The Role of Carbon Payments in Anaerobic Digester Profitability on US Swine Farms

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Abstract

Anaerobic digesters (ADs) have the potential to increase energy production and reduce methane emissions from manure management. Anaerobic digesters capture methane and produce a biogas that can be used to generate electricity or sold as a renewable natural gas (RNG). As of July 2023, there were 343 livestock anaerobic digesters in the United States. The adoption of anaerobic digesters has been limited by relatively high digester construction costs and low financial returns from the sale of biogas-end products. This study quantifies the energy prices and carbon payments that may be required to incentivize the construction of anaerobic digesters on swine operations, depending on the manure management system and location of the operation. Results indicate energy prices have a relatively small effect on the profitability of anaerobic digester projects, though the projects influence the optimal choice of biogas end use (e.g., RNG, electricity). In contrast, carbon payments for the methane reductions from anaerobic digesters could be a strong determinant in farm-level decisions to install anaerobic digesters. We discuss how cost-share programs and long-term contracts—both for energy and carbon payments—could help spur investment in anaerobic digesters by reducing producers' investment costs and uncertainty.

Keywords: energy security, carbon markets, methane emissions, renewable natural gas, compressed natural gas, sustainability, electricity.

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Report Summary

What Is the Issue?

Using anaerobic digesters (AD) to produce biogas can reduce methane emissions[1] and contribute to renewable energy production, either in the form of electricity or renewable natural gas (RNG). In

[1] Methane emissions refer to emissions of CH_4 produced from anaerobic (without oxygen) decomposition of liquid manure in lagoons or pits.

California, the Low Carbon Fuel Standard (LCFS) of the California Air Resource Board (CARB) has provided incentives for investments in anaerobic digesters on livestock operations. However, in most U.S. States, high capital costs, low rates of return, and uncertain energy prices have inhibited a wider scale adoption of anaerobic digesters. Payments to livestock producers for the reductions in carbon dioxide-equivalent emissions could increase the number of anaerobic digesters. Opportunities for payments to producers are increasing, given interest in reduction of carbon dioxide-equivalent emissions and the emergence of agricultural carbon markets. In this report, we quantify the financial returns from constructing anaerobic digesters on swine farms under different assumptions about carbon payments[2], swine inventory, current manure management system, type of swine, and energy prices.

What Did the Study Find?

- With no payments for reducing carbon dioxide-equivalent emissions, only large swine farms could earn a positive rate of return on an anaerobic digester project. For market swine producers, the internal rate of return for an anaerobic digester never exceeds 4 percent, even with high energy prices.
- Payments for reductions in carbon dioxide-equivalent emissions could provide substantial incentives for the construction of anaerobic digesters on swine farms—particularly for farms with an anaerobic lagoon system. This study finds that payments of $50 per metric ton of carbon dioxide-equivalent emissions allow swine farms as small as 2,000 to 3,000 head to earn a positive internal rate of return from an anaerobic digester project.

[2] Producers can receive a carbon incentive through a carbon tax on products (resulting in a carbon price), a carbon payment (through a program that pays for carbon dioxide-equivalent emission reductions (e.g., the LCFS), or a cost share program for adopting a carbon dioxide-equivalent emission-reducing technology (as in the Rural Energy for America Program (REAP)).

- Even large fluctuations in energy prices have a relatively small effect on anaerobic digester profitability. However, energy prices are likely to influence the choice of digester biogas end use (i.e., natural gas or electricity production).
- Farms that currently use anaerobic lagoons could financially benefit more from an anaerobic digester that farms with liquid/slurry or deep pits manure systems because lagoons have higher baseline GHG emissions. Anaerobic digesters can reduce emissions more on farms with an anaerobic lagoon and thereby could generate higher returns from carbon payments.
- The manure management method used by farms will likely play an important role in determining where future anaerobic digester investment will occur if carbon payments are expanded. For example, Iowa uses mostly deep pits whereas swine farms in North Carolina employ mostly anaerobic lagoons. Thus, this analysis implies carbon payments would have a larger effect on anaerobic digester profits, and hence new construction, in North Carolina.

How Was the Study Conducted?

The profitability (internal rate of return) of an anaerobic digester project was estimated for swine farms differentiated by inventory, farm type, climate, and current manure management system. Costs, returns, and the production of biogas and methane emission reductions with an anaerobic digester (compared to the baseline manure management system) were calculated for various biogas end uses (i.e., renewable natural gas, electricity production, and compressed natural gas). Accounting for State-specific energy prices, we also calculated anaerobic digester profitability in each of the main swine producing States for a range of farm sizes and different biogas end uses.

Introduction

In the United States and globally, there is increasing interest in involving farmers in efforts to mitigate carbon dioxide-equivalent (CO_2-e) emissions. Livestock producers can reduce emissions by adding anaerobic digesters (AD) to their manure management systems. Anaerobic digesters can also help control manure pathogens, manage odor, and produce organic fertilizer and energy (Schulte et al., 2022; Lim et al., 2023). Since emission mitigation efforts usually involve high operating costs and large upfront capital investments, producers may need additional financial incentives to adopt emission-mitigating practices and to remain profitable after adoption (Key & Sneeringer, 2012). A voluntary carbon offset market may provide the necessary financial incentives by allowing farmers who accrue credits from reducing emissions to sell the credits to entities interested in offsetting their own emissions[3]. This study estimates the energy prices and carbon credit payments required to incentivize the construction of anaerobic digesters on swine operations, depending on the manure management system and location of the operation.

Farmers can benefit from the produced biogas in several ways. Biogas can be used to generate on-farm heat and/or electricity to lower on-farm energy expenses (USDA, 2011). Additional revenue is possible if the generated electricity can be sold to a utility company. Biogas can also be upgraded to renewable natural gas (RNG) to be fed either into the natural gas grid or compressed as a transportation fuel in the form of compressed natural gas (CNG). The upgrading of biogas separates out the methane of biogas and removed impurities. In the absence of specific emission policies, the profitability of an anaerobic digester depends primarily on energy prices, which, in the United States, have not been sufficiently high to trigger widespread adoption. Return uncertainty from volatile energy prices may also have discouraged investment in anaerobic digesters (Anderson & Weersink, 2014). Coupled with investor risk aversion and an initial learning curve, the anaerobic digester adoption rate in the U.S. has been low.

[3] For an explanation of existing carbon-offset markets and protocols, we direct readers to Wongpiyabovorn et al., 2022.

In this report, we quantify the financial incentives that may be necessary for U.S. swine producers to implement anaerobic digesters on their farms and monetize the biogas-based production of electricity and/or renewable natural gas both in the absence and presence of carbon markets. By calculating the investment returns for different types of farms in different regions, the study sheds light on the number and characteristics of farms that could be incorporated into a domestic carbon offset market. The analysis accounts for heterogeneity in farm size, animal waste characteristics, State-specific energy prices, and end use, which are financial determinants of anaerobic digester adoption (Varma et al., 2021). The model also considers the farm's initial manure-management system, which significantly affects the emission mitigation payments a farm could receive for installing an anaerobic digester (USDA, 2011). In addition to illustrating the impact of carbon payments on the rate of return for anaerobic digesters, the study assesses anerobic digester profitability separately in each of the 10 States representing 89 percent of U.S. hog inventory in 2021.[4]

Agriculture is responsible for 593 million metric tons CO_2-e of total emissions, representing 9.4 percent and 10.8 percent of gross and net emissions, respectively.[5] Manure management contributes 65 and 17 million metric tons CO_2-e of methane (CH_4) and nitrous oxide (N_2O) emissions, respectively. In 2022, 82.9 percent of CO_2-e emissions from swine operations were attributed to CH_4 from manure management (U.S. Environmental Protection Agency (EPA), 2024). To mitigate those CH_4 emissions, livestock producers can install anaerobic digesters that capture methane to generate biogas. Biogas produced during the anaerobic process is composed of approximately 50 percent to 66 percent methane, with the rest being carbon dioxide (CO_2) (Lisowyj

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[4] Those States are (in descending order of 2021 inventory) Iowa, Minnesota, North Carolina, Illinois, Indiana, Nebraska, Missouri, Ohio, Oklahoma, and South Dakota.
[5] In 2022, U.S. gross CO_2-e emissions were 6,343 million metric tons (EPA, 2024). Accounting for the carbon sequestration associated with land use, net emissions were 5,489 million metric tons CO_2e.

& Mba-Wright, 2020). When the captured methane is burned, emissions are reduced from 28 tons to 1 ton.

As of July 2023, there were 343 livestock anaerobic digesters in the United States, which are estimated to have avoided 10.49 million metric tons of CO_2-equivalent (CO_2e) on an annual basis.[6] California has seen an increase in the use of anaerobic digesters in recent years—likely as a response to the 2007 enactment of the Low Carbon Fuel Standard (LCFS). The implementation of these standards has resulted in a reduction in the amount of CO_2-equivalent emitted (figure 1). The end uses associated with most of the emission reductions in California are compressed natural gas and electricity, whereas for Missouri and Oregon, most of the emissions reductions are from renewable natural gas. Anaerobic digesters using dairy manure are responsible for 80.8 percent of the emissions reductions, followed by swine manure with 15.7 percent.

There are four regulated carbon markets in the United States, spanning 14 U.S. States. These markets include the Low Carbon Fuel Standard programs in California, Oregon, Washington, and a regional initiative comprising 11 States in the Northeast. Previously, USDA, Economic Research Service (ERS) estimated dairy and hog operations could offset about 62 percent of their CO_2-e emissions at a carbon price of $15 (2011 U.S. dollar values) (USDA, 2011). ICF (a global consulting and technology services company) estimated the break-even carbon price (in U.S. dollars per metric ton of carbon dioxide-equivalent) for a 2,500 head swine farm in the Appalachia region to switch from an anaerobic lagoon to an anaerobic digester was between $1–$15 (2013 U.S. dollar values), depending on the digester design (ICF, 2013).[7] Those values suggest a relatively low break-even

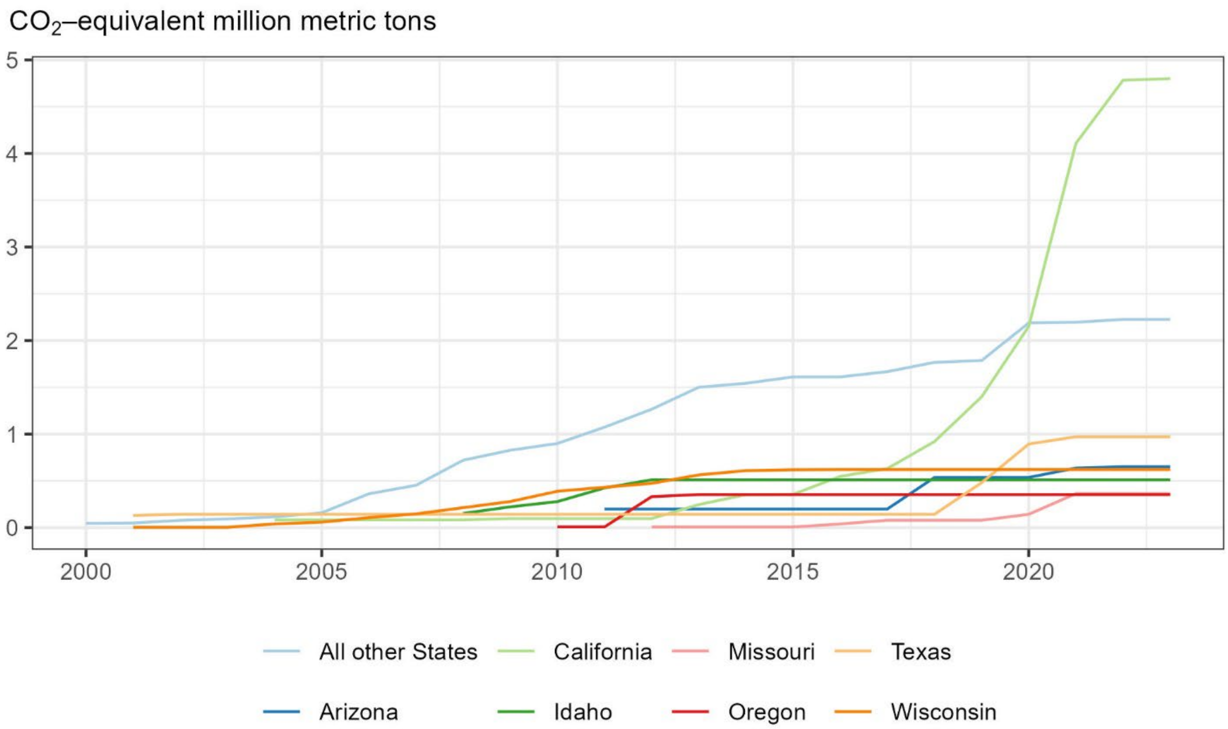
[6] The number of anaerobic digesters, as well as their basic attributes (e.g., yearly emission reduction), are from the AgStar Livestock Anaerobic Digester Database, which is maintained by the U.S. Environmental Protection Agency. The referenced value includes "operational projects" and "under construction."

[7] The Appalachia region contains North Carolina, one of the largest swine-producing States. According to the 2017 USDA, Census of Agriculture, 93.4 percent of U.S. hogs and pigs are located on farms with a herd size of more than 2,000.

carbon price to trigger investment. However, given alternative investment opportunities, a modestly positive net present value and return may not be sufficient for investment in CO_2-e emissions mitigation in general, or in anaerobic digesters, in particular (Wongpiyabovorn et al., 2022). In this study, we estimate the internal rates of return for anaerobic digesters over a range of carbon prices, which allow for different assumptions about the minimum returns required to stimulate investment.

