Journal of Agricultural and Applied Economics, 43,4(November 2011):569–590

Carbon Markets and Methane Digesters: Potential Implications for the Dairy Sector

Nigel Key and Stacy Sneeringer

Anaerobic digesters that capture and burn manure methane can provide a renewable source of energy and reduce greenhouse gas emissions. Paying producers for these emission reductions—either directly or through a carbon offset market—could substantially increase digester adoption. However, there is likely to be wide variation in the scale, location, and characteristics of adopters, so these policies could have long run structural implications for the livestock sector. Using a model of digester profits and data from a nationally-representative survey of dairy operations we estimate the likely distribution of digester adoption and profits under different carbon price scenarios.

Key Words: anaerobic digester, carbon offsets, climate change, distribution, livestock, methane

JEL Classifications: Q12, Q16, Q42, Q54, Q58

Methane digesters that collect and burn methane from manure can provide numerous benefits to livestock producers and the environment. Digesters can supply a renewable source of electricity that can power farm equipment or be sold. They can reduce odors from manure, lower the potential for surface water contamination, and aid in recycling manure solids for animal bedding material. Despite these benefits, anaerobic digesters have not been widely adopted: currently, there are only 167 systems operating in the United States, of which 137 are on dairies and 23 are on hog operations (U.S. Environmental Protection Agency [USEPA], 2011).

Recently, methane digesters have received attention because of their potential to reduce greenhouse gas emissions. Methane is a potent greenhouse gas and burning one ton of it is equivalent to eliminating about 24 tons of carbon dioxide.[1] Paying farmers for these carbon emissions reductions would provide a greater incentive to adopt digesters and therefore could reduce greenhouse gas emissions. Farmers could be directly compensated for these emission reductions or they could sell them in carbon offset

---

Nigel Key and Stacy Sneeringer are economists, Economic Research Service in the U.S. Department of Agriculture, Washington, DC.

The views expressed are those of the authors and do not necessarily correspond to the views or policies of Economic Research Service or the U.S. Department of Agriculture.

Senior authorship is shared by both authors.

[1] A single ton of released methane has the same global warming potential as 25 tons of carbon dioxide over a 100-year time period (Intergovernmental Panel on Climate Change, 2007, Table 2.14). Burning a ton of methane reduces its warming potential to the equivalent of 1 ton of carbon dioxide – a reduction equivalent to eliminating 24 tons of carbon dioxide. The global warming potential of 25 is based on the Intergovernmental Panel on Climate Change Fourth Assessment Report. Some other studies and the Official U.S. Greenhouse Gas Inventory use a global warming potential of 21 based on the earlier Intergovernmental Panel on Climate Change Second Assessment Report (1996). This value from the Second Assessment Report has been retained in the U.S. Greenhouse Gas Inventory calculations so that results are comparable across years (U.S. Environmental Protection Agency, 2010a, pp. 1–7, 1–8).

markets. In an offset market, producers who burn methane from a digester sell offsets to other greenhouse gas emitters who face emissions caps or who voluntarily offset their own emissions.

Currently, U.S. livestock operations have the option to sell manure-methane offsets in regional or voluntary offset markets, but the carbon prices in these markets have generally been low. However, future federal and state efforts to reduce greenhouse gas emissions could substantially raise carbon prices. In 2009, the U.S. House of Representatives approved climate legislation (the American Clean Energy and Security Act of 2009) that would have created a national carbon offset market estimated to result in a carbon price of $13 per ton carbon dioxide equivalent (USEPA, 2009). The climate legislation was not voted on by the U.S. Senate, and the prospects for future Federal Climate legislation are uncertain. None-the-less, several states are actively creating a market for emissions reductions. In particular, California and five other U.S. states and four Canadian provinces are developing a regional carbon trading regime as part of the Western Climate Initiative (Western Climate Initiative, 2010) in which livestock producers will likely be able to sell carbon offsets (California Environmental Protection Agency, 2011).

The additional income that could be earned from offsets or government programs paying for emissions reductions could make digesters profitable for many more farmers, but there is likely to be wide variation in the scale, location, and characteristics of the benefitting operations. Substantial economies of scale in construction and maintenance of methane digesters suggest the main beneficiaries of higher carbon prices would be larger-scale operations. In addition, offset markets usually require verification that emissions reductions yield carbon levels lower than original baselines.[2] Consequently, only operators of livestock facilities that historically emit substantial quantities of methane – e.g. dairy and hog operations with anaerobic manure storage facilities such as lagoons – are likely to be able to sell carbon offsets. Regional variation in retail electricity prices, the price received for power sold back to the grid, and on-farm demand for electricity will also influence the location, size, and characteristics of the farms that would benefit from adopting biogas recovery systems.

