpreted to refer only to North Carolina's biogas resources. Thus, this analysis focuses only on biogas, which is derived from the anaerobic digestion 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

potential heating value (for context, North Carolina used 2,616.1 trillion British thermal units [Btu] of energy in 2018).[5]

2. North Carolina's biogas feedstock resources include swine waste, LFG, industrial food waste, WWTPs, cattle manure, crop residues, and poultry litter.
3. Of the state's total biogas production potential, 58% includes biogas which could be produced from feedstock that is currently releasing fugitive GHG emissions (i.e., swine waste, LFG, industrial food waste, WWTPs, and dairy manure). Thus, these feedstock types can provide a tool for mitigating GHG emissions by capture, and in addition, could potentially offset emissions, if available, from the fossil fuels they displace.

The key findings regarding North Carolina's biogas potential from swine waste include the following:

1. At 29 percent, swine waste–derived biogas represents the largest single feedstock source of biogas in the state, with a theoretical potential of approximately 28 bcf/yr (an equivalent potential heating value of approximately 17 trillion Btu/yr).
2. The practical potential (i.e., the amount of biogas that could be expected to be developed from currently available technology, regardless of cost) of the state's total swine waste–derived biogas resources is approximately 8.5 trillion Btu/yr.
3. Production of RNG from swine-derived biogas provides several potential revenue opportunities, based on available markets. These include the spot price for "brown" natural gas (approximately $3 per million Btu in November 2020) and federal Renewable Fuel Standard (RFS) credits (of approximately $27 per million Btu in November 2020). Other market drivers include the Low Carbon Fuel Standard (LCFS) for the use of low-carbon alternative transportation fuels in states such as California, where credits of approximately $70 per million Btu (in November 2020) could potentially be realized. It is to be noted that not all revenue opportunities might be simultaneously available for all RNG.
4. Nearly 70% of the state's practical biogas potential from swine waste could be economical to produce if the gas had a pathway to an incentive market such as California's LCFS (i.e., could earn $70 per million Btu) by using an optimal farm network that captures low-pressure biogas from farms and upgrades and injects it into existing natural gas pipelines.
5. Even if just a subset of the farm networks capable of producing RNG for <$30 per million Btu were developed, then the indirect and induced value to the economy could potentially reach nearly $40 million per year. Approximately 350 indirect and induced jobs could be supported, and nearly $10 million in taxes could be collected annually in this scenario.

5 Note that the American Biogas Council's estimates of North Carolina's biogas potential are not far off. For more information, see the following website: https://www.eia.gov/state/seds/data.php?incfile=/state/seds/sep_fuel/html/fuel_te.html&sid=US

6. If only 7 of the largest biogas networks were developed, then reductions in the state's GHG emissions of up to 90,000 tons of CH_4 per year (equivalent to 2.3 million tons of CO_2 [MTCO2e]) could be realized.
7. In addition to an increase in energy generation, the swine waste-to-RNG systems as are currently being proposed for implementation by developers in the state (i.e., an in-ground AD with a secondary lagoon to accept digester effluent, termed as Lagoon + New In-Ground AD system) are expected to result in some mitigation of odors and pathogens associated with traditional lagoon-and-sprayfield swine waste management systems and possibly provide some downstream water quality benefits. Further analysis is needed to determine how proposed AD systems affect current waste management practices and to quantify consequent environmental and community benefits and impacts.

Uncertainty regarding how RNG production from swine waste, particularly using a Lagoon + New In-Ground AD system alone, as has been currently proposed, affects environmental performance (including the reduction of ammonia, nutrients, pathogens, odors, and release of waste to surface and groundwater) can create skepticism among key stakeholders such as community groups and environmental advocates. This skepticism, in turn, can impede efforts to harness not only swine waste but also other available organic waste feedstocks. Thus, the team recommends that the state proactively works to encourage the adaptation of comprehensive waste management solutions which addresses all pollution concerns.

During Phase II, the analysis will extend to and expand 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 will be augmented by stakeholder outreach and evaluation of policy options to address what the state's objectives for the captured emissions should be, and physical, policy, economic, and political challenges to potential objectives.

Finally, because harnessing organic waste for energy production will require consideration of issues and stakeholder perspectives beyond the technical and economic consideration on which this report focuses, the team suggests that North Carolina policy makers 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 which 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), North Carolina is one of the top states in the nation for biogas production potential, ranking third in the country (National Renewable Energy Laboratory (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) for energy, fuel, heat, and other uses (American Biogas Council, 2020). The findings from the present analysis confirmed this volume.

In 2018, the North Carolina Energy Policy Council (EPC),[6] acknowledging the state's bioenergy potential (which, for the purposes of this report and underlying analysis, includes only biogas), sought 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 *2020 EPC Biennial Report*

In response to the EPC's list of recommendations, this report discusses 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

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

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6 In the *2018 Energy Policy Council 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 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 *2018 Energy Policy Council Biennial Report*, "[A]lthough 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…"

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 remainder of this report is organized into the following sections, described below:

- **Section 2**—Presents an overview of biogas, describes options for its use, and discusses potential revenue streams for each use.
- **Section 3**—Includes the full inventory of North Carolina's biogas potential by feedstock.
- **Section 4**—Discusses the practical biogas potential that can be derived from swine waste, including the methodology for the geospatial analysis that identifies the swine farms that could form clusters to minimize the cost of RNG production from biogas, the results of which constitute North Carolina's realistic biogas-to-RNG production potential from swine waste. It is important to note that this report can only offer recommendations related to the extent of RNG development that the state might reasonably expect for biogas from swine waste 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 (R-CNG) as transportation fuel to power the state's vehicle fleets.
- **Section 5**—Applies the realistic swine waste-to-RNG potential to determine the economic effects of biogas development on the farm networks with the highest potential impact.
- **Section 6**—Considers the environmental and community benefits and impacts of swine biogas development, with a focus again on the area of the state where swine biogas development would be expected to occur and a discussion of the non-market barriers to such development.
- **Section 7**—Includes conclusions and recommendations, as well as anticipated next steps that will preview the work to be conducted during Phase II of the analysis.

To determine what level of RNG production the state could expect from all its various biogas resources and how best to deploy them, including, but not limited to, using biogas resources to power the state's vehicle fleets, will require the completion of a Phase II analysis of the remainder of the state's biogas feedstock resources. The Phase II analysis also will include an evaluation of the policies and incentives that the state could adopt to better promote biogas development and deployment, as well as stakeholder outreach for each biogas feedstock.

2. Biogas Basics

2.1 Composition, Production, and General Benefits

Biogas primarily consists of methane (CH_4), carbon dioxide (CO_2), water, and trace concentrations of other gases, with CH_4 accounting for approximately 50% to 75% of biogas and CO_2 accounting for approximately 25% to 50%. Biogas is sourced from biological materials such as organic waste (e.g., human, animal, food) and other types of biomass (e.g., organic material such as crop residues). The list of organics most often used to produce biogas includes animal manure, food waste, crop waste, and food scraps. Other sources can include fats, oils, and greases, industrial organic residuals, and sewage sludge (also referred to as biosolids), which are a product of the wastewater treatment process.[7]

Although various methods can be used to generate biogas, this analysis focuses on biogas produced by anaerobic digestion (AD), which involves the decomposition of organic material in anaerobic or oxygen-free environments.[8] Anaerobes are bacteria that flourish in oxygen-free environments, and they feed on or digest organic material and produce biogas. Biogas is a natural by-product of the decomposition of animal or other organic waste managed in environments starved of oxygen. Using an anaerobic digester creates an oxygen-free environment in which anaerobic microorganisms can grow and digest the organic materials fed into the digester, thus expelling biogas.

Although ADs differ in design and organics conversion efficiency, all AD systems follow essentially identical principles regardless of the feedstock.[9] **Figure 1** illustrates how various organic materials are converted by using the AD process into various value-added products and uses, including the following:

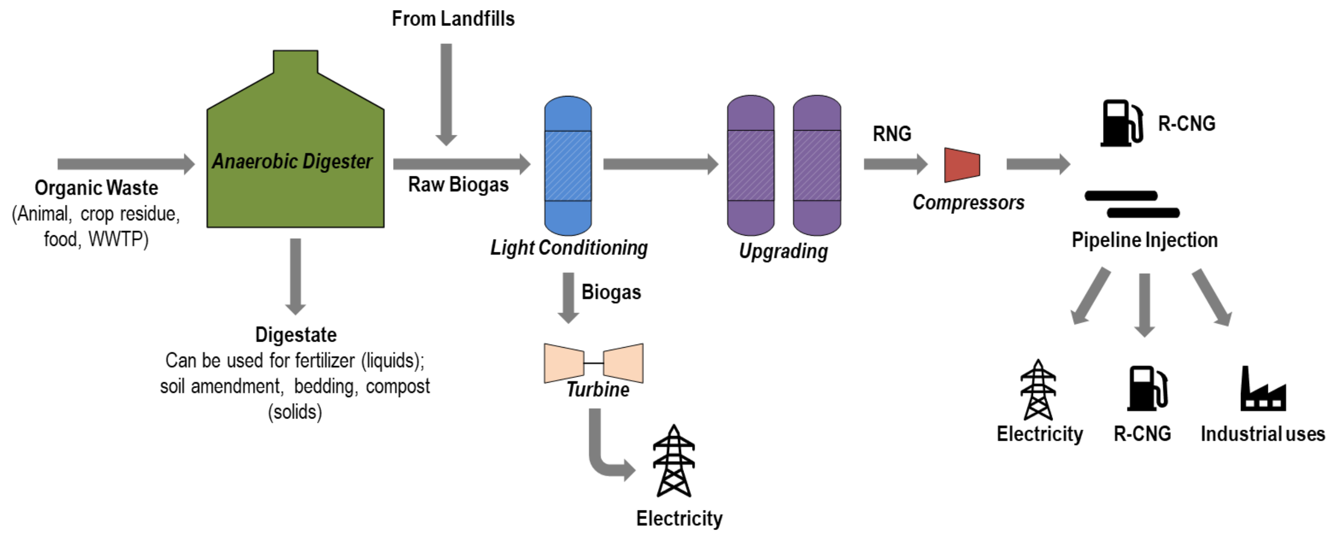
- Powering engines, heating and/or generating electricity (including combined heat and power)
- Fueling boilers and furnaces
- Heating digesters to accelerate the AD process and other spaces
- Running alternative-fuel vehicles, such as compressed natural gas (CNG) vehicles and heavy-duty equipment
- Supplying homes and business with energy (in the form of natural gas or as electricity generated at a natural gas–fired power generation facility)

7 More information about biosolids is available on the U.S. Environmental Protection Agency's (EPA's) website at https://www.epa.gov/biosolids/basic-information-about-biosolids.

8 "AD" refers to the process of anaerobic digestion, as well as the systems or enclosed vessels—often called "digesters"—built to facilitate the AD process. For more information, see EPA's website at https://www.epa.gov/anaerobic-digestion/basic-information-about-anaerobic-digestion-ad#AD%20products

9 For more information about what is made during the AD process and how the products are used, see EPAs website at https://www.epa.gov/anaerobic-digestion/basic-information-about-anaerobic-digestion-ad#AD%20products. To learn more about biogas recovery, see EPA's website at https://www.epa.gov/agstar/learning-about-biogas-recovery#adwork

Figure 1. Biogas Production and Upgrading Processes and Uses



The figure shows two possible uses of biogas: light conditioning followed by combustion for energy (heat and/or electricity) production, or "upgrading," which includes removal of CO_2 and impurities, thus making the gas suitable for pipeline injection or other uses identical to fossil-derived natural gas.

The value of biogas lies in its high CH_4 content. The high CH_4 content in biogas makes its capture and destruction in a flare and/or capture and use an important greenhouse gas (GHG) mitigation strategy. The CH_4 in biogas is also what makes it valuable as an energy resource and provides optionality with respect to end uses. For instance, biogas can be used on-site to produce electricity or can be upgraded to RNG for injection into the natural gas pipeline or use at CNG filling stations, thereby offering a non-fossil replacement for geologically derived natural gas.

As such, several terminologies are commonly used to describe biogas and its derivatives. In this report, ***biogas or raw biogas*** is the gas that is captured from the AD process. ***Lightly conditioned biogas*** is the raw biogas from which water and some impurities have been removed and can be used on-site or collected for treatment and/or upgrading. ***Biomethane and RNG*** refer to biogas that has been cleaned and upgraded to pipeline-quality product. RNG could also specifically refer to the pipeline-quality product that is eligible for federal RINS or certain state LCFS programs. ***Directed biogas*** is pipeline-quality RNG, from which electricity generated could be eligible to qualify as renewable energy certificates (RECs) that may be used for REPS compliance.[10] ***Brown or undifferentiated gas*** refers to a pipeline-quality product that is available after environmental attributes are separated, which renders it essentially equivalent to natural gas derived from geologic sources for purposes of renewable and greenhouse gas accounting.

[10] See North Carolina Utilities Commission, Order on Request for Declaratory Ruling, DOCKET NO. SP-100, SUB 29, Mar. 21, 2012 (stating that "as long as appropriate attestations are made and records kept regarding the source and amounts of biogas injected into the pipeline and used by the Facility to ensure that no biogas is double-counted, *the Directed Biogas would be a renewable energy resource and the resulting electric generation would be eligible to earn RECs that may be used for REPS compliance*.").

In the case of biogas derived from swine and dairy manure, industrial food waste, landfills, and wastewater treatment plants (WWTPs), naturally decaying organic waste currently releases biogas directly into the atmosphere as fugitive CH_4 emissions. The same holds true for other organic wastes or feedstocks collected in anaerobic environments such as storage ponds or waste lagoons. Thus, the use of biogas captured from biogas off-gassing facilities mitigates the CH_4 emissions from these facilities while providing a low-carbon, renewable energy substitute for fossil fuels. This ability to mitigate emissions and provide a renewable substitute for fossil fuel, when available in compliance with applicable state and federal law, is often referred to as a "double dividend" GHG mitigation effect.

CH_4 is 28 to 34 times more potent than CO_2 over 100 years in terms of global warming potential (U.S. Environmental Protection Agency (EPA), 2020b). When organic materials are managed in ways that release fugitive emissions, such as those from landfills, WWTPs, and livestock operations such as swine and dairy farms, capturing the raw biogas and using it to make energy means that fugitive CH_4 emissions are mitigated and that emissions from the fossil fuel that the biogas displaces are avoided. Biogas made from sources handled in ways that do not normally release fugitive emissions can still lead to the creation of a biogenic source of energy that can potentially curtail the use of fossil fuels. The use of biogas also reduces reliance on extraction processes such as drilling and hydraulic fracturing, although risks of CH_4 leakage from non-off-gassing feedstock should be considered.

Biogas can be used in several ways and forms, including for direct electricity production with little upgrading, or once upgraded to biomethane, as a natural gas replacement and as a low-carbon transportation fuel. Biogas also can be stored and can be transported via pipelines and trucks. Additionally, RNG can be stored in liquefied or compressed forms and accessed on demand.[11] If deployed appropriately, RNG could potentially provide a route to solve intermittency challenges of renewables such as wind and solar, thereby increasing the overall penetration of renewables into the power generation system. Although it is beyond the scope of this analysis, biogas and biomethane can be used for industrial products conventionally made from natural gas.

In addition to energy created from biogas, the by-products of AD include the leftover solids or digestate and nutrient-rich liquids, which can be used as fertilizer if in compliance with applicable environmental laws and regulation. Depending on the feedstock, the effluent from the digester can be a liquid or liquid slurry from which the solids must be separated. For instance, effluent from a typical in-ground swine waste anaerobic digester is in a liquid slurry form. Identifying economic uses for the by-products of AD is important because otherwise the digestate becomes a cost center and/or could become an environmental issue if allowed to accumulate on-site. The uses for all products and by-products of AD, potential revenue streams, and whether there should be policy incentives to create markets or otherwise to encourage recovery of such AD products are beyond the scope of the current analysis.