Figure 1

Annual CO_2-equivalent emissions mitigated from anaerobic digesters



CO_2-equivalent = carbon dioxide equivalent.

Source: USDA, Economic Research Service adapting Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining.*

Recent proposed and enacted agricultural laws in the United States may directly or indirectly enhance incentives to invest in anaerobic digesters. For example, the Inflation Reduction Act (IRA) of 2022, which focuses on reducing CH_4 emissions, includes a Production Tax Credit of up to 3.3 cents per kilowatt-hour (kWh) for qualifying projects (in addition to investment tax credits of up to

50 percent). In addition, the U.S. Environmental Protection Agency (EPA) proposed a framework for generating renewable energy credits if electricity for electric vehicles is produced from biogas.[8] The Consolidated Appropriations Act of 2023, signed into law at the end of 2022, could also play a role in the development of biogas markets by introducing more certainty in supplemental carbon markets.[9] The 2023 law authorizes USDA to establish a Technical Assistance Provider and Third-Party Verifier Program to assist producers with technical assistance and allows USDA to verify certifiers, similar to other agricultural certification programs, e.g., USDA-certified organic labeling. As stated in the February 2024 justification report by the USDA, the purpose of the program is "to reduce market confusion by serving as a trusted authority on relevant carbon market information" (USDA, 2024).

BOX: **Anaerobic Digesters and Energy Markets in Europe**

In Europe, anaerobic digesters are broadly used and there were approximately 20,000 biogas plants in 2020 (USDA, 2011; U.S. Department of Energy, International Energy Agency (IEA), 2020; European Banking Authority (EBA), 2021). European countries with a high number of anaerobic digesters benefit from country-specific financial incentives in the sale of electricity ranging from 0.085 Euros to 0.25 Euros per kWh (Whiting & Azapagic, 2014). The higher electricity prices are also due, in part, to the European Union (EU) Emission Trading System, which requires companies

[8] See Renewable Fuel Standard (RFS) Program: Standards for 2023–25 and Other Changes published in the Federal Register on December 30, 2022.
[9] See H.R.2617—Consolidated Appropriations Act, 2023 for more details.

must buy or receive allowances corresponding to their CO_2 emissions. Higher electricity prices increase the adoption of anaerobic digesters for two reasons. First, it becomes profitable to substitute on-farm generated electricity for grid electricity. Second, the surplus on-farm electricity generated can be sold back to the utility company at a higher price if net-= metering is in place.

In some countries, long-term electricity contracts of 20 years are available which reduce the revenue uncertainty associated with anaerobic digester income generation from electricity sales. The United Kingdom saw an increase in the number of anaerobic digesters following the implementation of feed-in tariffs (i.e., long-term contracts to purchase electricity above market price) in 2010 (Whiting & Azapagic, 2014). In Germany, farmers receiving price support are not authorized to use the produced electricity on farm and must feed all of it into the power grid. Although farmers in Europe do not benefit directly from carbon prices, they benefit from the higher electricity prices, resulting from carbon pricing in the EU Emission Trading System.

END BOX

This report analyzes the impact of carbon payments on the profitability of anaerobic digesters on swine operations in the United States. The study updates and expands on earlier related research (Key & Sneeringer, 2011) by considering multiple biogas end uses (electricity, compressed natural gas, and renewable natural gas), while accounting for variation across the United States in manure management systems, average air temperature, energy prices, and feedstock availability. The study's findings shed light on the scale, location, and type of swine farms that would find it profitable to construct anaerobic digesters under a range of energy and carbon prices. The results provide insight into the potential of policies or carbon prices to incentivize anaerobic digester adoption in the United States.

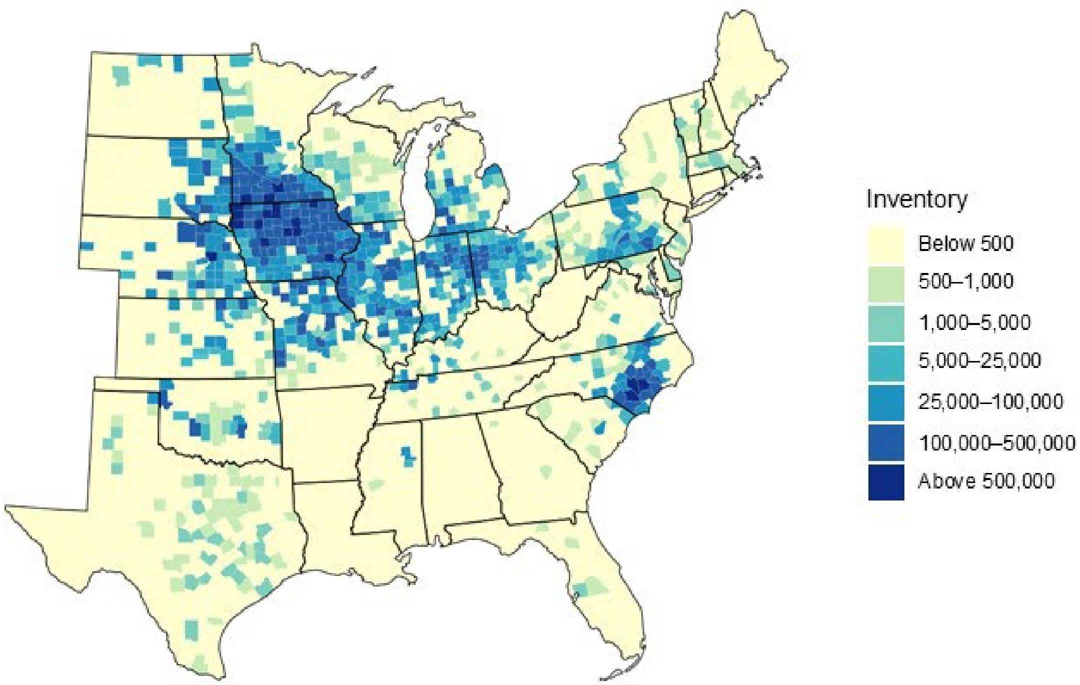
Background

Swine Manure Management Systems and Emissions

Swine is produced mainly in the Midwest and Southeastern regions of the United States and 5 States held 68 percent of all hog and pig inventory in 2022: Iowa, Minnesota, North Carolina, Illinois, and Indiana (figure 2). In 2019, the shares (weighted by hog inventory) of liquid/slurry, anaerobic lagoon, and pit systems for U.S. swine manure were 13.8 percent, 15.6 percent, and 69 percent, respectively (EPA, 2024). These shares, however, vary by region. For example, 49 percent of hog manure in North Carolina is stored in anaerobic lagoons, as opposed to 4 percent in Iowa.

Air temperatures vary across the United States and are a major determinant in the choice of manure management system (figure 3). Anaerobic lagoons are more prevalent in regions where the yearly average temperature is higher which allows for anaerobic decomposition to take place over a longer period throughout the year (Key et al., 2011; EPA, 2024). Another likely determinant of the manure management system choice is the nutrient demand from crops and the ability to use manure as a substitute for fertilizer. USDA, ERS has provided a review of regional differences and trends in manure management (Key et al., 2011).

Figure 2
Distribution of the number of hogs per county

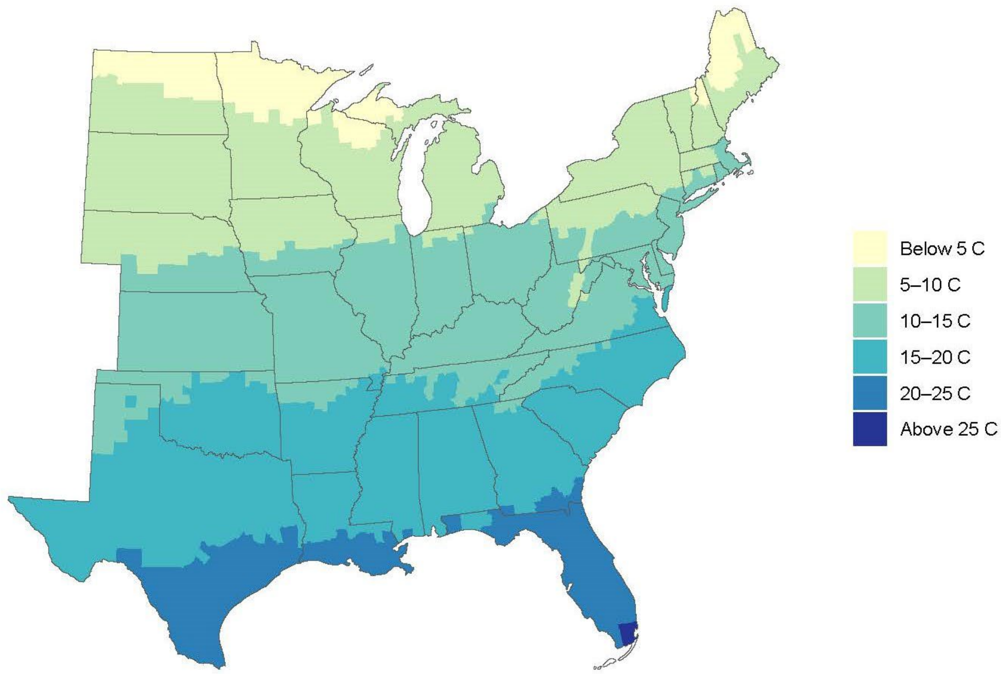


Source: USDA, Economic Research Service using data from USDA, National Agricultural Statistics Service, 2022 Census of Agriculture.

The focus of this analysis is on the mitigation of CH_4 produced from the anaerobic (without oxygen) decomposition of liquid manure in lagoons or pits. The analysis does not include CH_4 emissions from enteric fermentation and nitrous oxide (N_2O) emissions from manure management.[10] In 2022, manure management represented 89.2 percent of total CO_2-e emissions from swine (EPA, 2024). In an anaerobic digester, decomposition of solid manure occurs anaerobically, emitting methane (CH_4) that is captured and used for biogas (USDA, 2011).

[10] Enteric fermentation refers to the breakdown of carbohydrates by microorganisms in the digestion system leading to methane emissions. Those emissions are high for ruminant animals, such as cattle and sheep, but low for swine due to livestock-specific digestive systems.

Figure 3 Mean daily county temperature, Celsius (C), (2012–21)



Source: USDA, Economic Research Service calculations based on data from Northwest Alliance for Computational Science and Engineering, Parameter-elevation relationships on Independent Slopes Model (PRISM) Climate Group, 2024.

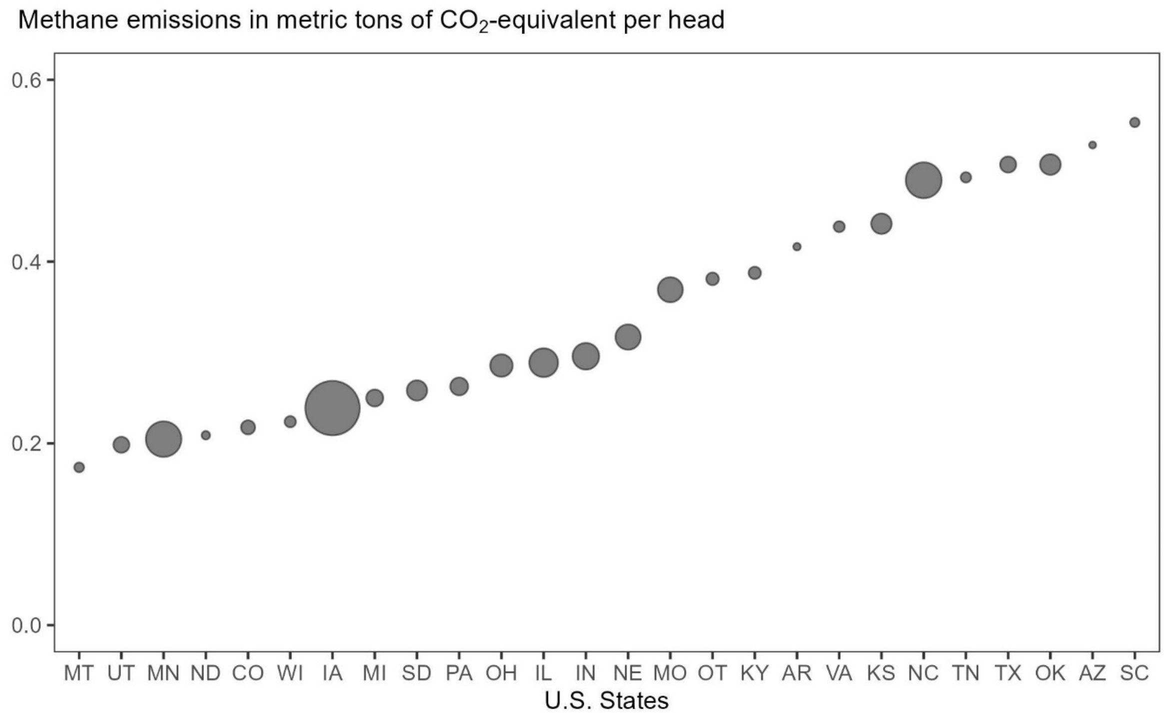
Emissions from manure management (prior to application to cropland) are influenced by a variety of factors such as animal feed composition, system used, storage time, and air temperature. Depending on the ambient temperature and the system used, there are regional differences in CH_4 emissions per swine head (figure 4). These differences play a key role in the presence of carbon markets since livestock producers with higher baseline emissions will benefit more from the construction of an anaerobic digester because the producers are able to claim larger emission reductions and, thus, receive higher payments.

