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Duke NICHOLAS INSTITUTE FOR ENVIRONMENTAL POLICY SOLUTIONS

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INTRODUCTION

Biogas is generated by the anaerobic decomposition of organic material by bacteria. It is composed of approximately 50–60% methane (CH_4) and 40–50% carbon dioxide (CO_2) as well as traces of other gases and impurities. The methane component of biogas is physically similar to natural gas and can be used to fuel electricity generation equipment, boilers, and other energy sources. Biogas can be generated in landfills, wastewater treatment plants, and livestock operations and through other forms of anaerobic biomass processing and is considered a renewable energy source.[1] Because biogas comes from non-fossil sources, interest has arisen in using it as a net "low-carbon" feedstock for energy generation and as a strategy for meeting companies' internal sustainability goals. However, little information exists on the costs of developing new biogas resources in North Carolina, a state with significant biogas supply potential.

Duke University has developed the OptimaBIOGAS tool to model the opportunities for and costs of developing, transporting, and generating usable energy from a variety of biogas sources. In this analysis, the tool is used to clarify the options for and costs of sourcing biogas from landfills within North Carolina. Other analyses with OptimaBIOGAS have examined opportunities for and costs of generating biogas at the state's many swine farms.[2]

According to data from the U.S. Environmental Protection Agency (EPA), biogas collection projects are operating in at least 24 landfills in North Carolina, and 25 to 30 additional landfills may make good candidates for biogas collection.[3] This analysis assesses whether emerging demands for biogas can be met economically by these additional landfills. Specifically, it estimates the costs of developing the biogas resource at each of these landfills and compares them to the costs of other energy sources. For each landfill, it examines two energy generation scenarios: (1) conditioning the biogas to pipeline quality and injecting it into the natural gas transport pipeline for use downstream, and (2) generating electricity on site.[4] Analysis of additional options for generating usable energy from biogas, including using a boiler or other equipment to generate thermal energy, is recommended.

[1] See for example, the North Carolina Renewable Energy and Energy Efficiency Portfolio Standard (G.S. 62-133.8 (a) (8)).

[2] D. Prasodjo et al., A Spatial Optimization Study of Swine Waste-Derived Biogas Infrastructure Design in North Carolina (Duke Carbon Offsets Initiative and Nicholas Institute for Environmental Policy Solutions, Duke University, 2013), http://nicholasinstitute.duke.edu/climate/spatial-economic-optimization-study-swine-waste-derived-biogas-infrastructure-design.

[3] See the discussion of data used for this analysis in the Methods section, below.

[4] High-pressure transport pipelines, rather than lower-pressure distribution pipelines, are used to ensure a more uniform gas mix.

The estimated energy costs at the evaluated landfills are based on best available information. Analysis of site-specific factors are needed to refine costs before a project at any particular landfill is initiated. For groups wishing to pursue this research, a variety of routes are available, including engaging the services of professional development firms specializing in energy sources similar to biogas.

METHODS

Data Sources

The EPA has done considerable work through its Landfill Methane Outreach Program (LMOP) to research and promote the collection of biogas from landfills.[5] The LMOP has created an extensive database of landfills in the United States, along with several tools to help estimate biogas generation rates and costs at each landfill. According to the LMOP database, 30 landfills in North Carolina might be good candidates for landfill biogas collection.[6] However, four of these candidate landfills are already generating energy from landfill gas, and another is preparing to generate electricity. These landfills were dropped from the analysis, leaving 25 candidate landfills (Table 1). Of these, six are collecting biogas but burning it in a flare. Because these landfills are not using the biogas for energy generation, the analysis retained them for consideration and assumed that they would incur no capital costs for biogas collection equipment but that they would incur operating and maintenance costs as well as the cost to purchase and operate energy generation equipment.

[5] For more information, visit the EPA LMOP website: http://epa.gov/lmop/index.html.
[6] The LMOP database defines candidate landfills as those that are still accepting waste or that have been closed for five or fewer years.

Table 1. Landfill IDs for Candidate Landfills in North Carolina

Landfill ID	Landfill Name
1042	Alleghany County Landfill
1045	Ashe County Landfill
1046	Austin Quarter SWM Facility
1055	Caldwell County Mt. Herman Landfill
1062	City of Albemarle Landfill
1065	Kersey Valley Landfill
1069	Cleveland County Landfill
1070	Cliffside South Rutherford County Landfill
1080	East Carolina Regional Landfill
1082	Edgecombe County Landfill
1091	Haywood County Landfill
1092	Haywood County White Oak Landfill
1103	Lenoir County Landfill
1113	New Hanover County Landfill
1128	Rockingham County Landfill
1129	Rowan County Landfill
1143	US Army Fort Bragg
1144	US Marine Corps Camp Lejeune
1153	Wilson County Landfill
1156	Wilkes County Landfill #2
2064	Rockingham County Landfill #2
2199	Upper Piedmont Environmental Landfill
2424	Chambers Development MSWLF
10620	South Wake Landfill
10781	Onslow County Landfill #2

As its primary data source, the analysis used the LMOP database, and then filled in gaps and updated information using the landfill permit database maintained by the Division of Waste Management of the North Carolina Department of Environment and Natural Resources (NCDENR.[7] Together, these databases contain the most up-to-date information on waste in place, waste acceptance rates, and landfill area for operational landfills. According to the NCDENR database, some of the candidate landfills have closed and are no longer accepting waste, yet contain a considerable amount of organic material, making them good candidates for biogas projects. Because these closed landfills were not listed

[7] NCDENR Division of Waste Management, *Landfill Capacity Report, Fiscal Year 2011–2012,* http://portal.ncdenr.org/c/document_library/get_file?p_l_id=4649434&folderId=9377383&name=DLFE-59119.pdf.

in the NCDENR database, and because the LMOP database does not include information on landfill area, the area of the closed landfills was estimated using statistical linear regression methods to determine the relationship between overall volume of waste and landfill acreage of the 13 active listed in the NCDENR database landfills (Figure 1).