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[11] Liquefaction of biomethane or RNG is likely to cost more than purification and upgrading of biogas. These technologies are offered by several companies including Cryo Pur (http://www.cryopur.com/en/our-solutions/) and Cryonorm (https://cryonorm.com/liquefied-natural-gas/liquefaction-plants/biogas-liquefaction/) among others.

In terms of on-site uses, biogas can be used to run small-scale power generating equipment such as microturbines and generators, which can supply electricity to the power grid, support distributed power generation, or be used on-site as a replacement or supplemental source of electricity. Having the capacity to use biogas on-site also provides an emergency source of electricity and thus offers resiliency benefits, which can be advantageous considering the increasing severity and frequency of severe weather events brought on by climate change.

Alternatively, biogas can be refined on- or off-site into RNG and injected into the natural gas pipeline or delivered via truck transport to a CNG filling station to fuel vehicles. RNG is beneficial because it can be used in place of geologically derived natural gas—a fossil fuel—which means that its use avoids the emissions of CH_4 that would otherwise have been released directly into the atmosphere.

2.2 Biogas Uses and Corresponding Revenue Streams

Because of its high CH_4 content, biogas can be used as a renewable fuel source for heating, transportation fuel, or power generation, either on-site or, after purification, processing and transportation, in centralized power generation plants. The end use of the biogas is influenced by the cost of production and the availability of revenue streams, both of which are dictated by the type of feedstock.[12] Revenues are also largely influenced by policies designed to encourage renewable energy production or offset or reduce GHG emissions. Other considerations include the location and volume of the feedstock, the distance of a project to a natural gas pipeline injection point, the location of vehicle fueling stations or other end users, and the ability of the project developer to secure access to an injection point or pathway to an end user or market.

2.2.1 On-site Electricity Generation

Raw biogas, in addition to CH_4 and CO_2, contains moisture and impurities such as sulfur. The raw biogas can undergo light conditioning, which includes drying and sulfur removal. Lightly conditioned biogas can be used to run small-scale power generating equipment, such as microturbines and generators, to produce electricity. Electricity produced from biogas on-site can be used to reduce energy costs or to generate back-up power during emergency situations. The electricity generated can also be supplied to the electricity grid through an interconnection agreement with the site's electric utility service provider. Two primary revenue streams exist for on-site electricity generation: electricity sales and, for registered new renewable energy facilities, renewable energy certificate (REC) payments. These two revenue streams are described in the remainder of this subsection of the report.

Electricity Sales

Through an arrangement with the utility provider, a project developer can be paid the cost that the utility otherwise would have spent to produce the same amount of electricity, otherwise referred to as the

12 Entities that handle organic waste, such as sewage treatment plants, landfills, livestock operations, and farms, can take advantage of the biogas that their waste creates, by using it to generate power, thereby reducing fuel costs and avoiding carbon emissions. The entities can also convert biogas to RNG.

utility's avoided cost.[13] This is possible in circumstances that meet the legal requirements pursuant to the Public Utility Regulatory Policies Act. The North Carolina Utilities Commission establishes the avoided cost rate for regulated electric utilities in the state. For those projects located in the service territory of an electric membership cooperative or municipality, the avoided cost rate is established by the service provider.

Renewable Energy Certificate Payments

RECs are market-based instruments that represent and convey the property rights to the environmental, social, and other non-power attributes of renewable electricity generation (U.S. Environmental Protection Agency (EPA), 2019a). RECs represent the environmental attributes associated with 1 megawatt-hour (MWh) of renewable electricity generated, and they are tradeable. In addition, RECs can be used to substantiate voluntary claims that an entity's electricity purchases have been obtained from renewable sources or used to prove compliance with a renewable energy production or purchasing requirement. Several systems exist for tracking REC transactions (i.e., to register, trade, or retire RECs). The system of record for RECs generated from renewable energy projects in the state is the North Carolina Renewable Energy Tracking System (NC-RETS). The North Carolina Utilities Commission established NC-RETS to issue and track RECs and interact with other REC tracking platforms.[14]

The value of a REC will depend on whether it is sold into voluntary or compliance markets. In North Carolina, RECs from swine and poultry waste can garner a premium because North Carolina utilities must generate a specific percentage of their electricity from swine and poultry waste, pursuant to the North Carolina Renewable Energy and Energy Efficiency Portfolio Standard (REPS).[15,16]

2.2.2 Upgrading Biogas to RNG

To upgrade biogas to RNG, the CO_2 and trace contaminants, including water, are removed. Several commercially available processes, including pressure swing adsorption (PSA), membranes, water scrubbing, and solvent washes, can be used to produce RNG that is nearly pure CH_4. The choice of technology typically depends upon the volume of raw biogas being upgraded, with larger volumes costing less because of economy of scales. RNG can be substituted seamlessly for conventional natural gas, including as R-CNG, to fuel natural gas–powered vehicles.

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13 "An avoided cost (also known as net-metering) is the minimum amount an electric utility is required to pay an independent power producer, under the Public Utility Regulatory Policies Act (PURPA) regulations of 1978, equal to the costs the utility calculates it avoids in not having to produce that power (usually substantially less than the retail price charged by the utility for power it sells to customers)." More information is available on the U.S. Solar Institute's website at https://www.myussi.com/glossary/avoided-cost/

14 More information is available on NC-RETS's website at https://www.ncrets.org/

15 Technically, electricity produced by other feedstocks qualify under REPS, but they are not eligible for the premium related to the swine waste and poultry waste set-asides.

16 This is known as "directed biogas," whereby the electric utility nominates RNG to supply a specific power plant and calculates the RECs based on the efficiency rate of the power plant to which the RNG is nominated. The North Carolina Utilities Commission approved the "directed biogas" approach in 2012. An analysis performed in 2013 by the Nicholas Institute for Environmental Policy Solutions and the Duke Carbon Offsets Initiative, which employed the Optima Biogas Geospatial and Economic Model, compared various scenarios by which the North Carolina REPS swine waste set-aside could be met. Based on the findings from the analysis, it was determined that directed biogas would be the least cost approach to meet the mandate, but it did not try to determine the best and least cost approach to developing all swine biogas resources.

Depending on the volume of biogas available at a site, upgrading to RNG can occur on-site and then be trucked to an end user such as a vehicle fleet operator to supply a CNG filling station. RNG produced on-site can also be injected into the natural gas pipeline. Alternatively, the biogas can be collected via in-ground low-pressure pipes connected to a centralized upgrading and natural gas pipeline injection point or trucked from the biogas capture site to the upgrading and injection point. This RNG can be used either to generate electricity off-site advantageously by using high-efficiency large-scale power generation plants (referred to as directed biogas), or as transportation fuel for R-CNG applications.

Because the economics of on-site versus off-site RNG production can vary considerably, the team's Phase 1 analysis evaluates these options separately, even though the resulting RNG can be used in the same ways and be eligible for the same revenue streams. The trend over the past decade has been to upgrade biogas to RNG, with the end uses of that RNG shifting as incentives and markets have shifted. For instance, although nearly all RNG production in the United States was directed toward off-site electricity production in 2011, a strong renewable transportation fuel market has resulted in nearly 76% of RNG projects directed toward transportation fuels in 2017 (Escudero, 2017). Thus, various revenue streams are available for RNG development depending upon the available use of the RNG.

The remainder of this subsection discusses the potential revenue sources from these different uses. These potential revenue sources are not all available simultaneously for any particular biogas. These can include revenue for the thermal value of the gas (brown gas payments); revenue from directed biogas, which can include revenue representing the value of REC; and revenue when used as renewable transportation fuel. The remainder of this subsection also discusses the federal Renewable Fuel Standard (RFS) and associated Renewable Identification Numbers (RINs), state-enacted Low Carbon Fuel Standards (LCFS), and other biogas-related revenue potential.

Revenue for the Thermal Value of the Gas (Undifferentiated Gas Payments)

A project developer who injects biomethane into a natural gas pipeline can earn revenue for the thermal value, measured in dekatherms or million British thermal unit (Btu), receives a payment for the thermal value of the gas or "undifferentiated gas," which, for example, can be priced on the basis of a formula tied to the Henry Hub price for natural gas. The price for undifferentiated natural gas tends to vary by region.

North Carolina Renewable Energy and Energy Efficiency Portfolio Standard, Directed Biogas, and Renewable Energy Certificate Payments

As previously mentioned, RNG produced from biogas feedstocks can be used as a substitute for natural gas to generate electricity, and a utility combusting such RNG potentially generates RECs. In North Carolina, biogas developers can inject RNG made from biogas into a natural gas pipeline and receive payments for the gas that a power plant then consumes to generate energy, with the RECs going to the owner of that power plant, hence the term directed biogas. For some developers, this directed biogas approach can be preferable because, although on-site electricity production requires less processing of the gas and may be attractive because it can be more straightforward to connect electricity to the grid, the amount of electricity that can be produced via highly efficient power plants through a directed biogas approach is far greater than what can be produced on site, therefore justifying the increased cost and difficulty associated with pipeline injection.

Renewable Transportation Fuel Payments

Under regulations at the federal and state levels, two primary programs currently exist that reward the production of transportation fuel from biogas. The programs discussed here include the federal RFS administered by the U.S. Environmental Protection Agency (EPA) to increase the use of renewable fuels, as well as California's LCFS, which is administered by the California Air Resources Board (CARB) and designed to curb the GHG content of California's transportation fuel sector. In addition, other states such as Oregon have instituted renewable fuel standards for which RNG from North Carolina-specific feedstocks could be viable. This report does not suggest or recommend using the same biogas for compliance with multiple programs, but rather identifies potentially available alternative markets.

Federal Renewable Fuel Standard and Renewable Identification Numbers

The RFS is a federal program established through the Energy Policy Act of 2005. The RFS was later expanded and extended by the Energy Independence and Security Act of 2007. This Act of 2007 requires transportation fuel sold in the United States to contain a minimum volume of renewable fuels in increasing amounts each year, rising to 36 billion gallons per year by 2022. The intent of the RFS is to reduce GHG emissions, expand the U.S. renewable fuels sector, and reduce dependence on imported oil.

The volumes that regulated entities must purchase according to the RFS are based on a percentage of their petroleum product sales. Oil refiners and gasoline and diesel importers, which are collectively referred to as obligated parties, can meet their renewable volume obligations (RVOs) by either selling required volumes of biofuels or purchasing RINs from parties who exceed their renewable fuel production or purchasing requirements and have RINs to spare.

A RIN, which is an identifier for 1 gallon of renewable fuel, is the tracking instrument used by obligated parties to prove compliance with their RVOs and which EPA employs to track compliance. A RIN is assigned to specific renewable fuel categories based on feedstock, with D3 and D5 RINS being the relevant categories for biogas-derived transportation fuels. D3 RINs are cellulosic RINs, sourced from cellulosic materials, but thanks to regulatory action which expanded the category to other feedstocks, RNG derived from landfills, municipal wastewater treatment facility digesters, agricultural digesters, and separated municipal solid waste (MSW) digesters can also qualify. D5 RINs include advanced biofuels RINs, sourced from other types of carbonaceous feed material, and, like D3 RINS, also can be sourced from landfills, WWTP digesters, agricultural digesters, and separated MSW digesters. D3 RINS typically command approximately three times the price in the market as D5 RINs, which means that biogas developers will strive to get their feedstock recognized as a D3 RIN. Notably, all landfill gas (LFG) RINs qualify for D3 status (Greene, 2017).

States' Low Carbon Fuel Standard

A growing number of states, the most notable of which being California, require their transportation fuel providers to reduce the GHG content of their overall fuel supply. One way to accomplish this is by incorporating low-carbon fuel into their supply pool, which reduces the overall CI of their fuel supply and that of the state's transportation fuel sector.[17] The CI calculates the emission of CO_2 equivalents per million Btu (or megajoules) of a given energy source as determined by a well-to-wheels life cycle assessment. In the United States, Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) is used as a standard model to determine CI. **Table 1** provides average CIs for typical RNG feedstocks. Because RNG from swine and dairy manure scores very well in terms of CI (i.e., RNG from swine and dairy projects offsets a significant amount of CO_2 equivalents per million Btu), it is in extremely high demand and can fetch significantly high prices.[18]

Table 1. The Average CI for RNG from Various Sources

Feedstock	Average CI (gCO_2e/MJ)
LFG	46
Digested manure	-271
WWTP	30
Food and green waste (stand-alone digester)	-11

Note: gCO_2e/MJ = grams of CO_2 equivalent per megajoule.

For North Carolina, demand for very low CI RNG from markets such as California means that developers of RNG derived from swine waste can receive extremely high revenue for their gas, if they can secure an approved pathway to such a market. The main requirements for securing an approved LCFS pathway include getting the gas into a pipeline with a local brown gas sale. However, all environmental attributes are necessary to be rebundled before the RNG is delivered to the transportation fuel purchaser. It is important to note that it is not required to physically transport the gas to California.

It is worth pointing out that a project's ability to succeed financially depends on the strength of the market into which the developer plans to sell the gas. With more than $1 billion in investment and growth of 210% of RNG use as a transportation fuel in the past 5 years, the California market provides a strong indicator of continued growth. For North Carolina RNG developers, this means that, depending

17 The LCFS in California is tied to Assembly Bill 32, which is the law passed by the California legislature to create a statewide cap-and-trade program. The program established the use of carbon offsets as one instrument to comply with emission reduction targets, as previously discussed, and created targets for decreasing the GHG intensity of transportation fuels. For more information about the LCFS, see the California Air Resources Board's website at https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard. Also see sections 95480 through 95503 of Title 17 of the California Code of Regulations.

18 The Oregon Clean Fuels Program, also known as the LCFS, is designed to reduce the "lifecycle carbon intensity" of fuels, or the total emissions that come from the production, processing, transportation, and consumption of each unit of fuel consumed in that state. In 2009, the legislature set a target of reducing the carbon intensity of Oregon's transportation fuel mix to 10% below 2015 levels by 2025. The program serves as an incentive to transportation fuel providers to "blend more low-carbon fuels," which include CNG sourced RNG "into their overall mix." For more information, see the following publication: (Sickinger, 2020).

on the actual CI score of an individual project, RNG from swine waste can fetch upwards of $70 per million Btu (NGVAmerica & The Coalition for Renewable Natural Gas, n.d.). It is also possible to receive LCFS and RIN credits under the RFS in a process known as "stacking," which further increases the revenue potential (Baker, 2020). It is also important to note that aside from the federal RINS, RNG sold into markets such as the California LCFS cannot be stacked with any other GHG or RPS programs including RECs in any other state's program or offset revenue.

Although the price signal from the LCFS has catalyzed increased interest in RNG development, particularly from developers of swine waste-to-RNG projects, high demand from buyers within California are driving up the cost for potential buyers in North Carolina such as entities who have made commitments to reduce GHGs or use renewable energy. It is reasonable to expect that interest in high-demand, out-of-state markets will only increase if more states pass low carbon fuel standards or other RNG-driven mandates.

This outside demand pressure on prices will be one that policy makers must consider if the goal is for North Carolina's biogas to play a larger role in its own clean energy and GHG reduction targets. Nevertheless, California's LCFS is generally touted as a highly successful method for reducing GHG emissions from California's transportation sector. At the very least, programs such as the LCFS should be considered for North Carolina to promote greater GHG reduction targets.[19]

Other Biogas-Related Revenue Potential

In addition to mandates established to increase renewable energy and fuel use, some project developers are motivated by a growing number of companies, organizations, and individuals seeking to reduce their GHG footprints voluntarily via biogas-related purchases. These climate-conscious purchasers see biogas as an opportunity to directly displace fossil fuel use and/or offset their GHG emissions via instruments such carbon offsets.

Voluntary Energy Purchases

Rather than purchasing biogas or RNG to comply with governmental mandates, some entities are interested in purchasing biogas or RNG via bilateral agreements to displace their use of fossil fuels and/or offset their GHG emissions. Although the North Carolina REPS mandates that a specific percentage of North Carolina's electricity be sourced from animal waste, a significant driver of biogas development in the state has been private investment in biogas projects to meet GHG reduction goals. One in-state example includes Duke University, which for more than a dozen years has targeted voluntary emission reductions from biogas capture and destruction and from the purchase of RNG to meet its voluntary GHG or "climate neutrality" commitment.[20] There is also interest across the country from public institutions (e.g., the University of California system) and private companies (e.g., Amazon)

19 The California Air Resources Board recently released data showing that the average "carbon intensity" of all RNG vehicle fuel in the state's LCFS program was negative for the first time in program history. For more information, see the following article: (2020).