Due to its nutrient content, almost all manure is ultimately applied to cropland for fertilization (Lim et al., 2023). Long-term storage of liquid manure before applying the manure to land contributes significantly to CO_2-e emissions. Hog producers in the Southeast use irrigation systems to apply manure from their lagoons to cropland. The use of irrigation systems to apply manure leads to a higher volatilization of nitrogen compared to other manure management systems and results in fewer nutrients available for plant growth (Key et al., 2011). Carbon dioxide-equivalent emissions from manure application to cropland also depend on the amount and timing (Aguirre-Villegas & Larson, 2017). Although an important aspect given the use of digestate (i.e., the byproduct of an anerobic digester besides biogas) on cropland, the emissions from nitrous oxide are beyond the scope of this report.

The application of manure to cropland has complex environmental implications, and previous research has provided an extensive review of the various aspects of manure management systems (Varma et al., 2021; Lim et al., 2023). Since 2011, the EPA has required Concentrated Animal Feeding Operations (CAFO) to have a nutrient management plan under the U.S. Clean Air Act. Nutrient management plans are designed to optimize the nutrient requirements for plant/forage growth, while avoiding nutrient discharge, which leads to lower pollution.

There are differences in the nutrient uptake of crops, depending on the regions and crops planted. For example, the amount of nitrogen produced by livestock in North Carolina may be the same as in Iowa, but the uptake per acre may be lower because crop yields in North Carolina are lower.

Figure 4
Per head manure management methane emissions for the 25 largest hog-producing U.S. States (2020, measured in metric tons of carbon dioxide-equivalent)



Note: Circle sizes represent herd size, with Iowa's (IA) inventory being 24.2 million. OT represents other States, accounting for 1 percent of U.S. hog inventory. Data in this figure represents more than 99 percent of the total U.S. hog inventory. CO_2-equivalent is carbon dioxide-equivalent.

Source: USDA, Economic Research Service adapting Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining* and using U.S. Environmental Protection Agency, 2024.

Existing literature assesses the emissions from manure management systems with results depending on whether manure is treated as waste or analyzed from a life-cycle perspective in which it is a co-product from livestock production that can substitute for mineral fertilizer (Corbalá-Robles et al., 2018; Leip et al., 2019). An integrated crop and livestock system allows farms to produce manure and allows for the subsequent application to cropland without the need for large transportation distances to haul manure to the fields. Market swine barns generally have a capacity of less than 5,000 head to avoid long-distance manure hauling and to diversify against disease risks which might result in liquidating the entire barn (Key et al., 2011). Furthermore, contractual agreements allow hog producers to concentrate on one phase of hog production, which lead to economies of scale in breeding swine farms (Key et al., 2011). The application of manure to cropland may also depend on the price of fertilizer and types of crops. In Iowa, fertilizer price increases have also been met with increased use of manure (Pudenz & Schulz, 2022). Other side effects of hog manure management include ammonia emissions and a trade-off between water and air pollution. Livestock operators may store manure in uncovered lagoons to reduce the nutrient load to meet water quality standards but, at the same time, uncovered lagoon storage increases air pollution (Key et al., 2011).

Anaerobic Digesters Characteristics

In the United States, three anaerobic digester designs are commonly used: (1) covered lagoon, (2) complete mix, and (3) plug flow (EPA, 2024).[11] Plug-flow systems are less common for swine operations in the United States, with only four active systems listed in the EPA's AgStar Database. In addition, active plug flow systems tend to be older and serve on farms with low hog inventory numbers. A covered lagoon is a passive system in which the anaerobic digester's temperature cycles with outside temperature and methane production ceases if the temperature is below 20°C. Thus, for colder climates such as those prevalent in Iowa and other Midwestern States, this type of design would not be optimal for methane production. The viability of anaerobic digesters depends on the

[11] The USDA, Natural Resources Conservation Service uses code 366 for the anaerobic digesters discussed in this section. See definitions and details in Conservation Practice Standard and Recovering Value from Waste: Anaerobic Digester System Basics (USDA, NRCS).

ambient temperature. Figures 3 and 4 depict the county-level distribution of hogs and temperatures in the United States. The two other designs, differing based on temperature, are actively heated to a range of 30–40°C for mesophilic anaerobic digesters and 50–60°C for thermophilic anaerobic digesters. The percent of solids is lowest in a covered lagoon (0.5–3 percent) and highest in a plug flow digester (11–13 percent) with a complete mix digester covering the range in between. The hydraulic retention time—the time interval in which the feedstock remains in the anaerobic digester—is at least 15 days for complete mix and plug flow and 40–60 days for covered lagoons.

Biogas yields in anaerobic digester systems can vary significantly, based on feedstock characteristics. For example, the biogas yield from manure and corn stover is 333 and 585 cubic meters per kilogram of volatile solids ($m^3\ kg^{-1}$), respectively (Aui et al., 2019). Co-digestion, the use of more than one feedstock, can increase the biogas yield of an anaerobic digester system and is necessary to obtain a sufficient percentage of solids in the digester. We assume that the composition of biogas and the overall CO_2-e emission reduction is unchanged by the addition of the co-digestate. Biogas produced from anaerobic digesters is largely composed of equal parts of CH_4 and carbon dioxide (CO_2).

Life cycles of CO_2-e emissions from solid/liquid separation, anaerobic digestion, and a combination of the two systems were assessed for dairy farms in Wisconsin and compared to the base-case (i.e., manure collection, storage, and subsequent land application) (Aguirre-Villegas et al., 2014; Aguirre-Villegas & Larson, 2017). Aguirre-Villegas et al., 2014 concluded the anaerobic digester system reduced CO_2-egas emissions by 48 percent, compared to the base-case. A study conducted in Finland yielded similar results, with emissions for breeding swine farms being reduced more than from market swine farms, which is in line with our findings (Kaparaju & Rintala, 2011). Theory and practice suggest that once the anaerobic digester is constructed, various biogas end uses are possible, which result in a decrease in methane emissions. There are also emission-life cycle effects involved with the handling of manure due to its multiple uses as fertilizer substitute (with subsequent impacts on soil emissions compared to mineral fertilizer), anaerobic digester feedstock, and/or source for carbon offsets (Fleming et al., 1998; Keplinger & Hauck, 2006; Gloy, 2011; Pudenz & Schulz, 2022).

Most of the previous research on digesters has dealt with dairy operations (Astill & Shumway, 2016; Bishop & Shumway, 2009). There are a few economic studies of swine digesters (Cowley et al., 2019; Putmai et al., 2020). Due to factors discussed above, adoption of anaerobic digesters is typically more cost efficient, and hence more common, on existing dairy operations than for existing swine operations (Hoffman et al., 2024).

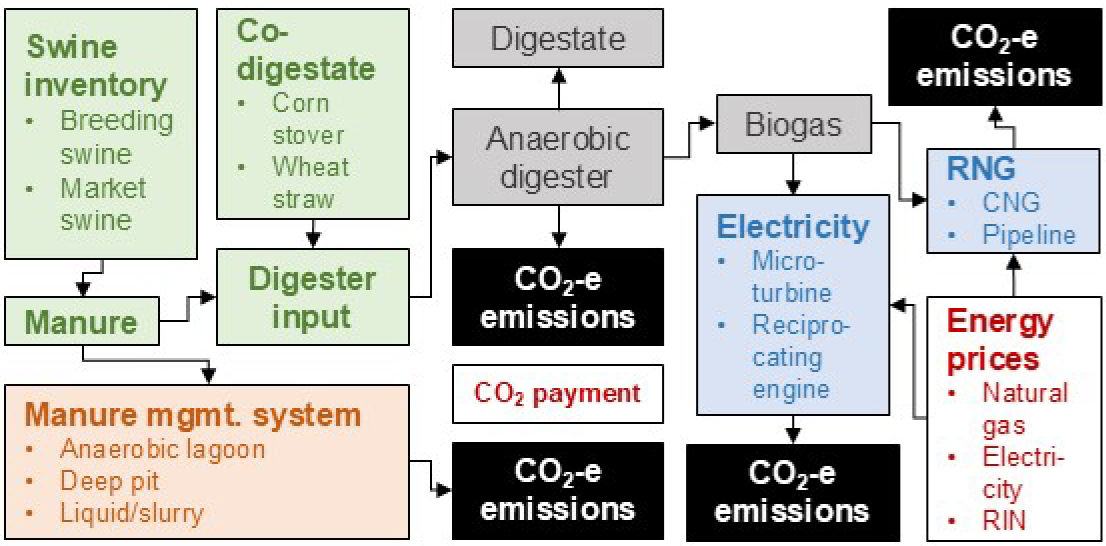
Digester End Products

A carbon market may make it possible for producers to earn revenue from the reduction in emissions from the digester. There are also non-market benefits associated with anaerobic digestors—such as odor control, water quality protection, and land conservation (EPA, 2018).The anerobic digestion process can reduce odor by transforming the odor-emitting volatile organic compounds to odorless gases (methane and carbon dioxide). Furthermore, the digestion process eliminates most pathogens that are harmful both to people and animals that otherwise would flow into local waterways (Key et al., 2011; EPA, 2018). Likewise, the digestate (a co-product of anaerobic digestion) itself can be used or sold as an organic fertilizer if markets provide the right incentives (Lim et al., 2023). In addition, the biogas collected in the digester can provide a valuable source of revenue.

The use of biogas resulting from anaerobic digesters can be divided into three broad categories: (1) flaring, (2) electricity, and (3) renewable natural gas. Flaring means to burn off CH_4, which mostly converts CH_4 to CO_2 emissions. By flaring, emissions are reduced 28-fold: 1 unit of CH_4 saves about 28 units of CO_2 (EPA, 2024). The disadvantage of flaring is the loss of biogas as an input to the production of higher valued outputs. Given the possibility of carbon credits and the value of energy, it is unlikely flaring will become the dominant biogas use. Hence, flaring will be excluded from this analysis. We keep the analysis separate between electricity and renewable natural gas.

Electricity can be generated with either a reciprocating engine or a gas turbine (EPA, 2016). While there is some electricity production occurring from biogas in the United States, most anaerobic digesters convert biogas to renewable natural gas for injection either into the natural gas grid or for sale as compressed natural gas. Since its implementation in 2007, the California's Low Carbon Fuel Standard (LCFS) program, in which compressed natural gas used for transportation fuel can earn emission reduction credits, has contributed to greater construction of anaerobic digesters (Cuéllar & Webber, 2008; Scheitrum et al., 2017). In 2018, electricity or heat/power was produced by 79 percent of the operational digesters (O'Hara et al., 2023). In this report, we focus on electricity production with either a reciprocating engine or a microturbine, and renewable natural gas production for either an on-farm compressed natural gas fueling station or injection into a natural gas pipeline (figure 5).

Figure 5
Overview of the model components



CO_2= carbon dioxide. CO_2-e = carbon dioxide-equivalent. RNG = renewable natural gas. CNG = compressed natural gas.

Note: Digester inputs (green), manure management (orange), anaerobic digesters (grey), and biogas use (blue). Energy and carbon payments are varied across a range of values. The carbon payments are calculated based on the differences in CO_2-e emissions from initial manure management system and biogas use (including emissions from anaerobic digester).

Source: USDA, Economic Research Service adapting Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining.*

Besides biogas, anaerobic digesters also produce digestate, which is the nutrient-rich residue after anaerobic digestion. Digestate is either liquid or solid, following a separation process. Liquid outputs can be used (for example) as organic fertilizer, whereas solid outputs can be used as soil amendments (Lim et al., 2023). Using digestate as an organic fertilizer also reduces synthetic fertilizer cost and emissions. Compared to raw manure, animal pathogens are also reduced due to the bio-physical treatment inside an anaerobic digester.

Methods and Models

The methods outlined in this section are grouped into three main categories: (1) digester inputs, (2) anaerobic digestion, and (3) biogas use. Digester inputs include swine inventory, manure production, and co-digestion inputs. The current manure management practice determines baseline CO_2-e emissions, which are compared to the emissions from anaerobic digestion to calculate potential carbon payments. The manure-management emission calculations are straightforward and closely follow the EPA inventory methodology (EPA, 2024). The Global Warming Potential (GWP) used are 1, 28, and 298 for carbon dioxide, methane, and nitrous oxide, respectively.[12]

For the calculations, the swine inventory from USDA, National Agricultural Statistics Service is subdivided into 5 categories (1) breeding, (2) market under 50 pounds (23 kilograms), (3) market 50−119 pounds (23−54 kilograms), (4) market 120−179 pounds (54−81 kilograms), and (5) market 180 pounds and over (greater than 81 kilograms). The EPA specifies five manure management systems (MMS) used in the various States: (1) pasture, range, and paddock, (2) liquid/slurry, (3) anaerobic lagoon, (4) deep pit, and (5) deep pit (less than 1 month).[13] The manure

[12] Global Warming Potential (GWP) is a measure used to compare the global warming impacts of different gases. The larger the GWP of a gas, the more the given gas warms the Earth compared to CO_2 over that same time period.
[13] For an explanation of the various manure management systems used in EPA (2024), see table A-164 in annex 3.

management system solid storage is not used for swine and we also do not include pasture, range, and paddock.