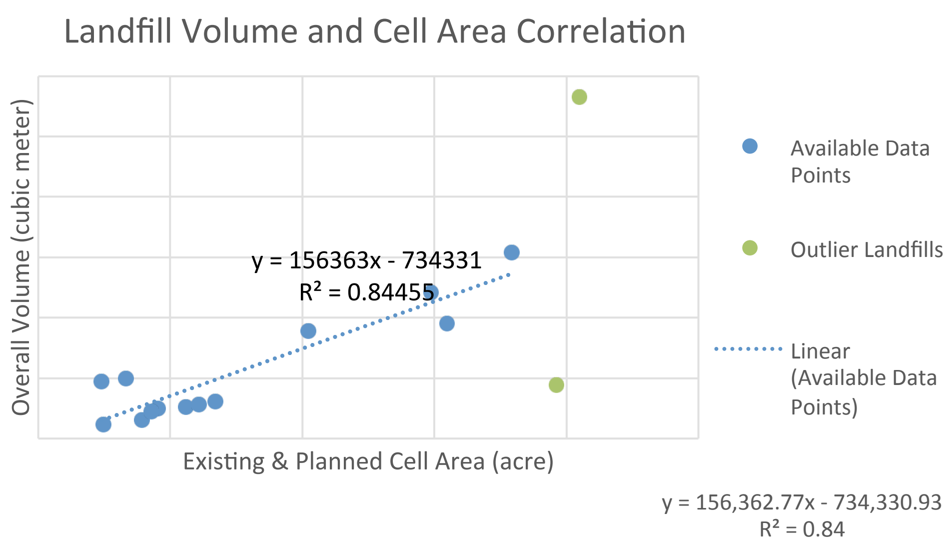

Figure 1. The relationship between landfill volume and landfill acreage among available data points. Excluded outlier landfills: New Hanover County Landfill (upper point) and Sampson County Landfill (lower point).

Cost information for the equipment necessary to collect, process, and transport biogas was taken from a previous report on the development of biogas resources from swine farms (see Table 2).[8] These data were collected directly from equipment vendors. The equipment options were discussed with experienced landfill biogas project developers to ensure that they would be sufficient for developing landfill gas projects, and where necessary, additional price quotes were obtained from vendors. The complete list of equipment options can be found in the appendix.

[8] See D. Prasodjo et al., A Spatial Optimization Study of Swine Waste-Derived Biogas Infrastructure Design in North Carolina.

Table 2. Capital, Operating, and Other Costs in Each Landfill Biogas Collection Scenario over a 15-Year Period

Electricity generation scenario	Pipeline injection scenario
• Biogas collection equipment, including biogas wells and a blower system • Biogas conditioner to remove moisture and impurities from biogas prior to electricity generation • Electricity generation equipment	• Biogas collection equipment, including biogas wells and a blower system • Biogas conditioner to remove moisture, carbon dioxide, siloxanes, and impurities from biogas prior to pipeline injection • Biogas compressors to compress gas to pipeline specifications • New pipeline and right of way to inject biogas into the natural gas pipeline network • Pipeline injection costs

Models and Tools

This analysis uses several models to estimate the biogas generation rates and project development costs for each candidate landfill in North Carolina. These models include the OptimaBIOGAS model, developed at Duke University, as well as the Landfill Gas Estimation Model (LandGEM) and the Landfill Gas Cost Model (LFGCost) developed by the EPA. Each model is described below.

OptimaBIOGAS

The OptimaBIOGAS model was developed by researchers at Duke University to model the costs of developing, transporting, and generating usable energy from biogas resources, including landfills and agricultural operations. The model uses geographic information systems (GIS) for spatial mapping and the General Algebraic Modeling System (GAMS) for cost optimization to determine optimal solutions to questions about sourcing and transporting biogas.[9]

The model operates in two stages: first, it selects the optimal arrangement of equipment necessary to handle all the biogas generated at each landfill, and then, for the pipeline injection scenario, it determines the optimal spatial path of new pipeline construction to deliver the gas to the existing natural gas pipeline network in North Carolina.

Equipment options are listed in the appendix and include biogas conditioners and electricity generation equipment. Depending on the scenario, the model can choose to select the optimal arrangement of equipment, that is, the arrangement with capacity sufficient to handle all the biogas generated at each

[9] For a more detailed explanation of the OptimaBIOGAS model, see D. Prasodjo et al., A Spatial Optimization Study of Swine Waste-Derived Biogas Infrastructure Design in North Carolina..

landfill. Pipeline cost data are presented as a range due to the variety of construction conditions, land use, soil types, and right-of-way issues that could be encountered during installation of new gas pipelines.

Pipeline path selection is based on a spatial optimization model using ArcGIS software and a cost surface that indicates areas of the region where pipeline construction would be most expensive. These areas include waterways, protected areas, and steep areas. OptimaBIOGAS uses this information to determine the least-cost path to connect the landfill to the existing natural gas pipeline. The data used to estimate new pipeline construction costs were taken from the report on developing North Carolina's swine biogas resources.[10] These data are broadly representative numbers and should not be augmented with specific data applicable to a particular project; each project would face unique circumstances that would affect its overall costs.

Landfill Gas Estimation Model (LandGEM)

The EPA developed LandGEM to provide estimates of biogas generation potential at landfills.[11] The model uses several inputs, including landfill start and closure years and waste acceptance rates. For a complete list of the required inputs, see Table 3. The biogas estimation is based on a first-order decay function, which assumes that biogas generation will peak shortly after waste is placed and begins to decay and that it will decrease exponentially thereafter (Figure 2).

Table 3. Inputs to the LandGEM Model to Estimate Biogas Generation Potential at Each Landfill

LandGEM input	Unit	Value
Start and closure years	Year	From NCDENR/EPA data
Waste design capacity	Megagrams (Mg) or "metric ton"	From NCDENR/EPA data
Waste acceptance rate	Mg/year	From NCDENR/EPA data
Methane generation rate (*k*) • Primarily determined by moisture content • Bioreactor and leachate recirculation landfills should use a larger *k* value	$year^{-1}$	Default value of 0.04
Potential methane generation capacity (L_o) • Determined by organic content of the waste	m^3 / Mg	Default value of 100
Methane content of biogas	% by volume	Default value of 50%

[10] See D. Prasodjo et al., A Spatial Optimization Study of Swine Waste-Derived Biogas Infrastructure Design in North Carolina..
[11] The LandGEM model can be downloaded from the EPA at http://www.epa.gov/ttn/catc/products.html#software.