20 For example, see Ouzts, E. (2018, April 11). Duke University counting on hog waste biogas to meet climate goal. Retrieved from Energy News Network's website at https://energynews.us/2018/04/11/southeast/duke-university-counting-on-hog-waste-biogas-to-meet-climate-goal

in biogas and RNG as an energy and GHG reduction tool. For example, Amazon recently announced a purchase of more than 700 R-CNG-powered vehicles and Berkshire Hathaway's South Carolina natural gas holdings, Carolina Gas Transmission, has committed to the purchase of RNG harvested at a large produce processing facility which will help the company neutralize its carbon emissions. (Saniocola, 2021; University of California, 2020).

Biogas Capture and Destruction for Carbon Offset Payments

Perhaps the most straight-forward way, particularly in terms of physical infrastructure, to derive monetary value from biogas is revenue from capturing and destroying fugitive CH_4 emissions to achieve certified GHG reductions which can be sold as carbon offsets. Although carbon offsets can serve as a compliance instrument depending on the jurisdiction and program,[21] they are also pursued voluntarily as a carbon offsetting tool.[22] In both cases, carbon offsets provide a way to reduce an entity's carbon footprint when it is not physically possible to reduce emissions on-site or when it is too expensive to achieve on-site GHG reductions or fuel switching.

Carbon offsets may be best associated with feedstock that releases fugitive CH_4 emissions, such as swine waste, dairy manure, LFG, WWTPs, and food processing operations, the emissions from which are instead captured and destroyed in a manner that is measured, monitored, and verified pursuant to an applicable carbon offset protocol to create an emission reduction instrument. Carbon offsets are measured in metric tons (1 tonne = 1 metric ton) of carbon dioxide equivalent ($MTCO_2e$). In the case of biogas projects, payments for carbon offsets depend on the CH_4 content of the biogas captured, the difference between the baseline biogas emissions of the facility or operation, and the reduced CH_4 emissions achieved because of efforts taken to capture and use or flare the biogas. Thus, not all biogas destruction projects qualify for creation of an offset. An offset can only be rewarded if a project can show that it reduces overall GHG emissions as compared to the project's baseline or historical emissions and other requirements are met.

Notably, it is sometimes possible to generate both carbon offsets and RNG that when combusted creates renewable energy from livestock projects involving the capture and use of biogas to produce on-site electricity or RNG. Revenue for both the reduction or a certain quantity of offsets beyond those necessary to offset the emissions from RNG combustion can be possible depending on the precise allocation of attributes to the biogas using the remainder for the carbon offsets. There is also a possible revenue source with the RFS. However, in the LCFS, because the compliance unit is measured by the CI of the renewable fuel's feedstock, the fuel must carry the GHG reduction attribute, which means that neither the carbon offset not renewable energy attributes may be unbundled or sold separately to a party other than the buyer of the rebundled RNG in California.

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21 The capture and destruction of biogas from livestock operations qualifies as a carbon offset pursuant to the Climate Action Reserve's U.S. Livestock Project Protocol. This protocol is one of five protocols recognized for compliance purposes under California's Cap-and-Trade Program, which California implemented as part of its 2006 Global Warming Solutions Act or Assembly Bill 32.

22 Because of project economics or lack of access to a pipeline injection point, note too that compliance markets limit the amount of carbon offsets that can be used to meet reduction targets. In California, it is 4 percent (https://ww2.arb.ca.gov/our-work/programs/compliance-offset-program/about)

Revenue for voluntary carbon offsets can be variable and depend largely on an individual project's characteristics. However, carbon offset pricing has been between $5 and $10 (Kaplan, 2020). This cost is generally not large enough payment to justify the physical infrastructure plus administrative costs associated with registering, measuring, and verifying a swine waste-to-biogas destruction project, but it can make project economics work if offset payments can be stacked with energy payments. If North Carolina wished to reward the capture and destruction of CH_4 in instances in which projects some type of energy or fuel production was not financially, technologically or geographically viable, then it would need to consider what policies could be established to incentivize carbon offsets. (California Air Resources Board, 2014; Kaplan, 2020; Key & Sneeringer, 2011; Parajuli et al., 2019; Wildish et al., n.d.-b).

Table 2 lists the type of biogas, its related use, and revenue opportunities by feedstock type.

Table 2. Biogas-Related Use and Revenue Opportunities

	Biogas-Related Uses			
	On-Site Electricity Production	**Upgrade to RNG On-Site or Centralized Location**	**On-Site Biogas Capture & Destruction**	**Co-Digest**
Type	**Payment Opportunities**			
Swine manure	North Carolina REPS for swine waste–derived RECs; electricity payment (avoided cost rate when available) or savings from supplemental power source; carbon offset payment possible (voluntary or compliance-grade)	Injection for electricity production: North Carolina REPS (via directed biogas) **or** Use as transportation fuel: RFS RINs, local injection and rebundled pathway to California purchasers for transportation uses = California LCFS	Compliance-grade or voluntary carbon offsets in applicable circumstances	—
Dairy manure	RECs (NC REPS general renewable pool); electricity payments (avoided cost rate); supplemental power source	North Carolina REPS (via directed biogas) **or** Use as transportation fuel: RINs (RFS), California LCFS	Compliance-grade or voluntary carbon offsets in applicable circumstances	—
Food waste	RECs (NC REPS general renewable pool); electricity payments (avoided cost rate); supplemental power source	North Carolina REPS (via directed biogas) **or** Use as transportation fuel: RINs (RFS), California LCFS	Voluntary carbon offsets in applicable circumstances	—
WWTP	RECs (NC REPS general renewable pool); electricity sales (at avoided cost rate); savings from supplemental power source;	North Carolina REPS (via directed biogas) **or** Use as transportation fuel: RINs (RFS), California LCFS	Voluntary carbon offsets in applicable circumstances	—
Landfill gas[a]	RECs (general renewable pool); electricity payments (avoided cost rate); supplemental power source	North Carolina REPS (via directed biogas) **or** Use as transportation fuel: RINs (RFS), California LCFS	Voluntary carbon offsets in applicable circumstances	—
Crop residues	—	—	—	On-site electricity production; RECs (general renewable pool); electricity payments (avoided cost rate when available); supplemental power source; upgrade to RNG

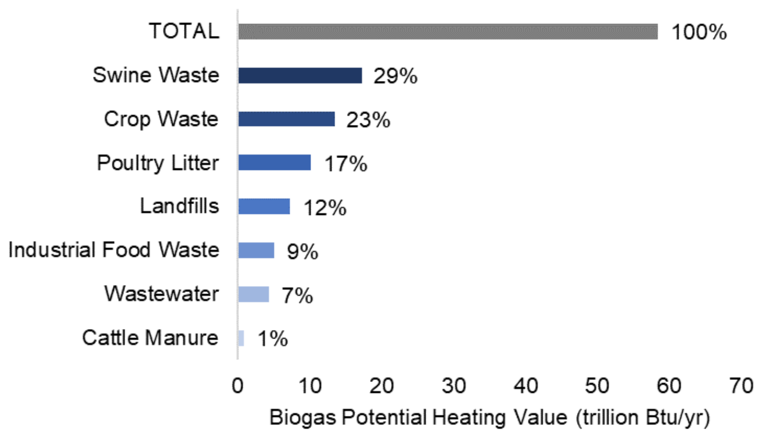
	Biogas-Related Uses			
	On-Site Electricity Production	**Upgrade to RNG On-Site or Centralized Location**	**On-Site Biogas Capture & Destruction**	**Co-Digest**
Type	**Payment Opportunities**			
Poultry litter	RECs (North Carolina REPS poultry waste set-aside); electricity payments (avoided cost rate when available); supplemental power source	—	—	On-site electricity production; RECs; electricity payments (avoided cost rate when available); supplemental power source; upgrade to RNG

[a] Municipal Solid Waste landfills.

3. North Carolina's Total Biogas Potential Inventory

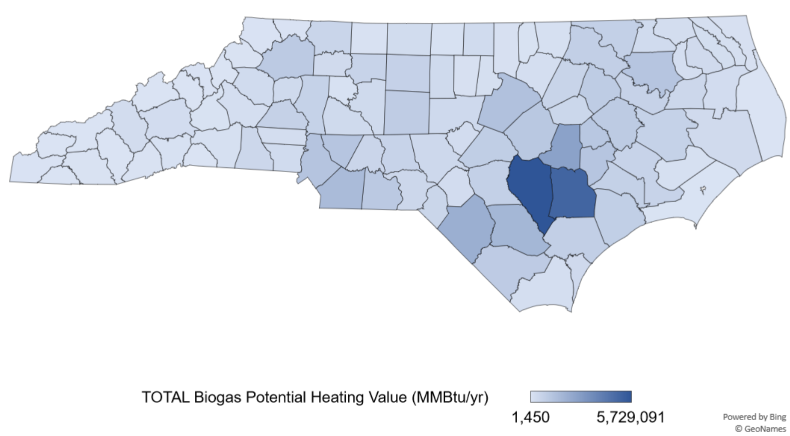
If it were possible to anaerobically digest all of North Carolina's organic feedstock without technical and economic limitations, the team estimates that the state could produce approximately 97 billion cubic feet per year (bcf/yr) of biogas, which would provide an equivalent total potential heating value of approximately 58 trillion Btu/yr (based on a biogas heating value of 600 British thermal units per standard cubic foot (Btu/scf). Translated into practical terms, 58 trillion Btu/yr could displace approximately 10% of North Carolina's natural gas use if technical and economic limitations did not exist (U.S. Energy Information Administration (EIA), 2020a). A detailed inventory of seven feedstocks (see **Figure 2**), shows that the biogas potential of swine waste feedstocks is the largest source category, followed by crop waste and waste from poultry operations. A detailed methodology to determine the potential inventory of biogas for each feedstock is provided in **Appendix A** of this report.

Figure 2. Total Potential Heating Value from Biogas by Feedstock



Notably, most of the biogas potential in the state is concentrated in the agriculture-heavy Coastal Plain (**Figure 3**).

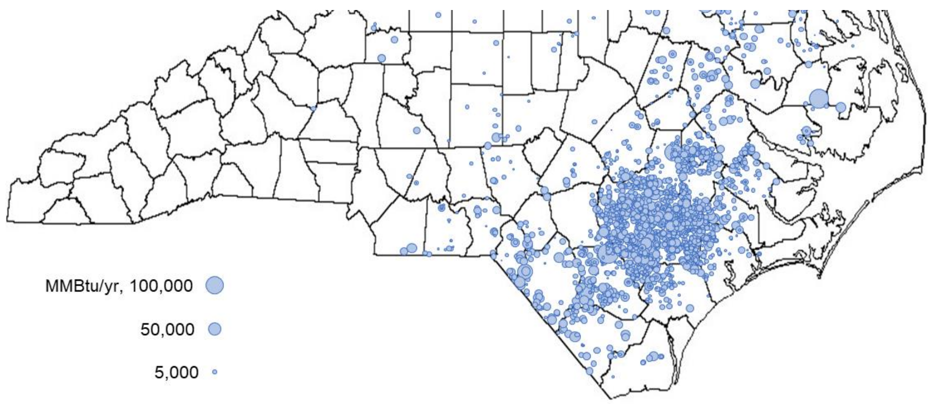
Figure 3. Geographical Distribution of Total Biogas Potential Heating Value by County



3.1 Swine Waste

With more than 2,100 swine operations in the state, biogas recovered from swine waste represents the largest resource, comprising approximately 17 trillion Btu/yr (or 29%) of the total. Assuming all of the state's biogas were to be converted to RNG, injected into the natural gas pipeline, and used to generate electricity—a process known as directed biogas—an estimated 4.4 million $MTCO_2e$ emissions could be averted annually from the replacement of fossil fuels alone. In other words, the GHG reduction estimate does not include the avoided emissions that would be achieved by preventing fugitive emissions from being released from feedstock managed in anaerobic environments that currently emit CH_4 into the atmosphere. The distribution of biogas potential on a per-farm basis (**Figure 4**) indicates that a significant majority of the potential is heavily concentrated in just five counties which corresponds to the counties with the highest concentration of swine: Bladen, Duplin, Robeson, Sampson, and Wayne.

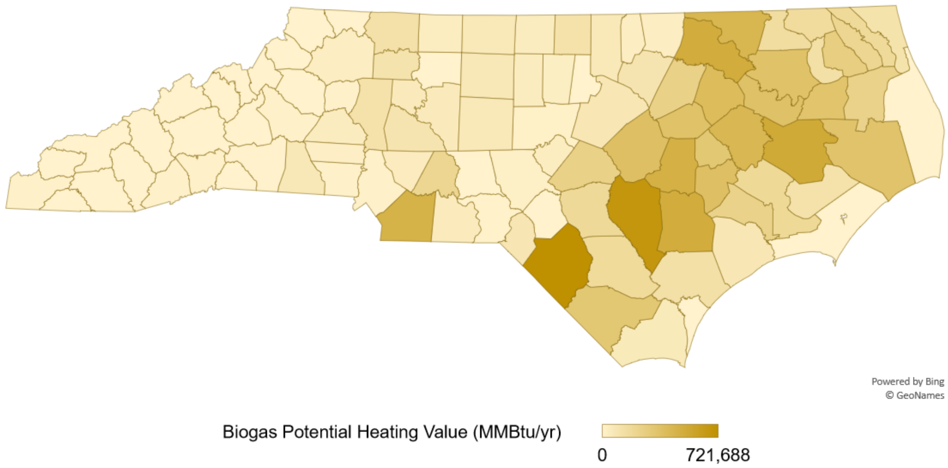
Figure 4. Distribution of Biogas Potential on a Per-Farm Basis from Swine Waste



3.2 Crop Residue

Although a feedstock not currently managed using AD, the team estimates that crop residues could have the second highest potential to generate biogas in the state. The team considered the seven most widely grown crops in North Carolina (i.e., corn, cotton, peanuts, soybean, sweet potato, tobacco, and wheat) for this analysis. The potential availability of residues from these crops for AD is limited by the amounts typically sold to paying markets, such as for animal feed or amounts required to be left on the field to minimize soil erosion and nutrient losses, which serves to increase soil carbon sequestration. Nevertheless, dominated by corn and soybean residue, the biogas potential in the state is highest in counties with the highest crop production (**Figure 5**).

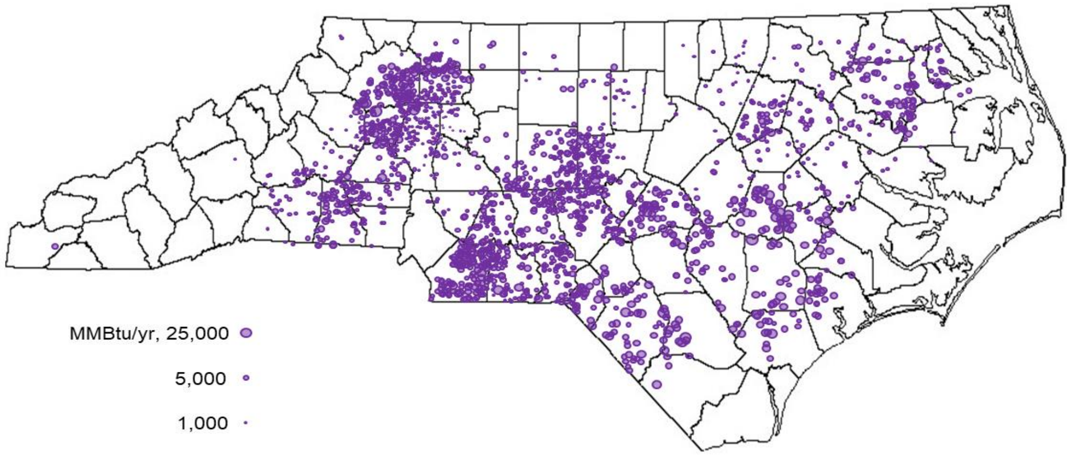
Figure 5. Biogas Potential from Crop Residues by County



3.3 Poultry Litter

Because of the characteristics of poultry operations, biogas production in a poultry farm is not as straightforward to accomplish as it is for facilities with other types of feedstock and operations. Mainly, poultry facilities willing to generate biogas from manure must implement a system for daily litter collection, another system to decrease the total solids concentration of the waste (through water addition, flush or pit recharge mechanisms), and a final system to eliminate the excess bedding present in the litter (U.S. Environmental Protection Agency (EPA) & AgSTAR, 2018). These considerations render the generation of biogas from poultry farms not viable in most cases, as evidenced by the small number of biogas plants being implemented. For example, only seven biogas facilities were constructed at U.S. poultry farms in 2018 (U.S. Environmental Protection Agency (EPA) & Combined Heat and Power Partnership, 2011). Nevertheless, the biomass which could be converted to biogas is substantial as compared to other available feedstocks. **Figure 6** shows the distribution of biogas potential from poultry facilities in North Carolina.