Biogas is potentially a valuable product if converted to renewable natural gas or electricity. Four biogas uses are assessed based on cost data (EPA, 2016): (1) microturbine, (2) reciprocating engine, (3) compressed natural gas, and (4) renewable natural gas. The first two uses generate electricity, whereas the last two produce natural gas. There are additional uses (i.e., fuel cell, flaring, and gas turbine) which we do not include in this analysis for the following reasons. First, electricity production through a gas turbine is used in landfills, which is characterized by a high volume of biogas exceeding that of even the largest swine farms. Second, flaring is unlikely given the modeled carbon payments and the current incentives set forth in the Inflation Reduction Act on payments for biogas electricity production. And lastly, biogas use in fuel cells to produce electricity has the highest cost and thus seems unlikely as an alternative to microturbines or reciprocating engines.

Regarding energy price assumptions, long-term natural gas prices (in million metric British Thermal Units (MMBTU)) are projected to be in the range of \$3.41–\$3.90, depending on economic growth and oil price trajectories (EIA, 2022). Natural gas spot prices have been outside this range in the past, \$2.03 (2020) to \$8.86 (2008).[14] Thus, we conduct our analysis using natural gas prices ranging from \$2.00–\$5.00 in increments of \$1.00, since annual natural gas prices have been above \$5 only during the financial crisis in 2008 and at the beginning of the war in Ukraine.

Electricity prices are projected to be close to constant at \$0.10 per kWh until 2050 in the 2022 Annual Energy Outlook (AEO) (EIA, 2022). Since there are large regional differences in the contiguous United States, with 2021 commercial prices ranging from \$0.08 (Nevada) to \$0.20 (California), we use electricity prices of \$0.08–\$0.20 in increments of \$0.02.[15]

[14] See EIA Natural Gas Spot and Futures Prices (NYMEX).
[15] See U.S. EIA Electric Sales, Revenue, and Average Price.

Renewable natural gas derived from biogas potentially qualifies for Renewable Identification Number (RIN) payments, specifically D3 (cellulosic biofuel) RINs generated from cellulosic biomass including biogas.[16] Pathways generating D3 RINs achieve a CO_2-e reduction of at least 60 percent, compared to a baseline of emissions from petroleum-based natural gas in 2005. D3 RIN prices have been fluctuating between $0.60 and $3.30 (per unit of gasoline gallon equivalent).

Digester Feedstock Characteristics for Swine Operations

In this analysis, we focus on anaerobic digesters tailored for two types of swine operations. The first type is breeding swine farms that are usually larger (in terms of inventory) and produce more manure due to the presence of lactating and gestating sows, which are generally larger animals. The second type are market swine operations that grow swine to market size (farrow-to-finish operations). Market-swine operations can be further subdivided depending on the pig's life cycle, but, for the purpose of this analysis, those stages are assumed to occur in the same facility. For CO_2-e emission inventory purposes, as well as for our analysis, the breeding swine are assumed to be 80 percent gestating, 15 percent farrowing, and 5 percent boars (EPA, 2024). Although artificial insemination of sows is increasing, which leads to boars being obsolete on breeding swine farms, the EPA is still using boars for emissions calculation. For the farrow-to-finish distribution (labeled "Market swine" in figure 5), we assume an equal share among the four weight classes (EPA, 2024).

To increase biogas yield and ensure optimal solids/liquid ratio in a digester with swine manure as the primary input, co-digestion is used in most complete mix digesters (EPA, 2012). We assume the use of corn stover and wheat straw at rates of 7.14 percent and 2.65 percent (weight basis), respectively. Assuming the use of agricultural residues also minimizes possible land allocation changes as a response of the co-digestate demand. We assume the cost of those inputs to be $20 per

[16] See Renewable Fuel Standard Program for more detail.

ton (Aui et al., 2019). The bio-physical properties of the feedstock are summarized in table 1. To represent the current situation in terms of common manure management system and average annual temperature in the two large swine-producing States, North Carolina and Iowa, we focus on anaerobic lagoons at 18°C and deep pits at 9°C. The digester type is assumed to be complete mix anaerobic digester.

Table 1
Feedstock production in metric tons per year and feedstock characteristics for anaerobic digestion

Feedstock	Feedstock (metric tons per year^{-1})	Total solids (percent)	Volatile solids percent (VS percent)	Methane yield (m^3 kg^{-1} VS)
Gestating sow	1.83	10	9.2	275
Lactating sow	4.13	10	9.2	356
Boar	1.39	10	8.9	356
Market (under 23 kilograms)	0.47	10	8.8	356
Market, (23–54 kilograms)	0.93	10	8.3	356
Market, (54–81 kilograms)	1.61	10	8.3	356
Market, (over 81 kilograms)	2.16	10	8.3	356
Wheat straw		90	89.3	208
Corn stover		40	94.0	348

Note: Total solids (TS) and volatile solids (VS) are measured on a weight-basis in percent; m^3 is cubic meters.

Source: USDA, Economic Research Service adapting data from Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining;* and using data from USDA, Natural Resources Conservation Service and Aui et al. (2019), Techno-economic and life cycle analysis of a farm-scale anaerobic digestion plant in Iowa, *Waste Management*.

Anaerobic Digestion

To scale the capital investment for various anaerobic digester sizes, we use an exponential scaling expression (National Renewable Energy Laboratory (NREL), 2011). We assume the annual operating and maintenance cost of the anaerobic digester amounts to 5 percent of investment cost.

The temperature range is limited to 6–18°C. This number corresponds to the average temperature in the 386 counties, where 95 percent of U.S. swine are located. Accounting for the temperature fluctuations over the day and year is beyond the scope of this model. A covered lagoon is not actively heated and the temperature inside the lagoon fluctuates with ambient temperature. A complete mix digester is actively heated and the temperature remains constant throughout the year. Fluctuations (or the absence thereof) in biogas production have important implications, depending on the end use (i.e., renewable natural gas or electricity production).

Biogas Use

We assume the biogas produced contains 50 percent methane. This value is consistent with the Anaerobic Digester Screening Tool Version 2.2, developed by the EPA for the Global Methane Initiative (GMI). The tool has also been a source for feedstock characteristics. The energy content of biogas and methane is 0.0234 and 0.036 gigajoules (GJ) m^{-3}, respectively. We use data on cost and CO_2-e emissions from various biogas uses provided by previous literature to estimate the relationship between biogas input flow (m^3 $year^{-1}$) and (1) capital cost, (2) operating and maintenance cost, (3) product output (GJ $year^{-1}$), and (4) CO_2-e emissions (table 2) (EPA, 2016). The capital cost is constituted of a fixed and a variable part determined by the intercept and slope of a regression line linking capital cost to biogas flow as determined by the amount of manure produced. The cost components also include economies of scale with the production of biogas.

The cost calculations in this section are based on the EPA report Evaluating the air quality, climate and economic impacts of biogas management technologies (EPA, 2016). They were converted from standard cubic feet per minute (SCFM) and British thermal units (BTU) in 2016 U.S. dollars to GJ in 2021 U.S. dollars. Conversions to 2021 U.S. dollars were made using the Gross Domestic Product (GDP) deflator. To produce pipeline-quality natural gas, the costs were adjusted downward to account for the lower cost compared to California by using a multiplier of 0.59[17]. The analysis includes increases in efficiency for larger biogas plants. The EPA (2016) analysis includes large landfills, which have a much higher biogas production than swine farms. It is only at those very high values of biogas production—beyond what even a very large swine farm produces—at which gains in efficiency are realized. Thus, the linear functional forms used in the main part of the report appropriately represent the cost and product flow based on biogas input flow.

Table 2

Parameters for carbon dioxide-equivalent emissions, capital, and operation and maintenance (O&M) cost, and output calculation

		Capital cost (U.S. dollars)			
Biogas use	Metric tons CO_2-e GJ^{-1}	Fixed cost per digester installation	Variable cost per cubic meter of biogas	O&M (U.S. dollars)	Output (GJ m^{-3})
Microturbine	0.084	104,028	0.73466	0.04461	0.00617
Reciprocating engine	0.091	191,313	0.67947	0.05625	0.00832
Compressed natural gas	0.051	1,102,423	0.45657	0.08924	0.00924
Renewable natural gas	0.042	2,135,851	0.99344	0.15089	0.01348

Note: The carbon dioxide-equivalent emissions are measured in metric tons per gigajoules (GJ) of output. The non-fixed cost components are measured in U.S. dollars per cubic meter of biogas. The output is either electricity or renewable natural gas in GJ per cubic meter of biogas input flow.
Source: USDA, Economic Research Service based on U.S. Environmental Protection Agency (2016), Evaluating the air quality, climate and economic impacts of biogas management technologies.

Delivering electricity or renewable natural gas to the nearest electricity grid substation or natural gas injection point adds additional cost not considered in this analysis. Thus, the sale of compressed natural gas remains an important option. Compressed natural gas fuel stations in major swine-

[17] The California-cost of multiplier (EPA, 2016) was applied to other U.S. States.

producing States in the Midwest (such as Iowa and Illinois) are sparse. Whereas North Carolina does not have many natural gas pipelines, Iowa (as the leading U.S. State in terms of swine production) has a substantial amount of pipeline potential that serve as connection points.

Internal Rate of Return

We use the internal rate of return (IRR) to evaluate the profitability of alternative potential anaerobic digester investments. A livestock producer would compare the IRR of a digester project with the potential returns from alternative farm and non-farm investments and the costs of capital to decide whether to proceed with the investment. A higher IRR implies the investment provides a greater return over time. In this analysis, the IRR is the rate of return that sets the net present value of the stream of annual digester profits (which could be positive or negative in any year) equal to the initial investment cost.

Digester profits are calculated as the revenues from net carbon mitigation (given a carbon price), energy (electricity or gas) sales, and digestate, minus the costs of the co-digestate and operating and maintenance costs of the digester and energy systems. The initial cost of constructing the digester is assumed to increase with the scale of the digester at a decreasing rate. Additional details about the model are given in Dumortier et al. (2024).

Results

This section presents the IRR estimates for an anaerobic digester project for operations, producing either breeding or market hogs, with either of two manure management system/temperature combinations (i.e., deep pit at 9°C and anaerobic lagoon at 18°C), representing the situation in Iowa and North Carolina, respectively. Anaerobic digester profitability is calculated over a range of energy prices for three possible carbon market prices ($0, $50, or $100 per metric ton of carbon dioxide equivalent (CO_2e)).

The results are presented for electricity and natural gas prices of \$0.14 kWh^{-1} and \$4 $MMBTU^{-1}$, respectively, which correspond approximately to the average retail prices in major swine-producing States. We also assessed scenarios with electricity prices between \$0.18 kWh^{-1} and \$0.10 kWh^{-1}.The upper (\$0.18 kWh^{-1}) and lower (\$0.10 kWh^{-1}) bounds are represented as the shaded areas in figure 6. The D3 RIN value is set at \$3.00 per gallon of renewable fuel. The co-digestate is assumed to be corn stover. Given large variability in the costs of connecting individual farms to a natural gas pipeline, we do not include connection costs, although we recognize for some farms these costs may be substantial, and distance to a pipeline may be a contributing factor to cost.

No Carbon Payment

We first present the results in the absence of a carbon payment to establish a baseline corresponding to the current situation in major swine-producing States (table 3). Without a carbon payment, anaerobic digester profitability is not affected by emissions reductions and revenues derive only from the sale of electricity or gas. The model indicates the use of a microturbine to generate electricity results in the lowest rates of return across scenarios and farm sizes modeled. The use of a reciprocating engine is preferred over a microturbine to produce electricity in all but one instance where the electricity scenarios would be equivalent (table 3). The results suggest the returns on investment favor the production of renewable natural gas over electricity, given anaerobic lagoons as the initial manure management system. Only for swine farms of 7,000 head or more is the production of compressed natural gas and electricity (via a reciprocating engine) on par with the production of renewable natural gas.