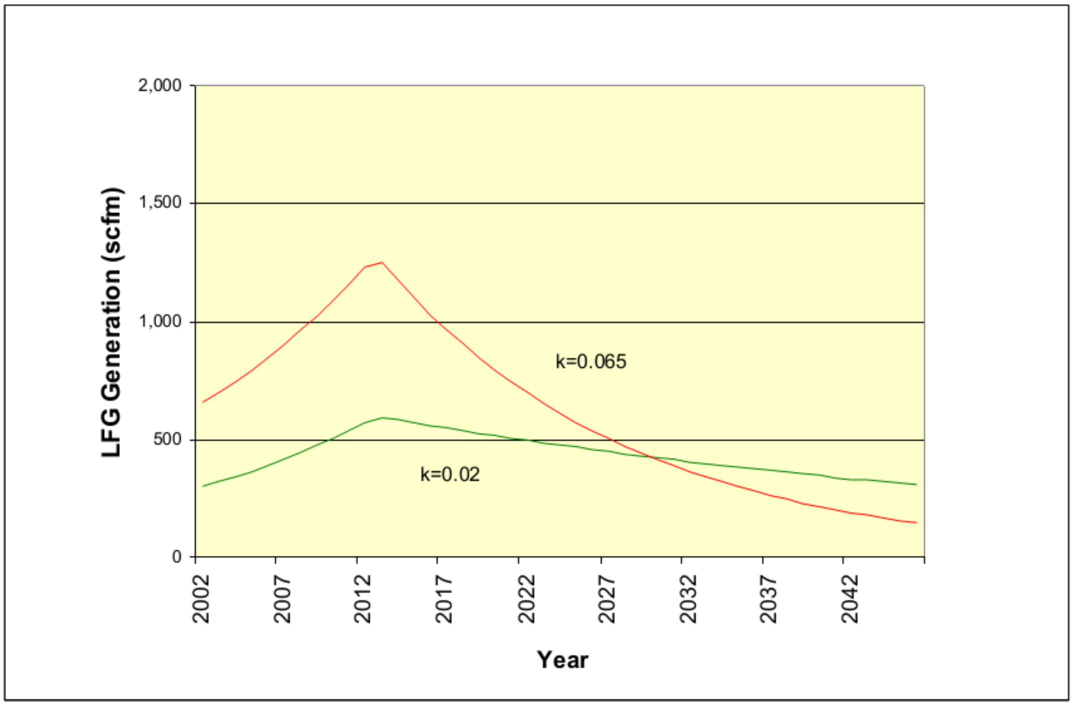

Figure 2. Landfill biogas generation rates based on methane generation rates (k) for wet (k=0.065) or arid conditions (k=0.02). Curves show generation rates for a landfill with approximately 2 million tons of waste in place at closure. *Source:* US EPA, Landfill Gas Project Development Handbook, chapter 2, page 2-3, http://epa.gov/lmop/publications-tools/handbook.html.

Landfill opening and closing years, waste design capacity, and waste acceptance rates were obtained from the NCDENR and EPA databases. The methane generation rate (k) and potential methane generation capacity (L_o) are set to default values suggested by the EPA (k = 0.04; L_o = 100 m^3 of methane per Mg of waste). These values are considered the appropriate parameters in estimating the overall methane generation rate for the conventional municipal solid waste landfills in this analysis.[12] A standard assumption that the methane concentration of biogas is 50% by volume was also used.

The output of the LandGEM model is the annual landfill gas generation rate, which is used as the input for OptimaBIOGAS modeling.

[12] See U.S. EPA, Landfill Gas Emissions Model (LandGEM) Version 3.02 User's Guide (2005), 16, http://www.epa.gov/ttn/catc/dir1/landgem-v302-guide.pdf.

Landfill Gas Cost Model (LFGCost)

The EPA developed LFGCost to provide estimates of landfill biogas project costs. LFGCost allows modeling of several scenarios, such as electricity generation, on-site thermal energy use, and pipeline-quality biogas conditioning. In this analysis, it was used to estimate biogas collection costs, which are dependent on landfill area (Table 4); the industry standard is to place one well per acre of landfill space.

Table 4. Inputs to the LFGCost Model to Estimate Biogas Generation Potential at Each Landfill

LFGCost input	Unit	Value
Start and closure years	year	From NCDENR/EPA data
Area of LFG wellfield to supply project	acres	From NCDENR data; modeled for landfills with missing data
Average annual waste acceptance rate	tons/year	From NCDENR/EPA data
LFG energy project type Options: direct use, turbine, engine, high Btu, microturbine, small engine, leachate evaporator, CHP engine, CHP turbine, or CHP microturbine	N/A	High Btu
Distance between landfill and direct end use, pipeline or CHP unit (for direct use, high Btu, and CHP projects only)	miles	From OptimaBIOGAS
Year LFG energy project begins operation	year	2014
Landfill gas collection efficiency	%	85%

The LFG energy project type for the pipeline injection scenario was set to high Btu. The distance between landfill and pipeline was obtained from the OptimaBIOGAS model and represents the distance of the optimal (least-cost) pipeline route from each landfill to the injection site. The landfill gas collection efficiency was set to 85%, the value recommended by the EPA.

The output of the model includes the total installed capital cost for construction, incurred in the first year, and the annual operating and maintenance cost normalized to the present value using a 10% discount rate and assumed project length of 15 years. The estimate can also include the biogas collection cost, which is determined by the area of LFG well field, depending on the needs of the analysis.

RESULTS

The results for both the pipeline injection and the electricity generation scenarios are discussed below. The included costs represent the capital and operating costs of equipment and pipelines. Primary estimates do not include the project developer's costs to plan and implement the transaction, which can be highly variable and project dependent. Therefore, the average costs of biogas or electricity should not be interpreted as the full cost of delivery to the network. This report does present ballpark estimates of project development costs but only for context. Each project will face unique challenges and opportunities that will alter its costs.

Pipeline Injection Scenario

In the pipeline injection scenario, an expensive conditioner is required to remove carbon dioxide and impurities from biogas, allowing it to meet pipeline quality standards. The biogas conditioner is the dominant cost component for most landfills. Figure 3 shows the average cost of biogas ($/MMBtu) from the 10 landfills with the lowest costs; in each of these landfills, the biogas conditioner makes up a majority of the project costs, which also include the costs of collecting biogas at the landfill and of transporting it to the pipeline. Several landfills are located near the existing natural gas pipeline (Figure 5). For those facilities, biogas transport costs, including pipeline construction, are not a significant component of project costs. The landfills with the highest costs tend to be located further from the existing natural gas pipeline. For these landfills, pipeline construction costs can account for up to 98% of project costs.