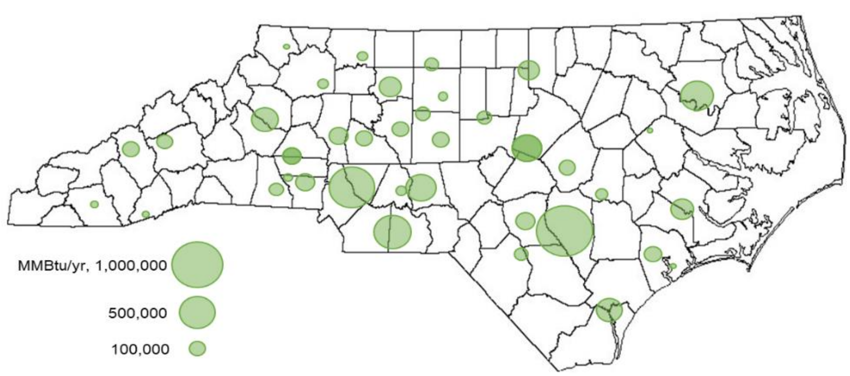
Figure 6. Distribution of Biogas Potential in North Carolina from Poultry Litter



3.4 Landfills

Although swine waste makes up the largest single category of North Carolina's biogas potential, landfills provide some of the largest single-site opportunities for biogas recovery. In fact, in several cases, landfills offer larger concentrated sources than swine farms. Landfills do not offer as high of a CI score as livestock operations. However, the ability of landfills to provide a very large volume of biogas from a single source makes them worth prioritizing as an early target of development. Although all landfills produce biogas from waste decomposition, it is not economical to harness and use this biogas at all landfills. Based on EPA's "candidate" designation, the biogas potential from candidate landfills in North Carolina are shown in **Figure 7**.

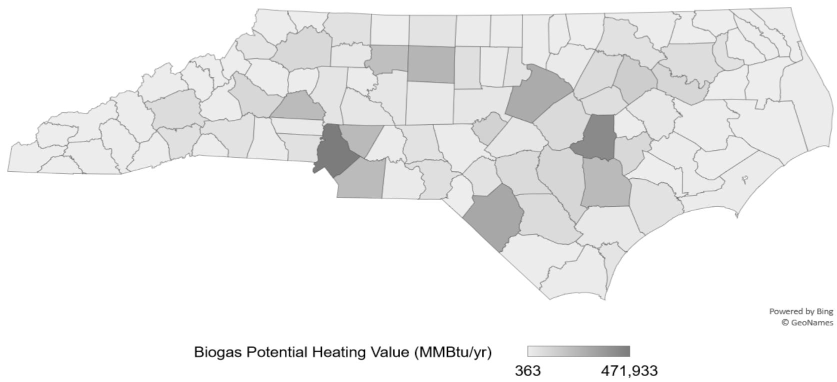
Figure 7. Distribution of Biogas Potential from Candidate Landfills



3.5 Industrial Food Waste

The team cataloged wastes from the top eight food production industries (see **Appendix A** for the detailed methodology), and then aggregated the information at the county level. Based on quantities of wastes and adjusting for the quantities sold to high-paying markets, such as for rendering and animal feed, the findings indicate that bakeries and meat product manufacturing have the highest biogas potential. **Figure 8** shows the biogas potential by county from industrial food waste.

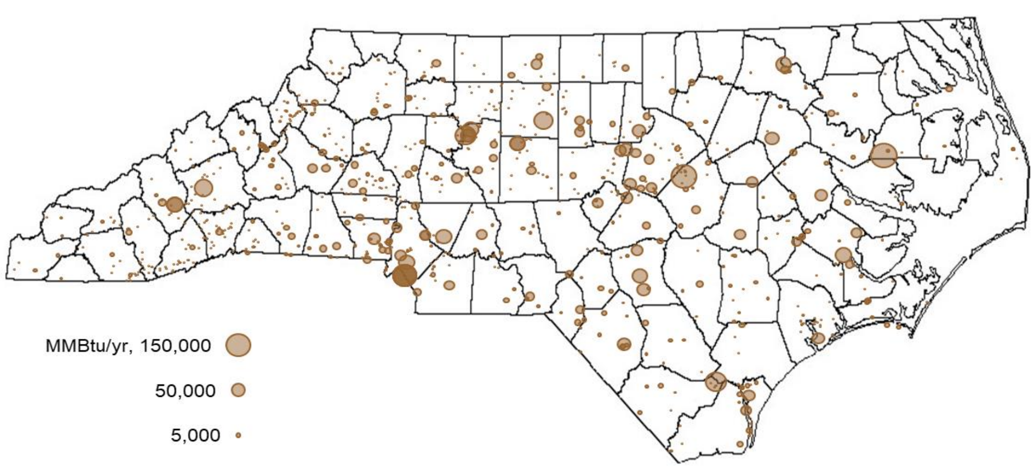
Figure 8. Biogas Potential by County from Industrial Food Waste



3.6 Wastewater Treatment Plants

Based on the location and annual flow of wastewater for all WWTPs in North Carolina, **Figure 9** shows the distribution of biogas potential in the state. Because these plants tend to be near populated areas, counties with the highest population have the highest biogas potential.

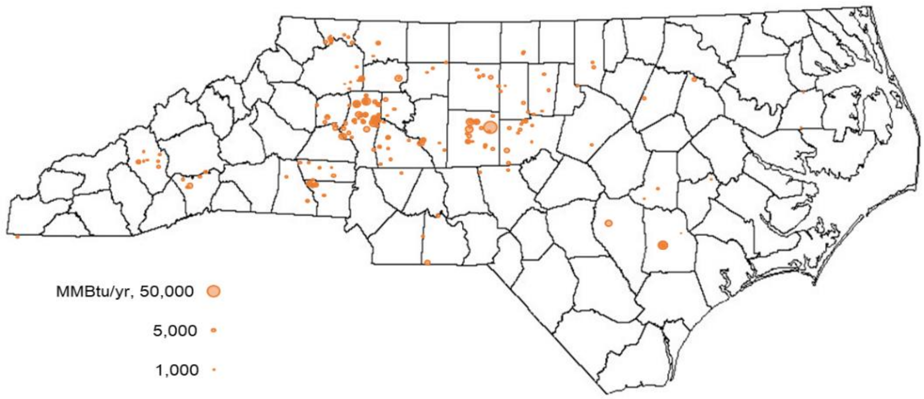
Figure 9. Distribution of Biogas Potential from WWTPs



3.7 Cow Manure

Because of the comparatively smaller number of dairy and cattle operations, the biogas potential from cow manure is not a large contributor to the biogas potential in the state, though RNG production from livestock manure digestion – and dairy manure in particular – achieves some of the lowest CI scores (hence the highest impact). **Figure 10** shows the biogas potential in the state from cow manure.

Figure 10. Biogas Potential from Cow Manure



4. North Carolina's Practical Biogas Production and Use Opportunities from Swine Waste

Phase I of this analysis considers a detailed analysis of biogas potential from the largest potential source, swine manure, and evaluates several scenarios for its monetization. For swine waste–derived biogas, the options include on-site electricity production, on- or off-site conversion to RNG, and/or receiving carbon offset payments for converting the CH_4 in the biogas to CO_2. Depending on the market or incentive program, a project developer can receive carbon offset payments in addition to payment for generating biomethane. A project developer may also be able to "stack" payments in limited circumstances, such as for RINs and LCFS credits.

To determine the feasible fraction or practical potential of the state's total biogas resources (in other words, the percentage of biogas that one could expect to develop considering available technology, cost of production, and revenue for end products), the team developed a modeling tool. The team used the tool to predict which sources would be realistic to expect to be developed, based on current biogas to RNG production costs and revenue opportunities.

As previously mentioned, raw biogas from an AD can be piped to on-site equipment, which includes a glycol chiller to remove moisture from the wet biogas and a low-pressure compressor to provide a small increase in pressure. These steps, collectively referred to as light conditioning, are required before biogas can be fed into power generation equipment such as microturbines or generators. The electricity can be used on-site to meet or supplement the operation's electricity needs or can, if the proper tariffs and agreements are available and have been executed, be fed to the grid via an interconnection point, much like a solar or wind project would be tied into the power grid. One project at Butler Farms captures biogas from the swine operation which is used to operate a microgrid that runs on both solar panels and biogas.

Because of the North Carolina REPS, projects registered as a renewable energy facility that produce electricity from swine waste can receive a payment for each megawatt-hour of electricity produced by their project. The electricity can be produced on-site, or the biogas can be converted to biomethane, injected into the natural gas pipeline, and nominated by the utility company to be used at a specific natural gas–fired power plant (a process known as directed biogas).

Regardless of where the electricity is produced, each megawatt-hour of electricity generated from swine waste could qualify for a REC. Currently, no publicly available information exists regarding the price that projects are paid for the RECs they produce from swine waste.

Another use for swine waste–derived biogas is to generate RNG and inject the gas into the natural gas pipeline or some other point at which the RNG can be used, such as a CNG filling station. It is also possible to store the RNG in liquefied natural gas form if a purchaser wants to do so. If the project developer can secure an approved pathway under a state incentive program such as the LCFS for the California transportation fuel market, then the gas can qualify for additional revenue opportunities, though the gas is sold locally as undifferentiated natural gas. Depending on the CI of the project and feedstock, LCFS revenue can be upwards of $70 per million Btu (as of November 2020). The gas can also qualify for or can receive a stacked payment through the federal RFS program, which is also tied to the feedstock used. RFS revenue does not require that the gas has a proven pathway to a specific location but can be stacked with LCFS only if the gas can secure a pathway to a transportation fuel buyer in California. Payments are measured by the number of RINs that the project can produce.

Knowing how much biogas North Carolina could produce, how its biogas-based renewable energy resources could be harnessed, and what revenue streams those biogas-based energy resources might realize tells part but not the entire story. To understand North Carolina's capacity to produce energy from biogas fully (i.e., the state's actual or practical biogas production potential), the cost to produce the biogas must be considered alongside these other known factors.

A major goal of this analysis, therefore, has been to take these different factors into account, including cost, and then model different production, delivery, and market scenarios for biogas-derived energy generated from organic waste resources in North Carolina. Therefore, the present analysis models three scenarios, which are briefly discussed as follows and are further described in Subsections 4.1 through 4.3 of this report:

Scenario A: On-Site Electricity Generation—This scenario assumes that each swine farm will install an in-ground, lined anaerobic digester, a chiller unit to dewater the biogas, and a microturbine to generate electricity.

Scenario B: On-Site RNG Production—In this scenario, an in-ground, lined anaerobic digester is installed at each farm, a chiller dewaters the biogas, a PSA process removes CO_2 and other contaminants to generate biomethane, and a high-pressure compressor compresses the biomethane to 3,000 pounds per square inch (psi) for R-CNG truck transport.

Scenario C: Networked Biomethane Production—In this scenario, each farm installs an in-ground, lined anaerobic digester and a chiller for dewatering. A low-pressure pipeline collects and transports biogas from multiple farms to central locations. At these locations, biogas is upgraded to biomethane, pressurized to 800 psi, and injected into a nearby existing natural gas pipeline for sale to electric utilities or other buyers of low-carbon fuels, for example, for transportation fuel providers subject to state LCFS requirements.

Model results for each scenario are summarized by using marginal supply curves. The curves provide a way to quantify the amount of electricity or biomethane that could be produced from swine manure as a function of the levelized cost of energy (LCOE). Cost functions for capital expenditure (CAPEX) and operating expense (OPEX) of each system component were derived from an extensive literature review (for detailed methodology employed to determine the production cost of biogas and biogas products, see **Appendix B** of this report). The CAPEX includes equipment and installation costs, whereas the OPEX includes maintenance, utilities, and labor costs. CAPEX and OPEX are together normalized to the amount of energy generated and results in LCOE calculations. Modeling of Scenario C includes annual pipeline right-of-way leases and natural gas pipeline interconnection costs. The assumptions for financial parameters used for calculating LCOE are presented in **Table 3**.

Table 3. Assumptions for Financial Parameters Used in LCOE Calculations

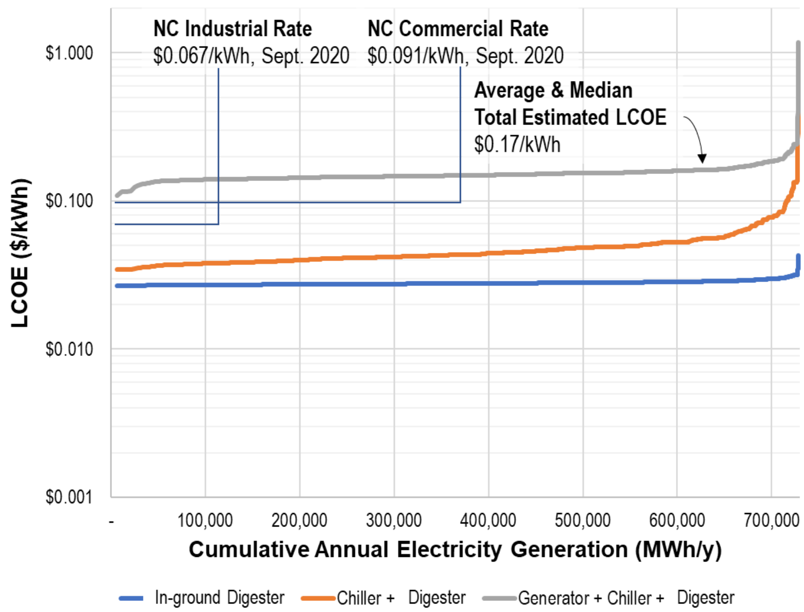
Parameter	Value
Federal tax rate	21%
State tax rate	7%
Depreciation schedule	5-MACRS (Modified Accelerated Cost Recovery System)
Debt fraction	60%
Debt rate	5%
Equity fraction	40%
Equity rate	15%
Project life (years)	15

4.1 Scenario A: On-Site Electricity Generation

The marginal supply curve for Scenario A (On-Site Electricity Generation) is shown in **Figure 11**. The grey curve in **Figure 12** indicates the LCOE required to bring on increasing amounts of electricity generated at North Carolina swine farms. The plot also indicates the LCOEs for each component in the waste-to-electricity systems at the farms, with the blue curve being the LCOE for an in-ground, lined anaerobic digester; the difference between the blue and orange curve being the LCOE for the chiller unit; and the difference between the orange and grey curve being the LCOE for the system with a generator. All LCOEs increase with higher on-site electricity generation as smaller, more expensive to equip farms (on a dollar per million Btu basis) are added to the marginal supply curve.

Note the significant amount of electricity generation that the team estimates can be obtained from swine farms for an LCOE ≤\$0.17/kWh. This estimate, however, does not consider the cost of connecting the on-farm generators to the electric grid; therefore, all of the generation would be "behind the meter." Given that commercial electricity rates in North Carolina are <\$0.10/kWh, with industrial rates even lower at <\$0.07/kWh, the team does not anticipate an advantage for farms to generate electricity on-site to offset utility costs. A program that can provide an incentive of several cents/kWh for the electricity generation and/or emissions reductions, however, could make power purchase agreements for the electricity generated from swine waste an economic endeavor at many farms, particularly those at which biogas conversion to RNG would not be economic.