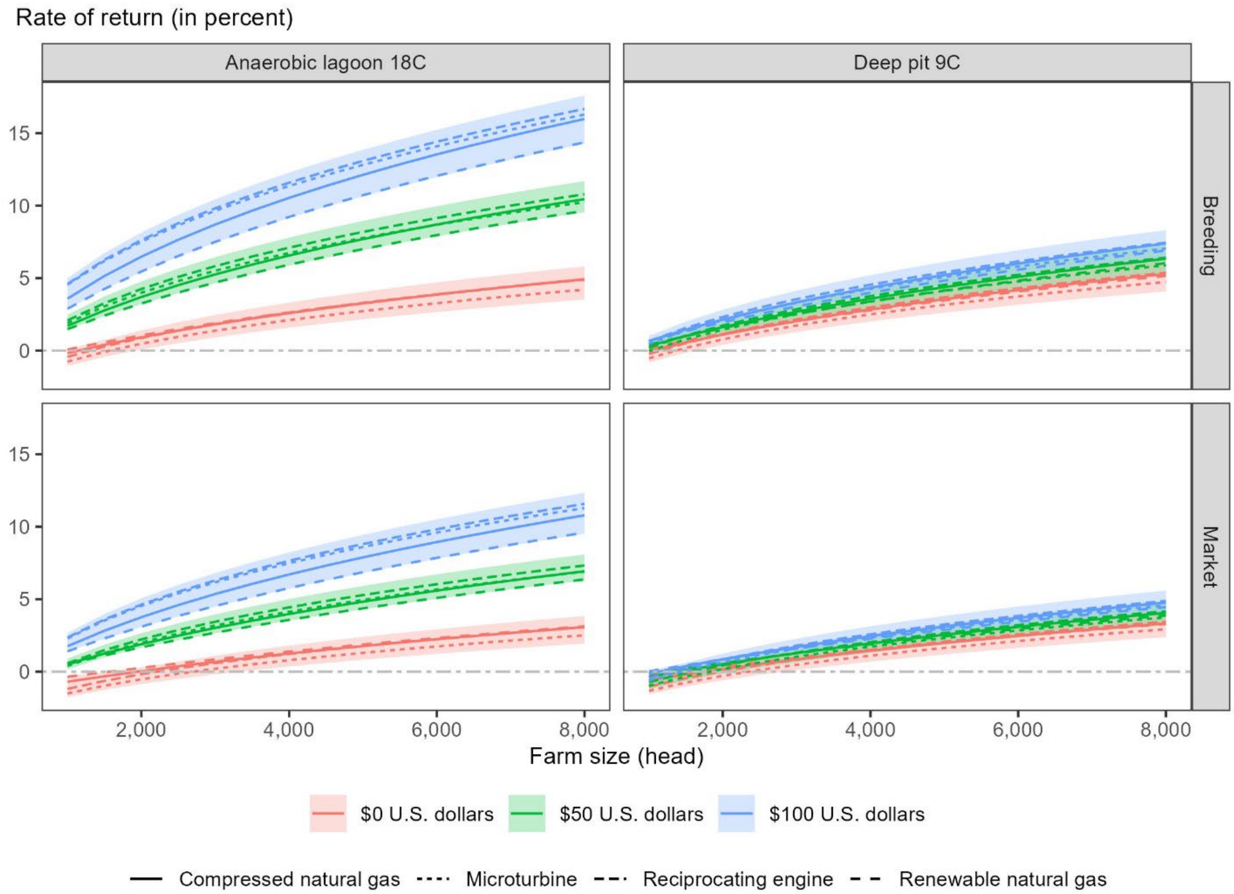
Given deep pits as the initial manure management system—which are in a cooled environment in the results presented here—the production of renewable natural gas generally leads to higher returns for swine farms below 2,000 head. And the model indicates electricity production provides a higher return on investment for larger swine farms with at least 5,000 head (table 3). For example, for a \$100 carbon payment, a market swine farm moving from a deep pit to an anaerobic digester an anaerobic digester investment produces internal rates of return from a 0.0 percent rate of return for swine farms with 1,000 head or less compared to negative returns for electricity production. Furthermore, the model indicates the internal rates of return from an operation with 5,000 to 8,000 head under the same scenario would provide a 3.04.9 percent rate of return for electricity generation, as compared to 2.0-4.4 percent for renewable natural gas production. Overall, however, the differences in profitability are relatively small across all end uses.

The findings in the absence of a carbon payment are twofold. First, the overall rate of return does not exceed 4 percent, except for breeding swine farms of more than 6,000 head. Given available data, current projections do not indicate energy price increases will be sufficient to trigger significant anaerobic digester investment in the next few years. These results reflect the baseline situation (i.e., absence of carbon payments) in major U.S. swine-producing States and show expected returns insufficient to trigger investment in anaerobic digesters on swine operations generally. The exception, due to economies of scale, may be farms with more than 5,000 head.

Second, if we exclude microturbine use, then the maximum rate of return difference is 0.3 percentage points across the biogas uses at a given farm size. Returns from microturbine use were lowest across the farm types and sizes and fall outside the 0.3 percentage point range difference across biogas uses. A 0.3 percentage point difference may not be a sufficient difference given uncertainty to warrant a specific choice between reciprocating engine, compressed natural gas, and renewable natural gas unless an investor expected sufficient increases in future energy prices. This suggests expected energy price levels in the future are determinants in the decision of the biogas end use. That is, if producers foresee energy price levels as low and likely to remain low, there is not an incentive to invest in an anaerobic digester and produce energy. However, producers in certain locations may have reason to forecast that their energy prices will be sufficiently high within the investment horizon for an anaerobic digester investment to provide a financial return with sufficient internal rates of return to invest.

Figure 6

Rates of return for a complete mix anaerobic digester in the absence of carbon payments, at carbon payments of $0 U.S. dollars, $50 U.S. dollars, and $100 U.S. dollars



The dashed horizontal line denotes the 0 percent threshold.

Note: The anaerobic lagoon at 18°C and the deep pit at 9°C examples are representative for the situation in North Carolina and Iowa, respectively. The values for carbon payments of $0, $50, and $100 are also reported in table 3. The shaded areas represent the upper and lower bound from varying the electricity price from $0.10 kWh^{-1} to $0.18 kWh^{-1} while keeping the carbon payments fixed. See the Energy Prices Sensitivity Analysis section of this report for more details.

Source: USDA, Economic Research Service adapting Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining.*

Carbon Payments

With payments for CO_2-e emission reductions, the type of manure management system used by the operation is an important determinant of anaerobic digester profitability. Because anaerobic lagoons have higher CH_4 emissions, the construction of an anaerobic lagoon is more profitable (has a higher IRR) compared to a deep pit system, at a carbon price $50 or $100 per metric ton of CO_2-e (figure 6). The shaded bands in the figure show profitability across a range of electricity prices. The narrowness of these bands suggests energy prices play a minor role in deciding to construct an anaerobic digester once carbon payments are in place.

The CO_2-e emissions from biogas end uses also impact anaerobic digester profitability, since these emissions lower the carbon payments. Note from table 2 that microturbines have relatively higher (on-farm) CO_2-e emissions of 0.084 metric tons CO_2-eGJ^{-1} compared to compressed natural gas and renewable natural gas (0.051 metric tons CO_2-eGJ^{-1} and 0.042 metric tons CO_2-eGJ^{-1}, respectively). In other words, natural gas production (renewable or compressed) is associated with lower on-farm emissions, compared to electricity production. This advantage disappears if natural gas is converted to electricity at a later stage. As with no carbon payment, microturbines are less profitable than reciprocating engines at a carbon payment of $50 but become comparable at a carbon payment of $100 due to the higher emissions from reciprocating engines (.091 metric tons CO_2-eGJ^{-1} for reciprocating engines versus .084 metric tons CO_2-eGJ^{-1} for microturbine engines, tables 2 and 3). At a $50 carbon payment, a positive rate of return is achieved for breeding and market swine farms larger than 1,000 head. As opposed to the situation without carbon payments, reciprocating engines are the most profitable form of biogas end use across all farm types and for inventory sizes of 3,000 head or more.

There is a significant difference in returns between the 9°C deep pit and 18°C anaerobic lagoon cases. For a breeding swine farm of 8,000 head and at a carbon payment of $100, the return for lagoons is 9.3 percentage points higher. The difference decreases with lower inventories (e.g., 7.1 percentage points for 4,000 head) (table 3). As with no carbon payments, the range of returns across the biogas end uses is relatively small with a maximum of 2.4 and 0.8 percentage points for the 18°C anaerobic lagoon and 9°C deep pit cases, respectively. Plotting the rates of returns as a function of carbon payments and inventory shows the trade-off between both components. That is, a higher carbon payment reduces the swine inventory required for a given rate of return (figures 7 and 8).

Table 3

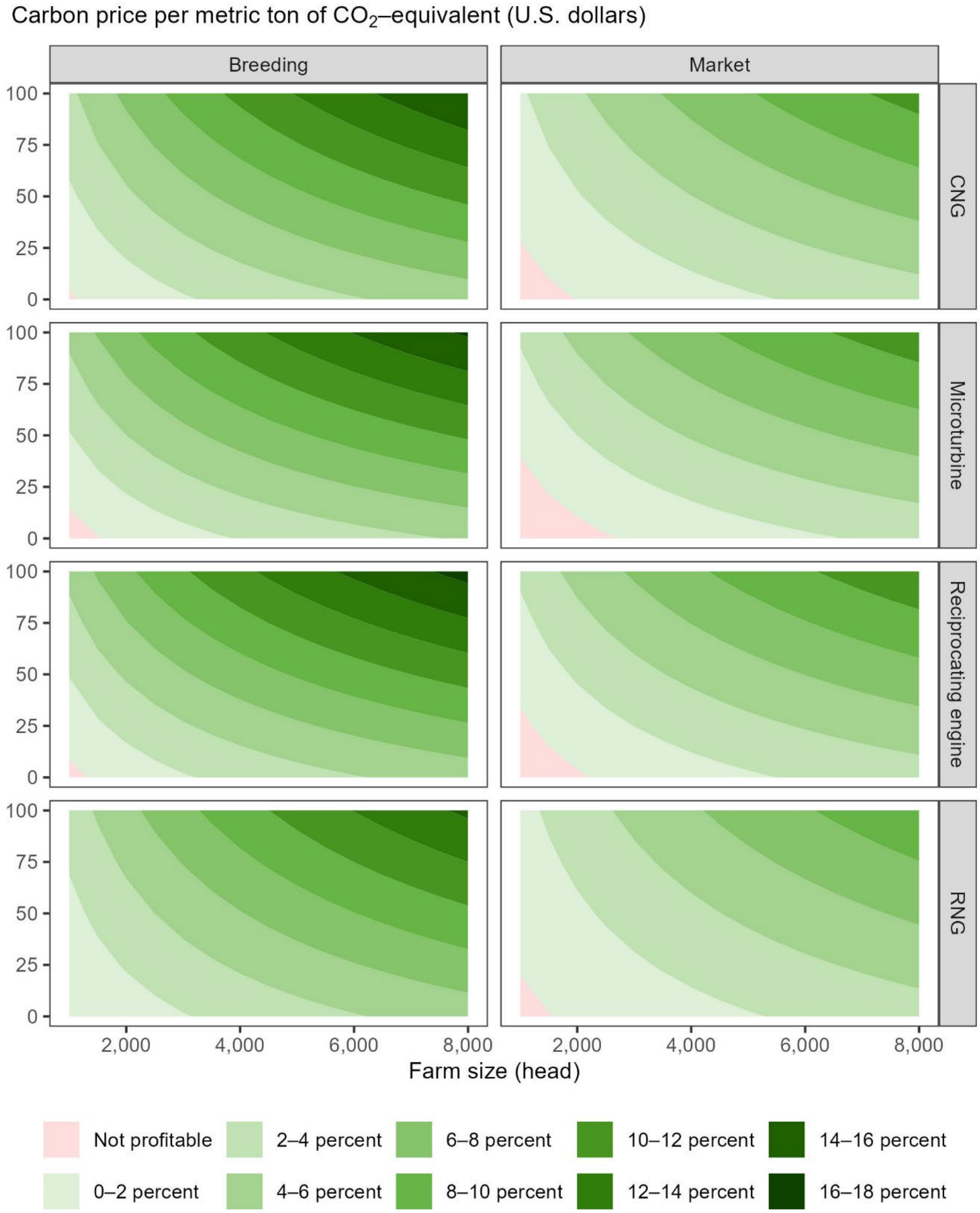
Rate of return in percent for a carbon payment of \$0, \$50, and \$100 per metric ton of CO_2-equivalent for compressed natural gas (CNG), microturbine (MTU), reciprocating engine (REC), and renewable natural gas (RNG)