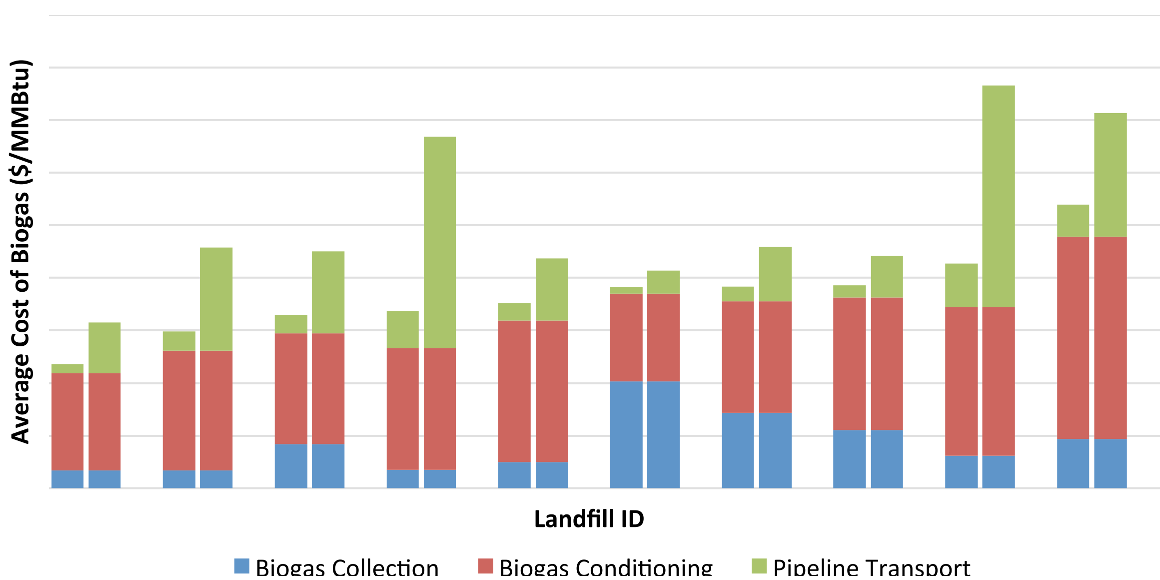

Figure 3. Average cost of biogas ($/MMBtu) for the pipeline injection scenario for the 10 landfills with the lowest average costs. Grouped bars include costs calculations using the low- and high-end pipeline cost estimates. Costs include capital and operating costs over a 15-year period and are separated by the cost to collect the biogas at each landfill, the cost of equipment to condition the gas to prepare it for pipeline injection, and the cost to install new pipeline between the landfill and natural gas pipeline. For a list of the landfills associated with each ID, see Table 1.

Because the pipeline construction cost data were presented as a range, the results for the pipeline injection scenario are also presented as range, based on low and high ends of the range of pipeline costs. The average costs of biogas range from a low of $4.73 ($6.29) per MMBtu to a high of $406 ($2,281) per MMBtu using the low-end (and high-end) pipeline cost estimates. Total project costs over a 15-year period range from $3.8 million ($4.8 million) to $34 million ($149 million) using the low-end (and high-end) pipeline costs. The generation potential of each candidate landfill can be ordered from lowest to highest average cost and used to develop a supply curve for landfill biogas (Figure 4).

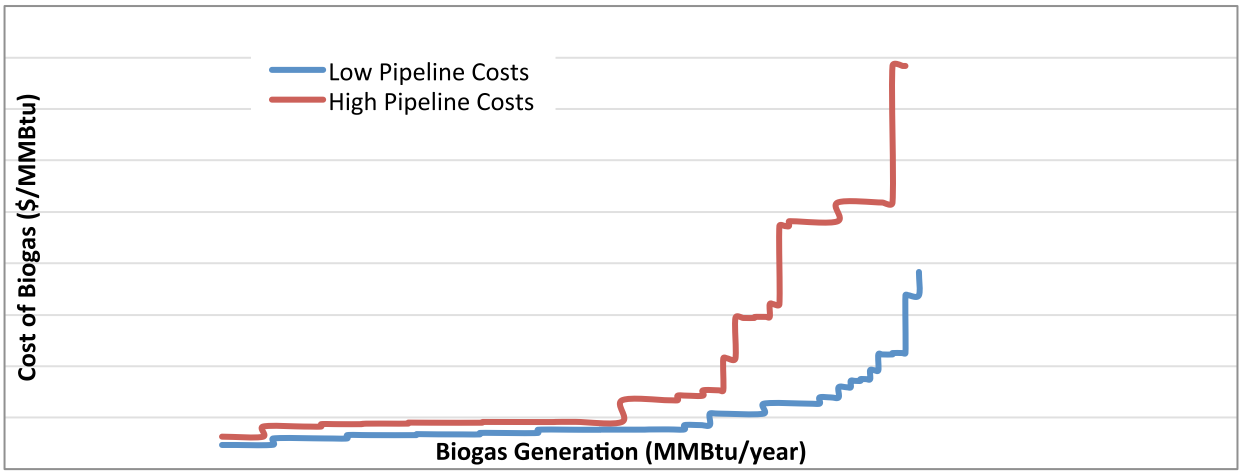

Figure 4. Supply curve for landfill biogas from candidate landfills in North Carolina for the pipeline injection scenario. Blue and red lines indicate supply curves constructed with low- and high-end pipeline costs, respectively.

To estimate the potential economic viability of landfill biogas projects for parties interested solely in generating and selling biogas for profit, the net present value (NPV) for each project was calculated, with the assumption that the gas would be sold at the industrial natural gas price projected by the Energy Information Administration (EIA; Table 6). The NPV calculation uses the 10% discount rate and 15-year time horizon. Given these assumptions, two of the modeled landfill projects have a positive NPV if low-end pipeline costs are used (Table 7). If high-end pipeline costs are used, none of the landfills has a positive NPV. In other words, if a project fails to result in a positive NPV at a 10% discount rate, its internal rate of return (IRR) is less than 10%.

Table 6. Projected Industrial Natural Gas Prices ($/MMBtu) and Industrial Electricity Prices ($/kWh) for the South Atlantic Region, 2014–2028

Year	$/MMBtu	$/kWh
2014	$5.25	$0.0631
2015	$5.29	$0.0633
2016	$5.72	$0.0635
2017	$5.87	$0.0637
2018	$6.11	$0.0639
2019	$6.21	$0.0641
2020	$6.29	$0.0644
2021	$6.39	$0.0646
2022	$6.57	$0.0648
2023	$6.76	$0.0650
2024	$6.87	$0.0652
2025	$6.94	$0.0654
2026	$7.07	$0.0657
2027	$7.11	$0.0659
2028	$7.22	$0.0661

Source: Energy Information Administration's *Annual Energy Outlook 2012*.

Table 7. Net Present Values for Landfills with Positive Returns Modeled Using Projected Natural Gas Prices

Landfill	Net Present Value
East Carolina Regional Landfill	$6,543,068
South Wake Landfill	$321,074

As shown in Figure 5 (below) and Table 8 (in the Discussion and Conclusions section), the average costs of biogas for most candidate landfills (using either the low- or high-end pipeline costs) are well above projected natural gas prices. Furthermore, the costs used to calculate these average costs do not include costs incurred by the project developer to plan and implement the project. Informal discussions with landfill biogas project developers suggest that project development costs are highly variable and project dependent but that they could increase the average cost of biogas by up to $2.50/MMBtu. If these costs are added, none of the landfill projects would have a positive NPV, even with the low pipeline costs. In other words, these projects would likely not be financially viable at projected natural gas prices if project development costs were included and if the objectives were purely to produce gas for the energy market in direct competition with fossil supplies.