Figure 11. Marginal Supply Curve for Scenario A: On-Site Electricity Generation (Without Grid Connection) at Swine Farms in North Carolina

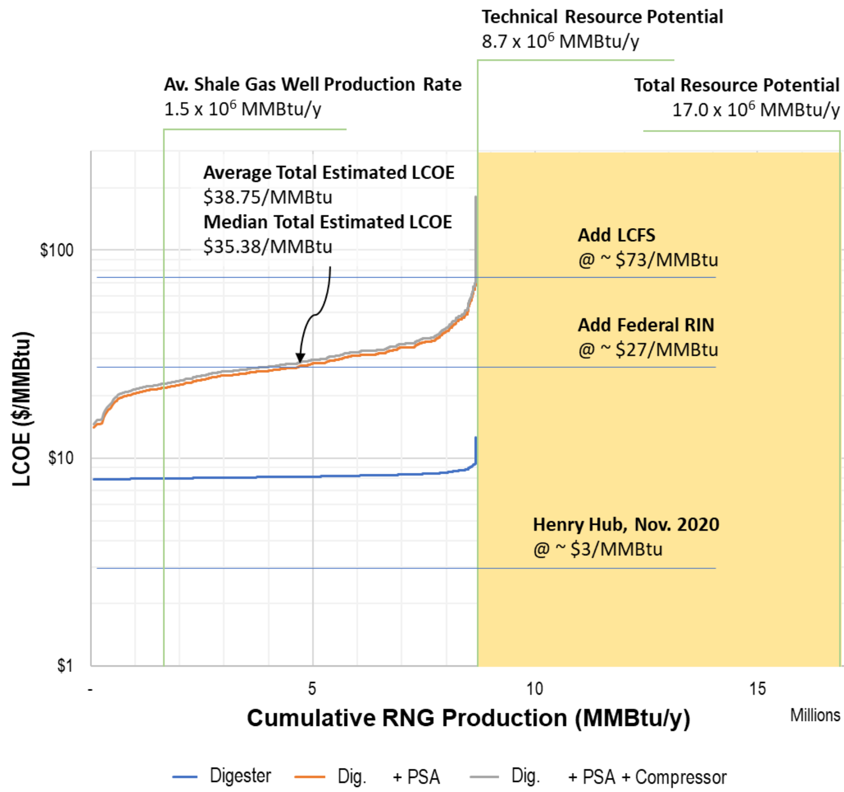


4.2 Scenario B: On-Site RNG Production

The state's swine farms could capture >8.5 trillion Btu/yr simply by installing covered, in-ground anaerobic digesters (i.e., technically recoverable biogas potential regardless of cost is approximately 8.5 trillion Btu/yr). The total cost of biomethane varies from less than $15 per million Btu to well over $150 per million Btu depending on the farm. Nonetheless, much of this range is still within market prices for RNG. For example, when accounting for the spot price of conventional natural gas (Henry Hub) and adding in the value of federal RIN payments, RNG would receive approximately $30 per million Btu, a price at which the team estimates that approximately 50% of the technically recoverable RNG reserves can be produced (**Figure 12**) (U.S. Environmental Protection Agency (EPA), 2020a). It is important to note that the team did not factor the costs for temporary on-site storage of the R-CNG and its delivery to market via CNG trucks into this scenario.

The RNG would receive an even higher price if the on-site projects could access a state incentive program such as California's LCFS. Since qualification for sale into such a state incentive program requires injection into a local natural gas pipeline system, costs to enable such an injection, in addition to those shown in **Figure 12**, will need to be considered.

Figure 12. Marginal Supply Curve for Scenario B: On-Site RNG Production



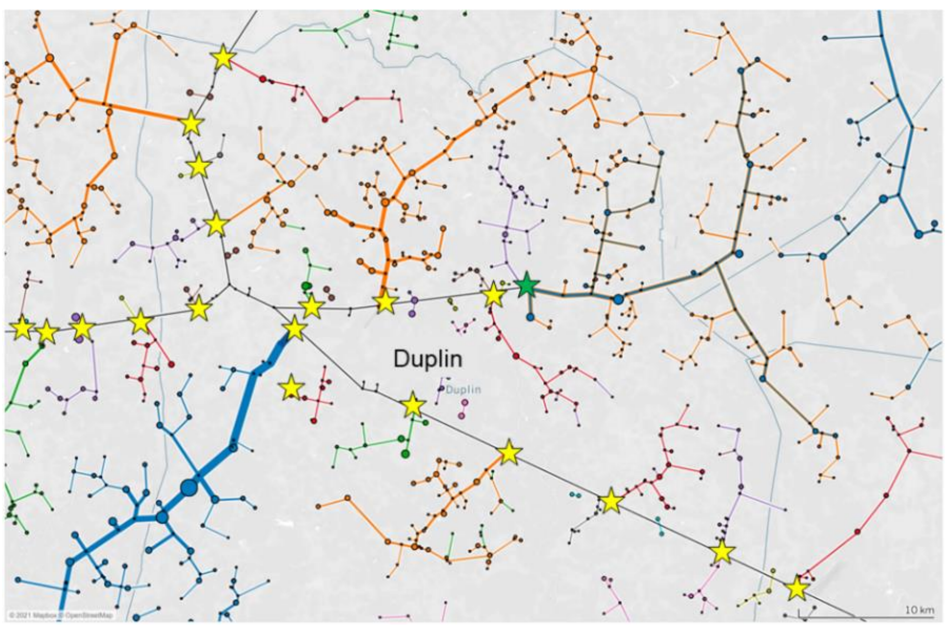
4.3 Scenario C: Networked RNG Production

Scenario C models a pipeline network gathering of lightly conditioned biogas from multiple farms to central locations where the biogas is upgraded to RNG, pressurized, and injected into a nearby existing natural gas pipeline. In contrast with modeling in Scenario B, all production and delivery costs are accounted for in this pipeline gathering scenario (i.e., Scenario C). This networked scenario could offer the best potential for RNG production in North Carolina to qualify for sale either to electric utilities (directed biogas) or other buyers of low-carbon fuels, for example in states with incentive programs (e.g., California, Oregon) and thus could offer the highest revenue potential.

The network modeling conducted in this analysis differs from both the Duke University 2013 (henceforth referred to as the Directed Biogas Study) study and the University of California, Davis Sustainable Transportation Energy Pathways (STEPS) study published in 2016 (Jaffe et al., 2017; Prasodjo et al., 2013). In both studies, farms were grouped into clusters, which in turn were interconnected by a biogas gathering pipeline network leading to an RNG upgrading facility and then onto the nearest natural gas pipeline. The Directed Biogas Study performed by Duke University's Nicholas Institute for Environmental Policy Solutions and the Duke Carbon Offsets Initiative in 2013 used the university's Optima Biogas Geospatial and Economic Model to compare various scenarios by which the North Carolina REPS swine waste set-aside could be met. The analysis determined that directed biogas would be the least cost approach to meet the mandate, but it did not try to determine the best and least cost approach for treating all swine waste in the state.

In contrast, in the present analysis, network initiation began by connecting the largest swine farm to a nearby natural gas pipeline at the shortest possible distance. Successively smaller farms were then connected to whichever was closer (i.e., the biogas pipeline modeled in a previous iteration of the network mapping algorithm or a new point along a natural gas pipeline). If the latter, then a new biogas network was initiated. The process continued until all swine farms were connected to a network. The advantage of mapping the farm networks in this way is that it makes it possible to calculate the necessary diameter and length of each pipeline segment which makes up a network, along with that network's total CAPEX, OPEX, and LCOE as each new farm is added to the network. Thus, the result of this model is an identification of farms that can optimally be part of a network to minimize costs of RNG production and injection into a natural gas pipeline, an example of which is shown in **Figure 13**.

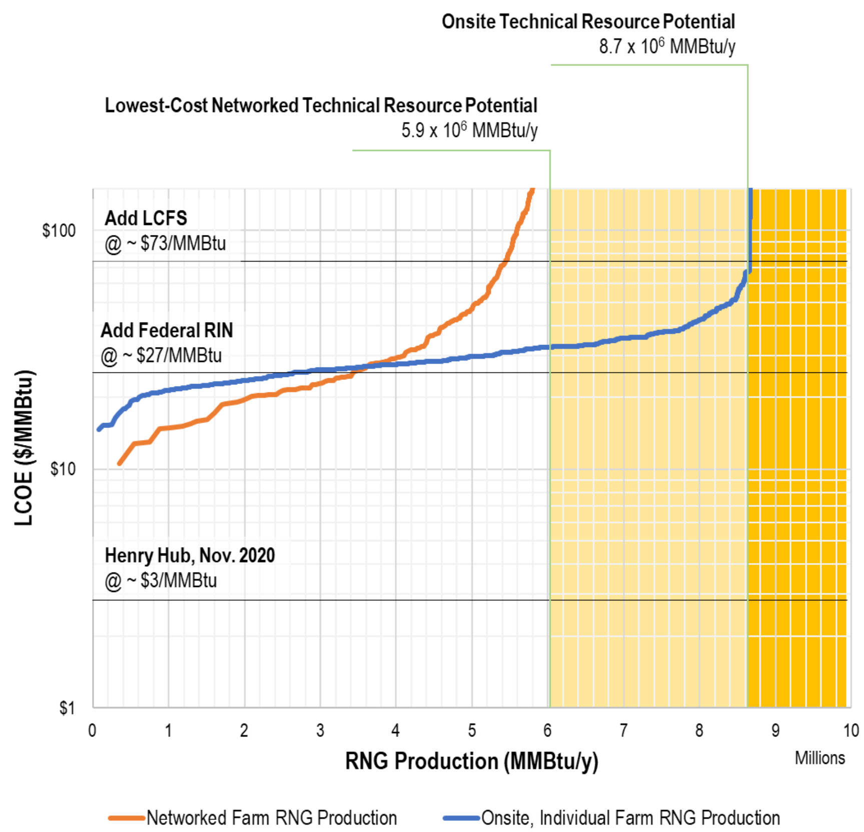
Figure 13. An Example of an Optimal Farm Network Scenario (Scenario C) to Produce RNG in Duplin County, NC



Each dot represents a farm, and lines represent pipelines that make up the farm network. Networks are multicolored to represent the cost of each network. For example, the network in deep blue has an LCOE ≤$15 per million Btu. Networks can connect to existing natural gas pipelines (in black) at hypothetical interconnect points (stars).

The marginal supply curve for networks with an LCOE ≤$200 per million Btu is shown in **Figure 14** and is compared with Scenario B: On-Site RNG Production. At first glance, it may appear that Scenario B makes as much or more sense than networking farms to produce RNG, but keep in mind that Scenario B does not include the costs to move RNG to an injection site and inject it into a natural gas pipeline. Although the LCOE of Scenario C climbs more rapidly than the LCOE for Scenario B after approximately 4 million Btu/yr, Scenario C still indicates that approximately 50% of the state's technically recoverable reserves would be economic to produce at the previously mentioned $30 per million Btu level. If RNG from networked farm projects were able to qualify for sale under California's LCFS program, approximately 70% of the state's technically recoverable resource would be economic to produce.

Figure 14. A Comparison of Marginal Supply Curves for Networked Farms (Scenario C) and On-Site RNG Production (Scenario B)



4.4 Key Takeaways and Planned Refinements

The present analysis adds significant new insights when compared with previously published reports about swine waste monetization in North Carolina. Using updated capacity and cost functions, the team shows that the vast majority of North Carolina's technically recoverable energy resource in swine waste can be converted into electricity at an LCOE of between $0.10/kWh to $0.20/kWh. This range is slightly higher than what Lazard calculates for commercial- and industrial-scale solar installations ($0.07/kWh to $0.18/kWh, after accounting for federal subsidies) and within Lazard's range for residential solar ($0.13/kWh to $0.20/kWh, again, after accounting for federal subsidies). Converting swine waste to RNG appears to be even more economically attractive. The team estimates that most of the state's RNG potential could be profitably produced either on-site at individual farms or by using the networked biogas output of multiple farms if RNG receives federal RINs while also selling at a price equivalent to or greater than the spot price of conventional natural gas. Furthermore, RNG from networked farms could fetch a total price up to three times higher, if such RNG were able to qualify for sale in California's LCFS market.

The network mapping algorithm currently relies on several significant, simplifying assumptions. One assumption is that the chiller and low-pressure compressor units at the farms, which would compress the biogas to 100 psi before injecting it into the biogas pipeline network, are sufficient for moving the gas to the network terminus and that additional pumps along the network are not required. Another assumption is that the PSA and compressor units for each network are located where it terminates at an interconnection point along a natural gas pipeline, thereby removing the need for a high-pressure pipeline interconnect. The most significant assumption, however, is that a biogas network can be initiated at any point along a natural gas pipeline (see the stars in Figure 13). The team recognizes that this assumption is highly unrealistic, but because no regulatory guidelines currently exist regarding where such interconnections would in fact be feasible but rather rest at the discretion of the LDCs, we have opted to not use an ad hoc criterion for limiting such interconnections. As such, during Phase II, we will use feedback from stakeholders, including LDCs and the North Carolina Utilities Commission, to refine the assumptions on interconnections.

5. Economic Impact of Monetizing North Carolina's Swine Waste RNG Potential

Several recent analyses have modeled the cost of biogas production (for compliance with the North Carolina REPS swine waste set-aside) and the economic effects associated with a directed biogas approach to North Carolina REPS compliance, as mapped out in the 2013 analysis (Prasodjo et al., 2013). In 2016, an analysis by the American Jobs Project predicted the job creation potential associated with the establishment of a robust biogas industry in North Carolina. The analysis included swine waste feedstock sources and other biogas feedstock, stating that if "North Carolina's biogas companies [were] able to develop all candidate biogas projects from swine, dairy, and landfill operations, nearly 34,000 direct, indirect, and induced job-years" could be supported, of which 13,000 would be direct job-years and approximately 21,000 would be indirect and induced job-years (North Carolina Department of Environmental Quality (NCDEQ), 2018).

The American Jobs Project, however, evaluated economic opportunities related to biogas based on market conditions that existed prior to 2016, a significant part of which included the North Carolina REPS swine waste set-aside. The present analysis considers how the emergence of programs such as California's LCFS and Federal RFS affect economic outcomes in the counties with the highest swine biogas concentrations, where the greatest development is expected.

A preliminary economic impact analysis was completed using an Impact Analysis for Planning (IMPLAN) model which considered farm networks that included more than 1,400 farms generating approximately 5.7 million Btu per year with a mean LCOE of $29.43 per million Btu and a median LCOE of $31.33 per million Btu. These farm networks were chosen since their RNG production costs are approximately equal to the revenue potential from the sale of RNG (at a Henry Hub spot price of approximately $3 per million Btu) and adding in federal RIN credits of approximately $27 per million Btu resulting in a total income potential of approximately $30 per million Btu. The preliminary analysis did not include potential revenue from the California LCFS because of the challenges associated with securing a pathway to the California market. However, the revenue potential is expected to be much higher for those projects capable of accessing the California LCFS or other equally lucrative state programs.

5.1 Potential Value Added

The production of biogas directly adds value to a regional economy through facility spending to produce biogas (e.g., labor compensation, property costs). This direct value added is included in the calculation of LCOE. However, this economic activity generates business-to-business transactions along the supply chain, which also add value to the economy (e.g., as purchases to suppliers). These transactions are classified as indirect value added, and they are not incorporated in the LCOE. The team estimates that the indirect value added to the region from RNG production from just the subset of selected candidate farms is approximately $36 million per year.

Another type of value added not included in the LCOE is the induced value, which represents the spending of the employees of the biogas facilities within the supply chain. This spending is possible through the labor compensation generated by the economic activity, and thus must be considered. The team estimates the induced value added of RNG production for the candidate farms to be approximately $3.4 million per year.