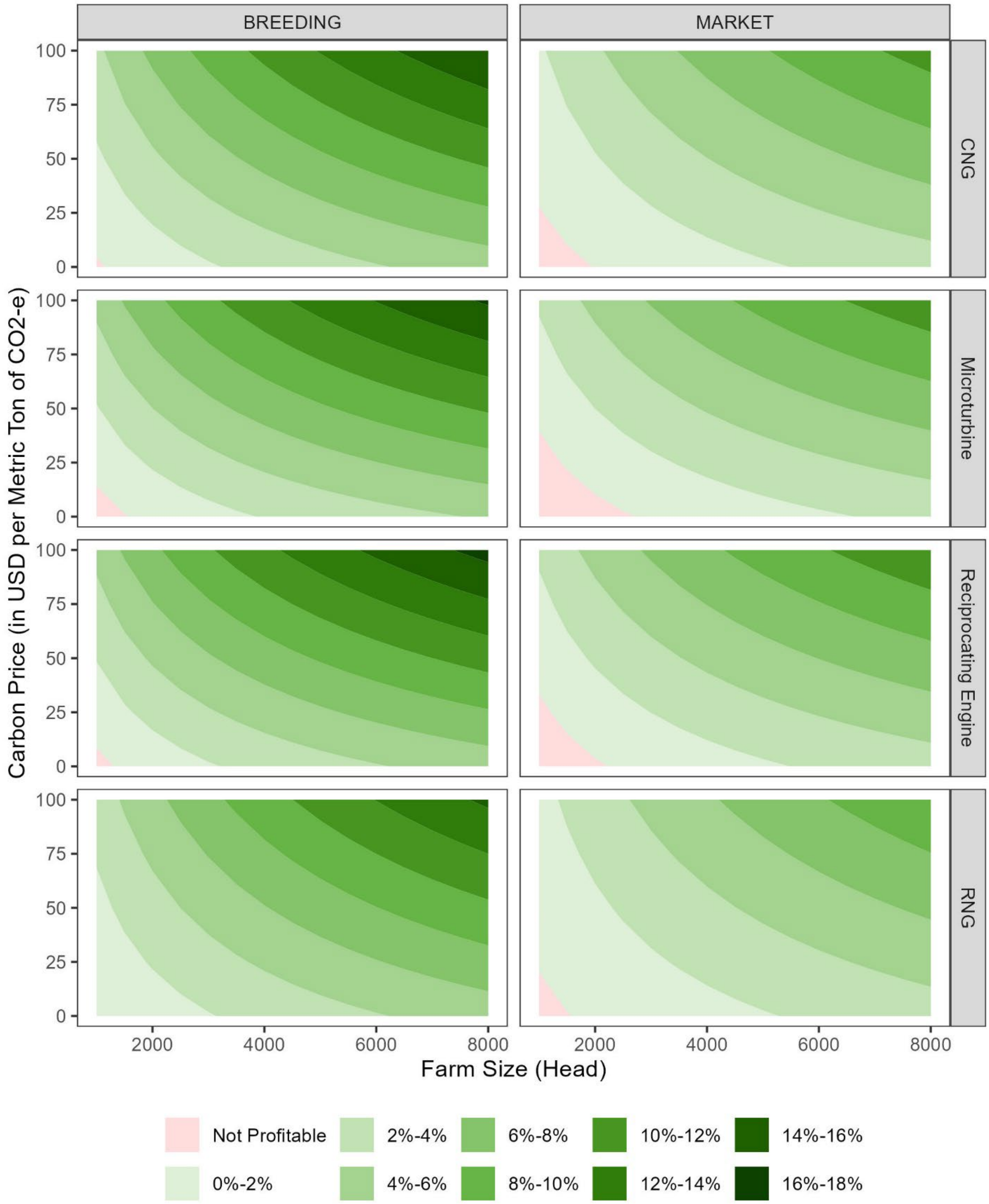
	Anaerobic lagoon (18°C)				Deep pit (9°C)			
	CNG	MTU	REC	RNG	CNG	MTU	REC	RNG
\$0, Breeding-swine farm								
1,000	-0.2	-0.8	-0.4	0.1	0.0	-0.5	-0.2	0.2
2,000	0.9	0.5	0.9	1.1	1.1	0.8	1.1	1.2
3,000	1.8	1.4	1.8	1.9	2.0	1.7	2.2	2.0
4,000	2.6	2.1	2.6	2.6	2.8	2.5	3.0	2.8
5,000	3.3	2.7	3.3	3.3	3.5	3.2	3.7	3.5
6,000	3.9	3.3	3.9	3.9	4.2	3.7	4.3	4.1
7,000	4.4	3.8	4.4	4.4	4.8	4.3	4.9	4.6
8,000	4.9	4.2	4.9	4.9	5.3	4.7	5.4	5.2
\$0, Market-swine farm								
1,000	-0.7	-1.5	-1.2	-0.4	-0.6	-1.3	-1.0	-0.3
2,000	0.0	-0.5	-0.2	0.3	0.2	-0.3	0.0	0.4
3,000	0.7	0.2	0.6	0.8	0.9	0.5	0.8	0.9
4,000	1.3	0.8	1.2	1.4	1.4	1.1	1.5	1.5
5,000	1.8	1.3	1.8	1.9	2.0	1.6	2.1	2.0
6,000	2.2	1.7	2.2	2.3	2.5	2.1	2.6	2.5
7,000	2.7	2.1	2.7	2.7	2.9	2.5	3.0	2.9
8,000	3.1	2.5	3.1	3.1	3.3	2.9	3.4	3.3
\$50, Breeding-swine farm								
1,000	1.7	1.9	2.1	1.5	0.3	0	0.2	0.4
2,000	3.7	4.0	4.3	3.3	1.6	1.4	1.7	1.6
3,000	5.3	5.5	5.8	4.7	2.7	2.5	2.9	2.5
4,000	6.6	6.7	7.1	5.9	3.6	3.4	3.8	3.4
5,000	7.7	7.8	8.2	7.0	4.4	4.1	4.5	4.1
6,000	8.7	8.7	9.1	8.0	5.1	4.8	5.2	4.8
7,000	9.6	9.5	10.0	8.8	5.7	5.4	5.8	5.5

8,000	10.5	10.2	10.8	9.6	6.3	5.9	6.4	6.0
$50, Market-swine farm								
1,000	0.5	0.4	0.6	0.5	-0.4	-1.0	-0.7	-0.1
2,000	1.9	2.0	2.2	1.7	0.5	0.2	0.4	0.6
3,000	3.0	3.2	3.4	2.7	1.3	1.0	1.3	1.3
4,000	4.0	4.1	4.4	3.6	1.9	1.7	2.0	1.9
5,000	4.8	4.9	5.3	4.4	2.5	2.3	2.7	2.4
6,000	5.6	5.7	6	5.1	3.1	2.8	3.2	3.0
7,000	6.3	6.3	6.7	5.7	3.6	3.3	3.7	3.4
8,000	6.9	6.9	7.3	6.4	4	3.7	4.2	3.9
$100, Breeding-swine farm								
1,000	3.6	4.6	4.6	2.9	0.7	0.5	0.7	0.7
2,000	6.5	7.5	7.6	5.5	2.1	2.1	2.3	2
3,000	8.7	9.6	9.8	7.5	3.3	3.3	3.6	3.1
4,000	10.5	11.4	11.6	9.2	4.3	4.3	4.5	4
5,000	12.1	12.8	13.1	10.7	5.2	5.1	5.4	4.8
6,000	13.5	14.1	14.4	12.1	6.0	5.8	6.2	5.6
7,000	14.8	15.2	15.6	13.3	6.7	6.5	6.8	6.3
8,000	16.0	16.3	16.7	14.4	7.4	7.0	7.4	6.9
$100, Market-swine farm								
1,000	1.8	2.3	2.4	1.4	-0.1	-0.6	-0.4	0.0
2,000	3.8	4.5	4.6	3.1	0.9	0.7	0.8	0.8
3,000	5.4	6.2	6.3	4.5	1.7	1.6	1.8	1.6
4,000	6.7	7.5	7.6	5.8	2.4	2.3	2.6	2.3
5,000	7.9	8.6	8.8	6.9	3.1	3.0	3.3	2.9
6,000	8.9	9.6	9.8	7.8	3.7	3.6	3.8	3.4
7,000	9.9	10.5	10.7	8.8	4.3	4.1	4.4	4.0
8,000	10.8	11.3	11.6	9.6	4.8	4.6	4.9	4.4

Source: USDA, Economic Research Service adapting Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining.*

Figure 7
Rates of return for the conversion from an anaerobic lagoon to a complete mix digester exposed to an ambient temperature of 18°C



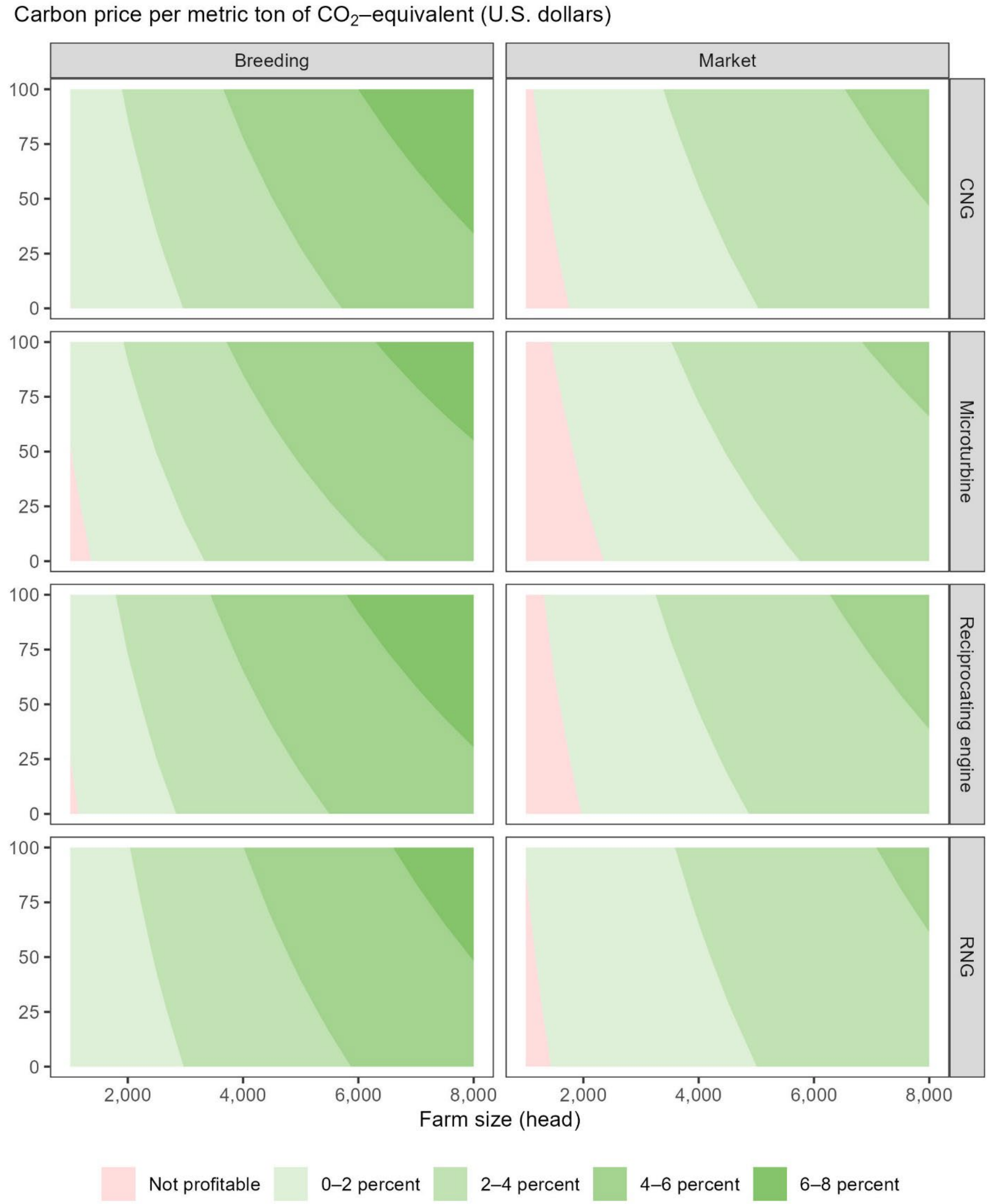


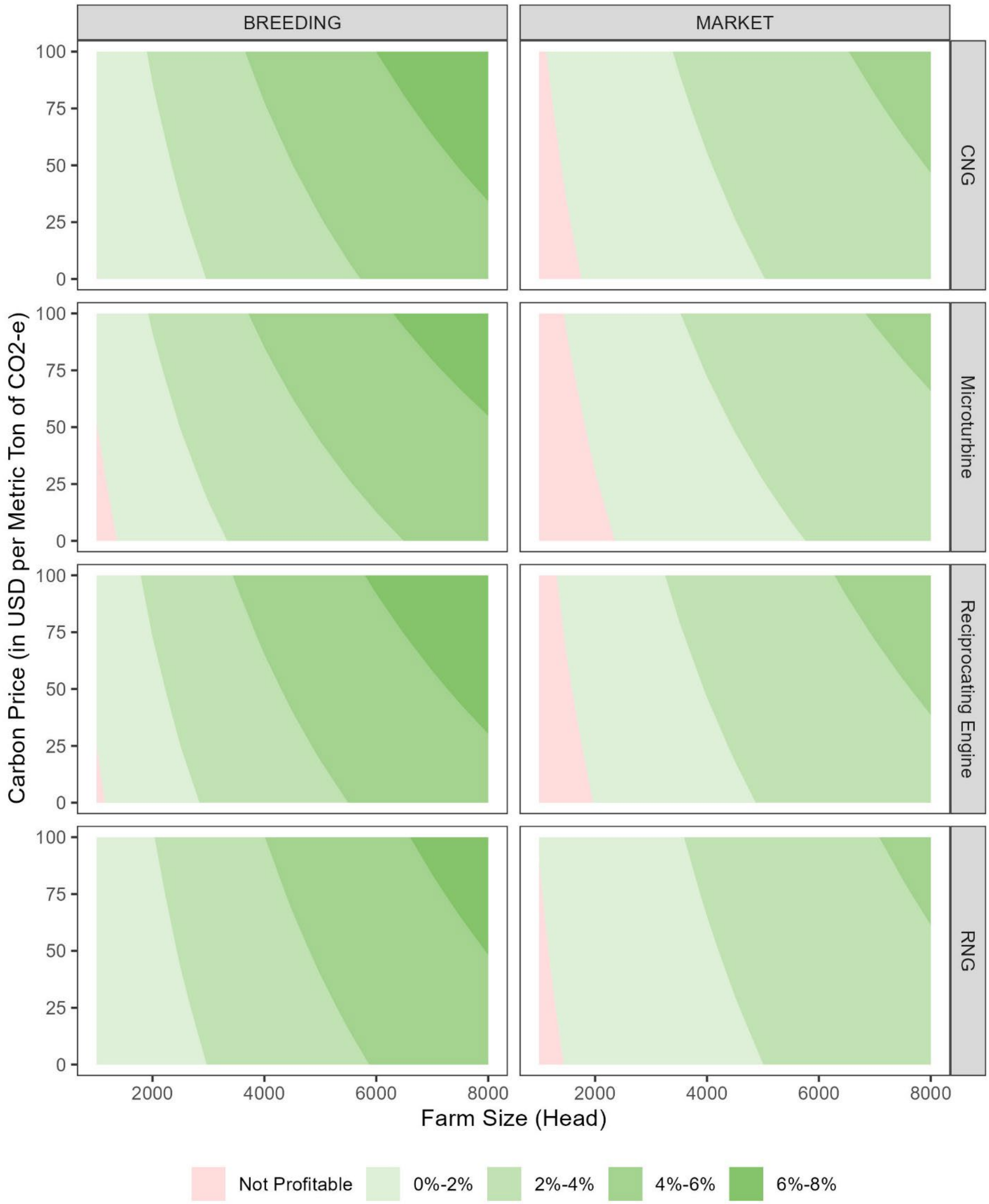
CNG = compressed natural gas. RNG = renewable natural gas. CO_2-e = carbon dioxide-equivalent.