However, even if these projects cannot compete with the current and projected price of natural gas, they might become more competitive if the biogas could be sold at a premium. If the biogas buyer is seeking a lower-GHG alternative to natural gas and is willing to pay a premium for it (perhaps to comply with a mandatory or voluntary GHG reduction program or a renewable energy requirement), financial viability could improve. The amount of the premium payment could be determined by taking the average cost of biogas (plus project development costs) and subtracting from it the cost of natural gas. For example, if the average cost of biogas from the lowest-cost landfill is $4.73 to $6.29/MMBtu, depending on pipeline costs, and the average cost of natural gas is $3.82/MMBtu, the required premium would be $0.91 to $2.47/MMBtu, not including project development costs.

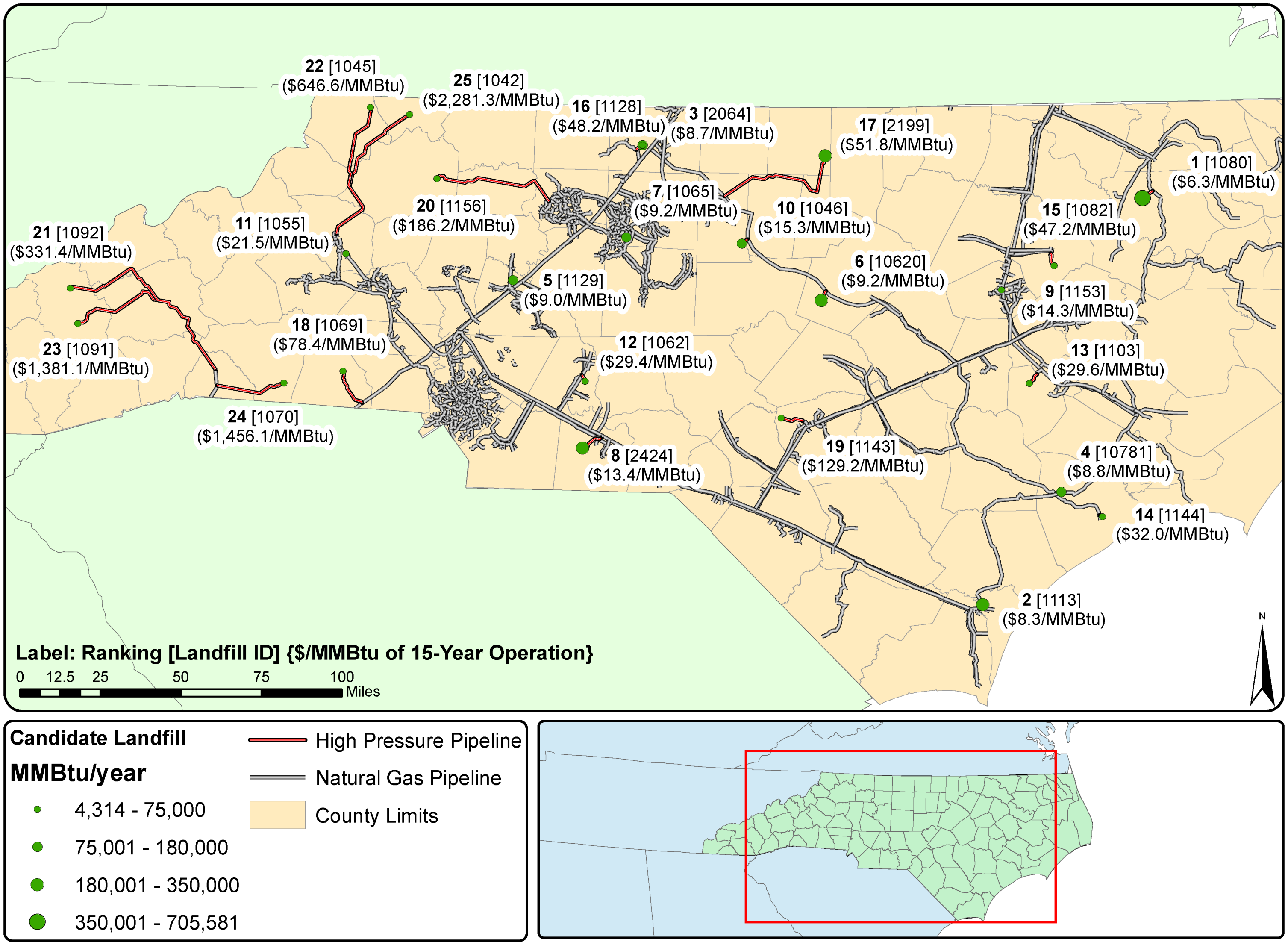

Figure 5. Map of candidate landfills, existing natural gas pipelines, and new pipelines necessary to connect landfills to natural gas pipelines. Data labels include the rank of the landfill (using the high-end pipeline costs), the landfill ID, and the average cost of biogas ($/MMBtu). Source: PennWell Corporation, MAPSearch.

Electricity Generation Scenario

In the electricity generation scenario, biogas need not necessarily be purified to the same quality as in the pipeline injection scenario, because most options for on-site electricity generation from biogas, including microturbines and some internal combustion engines, can operate with higher levels of biogas impurities than acceptable for a commercial pipeline. Therefore, biogas conditioning costs are not the dominant driver of costs for most landfills in the electricity generation scenario. Figure 6 shows the average cost of electricity generation ($/kWh) for all candidate landfills in North Carolina. In most of these landfills, electricity generation equipment makes up a majority of project costs, which also include the cost to collect and condition the biogas at the landfill, as in the pipeline injection scenario.