Little empirical research assesses the potential distributional impacts of higher carbon prices, or other policies that would pay farmers for methane emission reductions. Instead, most studies model digester adoption for particular regions, markets, or types of farms (e.g., Bishop and Shumway, 2009; Lazarus and Rudstrom, 2007; Leuer, Hyde, and Richard, 2008; Stokes, Rajagopalan and Stefanou, 2008). The research that attempts national-level analyses is USEPA (2006) and Gloy (2011). The Environmental Protection Agency (EPA) estimates that 6,900 mostly large-scale dairy and hog operations are potential candidates for installing biogas recovery systems. However, the EPA study does not include a benefit-cost analysis, instead defining candidates for digester adoption solely on the basis of size and manure management method. Gloy (2011) develops a general model of digester profitability for dairies to estimate the potential supply of carbon offsets from the sector, although he does not consider the potential distributional implications of a national offset market.

In this article we estimate the likely distribution of benefits to dairy operations from digester adoption under different carbon prices. Expanding on Gloy (2011) we develop a model of digester profitability based on farm size, manure management method, electricity prices, and digester costs to estimate how carbon price affects producers' decisions to adopt methane digesters. We parameterize the model using information from multiple case studies to reflect farm-level costs and experiences with energy production. State-level data are used to account for regional variation in electricity prices, methane emissions, and energy sources. We use the model to estimate discounted

---

[2] The determination of baseline emissions, and therefore what emissions reductions qualify for offsets varies somewhat across emission trading regimes. The Environmental Protection Agency guidelines suggest that the "emission baseline for a manure management methane collection and combustion project is the manure management system in place prior to the project" (USEPA, 2008).

digester net revenues for every farm in the 2005 dairy version of the nationally representative U.S. Department of Agriculture (USDA)-Agricultural Resource Management Survey (ARMS), and thereby predict the number, size, and location of farms adopting digesters at given carbon offset prices. Results provide insight into the distributional implications for the dairy sector and point to several policy approaches that could increase the number of small-scale producers benefiting from higher carbon prices.

Methane Emissions and Carbon Markets

Many livestock operations store manure mixed with water in lagoons, ponds, pits, or tanks, yielding anaerobic (without oxygen) conditions. In such conditions, the decomposition of manure produces a biogas containing about 60% methane (the remaining gas consists primarily of carbon dioxide, plus small amounts of toxic gases, including hydrogen sulfide, ammonia, and sulfur derived mercaptans). When manure is handled as a solid or deposited on fields it tends to decompose aerobically (with oxygen) and produce much less methane. The quantity of methane released also depends on climate (temperature and rainfall), with more methane generated at warmer temperatures.

In 2008, the "Agriculture" sector, as defined by the United Nations Framework Convention on Climate Change, generated 6.1% of total U.S. greenhouse gas emissions (USEPA, 2010a, pp. 2–12);[3] methane from manure management comprised 10.5% of these agricultural emissions.[4] Dairy and hog operations, which often use anaerobic storage, were responsible for 43.1% and 43.6% of methane emissions from manure management, respectively (USEPA, 2010a, Table 6–6). Beef cattle, sheep, poultry, and horses were collectively the source of only 13.3% of total manure methane, as these sectors generally handle manure aerobically. Geographic shifts and increasing scale of production have led to a greater share of dairy cattle and swine in facilities using anaerobic storage, resulting in a 54% increase between 1990 and 2008 in methane emissions from manure handling (USEPA, 2010a, Table 6–2).

A methane digester, also called an "anaerobic digester," "biogas recovery system," or "biodigester" collects manure from anaerobic storage facilities, optimizes it for the production of methane by adjusting temperature and water content, captures the resulting biogas, and burns it for heat or electricity generation. There are three main of types of digesters that can be used with either lagoon or pit-based manure storage facilities: complete-mix, plug flow, and covered lagoon. A complete-mix digester is a large concrete or steel container, usually circular in shape. A plug-flow digester is often a below-ground trough with an air-tight expandable cover. A covered lagoon digester is an earthen pond fitted with an impermeable cover on its surface. Covered lagoon digesters are generally less expensive to construct than complete-mix and plug flow digesters, but lagoon digesters cannot be heated to increase methane output in cooler climates.