Note: The initial manure management system is an anaerobic lagoon. This example is representative of a farm in North Carolina.

Source: USDA, Economic Research Service adapting Regional Economic Aspects of Carbon Markets and Anaerobic Digesters in the USA: The Case of Swine Production, *Biofuels, Bioproducts, and Biorefining.*

Figure 8
Rates of return for a conversion from deep pit to a complete mix digester exposed to an ambient temperature of 9°C




BREEDING
MARKET
CNG
Microturbine
Reciprocating Engine
RNG
Carbon Price (in USD per Metric Ton of CO2-e)
Farm Size (Head)
0
25
50
75
100
2000
4000
6000
8000
Not Profitable
0%-2%
2%-4%
4%-6%
6%-8%

CO_2-e = carbon dioxide-equivalent.

Note: The initial manure management system is a deep pit. This example is representative of a farm in Iowa.

Source: USDA, Economic Research Service adapting Regional Economic Aspects of Carbon Markets and Anaerobic Digesters in the USA: The Case of Swine Production, *Biofuels, Bioproducts, and Biorefining.*

Cost Share

The USDA, Rural Energy for America Program (REAP) provides agricultural producers and rural business owners the opportunity to apply for guaranteed loan financing and grant funding to invest in practices such as anaerobic digesters.[18] This program announced $145 million in funding, in part, due to the Inflation Reduction Act. Because anaerobic digesters fall short of zero CO_2-e emissions, they do not qualify for 50 percent cost share; however, they can qualify for a 25 percent cost share. Funding is capped at $1 million per project. An operation that demonstrates the ability to raise at least $3 million of the investment capital needed may qualify for up to $1 million. Applications include payback periods of 4 to 25 years and a letter of commitment from a bank attesting to the farm's ability to fund its share of the costs can be included in the application.

The rate of return calculations (see figure 6 and table 3) indicate that, within a given carbon payment range, breeding swine farms can achieve the REAP payback target. In the absence of a carbon payment, financial returns are insufficient to achieve payback targets. With a carbon payment, the internal rate of return (IRR) to anaerobic digester adoption can increase and expand use of matching programs if all other costs remain equal. In other words, the results indicate carbon

[18] See Rural Energy for America Program (REAP) Renewable Energy Systems and Energy Efficiency Improvement Guaranteed Loans and Grants. We use REAP as an example. Additional financial assistance programs may apply to producers investing in anaerobic digesters such as the Environmental Quality Incentives Program (EQIP), which provides financial and technical assistance to agricultural producers.

payments increase the likelihood producers will install anaerobic digesters by lowering initial investment costs.

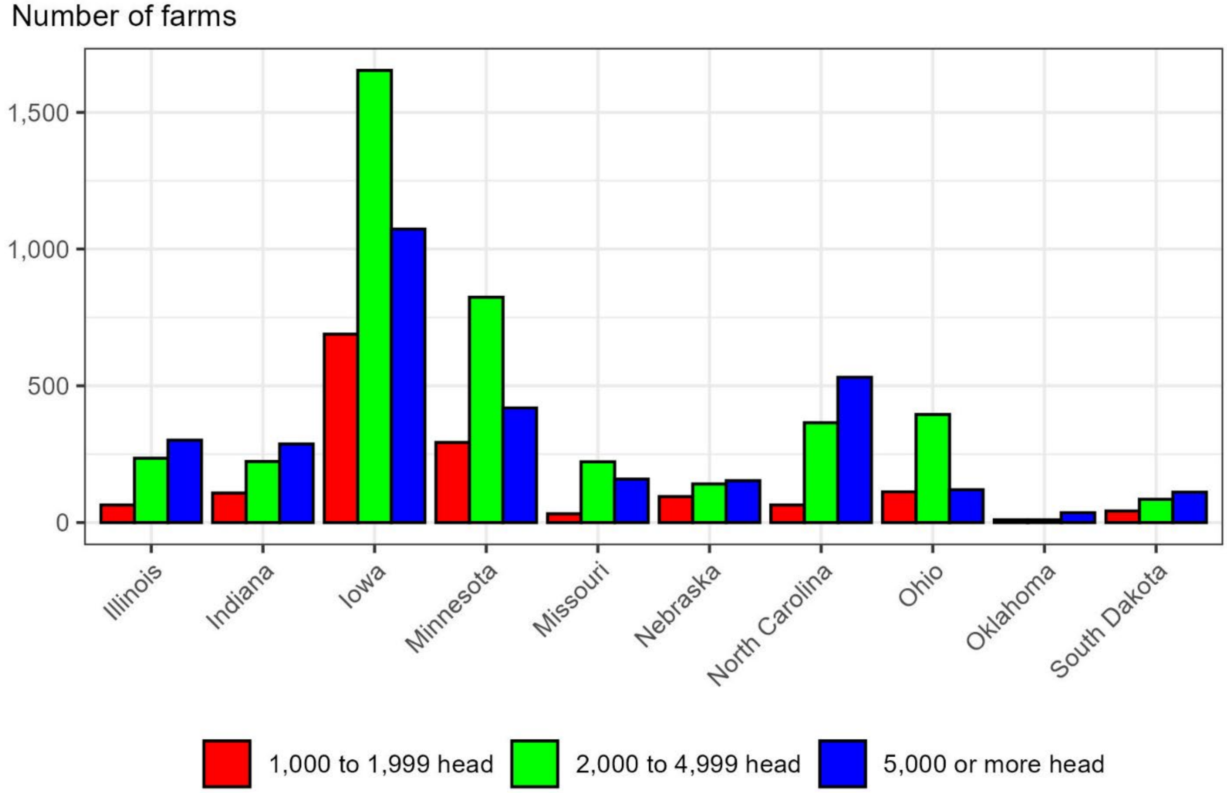
State-Specific Analysis

There are relatively large differences in energy prices across U.S. States (table 4). The mean electricity prices measured in U.S. dollars per million metric British Thermal Units (MMBTU) vary from $23.87 in Oklahoma to $31.04 in Minnesota. For natural gas prices, Oklahoma had the lowest average ($5.04) and Missouri had the highest average ($8.56). There is also variability in prices over the years 2017–22, Missouri and Illinois are highest for electricity (range of $3.36) and natural gas ($2.21), respectively.

Table 4 lists the share of each manure management system used in the 10 largest swine producing U.S. States. For all States except North Carolina and Oklahoma, the initial manure management systems and co-digestate are assumed to be a deep pit and corn stover, respectively. The initial manure management system for North Carolina and Oklahoma is an anaerobic lagoon. In addition, Oklahoma uses wheat straw as a co-digestate.

There is also variability in the average size of swine operations across U.S. States. For example, swine in North Carolina are much more concentrated on large farms of more than 5,000 head than in Midwestern States such as Iowa and Minnesota, except for Missouri and Illinois (figure 9).

Figure 9
Number of U.S. farms by inventory size



Source: USDA, Economic Research Service using USDA, National Agricultural Statistics Service, 2022 Census of Agriculture.

Table 4
Representative scenarios for the 10 largest swine-producing U.S. States in 2021, including distribution (in percent) of manure management systems in each State, as well as mean energy price in U.S. dollars per MMBTU over the period 2017-2021 and mean county temperature, Celsius, 2012-2021

State	Electricity price in $/MMBTU	Natural gas price in $/MMBTU	Slurry/ liquid (percent share)	Anaerobic lagoon (percent share)	Deep pit (percent share)	Pit (less than 1 month) (percent share)	Mean Daily Temperature
Illinois	28.69	7.37	15	7	71	5	11.56
Indiana	29.28	6.55	3	12	78	7	11.50
Iowa	26.32	5.80	10	4	80	5	9.18
Minnesota	31.04	6.36	3	2	88	5	5.37
Missouri	28.86	8.56	16	33	34	15	13.03
Nebraska	26.43	5.46	9	22	49	19	9.70
North Carolina	27.28	8.39	33	49	1	16	15.75
Ohio	28.64	7.24	10	9	67	13	11.13
Oklahoma	23.87	5.04	11	53	3	32	15.65
South Dakota	29.62	5.40	17	11	57	14	7.66

MMBTU = million metric British Thermal Units.

Source: USDA, Economic Research Service adapting Dumortier et al. (2024), Regional economic aspects of carbon markets and anaerobic digesters in the USA: The case of swine production, *Biofuels, Bioproducts, and Biorefining.*

Analyzing the optimal end uses in terms of return in each State using the same methodology as before, but with the State-specific parameters, suggests in most cases natural gas production would be the highest yielding use. Since the connection cost with the natural gas grid is not explicitly modeled in this report and the returns across the various end uses are relatively close to each other, each individual project likely needs a more detailed evaluation of the optimal end use.

For some States, the optimal end use depends on carbon prices. For example, the production of electricity is more profitable in Oklahoma with carbon payments (figures 10 and 11). In the case of no carbon payments, the production of natural gas is more profitable. Focusing only on compressed natural gas and electricity production (as well as breeding swine farms with 8,000 head or more and a carbon payment of $50 per metric ton of CO_2-e), electricity production using reciprocating engines is only the optimal choice in Oklahoma. In all other States, the production of compressed natural gas is more profitable. Although as noted before, the returns across the various end uses are relatively similar.

Table 5
Market swine operation rates of return (in percent) for biogas for the 10 largest swine-producing U.S. States, given energy prices and representative manure management systems in table 4

	$0 carbon price			$50 carbon price			$100 carbon price		
Head	1,500	3,000	8,000	1,500	3,000	8,000	1,500	3,000	8,000
				Illinois					
CNG	-0.2%	0.8%	3.2%	0.1%	1.3%	4.1%	0.4%	1.8%	4.9%
RNG	0.0%	0.9%	3.2%	0.2%	1.3%	3.9%	0.5%	1.7%	4.6%
				Indiana					
CNG	-0.3%	0.8%	3.2%	0.1%	1.3%	4.0%	0.4%	1.8%	4.8%
RNG	0.0%	0.9%	3.2%	0.2%	1.2%	3.8%	0.5%	1.6%	4.5%
				Iowa					
CNG	-0.2%	0.8%	3.2%	0.0%	1.2%	3.9%	0.3%	1.6%	4.6%
RNG	0.0%	0.9%	3.1%	0.2%	1.2%	3.7%	0.4%	1.5%	4.3%
				Minnesota					
CNG	-0.2%	0.9%	3.4%	0.1%	1.3%	4.1%	0.4%	1.8%	4.9%
RNG	0.0%	0.9%	3.3%	0.3%	1.3%	3.9%	0.5%	1.6%	4.5%
				Missouri					
CNG	-0.2%	0.8%	3.3%	0.2%	1.4%	4.2%	0.6%	2.0%	5.2%
RNG	0.0%	0.9%	3.3%	0.3%	1.4%	4.1%	0.6%	1.8%	4.9%
				Nebraska					
CNG	-0.3%	0.7%	3.2%	0.0%	1.2%	3.9%	0.3%	1.6%	4.6%
RNG	0.0%	0.8%	3.1%	0.2%	1.2%	3.7%	0.4%	1.5%	4.3%
				North Carolina					
CNG	-0.3%	0.7%	3.2%	1.3%	3.1%	7.0%	2.9%	5.4%	10.9%
RNG	0.0%	0.9%	3.2%	1.2%	2.7%	6.4%	2.3%	4.6%	9.7%
				Ohio					
CNG	-0.2%	0.8%	3.2%	0.1%	1.3%	4.0%	0.4%	1.7%	4.8%
RNG	0.0%	0.9%	3.2%	0.2%	1.3%	3.9%	0.5%	1.6%	4.5%
				Oklahoma					
CNG	0.1%	1.2%	3.8%	2.0%	4.1%	8.8%	3.8%	6.9%	13.7%
RNG	0.2%	1.1%	3.5%	1.5%	3.3%	7.5%	2.9%	5.5%	11.6%
				South Dakota					
CNG	-0.2%	0.8%	3.2%	0.1%	1.2%	4.0%	0.4%	1.7%	4.7%
RNG	0.0%	0.9%	3.2%	0.2%	1.2%	3.7%	0.4%	1.5%	4.3%

CNG = compressed natural gas. RNG = renewable natural gas. Carbon prices are in U.S. dollars per metric ton of CO_2-equivalent.