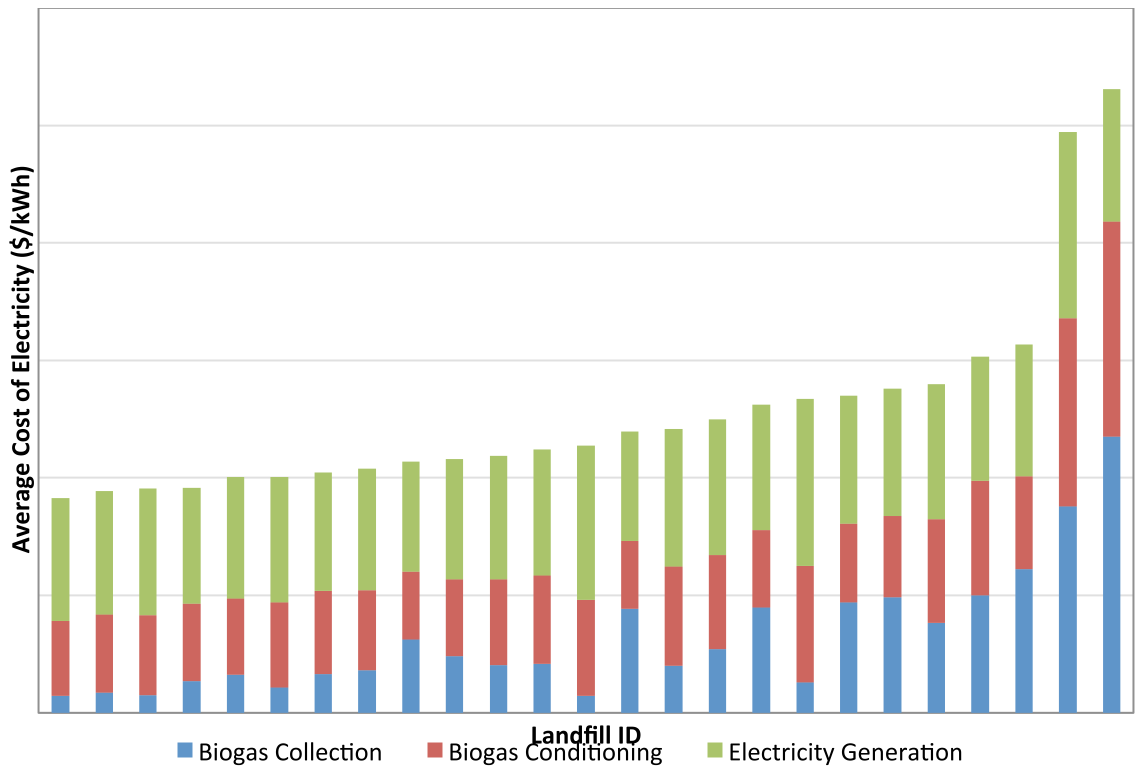

Figure 6. Average cost of electricity ($/kWh) for the electricity generation scenario for candidate landfills in North Carolina. Costs include capital and operating costs over a 15-year period and are separated by the cost to collect the biogas at each landfill, the cost of equipment to condition the gas for combustion, and the cost of electricity generation equipment. For a list of the landfills associated with each ID, see Table 1.

The average costs for each source, or the levelized cost of electricity (LCOE), range from $0.091 to $0.265/kWh. Total project costs over a 15-year period range from $856,000 to $44 million. As in the pipeline injection scenario, the electricity generation costs across landfills were used to construct a supply curve for electricity generation, ordering the cumulative generation potential from the least to most expensive sources (Figure 7).

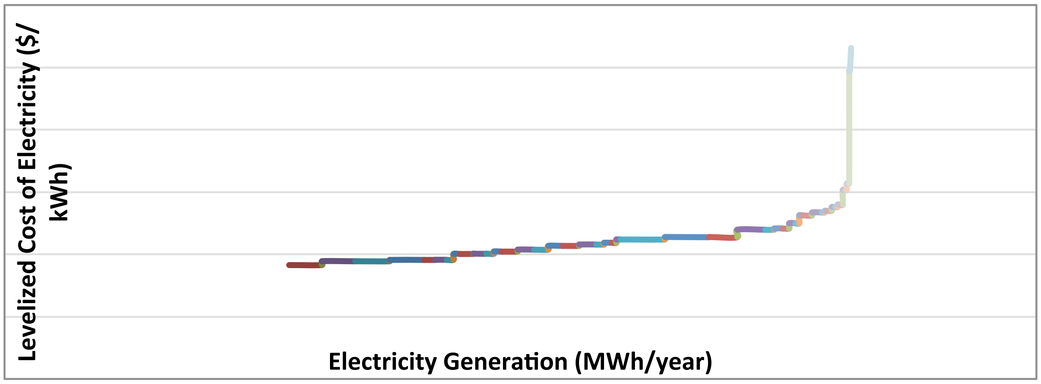

Figure 7. Marginal cost (supply) curve for electricity generation from candidate landfills in North Carolina.

As in the pipeline injection scenario, the NPV of each landfill project was calculated with a 10% discount rate, a 15-year timeframe, and secondary data from the EIA, this time for projected industrial electricity prices (Table 6).[13] None of the modeled landfill projects had a positive NPV, which means they each have an IRR less than 10%. Moreover, these numbers do not include project development (such as planning and implementation) costs, which, based on informal discussions with project developers, can add 2 to 3 cents per kWh. Thus, these projects are unlikely to emerge without a premium on the electricity or some objective other than to competitively sell electricity into the market. The cost of the premium on electricity could be calculated by taking the average cost of electricity generation at the landfills (plus project development costs) and subtracting from it the energy credit prices for Duke Energy or Progress Energy (approximately 6 cents per kWh). For example, the cost of electricity production at the lowest-cost landfill is approximately 9 cents per kWh, so the premium would need to be at least 3 cents per kWh, not including project development costs. In North Carolina, the premium payment for electricity could come in the form of a renewable energy certificate (REC), which is discussed further in the conclusions below.

[13] Landfills would actually sell power to Duke Energy or Progress Energy (which merged in 2012, but are currently maintaining separate operations with regard to their customer base). The prices at which they will purchase electricity are less than those from the EIA projection, so using them in the analysis will not result in landfills with a positive NPV at a 10% discount rate. The energy credit price from Duke Energy is as high as $0.0678 and $0.0520 per kWh for on-peak and off-peak power generation, respectively, for a 15-year contract (http://www.duke-energy.com/pdfs/NCPPN.pdf). The energy credit price from Progress Energy is as high as $0.07455 and $0.05382 per kWh, for on-peak and off-peak power generation, respectively, for a 15-year contract (https://www.progress-energy.com/assets/www/docs/company/nc-csp.pdf).

DISCUSSION AND CONCLUSIONS

The results of this economic analysis indicate that, in most cases, neither the pipeline injection nor the electricity generation scenario enables the candidate landfills to produce a positive NPV with projected prices for natural gas or electricity if they are simply trying to compete directly with conventional sources in the gas and electricity markets (Table 8). Two landfills have a positive NPV in the pipeline injection scenario—if low-end pipeline costs are used. However, if estimated project development costs are added, even these projects are likely to become unprofitable. As a result, an additional payment may be necessary to make these projects economically viable. In North Carolina, the Renewable Energy and Energy Efficiency Portfolio Standard (REPS) might offer such an opportunity.[14] The state law requires utilities to eventually generate 12.5% of their electricity from renewable sources. Although these landfill projects would be eligible to sell this renewable energy to utilities in the form of renewable energy certificates (RECs), the going rate for RECs is currently only $5 per MWh (or $0.005/kWh).[15] As discussed above, the lowest-cost landfill would require a premium of $0.03/kWh, so current REC prices would be insufficient to make the electricity generation scenario viable.