Burning methane leads to a considerable reduction in its potential to warm the atmosphere; as such, biogas recovery systems have received attention in efforts to reduce global warming. There is an expanding international effort to reduce methane emissions using market mechanisms. The U.S. government through the EPA and other agencies has partnered with 38 other countries in the Global Methane Initiative (formerly Methane to Markets Partnership) to promote methane recovery and use. The initiative targets several sources of methane emissions including livestock waste management (Global Methane Initiative, 2011). In 2010, the United States pledged $50 million over 5 years to the Global Methane Initiative (USEPA, 2010b).

---

[3] As defined by the United Nations Framework Convention on Climate Change, "Agriculture" sector emissions do not include emissions from those inputs to agricultural production that are attributed to other sectors, including fertilizer production, transportation, and electricity generation.

[4] Livestock also emit methane from enteric fermentation produced during digestion. In 2008, over three times as much methane was released from enteric fermentation as from manure management (USEPA, 2010, Table 2–8).

Pricing Emissions Reductions

One approach to mitigate greenhouse gas emissions from manure management is to compensate farmers for emissions reductions, either through government payments or a carbon offset market (other approaches include cost-share programs, technology or performance standards, emissions taxes, and subsidies for digester-generated electricity.) Such a market allows individuals or firms to "offset" their own emissions by paying someone else to reduce greenhouse gas emissions. Carbon offsets can be exchanged in compliance or voluntary markets. Compliance markets usually operate under a cap-and-trade regime that places a legal limit on the quantity of greenhouse gases that regulated firms can emit in a particular time period. To meet their emissions targets, regulated firms could reduce their own emissions or purchase emissions permits from other "capped" firms. Alternatively, such firms could pay non-regulated emitters, such as livestock operations, to reduce emissions by purchasing offsets.

Compliance markets have been established at the international, national, and regional levels. Regimes that govern international compliance markets include the Kyoto Protocol and the European Union's Emissions Trading Scheme. In the United States, 10 eastern states recently implemented the Regional Greenhouse Gas Initiative (RGGI), the first mandatory market-based greenhouse gas reduction effort in the United States Under the RGGI, the capped sector (power generation) can purchase offsets from projects that reduce manure-based methane emissions. In 2009, the U.S. House of Representatives approved climate change legislation (H.R. 2454, the American Clean Energy and Security Act of 2009) that, if signed into law, would have established a national cap-and-trade system and provided a further opportunity for farmers to sell offsets from reducing their manure methane emissions.

Voluntary offset markets function outside of compliance markets and allow companies and individuals to purchase carbon offsets without being legislatively compelled. For example, individuals might seek to offset their travel emissions or firms might seek to compensate for emissions related to their production. In the United States, the Chicago Climate Exchange (CCX) is a voluntary, but legally binding, carbon trading regime in which methane emissions reductions from livestock operations can qualify as offset projects.

In the major international compliance markets, carbon offset prices have ranged between \$15 and \$30 per ton of carbon dioxide equivalent emissions in the last decade.[5] In overseas voluntary markets, prices have ranged between \$5 and \$15/ton of carbon dioxide equivalent emissions (tCO_2e). In the United States, offset prices have been lower. The average price for carbon allowances in the RGGI has ranged between \$1 and \$3/tCO_2e between 2008 and 2010 (RGGI, 2011). The CCX carbon price has ranged between \$1 and \$7/tCO_2e since 2004, but has been trading at its floor price under \$1/tCO_2e between 2009 and 2010 (Chicago Climate Exchange, 2010). While a carbon price under a national cap-and-trade system is hypothetical, the EPA estimated that in the near-term, the proposed House bill (H.R. 2454) would have resulted in a price of \$13/tCO_2e (USEPA, 2009). However, the carbon price could fall short of or exceed this level over the medium or long term.

A livestock operation's potential offset revenues from a digester system depend on its pre-offset program "baseline" emissions, which are a function of type of manure storage and handling. Offset programs usually require documentation of baseline emissions and certification that emissions are reduced below this level (the so-called "additionality" requirement). Since certification is not without costs, only operations that generate significant quantities of methane would likely find enrolling in offset programs cost-beneficial. This largely limits the pool of potential offset providers to operations using anaerobic manure storage facilities such as lagoon or pit systems, which are largely in the

---

[5] Offsets are measured in tons of carbon dioxide equivalent emissions. Reductions in other greenhouse gases such as methane are converted to an equivalent quantity of carbon dioxide based on that gas's relative global warming potential.

swine and dairy sectors. Operations with aerobic manure management would likely not qualify to sell offsets by installing digesters, as this would require switching to anaerobic facilities with higher emissions.