Source: USDA, Economic Research Service adapting Regional Economic Aspects of Carbon Markets and Anaerobic Digesters in the USA: The Case of Swine Production, *Biofuels, Bioproducts, and Biorefining.*

Table 6
Market swine operation rates of return (in percent) for electricity for the 10 largest swine-producing U.S. States, given energy prices and representative manure management systems in table 4

	$0 carbon price			$50 carbon price			$100 carbon price		
Head	1,500	3,000	8,000	1,500	3,000	8,000	1,500	3,000	8,000
				Illinois					
Microturbine	-1.1%	0.0%	2.2%	-0.6%	0.6%	3.2%	-0.1%	1.3%	4.1%
Reciprocating engine	-0.9%	0.2%	2.6%	-0.5%	0.8%	3.4%	0.0%	1.4%	4.3%
				Indiana					
Microturbine	-1.1%	0.0%	2.2%	-0.6%	0.7%	3.2%	-0.1%	1.3%	4.1%
Reciprocating engine	-0.9%	0.3%	2.6%	-0.5%	0.8%	3.4%	0.0%	1.4%	4.3%
				Iowa					
Microturbine	-1.1%	0.0%	2.2%	-0.7%	0.6%	3.1%	-0.3%	1.1%	3.9%
Reciprocating engine	-0.9%	0.2%	2.5%	-0.5%	0.7%	3.3%	-0.2%	1.2%	4.0%
				Minnesota					
Microturbine	-0.9%	0.3%	2.7%	-0.4%	0.9%	3.5%	0.0%	1.5%	4.4%
Reciprocating engine	-0.7%	0.6%	3.0%	-0.3%	1.1%	3.8%	0.1%	1.6%	4.6%
				Missouri					
Microturbine	-1.1%	0.0%	2.1%	-0.6%	0.7%	3.3%	0.0%	1.5%	4.4%
Reciprocating engine	-0.9%	0.2%	2.5%	-0.4%	0.9%	3.5%	0.1%	1.6%	4.5%
				Nebraska					
Microturbine	-1.1%	0.0%	2.2%	-0.7%	0.5%	3.0%	-0.3%	1.1%	3.8%
Reciprocating engine	-0.9%	0.2%	2.5%	-0.6%	0.7%	3.2%	-0.2%	1.2%	3.9%
				North Carolina					
Microturbine	-1.3%	-0.2%	1.9%	1.0%	2.8%	6.3%	3.2%	5.8%	10.7%
Reciprocating engine	-1.0%	0.1%	2.3%	1.1%	2.9%	6.5%	3.2%	5.8%	10.8%
				Ohio					
Microturbine	-1.1%	0.0%	2.2%	-0.6%	0.6%	3.1%	-0.2%	1.3%	4.1%
Reciprocating engine	-0.9%	0.3%	2.6%	-0.5%	0.8%	3.4%	-0.1%	1.3%	4.2%
				Oklahoma					
Microturbine	-0.6%	0.7%	3.3%	2.4%	4.7%	9.2%	5.4%	8.7%	15.1%
Reciprocating engine	-0.4%	0.9%	3.5%	2.4%	4.7%	9.2%	5.2%	8.5%	15.0%
				South Dakota					
Microturbine	-1.0%	0.2%	2.5%	-0.6%	0.7%	3.3%	-0.1%	1.3%	4.1%
Reciprocating engine	-0.8%	0.4%	2.8%	-0.4%	0.9%	3.6%	0.0%	1.4%	4.3%

Note: Carbon prices are in U.S. dollars per metric ton of CO_2-equivalent.

Source: USDA, Economic Research Service.

Table 7
Breeding swine operation rates of return (in percent) for biogas for the 10 largest swine-producing U.S. States, given energy prices and representative manure management systems in table 4

	$0 carbon price			$50 carbon price			$100 carbon price		
Head	1,500	3,000	8,000	1,500	3,000	8,000	1,500	3,000	8,000
Illinois									
CNG	0.5%	1.9%	5.1%	1.0%	2.7%	6.4%	1.5%	3.5%	7.6%
RNG	0.6%	2.0%	5.0%	1.0%	2.6%	6.1%	1.4%	3.2%	7.1%
Indiana									
CNG	0.5%	1.9%	5.1%	1.0%	2.7%	6.3%	1.5%	3.4%	7.5%
RNG	0.6%	1.9%	5.0%	1.0%	2.5%	6.0%	1.4%	3.1%	7.0%
Iowa									
CNG	0.5%	1.9%	5.1%	0.9%	2.6%	6.2%	1.4%	3.2%	7.2%
RNG	0.6%	1.9%	5.0%	0.9%	2.4%	5.8%	1.3%	2.9%	6.7%
Minnesota									
CNG	0.6%	2.1%	5.4%	1.1%	2.8%	6.5%	1.5%	3.4%	7.6%
RNG	0.7%	2.0%	5.2%	1.0%	2.6%	6.1%	1.4%	3.1%	7.0%
Missouri									
CNG	0.5%	2.0%	5.2%	1.1%	2.9%	6.6%	1.7%	3.7%	8.0%
RNG	0.7%	2.0%	5.1%	1.1%	2.7%	6.3%	1.6%	3.4%	7.5%
Nebraska									
CNG	0.5%	1.9%	5.1%	0.9%	2.5%	6.1%	1.4%	3.2%	7.2%
RNG	0.6%	1.9%	4.9%	0.9%	2.4%	5.8%	1.2%	2.9%	6.7%
North Carolina									
CNG	0.5%	1.9%	5.1%	2.8%	5.3%	10.6%	5.2%	8.8%	16.1%
RNG	0.6%	2.0%	5.0%	2.5%	4.8%	9.7%	4.3%	7.5%	14.5%
Ohio									
CNG	0.5%	2.0%	5.2%	1.0%	2.7%	6.3%	1.5%	3.4%	7.5%
RNG	0.6%	2.0%	5.0%	1.0%	2.5%	6.0%	1.4%	3.1%	7.0%
Oklahoma									
CNG	0.9%	2.5%	6.1%	3.8%	6.9%	13.3%	6.8%	11.2%	20.6%
RNG	0.8%	2.2%	5.6%	3.0%	5.7%	11.6%	5.2%	9.1%	17.7%
South Dakota									
CNG	0.5%	2.0%	5.2%	1.0%	2.6%	6.2%	1.4%	3.3%	7.3%
RNG	0.6%	1.9%	5.0%	1.0%	2.4%	5.9%	1.3%	3.0%	6.8%

CNG = compressed natural gas. RNG = renewable natural gas. Carbon prices are in U.S. dollars per metric ton of CO_2-equivalent.

Source: USDA, Economic Research Service.

Table 8
Breeding swine operation rates of return (in percent) for electricity for the 10 largest swine-producing U.S. States, given energy prices and representative manure management systems in table 4

	$0 carbon price			$50 carbon price			$100 carbon price		
Head	1,500	3,000	8,000	1,500	3,000	8,000	1,500	3,000	8,000
				Illinois					
Microturbine	-0.3%	1.1%	3.9%	0.4%	2.1%	5.2%	1.1%	3.0%	6.6%
Reciprocating engine	0.0%	1.4%	4.3%	0.6%	2.3%	5.5%	1.2%	3.1%	6.7%
				Indiana					
Microturbine	-0.2%	1.2%	3.9%	0.5%	2.1%	5.3%	1.1%	3.0%	6.6%
Reciprocating engine	0.0%	1.5%	4.3%	0.6%	2.3%	5.6%	1.2%	3.1%	6.8%
				Iowa					
Microturbine	-0.2%	1.2%	3.9%	0.4%	2.0%	5.1%	1.0%	2.7%	6.2%
Reciprocating engine	0.0%	1.4%	4.3%	0.5%	2.1%	5.3%	1.0%	2.8%	6.3%
				Minnesota					
Microturbine	0.0%	1.5%	4.5%	0.7%	2.4%	5.7%	1.3%	3.2%	6.9%
Reciprocating engine	0.3%	1.8%	4.9%	0.8%	2.6%	6.0%	1.4%	3.3%	7.1%
				Missouri					
Microturbine	-0.3%	1.1%	3.8%	0.5%	2.2%	5.4%	1.3%	3.2%	6.9%
Reciprocating engine	-0.1%	1.4%	4.2%	0.7%	2.4%	5.7%	1.4%	3.3%	7.1%
				Nebraska					
Microturbine	-0.3%	1.1%	3.9%	0.3%	1.9%	5.0%	0.9%	2.7%	6.2%
Reciprocating engine	0.0%	1.4%	4.3%	0.5%	2.1%	5.3%	1.0%	2.8%	6.3%
				North Carolina					
Microturbine	-0.4%	0.9%	3.5%	2.7%	5.1%	9.6%	5.8%	9.2%	15.6%
Reciprocating engine	-0.2%	1.2%	3.9%	2.8%	5.2%	9.8%	5.8%	9.2%	15.7%
				Ohio					
Microturbine	-0.2%	1.2%	3.9%	0.4%	2.0%	5.2%	1.1%	2.9%	6.5%
Reciprocating engine	0.0%	1.4%	4.3%	0.6%	2.2%	5.5%	1.2%	3.0%	6.6%
				Oklahoma					
Microturbine	0.5%	2.1%	5.4%	4.7%	7.8%	13.7%	9.0%	13.4%	21.9%
Reciprocating engine	0.6%	2.3%	5.6%	4.7%	7.7%	13.7%	8.7%	13.2%	21.8%
				South Dakota					
Microturbine	-0.1%	1.4%	4.2%	0.5%	2.2%	5.4%	1.1%	3.0%	6.6%
Reciprocating engine	0.1%	1.6%	4.6%	0.7%	2.4%	5.7%	1.2%	3.1%	6.7%

Note: Carbon prices are in U.S. dollars per metric ton of CO_2-equivalent.

Source: USDA, Economic Research Service.

Discussion

The analysis in this report incorporated several key determinants of anaerobic digester profitability but could not account for all factors influencing the investment decision. For example, the results presented in the previous section assume perfect foresight in terms of carbon and energy prices. From the financial economics literature, it is well known that uncertainty makes revenues less valuable to investors and can hinder and delay investment (Anderson & Weersink, 2014). The analysis suggests carbon payments have a larger impact on the rate of return than energy prices and therefor on the decision to construct an anaerobic digester. It follows that long-term certainty is more important for carbon payments than energy prices. The long-term certainty in energy and carbon payments can be achieved through long-term contracts between energy end users and/or entities purchasing carbon credits.

The analysis also does not consider the connection cost to a local natural gas pipeline. Connection costs could substantially limit the profitability of a pipeline injection if swine farms are not close to injection points. The cost of a pipeline depends on many factors, including diameter and length. The cost of a 1 mile-long pipe 1 inch in diameter is estimated to be around $250,000. Because livestock farms are often located far from population centers due to the odor produced, connection costs for a pipeline could be prohibitive for many farms and may only be profitable for very large or cooperatively owned digesters. In Germany, for example, most digesters produce electricity rather than sell gas since it is much easier to connect to the grid than a natural gas pipeline.

Installing biogas facilities on a large scale might alter crop production in the surrounding areas. Manure is not the only feedstock for an anaerobic digester, which can also include food waste, agricultural residues, or other organic material such as maize silage. Hence, digester construction could incentivize the growing of feedstock for the biogas digester as opposed to other uses (Whiting & Azapagic, 2014).

A carbon price or tax on carbon emissions could have indirect effects on digester adoption through the electricity sector that were not accounted for in the model. Given such a carbon price or tax, electricity producers would likely seek to pass the higher cost of producing electricity to consumers (including farmers). Higher electricity prices would make it more profitable for farmers to adopt methane digesters (Dumortier & Elobeid, 2021).

A carbon market that increases the value of biogas produced by livestock operations could have unintended consequences if livestock producers increase their herd sizes to produce more biogas (USDA, 2011). On the other hand, anaerobic digesters are typically built for a specific herd size which may limit the financial incentives to increase herd size. Since carbon offsets reward producers for reducing CO_2-e emissions, some producers might seek to alter their manure-management system to increase their baseline CO_2-e emissions (USDA, 2011). Both of these unintended responses would be counter to the additional requirement of carbon offsets and could raise concerns about over-crediting and the accuracy of emission reduction claims in these markets.

Conclusion

There is potential for U.S. livestock producers to reduce CO_2-e emissions and produce energy from manure management by constructing anaerobic digesters. Since the biogas end-product can be either renewable natural gas or electricity—with various technology options available for the production—there is flexibility in anaerobic digester design, depending on energy prices and carbon payments. Livestock producers integrated into a carbon market will have multiple technology pathways available between manure production and sale of energy.

The analysis shows the construction of an anaerobic digester is much more likely for a wider range of farm sizes if producers are compensated for CO_2-e emission reductions. Without carbon payments, only large breeding swine farms benefit enough from economies of scale to make anaerobic digester construction profitable. We find that the production of renewable natural gas or compressed natural gas leads to a higher return than electricity generation, given the current price ratio of electricity to natural gas. However, the production of renewable natural gas may be hindered by high pipeline connection costs, which were not considered in the analysis. A higher electricity price (with or without carbon payments) could shift the end use away from natural gas.

With carbon payments, the construction of anaerobic digesters is more profitable on operations where the initial manure management system methane emissions are comparably higher, as is the case with the anaerobic lagoons common in warmer climates such as North Carolina. Regional variation in the construction of anaerobic digesters, as well as the biogas end use, may also be influenced by State policies. For example, some State incentives and policies could favor electricity over renewable natural gas production or vice-versa, independent of energy prices. One such example would be the Low Carbon Fuel Standard (LCFS) in California, which has spurred not only anaerobic digester construction but also compressed natural gas (for transportation fuel) as the end use.

Our results indicate biogas production (via anaerobic digesters) has the potential to provide a profitable alternative manure management structure for U.S. swine producers (depending upon specific farm characteristics, energy prices, and carbon market payments). Benefits associated with anaerobic digester adoption, such as production of local energy and compressed natural gas together with demand from consumers who have a high willingness to pay for low-carbon energy sources, can further bolster the adoption of anaerobic digesters by livestock producers in general, and swine in particular.

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