In some cases, large industrial or commercial users of natural gas may be willing to pay a premium for renewable biogas to satisfy voluntary internal sustainability goals. If project development costs, which can range from $2 to $3 per MMBtu, are added to the average costs of biogas shown in Table 8, the resulting figure would represent the price that an industrial user would have to pay to source renewable biogas.

The Eastern Carolina Regional Landfill had the lowest average costs for biogas in the pipeline injection scenario, at $4.73 and $6.29, using the low- and high-end pipeline costs, respectively. According to data from the EIA, the average industrial natural gas price in 2012 was $3.82/MMBtu. Therefore, sourcing renewable biogas from this landfill can be at least 24–65% more expensive than purchasing nonrenewable natural gas.

The Eastern Carolina Regional Landfill also had the lowest average cost in the electricity generation scenario, at $0.091/kWh. According to data from the EIA, the average industrial electricity price for North Carolina in 2012 was $0.061/kWh, which means that generating electricity from this landfill can be at least 49% more expensive than purchasing electricity from the grid.

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[14] N.C. G.S. 62-133.8.

[15] See the Duke Energy Standard Purchase Offer for Renewable Energy Certificates at http://www.duke-energy.com/pdfs/REC-Purchase-Offer-Info.pdf.

As discussed above, biogas conditioning equipment is the most expensive component of projects in the pipeline injection scenario. If the cost of this equipment could be reduced, the cost of biogas in the pipeline injection scenario could be reduced as well. Because many of the candidate landfills are located near natural gas transport pipelines, new pipeline construction does not appear to be a major driver of costs. Furthermore, biogas collection does not appear to be a major driver of costs; 10 of the 25 candidate landfills, including the highest-ranked landfills in each scenario, are already collecting biogas but flaring it rather than generating useful energy with it. Nevertheless, unless equipment costs, and specifically the cost of biogas conditioning equipment, can be reduced, it may not be economically viable to generate energy at these landfills without additional payments from parties willing to pay a premium to source their energy from biogas.

Table 8. Summary of Results for the Pipeline Injection and Electricity Generation Scenarios and Ranking of Landfills by Average Costs in Each Scenario

		Pipeline injection scenario						Electricity generation scenario		
		Total project cost		Marginal cost of biogas ($/MMBtu)		Rank	Rank	Total project cost	Marginal cost of electricity ($/kWh)	Rank
Landfill name	Average biogas generation (MMBtu/year)	*Low pipeline costs*	*High pipeline costs*	*Low pipeline costs*	*High pipeline costs*	*Low pipeline costs*	*High pipeline costs*			
Alleghany County LF	6,164	$20,339,313	$114,375,382	$405.69	$2,281.33	25	25	$1,139,283	$0.247	24
Ashe County Landfill	22,726	$20,410,455	$108,106,063	$122.08	$646.59	22	22	$2,149,896	$0.140	21
Austin Quarter SWM Facility	104,290	$6,547,874	$11,721,990	$8.55	$15.31	9	10	$6,733,332	$0.096	4
Caldwell County Mt. Herman Landfill	27,439	$3,827,147	$4,800,330	$17.15	$21.51	14	11	$2,691,417	$0.131	17
Chambers Development MSWLF	300,688	$14,582,087	$28,924,987	$6.75	$13.38	4	8	$18,988,907	$0.096	3
City of Albemarle LF	51,320	$5,833,526	$10,772,149	$15.91	$29.38	13	12	$4,212,127	$0.125	16
Cleveland County LF	65,580	$9,887,786	$34,348,608	$22.56	$78.36	18	18	$5,385,727	$0.134	18
Cliffside South Rutherford County LF	4,314	$9,989,407	$51,090,891	$284.69	$1,456.06	24	24	$856,690	$0.265	25
East Carolina Regional LF	705,581	$24,161,623	$32,137,991	$4.73	$6.29	1	1	$43,619,362	$0.091	1
Edgecombe County LF	35,686	$5,076,886	$13,709,116	$17.49	$47.23	15	15	$2,988,204	$0.112	12
Haywood County LF	12,413	$24,565,929	$139,445,464	$243.31	$1,381.12	23	23	$1,454,616	$0.157	23
Haywood County White Oak LF	61,174	$28,221,366	$149,194,580	$62.69	$331.40	21	21	$4,152,211	$0.100	5
Kersey Valley Landfill	137,050	$7,817,752	$9,354,828	$7.67	$9.18	7	7	$10,006,167	$0.107	9
Lenoir County LF	72,145	$7,085,808	$15,043,211	$13.94	$29.59	12	13	$5,647,347	$0.121	15
New Hanover County LF	266,084	$15,542,191	$16,806,415	$7.65	$8.27	6	2	$22,370,816	$0.120	14
Onslow County LF #2	153,192	$8,661,413	$9,925,637	$7.72	$8.84	8	4	$11,135,240	$0.108	10
Rockingham County LF	26,287	$4,765,194	$10,299,650	$22.29	$48.17	17	16	$2,711,148	$0.138	20
Rockingham County LF#2	111,182	$5,664,998	$7,037,795	$7.03	$8.74	5	3	$7,436,680	$0.100	6
Rowan County LF	147,869	$7,096,535	$9,688,635	$6.61	$9.02	3	5	$10,254,242	$0.104	8
South Wake LF (New)	332,255	$13,483,672	$20,696,056	$5.96	$9.15	2	6	$23,645,901	$0.114	13
Upper Piedmont Environmental Landfill	290,047	$26,683,318	$108,675,611	$12.72	$51.81	11	17	$18,212,302	$0.094	2

		Pipeline injection scenario						Electricity generation scenario		
		Total project cost		Marginal cost of biogas ($/MMBtu)		Rank	Rank	Total project cost	Marginal cost of electricity ($/kWh)	Rank
Landfill name	Average biogas generation (MMBtu/year)	*Low pipeline costs*	*High pipeline costs*	*Low pipeline costs*	*High pipeline costs*	*Low pipeline costs*	*High pipeline costs*			
US Army Fort Bragg	18,493	$5,082,800	$19,429,461	$33.79	$129.17	19	19	$2,096,597	$0.152	22
US Marine Corps Camp Lejeune	26,990	$4,217,448	$7,033,208	$19.21	$32.04	16	14	$2,722,359	$0.135	19
Wilkes County LF 2	68,943	$19,388,792	$94,241,024	$38.31	$186.23	20	20	$4,760,597	$0.102	7
Wilson County LF	59,920	$5,257,573	$6,958,359	$10.79	$14.28	10	9	$4,896,160	$0.109	11

APPENDIX

Biogas Equipment Costs for Pipeline Injection

The following tables summarize the specification data, including costs and capacities, for the equipment in the pipeline injection and electricity generation scenarios.