5.2 Potential Jobs Added and Associated Income

The operation and maintenance of a biogas production facility requires the employment of a skilled workforce. The number of workers needed and their compensation are already considered in the LCOE. The team estimates that nearly 300 indirect jobs (i.e., the number of jobs that are supported by business-to-business transactions because of the economic activity generated by the RNG production in the subset of networked farms) are not included in the LCOE calculation. Additionally, the team estimates that the indirect jobs could result in approximately $15.5 million paid in annual wages to employees of businesses in the supply chain of RNG production, with an average annual salary of approximately $52,000 per employee. Furthermore, nearly 50 induced jobs with a total of more than $1.6 million in annual salaries and wages are expected due to the spending of the employees of the RNG-producing facilities.

5.3 Potential Tax Revenue

As previously described in **Table 3**, the taxes at the federal and state levels from RNG-producing facilities have already been factored into the LCOE calculations. However, the economic activity generated from biogas production down the supply chain is taxable. Taxes include sub-county taxes (e.g., municipal, special districts), county, state and federal taxes that must be satisfied because of business-to-business trade. The team estimates that nearly $10 million in annual tax revenue could be collected because of the indirect economic impacts generated by RNG production from the subset of swine farm networks. The highest amount would go to satisfy federal (nearly $4 million), followed closely by state (nearly $3.5 million) tax revenues. The team also estimates nearly $2 million in indirect county and more than $500,000 in sub-county tax revenues annually. Finally, the team estimates nearly $800,000 in annual personal income tax revenue from the induced economic impact from the employees of RNG production facilities.

6. Environmental and Community Impacts of Monetizing North Carolina's Swine Waste

During Phase I, biogas and RNG produced from swine waste has been the primary focus of this report's assessment of environmental and community benefits and impacts. Using biogas to produce energy can provide alternatives to fossil-derived power and transportation fuel, lowering the CI of the energy sector, thus helping to address climate change. Using biogas to produce energy also offers a way to create a beneficial use from waste resources, including creating valuable by-products beyond renewable energy, thereby creating economic and environmental value from what is usually considered a cost center and environmental liability. Finally, as discussed in Section 5 of this report, biogas and RNG production provides economic benefits for the counties from which it is sourced.

The climate benefits of installing biogas capture systems on swine farms can be very significant. The manure collected and stored on large swine farming operations generates significant GHG emissions, primarily associated with containment of the mostly liquid manure in uncovered lagoons but also associated with sprayfields, with the emissions including CH_4 and nitrogen oxides (NO_x). CH_4 is formed during the anaerobic breakdown of manure in wastewater storage infrastructure such as lagoons, whereas NO_x forms during microbial nitrification/denitrification processes either during processing or field application of waste.

Based on guidelines published by EPA and the U.S. Department of Agriculture, the team estimates that, when considering just the seven largest farm networks with the lowest costs and highest potential to generate biogas (which account for nearly 40% of the practical biogas potential from North Carolina's swine farms), installing biogas capture systems (e.g., an in-ground anaerobic digester) would reduce CH_4 emissions by more than 90,000 tons per year, equivalent to reducing 2.3 million tons of CO_2 per year.

Although the market dynamics modeled in the analysis previously described in the report suggest that a significant build out of biogas supply is economic, development and deployment could be affected by several non-market forces. Examples of non-market forces can include opposition to use of RNG from concentrated animal feeding operations (swine, dairy, and poultry operations), construction of pipelines for transportation of biogas and RNG, and the continued use of lagoon-and-sprayfield systems. Thus, a strategy to address these organic waste streams needs to consider and address all stakeholder concerns. Note that actions to address other waste management issues beyond those that result in the capture and beneficial use of CH_4 could add costs. This analysis did not factor in such potential costs.

As of December 2015, North Carolina had 8.8 million hogs creating an average of 116 million tons of manure per year. In-state swine operations and their waste are concentrated in five contiguous, low-income counties. Considering identified correlations between poor health, environmental and property value outcomes associated with proximity to swine operations, residents of these counties face increased risk of adverse health and environmental effects. For example, wastewater from swine operations has been documented to have contaminated both surface water and well water of neighboring property through the transmission of pathogens such as *Escherichia coli* (E. coli).

Biogas capture systems provide some clear environmental as well as economic benefits when compared with traditional waste management (i.e., lagoon-and-sprayfield) systems, which include controlling GHG emissions, generating renewable energy, creating new income streams, supporting ways to create value from organic waste and the other by-products of AD (primarily digestate), and reducing the presence of odors and pathogens. ADs used to collect biogas also have the potential to curtail water pollution issues, particularly during heavy rain events, by containing contaminants. However, the volume of total liquids does not appreciably change and still requires some level of holding and application capacity of wastewater. Thus, although biogas capture systems (and subsequent RNG production) as currently proposed by developers (i.e., Lagoon + New In-ground digesters without further pollution controls) will help to address some odors and pathogens, thus potentially providing some improvements over current waste management practices related to community health and environmental outcomes, they are not intended to meet the environmental performance standards required for new and expanding swine farms. These standards include substantial elimination of atmospheric ammonia emissions, nutrient and heavy metal contamination of soil and groundwater, release of disease-transmitting vectors and airborne pathogens, odors beyond the farm's boundaries, and zero discharge of animal waste to surface and groundwater.[23,24] Nevertheless, because of the high demand for low-carbon energy and the potential for swine waste, like other feedstock types, to provide a flexible low-carbon energy source, it is expected that biogas capture systems such as AD systems will likely be an integral part of any waste management solution capable of addressing all environmental and community concerns.

To exemplify such a solution, Duke University, in partnership with Duke Energy and relying on Cavanaugh & Associates design and system oversight, led the development and field testing of an innovative and comprehensive swine waste-to-energy management system at Loyd Ray Farms (see **Figure 15**). The system was very similar in concept to systems currently proposed for construction within North Carolina, but in addition to an in-ground anaerobic digester, the Loyd Ray Farms system included an in-ground aerobic basin which received wastewater effluent post-digestion to further process the wastewater before it flowed back to the existing lagoon. Although the system stored post-digested and post-aerated effluent in the existing lagoon, the effluent returned to the existing lagoon contained far lower concentrations of ammonia, nutrients, and pathogens, which rendered the final effluent much cleaner as compared to the initial wastewater discharged from the swine houses. It also rendered the final effluent less odorous, even as compared to the reduction of odors expected with an AD-only

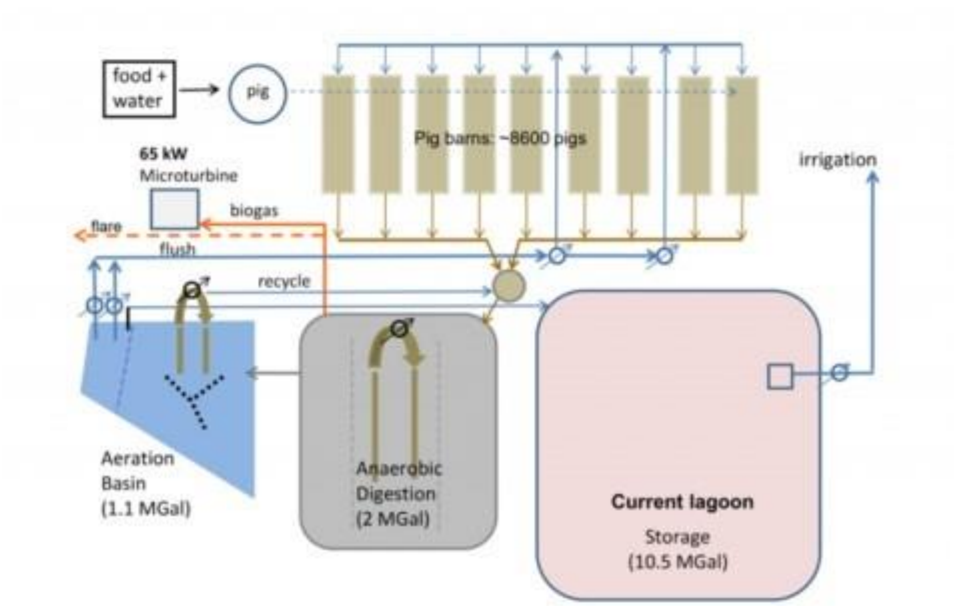
23 See N.C.G.S. § 143-215.10I. (Performance standards for animal waste management systems that serve swine farms; lagoon and sprayfield systems prohibited) available at https://www.ncleg.net/EnactedLegislation/Statutes/PDF/BySection/Chapter_143/GS_143-215.10I.pdf.

24 According to an article by the North Carolina State Extension (2019), there are challenges of lagoon sludge: "Swine lagoon sludge is challenging to use as a soil amendment because of its high phosphorus (P), zinc (Zn), and copper (Cu). These minerals can stress growing crops and increase nutrient losses. One way to overcome this challenge is through composting."

system. The processed effluent resulted in a cleaner source of flush water for the barns and re-charge pits, which improved the air quality inside the barns.

In the case of the Loyd Ray Farms project, the addition of an aeration basin post-digestion allowed the effluent to be aerated (i.e., pushed oxygen up through) the wastewater stream before it was returned to the existing lagoon for storage, which reduced concentrations of ammonia and other pollutants which would otherwise have remained. Thanks to the aeration basin, the farm was able to meet all of the environmental performance standards, which a digester alone cannot accomplish. Moreover, an added benefit of an aeration basin is that post-digested and aerated wastewater can be reused for irrigation without concern of nutrient application restrictions, which may provide farms with greater optionality regarding crop choices on nearby fields and help farms that are land-limited with respect to sprayfield acreage to participate in RNG projects.

Figure 15. A flow diagram of the comprehensive and innovative waste management system installed at Loyd Ray Farms. Image courtesy of Duke University Office of Sustainability, available at https://sustainability.duke.edu/offsets/projects/lrf



The biogas captured in the AD at Loyd Ray Farms was sent to an on-site microturbine, where the electricity generated was sold to the grid.[25] The waste-to-energy system installed at Loyd Ray Farms was the first swine waste-to-energy system in the state to also receive an innovative waste management permit, which means it not only met all the environmental performance standards established for new and expanding farms, but also could have made it possible for the farm to add more animals and/or take on more steady state live weight.[26]

25 Note that the electricity produced on-site can be routed to the farm to reduce its imported electricity

26 A performance evaluation of the system has been completed by Xu, et al. (2016).

The purpose of the Loyd Ray Farms project include confirmation that an AD system for biogas capture and on-site power generation can be successfully coupled with other pollution controls to meet the environmental performance standards. Certainly, as with any first-of-its-kind endeavor, improvements could be made to reduce installation and operational costs, improve overall system design and efficiency, and increase income. Nevertheless, the system offers an example of ways by which AD systems can be improved upon with respect to overall environmental performance. Notably, the project partners did not patent the system as the project was intended to facilitate future deployment and allow for iterations and improvements to the design.

Few publicly available analyses directly quantify and compare the environmental outcomes associated with swine waste-to-RNG systems as currently proposed for implementation in the state by developers (i.e., Lagoon System + New In-Ground AD systems) and existing lagoon-and-sprayfield–based waste management systems.[27] Nevertheless, **Table 4** attempts to provide at least a general characterization of the impacts that might be expected. Also included is a demonstration of how Lagoon System + New In-Ground AD systems could be further improved to yield even better environmental and community outcomes as part of a comprehensive waste management system. Typically, biogas capture (and RNG production) systems capable of meeting the environmental performance standards established for new and expanding farms will be the most beneficial in terms of environmental and community outcomes because they will address the pollutants and issues of greatest concern to communities and to health and environmental advocates.

27 See https://deq.nc.gov/about/divisions/air-quality/air-quality-permitting/biogas-processing-permitting-actions-and.

Table 4. A Comprehensive Waste Management System and Lagoon + New In-Ground AD System Compared with Existing Lagoon-and-Sprayfield–Based Waste Management

Systems	Odors	Pathogens	Nutrients	Ammonia	Waste Discharge	CH_4 Reductions	Other Effects
Comprehensive waste management system[28]	Substantially reduced	Substantially reduced	Substantially reduced	Substantially reduced	Zero	CH_4 captured. Extent dependent upon technology employed	Creation of income-producing by-products such as soil supplements, fertilizer, energy, carbon offsets
Lagoon + New In-Ground Anaerobic Digester system	Reduced	Potentially reduced	Likely unchanged; limited or no data	Likely unchanged; limited or no data[a]	Required pursuant to existing DEQ permit requirements	CH_4 capture[a]	RNG, electricity and/or carbon offsets depending on the program

[a] Both ammonia (NH_3) and hydrogen sulfide (H_2S) must be scrubbed or removed before energy generation or before biogas is injected in the pipeline. If one of these processes does not occur, then these non-criteria pollutants will be converted to nitric oxide (NO) and sulfur dioxide (SO_2), which are criteria pollutants, in the generator or the microturbine. Source: Aneja, V. (2020, November 10). Pollutant emissions from swine biogas. Virtual presentation at Biogas: Permitting, Pollutant Emissions, and Community Perspectives.

Another issue for swine biogas projects related to community benefits and impacts is the long history of using lagoons and sprayfields to manage waste and the disproportionate effect environmental issues associated with those systems have on neighboring communities and particularly communities of color. It may hence be an unreasonable expectation for Lagoon + New In-Ground AD systems to gain widespread acceptance from local communities and health and environmental advocates, even with the significant GHG reductions, renewable energy benefits, and improved odor and pathogen outcomes they can potentially provide, if they cannot meet all the environmental performance standards adopted in the 2007 Swine Environmental Performance Standards Act or make efforts beyond those inherent to biogas recovery (e.g., biogas to on-site electricity production, biogas-to-RNG production) to address pollution issues that pre-date the focus on climate pollutants.[29]

Environmental groups and community members living near swine production operations or in counties where swine waste–derived biogas production potential is greatest, contend that the installation of Lagoon+ New In-Ground AD biogas capture systems, as currently proposed by several developers, will

28 The standards for Swine Waste Management Systems subject to regulation pursuant to G.S. 143-215.10I include the following: (1) eliminate animal waste discharge to surface and groundwater, (2) substantially eliminate atmospheric emissions of ammonia, (3) substantially eliminate the emission of odors detectable beyond the property boundaries of the swine farm, (4) substantially eliminate the release of disease-transmitting vectors and airborne pathogens; and (5) substantially eliminate nutrient and heavy metal contamination of soil and groundwater.
Intensive monitoring was carried out to evaluate the performance of a full-scale innovative swine waste-to-energy system at the Loyd Ray Farms, a commercial swine farm with 8,640 heads of swine. Detailed mass balances over balances over each unit of the system showed that the system, which includes a 2 million–gallon AD, a 65-kW microturbine, and a 1.5 million–gallon aeration basin, was able to remove up to 92% of the chemical oxygen demand, 99% of the biological oxygen demand, 77% of the total nitrogen, and 82% of the total phosphorous discharged into the system as fresh pig waste. For more information see (Xu, et al. 2016).

29 For more information, see (Miller et al., 2020). For more information regarding the analysis of economic benefits for communities of innovative waste management systems, see the following publication: (Meeker et al., 2020).

prolong the use of lagoon-and-sprayfield systems rather than create an incentive for improving waste management practices (Ju et al., 2016).[30] According to these stakeholders, Lagoon + New In-Ground AD systems without additional pollution controls as currently permitted and proposed, do not do enough to mitigate the documented environmental[31] and health effects[32] associated with traditional lagoon-and-sprayfield systems. There is concern that a biogas capture system, particularly if it allows farms to continue to use their lagoons to hold the liquid effluent discharged from a newly installed in-ground AD, undermines commitments, documented in the Smithfield Agreement of 2000, to phase out lagoons.

Thus, for a swine waste management and biogas capture system to be widely accepted (as it relates to environmental, health, and community impacts), two factors need to be considered. The first factor is the need for a thorough understanding and/or analysis of how the proposed Lagoon + New In-Ground AD systems bring swine waste management closer to the environmental performance standards in the Smithfield Agreement, which are now required for new and expanded swine operations, but which existing operations are not required to employ.[33] The second factor is what other measures, such as practices or technologies, would need to be added to a waste management and biogas capture system to meet the performance standards or make significant strides towards the standards. Addressing these two factors could potentially realize significant GHG reductions, in addition to facilitating substantial economic development opportunities, particularly for state and local communities in rural areas of the state.[34,35] To achieve such an outcome, however, additional monetary resources to finance added environmental controls and/or capital improvements would need to be identified, including through public policy measures.

Another factor to consider is how the by-products of a comprehensive waste management systems (e.g., liquids and waste solids or digestate from an AD) can secure revenue streams for the constituents they are mitigating but for which markets do not currently exist. Although methods for recovering and

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30 In North Carolina, most swine waste is treated as a liquid slurry in earthen containment structures called lagoons in which anaerobic bacteria break down the waste. The treated effluent from the lagoon is then sprayed onto crop fields that are expected to take up the nutrients in the applied effluent. Together, the process is known as a lagoon-and-sprayfield system. These systems raise concerns with regards to potential environmental contamination from excess nutrients leaking from the lagoons, as well as leaching and runoff from land applications (Cheng et al., 2002). These systems can also lead to aerial emissions of ammonia, methane, pathogens, and odor, and release pathogenic bacteria to surface and groundwater (Vanotti 2012).

31 This results in excess nutrient supply and land application, thus imposing environmental risks on rural communities (Xu et al., 2012); rather than move farms to "innovative waste management systems" that do not rely on lagoons as a means of waste management.

32 For more information about health trends in populations living near swine farms, see: (Kravchenko et al.); see also UNC's 2020 analysis documenting health effects associated with proximity to swine operations.

33 Two actions have been filed to challenge permits granted for the construction of Lagoon + New In-Ground AD Systems at four hog farms located in Duplin and Sampson Counties. The first includes a permit challenge filed in the N.C. Office of Administrative Hearings in April 2020 by the Southern Environmental Law Center (SELC) on behalf of the Environmental Justice Community Action Network and Cape Fear River Watch. The second challenge, filed by SELC on behalf of the Duplin County branch of the North Carolina Conference of the NAACP and the North Carolina Poor People's Campaign in September 2021, includes a complaint filed with the U.S. Environmental Protection Agency alleging that the N.C. Department of Environmental Quality's issuance of the permits will constitute a disproportionate impact on communities of color in areas surrounding the farms.

34 Note that the environmental performance standards were identified and supported by industry representatives, scientists, community representatives and environmental advocates as sufficient to address environmental and public health concerns. See Smithfield Agreement report (https://projects.ncsu.edu/cals/waste_mgt/smithfield_projects/smithfieldsite.htm).

35 Note that the North Carolina General Assembly later codified the environmental performance standards in the Swine Farm Environmental Performance Standards Act of 2007. (https://www.ncleg.net/EnactedLegislation/Statutes/pdf/BySection/Chapter_143/GS_143-215.10I.pdf)

beneficially using liquids and waste solids exist, few economic incentives are available to farmers for these uses which would justify the expense to recover them. This means that some type of incentive is needed to prompt management of those materials. Thus, for waste management systems to produce the desired environmental and community benefits, economic incentives and markets must be properly aligned.

Finally, if policies such as California's LCFS are to be considered as important drivers for implementing waste management, biogas capture, and RNG production systems, it is worth noting that use of livestock waste-derived RNG is being challenged as a compliance instrument in jurisdictions such as California.[36] The state will thus need to consider such policy movements as it develops options for treating its organic waste feedstocks.

These discussions indicate that although swine waste-to-energy and/or swine waste GHG emission reduction projects are expected to produce energy, as well as some climate and health benefits from the digestion of the waste, identifying the challenges to its deployment and illustrating how those challenges could be addressed are crucial. Finally, it is important to recognize that this challenge is as much of a challenge of politics and policymaking as it is of economics and engineering. Thus, the team strongly recommends that an entity such as a Biogas Development Commission or similar body be created, to be empowered to consider not only biogas development from swine waste feedstocks but also other feedstocks with the full array of stakeholders participating, to ensure that waste management and biogas development is evaluated and implemented in a responsible and equitable fashion.

[36] Petition for Rulemaking to Exclude All Fuels Derived From Biomethane From Dairy and Swine Manure From the Low Carbon Fuel Standard Program, available at https://food.publicjustice.net/wp-content/uploads/sites/3/2021/10/Factory-Farm-Gas-Petition-FINAL.pdf, filed Oct. 27, 2021.

7. Conclusions and Next Steps

The current analysis confirms that North Carolina has tremendous biogas potential with approximately 97 bcf/yr, equivalent to 58 trillion Btu/yr. Swine waste is the largest contributing feedstock, making up approximately 29% of the state's biogas potential. LFG is also attractive in the near-term because landfills provide some of the largest single-source opportunities. Overall, biogas potential is concentrated in eastern North Carolina, particularly in counties with the highest pork production which warrants a deeper analysis of opportunities, options, and impacts of biogas capture from swine waste.

To determine the practical limits of biogas production from swine waste by using the current state of technology and resulting costs, the analysis considered the following three scenarios:

- **Scenario A:** On-Site Electricity Generation
- **Scenario B:** On-Site RNG Production (at each farm)
- **Scenario C:** Networked RNG production (and injection into existing natural gas pipelines).

The team estimated that most on-site electricity can be produced with an LCOE ≤$0.17/kWh, without considering the cost of interconnection with the grid. Because current industrial and commercial electricity rates are <$0.1/kWh, the team anticipates that significant incentives will be necessary for on-site electricity production to be an economic option for biogas from swine waste. On-Site RNG Production (Scenario B) can also be an attractive option with several sites capable of producing RNG as low as <$15 per million Btu (median cost of approximately $35 per million Btu). However, these costs do not account for storage and transport of RNG to its destination, which could either be R-CNG filling stations or pipeline injection sites. Market prices for RNG could range from $30 per million Btu (spot price of $3 per million Btu plus approximately $27 per million Btu from federal RFS RIN credits, all in November 2020) to more than $100 per million Btu if RNG can be sold into the LCFS market (LCFS credits were approximately $70 per million Btu in November 2020).

Perhaps the most attractive opportunity could be networked RNG production where low-pressure biogas generated on farms can be piped via low-pressure pipeline networks to a centralized upgrading facility to produce RNG and injected into a pipeline. The team has developed a geospatial optimization tool to determine optimal networking of farms that can maximize RNG production at minimal costs. Because the model already accounts for pipeline, compression, and injection costs, the team estimates that nearly 70% of the state's swine waste derived RNG can be economically produced if the gas can qualify for sale into a state incentive market such as LCFS. We also note that finding a pathway to such a market could be difficult.

In addition to the revenue and resulting taxes from the direct activities associated with harvesting biogas to produce and sell RNG, these activities can provide a significant economic boost to the state's economy. The economic benefits would result because of indirect activities associated with business-to-business activities and induced activities from increased spending within the supply chain. If only a subset of the farm networks capable of producing RNG for <$30 per million Btu were developed, the indirect and induced value to the economy could be nearly $40 million annually. Approximately 350 indirect and induced jobs could be supported, and nearly $10 million in annual taxes could be collected. Whether these jobs will be targeted towards North Carolina residents is still unclear but could be an issue for policymakers to consider in establishing policies and incentives to facilitate waste management and biogas capture.

Finally, the environmental impacts of harvesting biogas from swine waste could also be significant. Installing in-ground ADs at just seven of the largest farm networks that the modeling identified would result in reducing 90,000 tons of CH_4 emissions every year, equivalent to 2.3 million tons of CO_2. Installing ADs and harvesting biogas to produce RNG alone, however, is not expected to remediate all the environmental and health concerns associated with traditional swine waste management systems. ADs as part of a comprehensive waste management solution which includes solutions for water and nitrogen management, such as the one implemented by Duke Energy and Duke University with the technical expertise of Cavanaugh & Associates at Loyd Ray Farms, will be essential to address the full range of environmental, health, and community concerns.

The lack of a comprehensive waste management solution is a significant challenge to community acceptance of the development of RNG production opportunities from swine waste. If a solution is not provided, it is possible that the resistance to treatment of swine waste will affect other feedstock categories, thus hampering the state's ability to treat its organic waste resources more broadly. Another potential barrier to the development of this feedstock is the management of by-products such as the digestate and liquids from ADs which currently have beneficial uses but for which no meaningful incentives exist for developers to recover. Another barrier for developers is the availability and ease of access to markets for the injection of RNG into the natural gas pipeline.

Addressing these challenges requires a multi-pronged approach that encompasses technical, policy, and community engagement solutions. During Phase II, to be responsive to recommendations identified by the *EPC 2020 Biennial Report* (North Carolina Department of Environmental Quality (NCDEQ), 2020), the team will focus on activities discussed in the remainder of this report.

7.1 Refining and Expanding Scenario Modeling Analysis

During Phase I, the modeling analysis did not limit the number and location of sites for injection of RNG into existing natural gas pipelines. Using input from stakeholders, including LDCs, utilities, and the North Carolina Utilities Commission, the team will refine the injection locations. The team will also calculate pipeline pressures and optimize the location of compressors to integrate with the more realistic scenario of injection sites. These improvements will undoubtedly reduce the number of modeled biogas networks while increasing the number of farms – and potentially other feedstock resources – connected in a network—improvements that will help drive economies of scale that further reduce network LCOEs.

The team will expand the geospatial analysis to include other feedstock types in North Carolina to include LFG, WWTPs, industrial food waste, crop residues and poultry litter. The team will also evaluate the cost, biogas yield, associated GHG emission reductions and potential for co-digestion of these feedstocks as logistics dictate, thus identifying networked RNG hubs and creating a comprehensive plan to harness and monetize these resources.

7.2 Economic and Environmental Impact Analysis

The team will also assess how costs to meet established performance standards with comprehensive waste management solutions, which potentially could address community concerns, will affect the costs of biogas and RNG production from swine waste. The team will also assess what economic benefits would or could follow from meeting the standards. During Phase II, the team will also delve more deeply into the environmental impacts of biogas systems, not only for swine waste, but also with respect to other feedstock types.

7.3 Policy Analysis

During Phase II, the team will aim to determine and develop policy options by which the state could catalyze greater RNG production and use, possibly, but not limited to, an RNG standard as described in the North Carolina EPC's 2020 recommendations (North Carolina Department of Environmental Quality (NCDEQ), 2020). These policy recommendations are essential to identify what the best options are for the state to use its biogas resources. RNG standards and additional incentives will be essential to keep and use biogas and RNG in-state as opposed to moving it to more lucrative markets such as California and Oregon that have low carbon fuel standards. The policy analysis will include an extensive review of North Carolina's existing general statutes, laws, regulations, rules, and policies, as well as other state and federal laws, regulations, policies, and incentives regarding RNG development to identify ways by which the state could increase RNG use or otherwise improve its management of organic waste in a way that is equitable and environmentally sound. The work product will include a set of policy options with the advantages and disadvantages of each clearly articulated. The work product will also include a pathway for implementation described for each. The team will present this information to the NC EPC, the North Carolina Department of Environmental Quality (NCDEQ; related to its work to implement the 2019 Clean Energy Plan), the North Carolina Department of Agriculture and Consumer Services (via its New Agricultural Markets Initiative), the North Carolina Utilities Commission, and the North Carolina General Assembly. This work could also help to inform a Biogas Development Commission or similar entity's deliberations, should such an entity be created.

A major challenge will be to consider policies or incentives to encourage better use of the value-added by-products from AD such as digestate and liquids. Policy options could include incentives for the use of digester biosolids for soil carbon sequestration. Policy options could also include regenerative agriculture, as is being developed by companies such as General Mills (General Mills, n.d.); and carbon payments, as is being developed through protocols such as the soil carbon sequestration protocol approved by the Climate Action Reserve and is expected to be supported by the new administration (U.S. Department of Agriculture (USDA), n.d.).

7.4 Stakeholder Engagement

In parallel with the work described above, the team will develop a comprehensive understanding of the issues, opportunities, challenges, and dynamics regarding the implementation of biogas projects in areas with high biogas production potential to determine how policies can be developed so that they maximize socioeconomic benefits and support the development of biogas and biogas infrastructure in North Carolina. The stakeholders will include, but not be limited to, policy makers, industry leaders, RNG developers, service providers, and community members associated with and impacted by facilities that provide feedstock for RNG production and the pathways by which RNG is used. Some of the pathways include via pipelines, overland transport and use by local entities as a substitute for conventional natural gas or as an alternative transportation fuel source. To accomplish these goals, the team will use focus groups, stakeholder meetings, town hall meetings, and surveys. The team will use these activities iteratively to assist with creating a policy menu and options for the treatment and use of the state's organic waste resources that includes biogas and RNG production.

It is evident that the economic potential and associated GHG benefits of harnessing organic waste resources in the state to produce biogas and RNG can be very attractive. In the case of swine waste, barriers beyond technical capability and economic promise exist. ADs as part of a comprehensive waste management solution that can provide additional pollution controls could be key to gaining community support and acceptance of these technologies. The team recommends the formation of a commission or entity, such as a Biogas Development Commission, capable of overseeing a collaborative effort between policy makers, project developers, utility, service providers, technical experts, and most importantly community leaders to ensure an equitable solution for all stakeholders. A possible solution could involve providing additional incentives to promote fully monetizing by-products and pollution controls to maximize community benefits. Addressing and appreciating these factors will be essential to ensure decisions concerning the development of all organic waste feedstock types are appropriate in connection with achieving North Carolina's environmental, climate and clean energy goals.

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Appendix A—Methodology to Determine the Potential Inventory for Biogas

A-1 Biogas Potential from Livestock

To calculate the potential yield in North Carolina by using animal waste, information about all of the permits issued by the North Carolina Department of Environmental Quality (NCDEQ) to animal facilities was collected (North Carolina Department of Agriculture and Consumer Services, 2014). This information includes the location of such facilities, the type of operation (type of animal), and the type of activity or activities conducted there. Data regarding poultry operations were compiled from data provided by the Environmental Working Group and Waterkeeper Alliance (Environmental Working Group & Waterkeeper Alliance, 2016). However, poultry facilities with less than 30,000 birds, and facilities without a water-based manure collecting system do not require a permit; therefore, these facilities are not included in any available database. Even though the North Carolina Department of Agriculture and Consumer Services collects these data directly from farmers, the data cannot be distributed because of current regulations (North Carolina Department of Agriculture and Consumer Services, 2014). Other possible sources were investigated, but they lacked the reliability needed for a comprehensive analysis (Bruhn et al., 2012). Biogas potential was calculated from the amount of annual waste, density, and potential yield based on average values reported in literature (see **Table A-1**) (Arora, 2011; Chastain et al., 2003; Cucchiella et al., 2019; Hamilton, 2016; Jurgutis et al., 2020; Kime et al., 2001; Koelsch, 2007; Linville et al., 2015; Scarlat et al., 2018; Sharara, 2019; Sims & Maguire, 2004).(Jones et al., 2015; Jurgutis et al., 2020; Kephart, 2009; Kulesza & Gatiboni, 2021; Lorimor et al., 2004).