Biogas Conditioning for Pipeline Injection

Table A1 summarizes the costs and flow rates by model for pipeline-quality biogas conditioning. This conditioning removes water, CO_2, and other impurities from the gas so that it can be injected into the natural gas pipeline.

Table A1. Biogas Conditioning Unit Specification Data (Natural Gas Level)

Biogas conditioning unit	Unit* cost ($/unit)	Operation & maintenance cost ($/year)	Operating feed flow (SCFH)	Product output flow (SCFH)	Impurities removed (e.g. water, and/or CO_2, and or H_2S.)	Technology used for conditioning
Guild	845,000	36,535	6,000	3,240	Water,H_2S,CO_2,VOC	PSA
Guild	2,270,000	86,600	21,000	11,880	Water,H_2S,CO_2,VOC	PSA
Guild	3,000,000	132,000	42,000	23,700	Water,H_2S,CO_2,VOC	PSA
Guild	3,800,000	315,100	72,000	40,680	Water,H_2S,CO_2,VOC	PSA
Guild	5,200,000	526,200	120,000	67,740	Water,H_2S,CO_2,VOC	PSA
Guild	8,600,000	1,276,000	300,000	169,380	Water,H_2S,CO_2,VOC	PSA

Biogas Compressor for Pipeline Injection

Table A2 summarizes the costs and flow rates by model for compressors to compress the biogas to 800 pounds per square inch (psi) so that it can be injected into the natural gas pipeline.

Table A2. Biogas Compressor Specification Data

Compressor model	Unit cost ($/unit)	Operation & maintenance cost ($/year)	Input flow rate (SCFH)	Input flow pressure (psi)	Output flow rate (SCFH)	Output flow pressure (psi)
Regression	$132,500	$9,465	6,000	100	5,695	800
GE Gemini	$200,000	$16,400	21,000	100	19,920	800
GE Gemini	$225,000	$45,500	42,000	100	39,780	800
GE Gemini	$325,000	$119,900	72,000	100	68,220	800
GE Gemini	$450,000	$193,800	120,000	100	113,700	800
GE Gemini	$600,000	$474,000	300,000	100	284,220	800

Biogas Equipment Costs for Electricity Generation

Biogas Conditioning for Electricity Generation

Table A3 summarizes the costs and flow rates by model for the biogas conditioners necessary for electricity generation. These units remove water and filter particulates from the biogas before its combustion in a microturbine or internal combustion engine generation.

Table A3. Specification Data for Biogas Conditioning Units for Electricity Generation

Biogas conditioning unit	Unit cost ($/unit)	Operation & maintenance cost ($/year)	Operating feed flow (SCFH)	Product output flow (SCFH)	Technology used for conditioning
Unison	$192,000	$13,500	1,500	1,450	Glycol chiller
Unison	$266,000	$13,500	4,200	4,100	Glycol chiller
Unison	$550,000	$16,500	9,000	8,800	Glycol chiller
Unison	$810,000	$25,000	12,000	11,500	Glycol chiller

Biogas Electric Generators

Table A4 shows the fuel type, generation rating, fuel consumption, and cost by model for biogas generators and microturbines.

Table A4. Biogas Electric Generator Specification Data

Generator model	Fuel type (biogas/ natural gas)	Power generation capacity (kWh)	Fuel consumption rate (SCFH)	Generator cost ($/ unit)	Operation & maintenance cost ($/ year)	Energy conversion efficiency (%)
Capstone	Biogas	65	1,500	$106,500	$10,000	33
Capstone	Biogas	200	4,000	$325,000	$25,500	33
Caterpillar	Natural Gas	60	1,650	$85,000	$15,000	31
Caterpillar	Natural Gas	150	1,840	$155,000	$25,000	30
Caterpillar	Natural Gas	600	4,860	$850,000	$100,000	33
Caterpillar	Natural Gas	1,000	8,865	$1,500,000	$150,000	33
GE	Natural Gas	320	3,420	$1,325,000	$73,584	37.2
GE	Natural Gas	613	6,300	$1,740,000	$113,880	38.1
GE	Natural Gas	823	8,400	$1,900,000	$140,160	38.3
GE	Natural Gas	1,029	10,320	$2,085,000	$157,680	39

Pipeline Cost Data

Pipeline cost data were obtained from Prasodjo et al. (2013).[16] The costs provided here are general in nature; any developer seeking to install new biogas pipelines in North Carolina should contact the appropriate gas utility, pipeline operator, or both for more specific information. The costs are presented as a range due to the variable nature of construction conditions, soil types, and right-of-way issues that may be encountered during pipeline construction. Table A5 includes the low- and high-end cost-of-service estimates for pipeline, including installation and ongoing maintenance. Table A6 includes the annual cost of service for operating an interconnection point to the natural gas pipeline network.

Table A5. Annual Pipeline Cost of Service Estimates for the Biogas Pipeline Network

	Low-pressure pipe		High-pressure pipe	
Pipe size (inches)	Low end of range	High end of range	Low end of range	High end of range
2”	$6,947	$24,809	$34,733	$228,238
4”	$9,924	$29,771	$59,541	$396,935
6”	$13,894	$34,733	$198,468	$793,870
8”	$19,848	$44,656	$248,085	$992,337
Right of way	$11,909	$57,556	$11,909	$57,556

Note: Costs are presented as annual costs over a 15-year period on a per-mile basis and include capital, installation, operation and maintenance, and gas transport costs. Low-pressure pipes would be used to collect biogas between farms, whereas high-pressure pipes would be used to transport biogas between the two-stage compressor and the existing natural gas pipeline.

Table A6. Annual Cost-of-Service Estimates over a 15-Year Period for an Interconnection Point to the Existing Natural Gas Pipeline Network

Low end of range	High end of range
$59,995	$187,943

[16] D. Prasodjo et al., A Spatial Optimization Study of Swine Waste-Derived Biogas Infrastructure Design in North Carolina.

The Nicholas Institute for Environmental Policy Solutions

The Nicholas Institute for Environmental Policy Solutions at Duke University is a nonpartisan institute founded in 2005 to help decision makers in government, the private sector, and the nonprofit community address critical environmental challenges. The Nichols Institute responds to the demand for high-quality and timely data and acts as an "honest broker" in policy debates by convening and fostering open, ongoing dialogue between stakeholders on all sides of the issues and providing policy-relevant analysis based on academic research. The Nicholas Institute's leadership and staff leverage the broad expertise of Duke University as well as public and private partners worldwide. Since its inception, the Nicholas Institute has earned a distinguished reputation for its innovative approach to developing multilateral, nonpartisan, and economically viable solutions to pressing environmental challenges.

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