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

Operation	Activity	Manure Production (ton head^{-1} yr^{-1})	Moisture Content (%)	Biogas Potential from Wet Manure (m^3 ton^{-1}wet)	Biogas Potential Yield (ft^3 head^{-1} yr^{-1})	Biogas Heating Value (million Btu head^{-1} yr^{-1})
Swine	Gilt	0.49 ± 0.1	89	26 ± 2.1	400 ± 80	0.24 ± 0.05
	Boar/stud	1.5 ± 0	91		1200 ± 100	0.74 ± 0.06
	Farrow to wean (per sow)	6.1 ± 1.9	89		5000 ± 1600	2.9 ± 0.9
	Farrow to feeder (per sow)	6.3 ± 1.4	89		5100 ± 1200	3.0 ± 0.7
	Farrow to finish (per sow)	19.7 ± 1.3	90		16000 ± 1700	9.6 ± 1.0
	Feeder to finish (per pig)	2.3 ± 0.3	90		1900 ± 260	1.1 ± 0.2
	Wean to feeder (per pig)	0.9 ± 0.1	89		720 ± 110	0.43 ± 0.06
	Wean to finish (per pig)	1.9 ± 0.1	89		1500 ± 160	0.9 ± 0.9

(Continued)

Table A-1. Manure Production Rates, "As-Excreted," Including Urine and Feces, Biogas Potential, and Biogas Heating Value by Livestock Operation (Continued)

Operation	Activity	Manure production (ton head^{-1} yr-1)	Moisture Content (%)	Biogas Potential from Wet Manure (m^3 ton^{-1} wet)	Biogas Potential Yield (ft^3 head^{-1} yr^{-1})	Biogas Heating Value (million Btu head^{-1} yr^{-1})
Cattle	Beef brood cow	14.2 ± 3.1	88	29 ± 4.9	13000 ± 3500	7.6 ± 2.0
	Beef stocker calf	8.9 ± 1.8	92		8300 ± 2200	5.0 ± 1.3
	Beef feeder	10.6 ± 2.0	92		9900 ± 2500	5.9 ± 1.5
	Dairy heifer	9.9 ± 1.7	88		8800 ± 2200	5.3 ± 1.2
	Dairy cow	14.2 ± 1.3	88		22000 ± 4700	13 ± 2.7
	Dairy calf	3.3 ± 0.4	88		2900 ± 600	1.8 ± 0.4
	Dry cow	14.2 ± 1.3	88		13000 ± 2500	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

Note: ft^3 = cubic feet.

A-2 Biogas Potential from Crop Residue

Calculations of the biogas potential yield from crop residue was conducted by Ecostrat (Lamonaco et al., 2019). The seven most widely grown crops in the state were considered for this analysis. These crops are corn, cotton, peanuts, soybean, sweet potato, tobacco, and wheat. The quantity of residues from these crops were calculated based on factors available in literature (**Table A-2**). The potential availability of these residues for anaerobic digestion (AD) is limited by the amounts typically sold off to paying markets such as animal feed or that are required to be left on the field to minimize soil erosion and nutrient losses. The biogas yield for the specific crops were obtained from literature sources (see **Figure A-1**) (Fleming et al., 2009; Gould, 2007; Herrmann et al., 2016; Jurado et al., 2013; Liu et al., 2015; Mussoline & Wilkie, 2015; Naskeo Environnement, 2009; Nzila et al., 2010). Where crop-specific data was not available, a close analogue was used.

Table A-2. Estimated Agricultural Crop Residues in North Carolina

		Residue Generated		Available for AD	
Crop Type	**Type of Residue**	***dt/acre/yr****	***dtpy***	***Percentage (%)***	***dtpy***
Corn	Corn stover	2	1,696,900	35	593,915
Cotton	Stalks, stems	2.37	635,053	29	184,165
Peanuts	Stems, leaves	2.5	172,350	15	25,853

(continued)

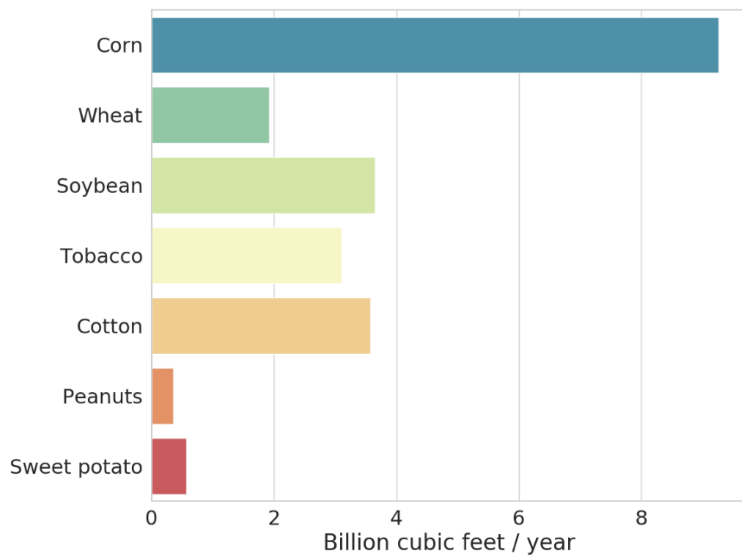
Table A-2. Estimated Agricultural Crop Residues in North Carolina

Crop Type	Type of Residue	Residue Generated		Available for AD	
		*dt/acre/yr**	*dtpy*	*Percentage (%)*	*dtpy*
Soybean	Stalks, leaves, pods	1.13	1,772,642	15	265,896
Sweet potato	Stalks, leaves	1.78	110,654	44	48,688
Tobacco	Stalks, seeds	1.78	263,734	100	263,734
Wheat	Wheat straw	1.6	541,648	35	189,577

Note: dtpy = dry tons per year; dt/acre/year = dry tons per acre per year.

*(Lal, 2005; Roberson, 2019; Shahbazi & Li, 2006; Wortmann et al., 2012)

Figure A-1. Total Biogas Potential from Agricultural Crop Residues in North Carolina (2019)



A-3 Biogas Potential from Wastewater Treatment Plants

The location and annual flow of wastewater for all WWTPs in North Carolina was collected by using the NCDEQ's permitting database. The reported biogas potential from wastewater was obtained from the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency (EPA) & Combined Heat and Power Partnership, 2011).

A-4 Biogas Potential from Landfills

The location of operating landfills in North Carolina was obtained from the EPA's website (U.S. Environmental Protection Agency (EPA), 2020c). With this information and the potential yield of biogas by using the organic fraction of municipal waste (U.S. Environmental Protection Agency (EPA), n.d.-a), the total potential biogas yield for each of the candidate landfills in North Carolina was calculated.

A-5 Biogas Potential from Industrial Food Waste

Calculation of the biogas potential from industrial food waste was conducted by Ecostrat. Wastes from the top eight food production industries were cataloged and aggregated at the county level. Total estimates of food waste generation have been adjusted to account for quantities that are most likely being sold to higher end markets such as rendering and animal feed. For example, it is estimated that approximately 70% of food waste generated by the meat product manufacturing sector is sold to markets such as rendering. Therefore, only 30% of the food waste generated by this sector is potentially available for biomethane production. A complete list of the estimated quantities going to paying markets for each food processing industry is included in **Table A-3**.

Table A-3. Typical Waste from Industry Sectors and Availability for AD

Industry Name	NAICS Code	Typical Waste Streams	Applicable Markets	Percentage (%) Potentially Available for AD
Grain and oilseed milling	3112	Mill run, elevator dust, millings	Feed, land application, compost	60
Sugar and confectionery product manufacturing	3113	Various solid and liquid food waste	Various	60
Fruit and vegetable preserving and specialty food manufacturing	3114	Fruit and vegetable waste, sludges, purees and culls	Land application, feed, compost	75
Dairy product manufacturing	3115	Whey, DAF, sludges	Feed, land application	60
Meat product manufacturing	3116	Activated sludge, blood, paunch, DAF, FOG, offal, peptone, mortality, wastewater, meat scraps, bone, shells	Rendering, feed, compost, wastewater	30
Bakeries and tortilla manufacturing	3118	Off-specification product, FOG	Feed, compost, rendering	60
Other food manufacturing	3119	Virtually all types of waste streams, including solid and liquid food wastes	Various	85
Beverage manufacturing	3121	Various liquid wastes	Ethanol production, wastewater	25

Note: DAF = dissolved air flotation; FOG = fats, oils, and grease; NAICS = North American Industry Classification System.

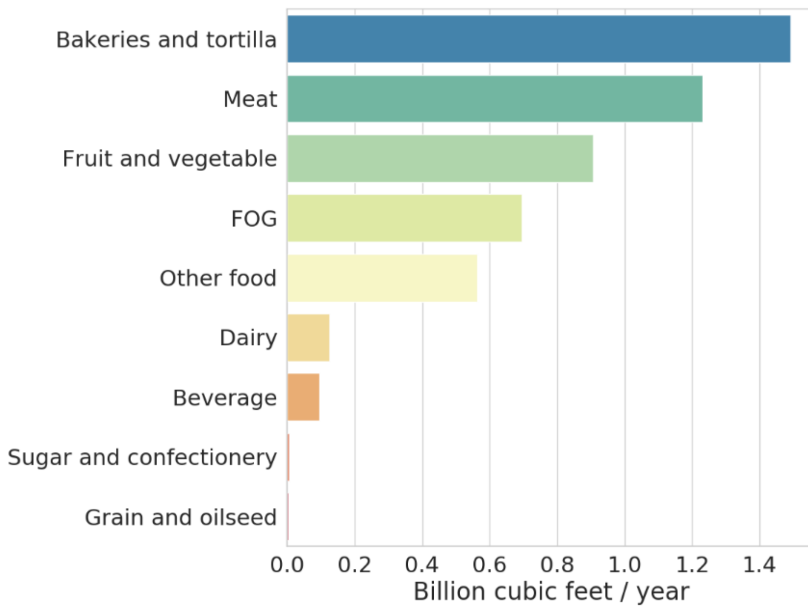
Data suggest that there is an estimated combined total of 1,698,840 tons per year (tpy) of industrial food waste and fats, oils, and grease (FOG) is generated in North Carolina (**Table A-4**). Of that amount, 82% is in the form of liquid food waste, with solid food waste and FOG accounting for 14% and 4%, respectively.

Table A-4. Industrial Food Waste Generated by Category

Type of Food Waste	Estimated Industrial Food Waste Generation (tpy)	Potentially Available for AD (tpy)
Solid	234,881	125,310
Liquid	1,397,182	670,488
FOG	66,777	66,777
Total	**1,698,840**	**862,575**

The average biogas potentials from the various industrial sectors are shown in **Figure A-2**.

Figure A-2. Average Biogas Yields for Waste from Different Industrial Food Processing Sectors



Appendix B—Methodology to Determine the Production Cost of Biogas and Biogas Products

All capital and operational costs are reported after correction to 2018 U.S. dollars (USD) by using the Chemical Engineering Plant Cost Index (CEPCI).

B-1 In-Ground Anaerobic Digester

The capital costs used for correlation development were for newly constructed, covered in-ground anaerobic digesters. At a minimum, cost-specific items contributing to the total capital cost included pit excavation, a pit liner and cover, pumps, piping, electrical, solid-liquid separators, and liquid storage. If a digester operated at mesophilic temperatures, then additional costs for a heat-exchanger and insulation were added to the previously stated items. Capital costs were extracted from case studies, literature reviews, government databases and news reports (Adair et al., 2016; Beddoes et al., 2007; Cash, 2018; Cheng et al., 2004; Ernest et al., 2021; Gloy, 2011; Guillory, 2011; Liggett, 2018; Lusk, 1998; Marsh et al., 2009; Moser et al., 2014; Murawski, 2018; Orchard, 2014; Roos & Martin, 2008; U.S. Environmental Protection Agency (EPA), 2014a, 2014b, 2014c).

To equalize the components contributing to the capital cost across the studies analyzed, the costs associated with odor removal and on-site electricity generation were excluded from the total capital cost whenever possible. For all studies analyzed, it was possible to remove the capital costs associated with on-site electricity generation through the creation of a cost ratio, defined as the cost of on-site electricity generation with respect to the total system capital cost. This ratio was created by using studies that presented itemized financial reports for new, covered in-ground ADs (n=20). The value of the cost ratio was calculated to equal approximately 0.41, which agrees well with other references (Kephart, 2009; U.S. Environmental Protection Agency (EPA), n.d.-a). When it was stated that on-site electricity generation was used, and an itemized report of the capital cost was absent, the reported lump capital cost was multiplied by (1-cost ratio) to obtain only the cost of the digester.

When possible, operational costs for covered in-ground anaerobic digesters were extracted from the case studies reviewed. Operating costs included repairs to the digester cover, staffing, utilities, and electricity.

B-2 Manure Digestion Rates

Cost curves for biogas capture using covered in-ground digesters were correlated to the amount of manure “as excreted” that was fed to the digester. Although the total influent flow rate to the digester was widely reported in the literature, function development using this independent variable caused poor correlation values (0.37). Because influent manure flow rates are lumped into the total influent flow rate (along with flush water and other dilutions), it was necessary to develop a methodology to extract only the amount of manure entering the digester.

When possible, the influent manure rate was extracted directly from case studies. When the manure flow rate was not provided, it was estimated based on the total number of animal heads feeding the digester and the manure production rates provided in **Table B-1**. **Equation B-1** shows a sample calculation for determining the amount of manure produced from a 1,000 farrow-to-finish swine farm.

$$1000\ animal \times \frac{19.7\ tons\ manure}{animal-yr} \times 2000\ \frac{lb}{ton} \times \frac{yr}{365\ day} = \mathbf{108{,}000}\ \frac{\mathbf{lb\ manure}}{\mathbf{day}} \qquad \text{(Eq. B-1)}$$

The error of this methodology—the tendency for overestimation or underestimation of manure production—was tested by using studies that reported the influent manure flow rate to the farm's digester. The error was defined as the difference between the reported and the estimated influent manure flow rate with respect to the reported manure flow rate entering the digester. The resulting percent error (n=9) was approximately -5 ± 10%. Overall, this methodology provided an accurate estimate of the manure entering a farm's digester. To compensate for any overestimation of manure production, the following logic flow was applied to the data: if the estimated influent manure flow rate exceeded the reported total influent flow rate, then the total influent flow rate would be used for the data point. In this way, error because of overestimating manure production was minimized.

B-3 Biogas Upgrading in a Pressure Swing Adsorption Process

Capital and operating costs for pressure swing adsorption systems were extracted directly from the literature (Angelidaki et al., 2018; Bauer et al., 2013; Collet et al., 2017; Götz et al., 2016; Hauser, 2017; Hayes et al., 2003; Khan et al., 2017; Muñoz et al., 2015; Ncibi & Sillanpaa, 2015; Olsson & Fallde, 2015; Patterson et al., 2011). Itemized costs contributing to the total capital cost included system parts, transportation of parts, commissioning, engineering, and analysis equipment to monitor performance.

When provided, the operating costs were extracted directly from the literature. Examples of operating costs included staffing, utilities, electricity, thermal gas treatment, and accumulated repair costs. When not provided, the operating costs were assumed to total 10% of the total capital investment costs. This is a reasonable assumption based on the studies that provided itemized operating costs.

B-4 Biogas Production Correlation

Biogas production data were extracted from the same set of references used for the covered in-ground anaerobic digester capital and operational costs acquisition. The biogas production value used for correlation development represented the yearly average produced at the farm. It should be noted that the biogas production value used here represents the actual yield. This actual biogas yield differs from the biogas potential yield reported in **Appendix A** of this report, the latter being a theoretical biogas production.

Biogas production rates were also correlated to the influent manure flow rate. The volume of biogas depends on the biological oxygen demand of the waste (suspended and dissolved). Some authors have found good correlation with the volatile suspended solids of the manure and the biogas production rate (Ciborowski, 2001). Most studies evaluated here reported the total influent flow rate to the digester. This was problematic however, because the total flow rate includes flush, recycle, and other water streams that do not contribute to biogas production, and thus was obvious when low regression values (0.37) were obtained from correlating biogas production to total influent flow rates. Thus, it was necessary to develop and use the methodology presented here to extract only the influent manure rate.

B-5 Cost Curve and Biogas Correlation Results

Table B-1 shows cost and biogas production equations generated.

Table B-1. Results from Cost Curve and Biogas Production Function Development

Curve Definition	Capital Cost Function (2018 USD)	Operating Cost Function (2018 USD)	Biogas Production Function (scf d^{-1})	Independent Variable
Covered in-ground digester	$2.7x^{1.03}$ | $R^2 = 0.81$	$4.86x^{0.66}$ | $R^2 = 0.90$	$0.33x$ | $R^2 = 0.90$	Manure digested (lb d^{-1})
Pressure swing adsorption	$81800x^{0.51}$ | $R^2 = 0.97$	10% of capital	Not applicable	Biogas treated (m^3 h^{-1})

Note: lb d^{-1} = pounds per day; m^3 h^{-1} = cubic meters per hour; R^2 = R squared; scf d^{-1} = standard cubic foot per day.

Appendix C—Additional Resources

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ICF. (2019, December). *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). (2020, March). *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). (2014, August). *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