Factors Affecting Digester Profits

Several factors influence the profitability of methane digesters, and consequently determine the characteristics of the producers who are likely to adopt the technology. These factors include the type of manure management system, the start-up and ongoing costs of digester technology, the price of electricity, and on-farm electricity expenditures. Many of these factors vary with operation size and region, suggesting that digester adoption and subsequent benefits will also vary by size and region.

A concentrated supply of methane is necessary for the effective running of an electrical generator associated with a digester. As such, only operations that store manure in anaerobic conditions generating significant quantities of methane are viable candidates for biogas recovery systems (unless an operation converts to a different management method). Anaerobic manure management systems can be categorized as either "lagoon" or "pit" type systems (these general categories encompass several types of manure management systems, as detailed in Appendix B). The 2005 ARMS data indicate that about 50% of dairies have an anaerobic manure system, 16% use an aerobic system (open slab or covered shed), and 34% report having no manure storage system.

Anaerobic manure management systems are generally less common on small-scale operations. For example, only 46% of dairy operations with fewer than 250 head use anaerobic manure management systems compared with 73–88% of operations in larger size categories (Table 1). Larger operations are also more likely to have lagoon manure systems, which have higher initial methane emission rates than pit systems. Consequently, larger operations produce relatively more methane per head. For example, dairies with more than 2,500 head are responsible for 18.8% of total emissions, though only produce 13.0% of total output (gross value of dairy enterprise production).

There is substantial variation across regions in manure management methods and consequently in methane emissions (Table 1). Dairies in the West and South are much more likely to have lagoon systems than those in the Midwest and Northeast, in part because of differences in climate. Dairies in the West and South produce 59.2% of all emissions from the dairy sector, despite producing only 42.5% of output.

Farm size is an important determinant of digester profitability because it is associated with manure management methods and because of economies of scale in construction and maintenance of methane digesters. As illustrated by the case study data described below, the costs of constructing, maintaining, and repairing the storage facility and generator generally decline on a per-unit basis. Finally, there are numerous fixed transaction costs associated with selling electricity or certifying and marketing offsets that do not vary substantially with farm size. Larger operations can spread these fixed costs over a larger revenue base.

Electricity price, on-farm use, and digester generation are also key determinants of digester profitability. As an operation's use and the retail price of electricity increase, so will the potential value of a digester. The ARMS data indicate that an average dairy with 154 head of cows used 128,918 kWh of electricity per year, or 1,048 kWh per head. While larger operations use more electricity overall, they use less per head (Table 1). Electricity use also varies across regions: on average, Midwestern dairies use 1,102 kWh of electricity per head compared with Southern dairies' 791 kWh per head, reflecting differences in average operation size and climate. Regional variation in the retail price (Table 1) may also yield heterogeneity in potential digester value. For example, dairies in the West paid an average of 5.8 cents per kWh compared with 8.5 cents in the Northeast.

In some cases, the value of the digester-generated electricity depends on an operator's ability to time generation to coincide with on-farm use. This coordination problem can be mitigated or eliminated in states with "net metering" laws. Under net metering, when surplus electricity is produced on-farm, the electricity meter spins backward, effectively saving the electricity until it is needed and replacing purchased electricity at

Table 1. Factors Determining Digester Profits Vary by Dairy Size and Region

	Unweighted Number of Farms in Category	Weighted Number of Farms in Category	% Of Total Gross Value of Production	% Of Total Methane Emissions	Proportion with Lagoon or Pit Manure System	Proportion with Lagoon (could also have pit)	Electricity Use per Head (kWh/year)	Electricity Price ($/kWh)
All farms	1,814	52,237	100%	100%	0.50	0.11	1,048	0.069
					(0.50)	(0.31)	(704)	(0.015)
Number of Head								
>2500	35	248	13.0%	18.8%	0.73	0.48	494	0.078
					(0.44)	(0.50)	(335)	(0.018)
1,000–2,499	116	917	18.3%	21.6%	0.81	0.39	723	0.081
					(0.39)	(0.49)	(904)	(0.016)
500–999	186	1,615	14.1%	17.1%	0.83	0.42	743	0.079
					(0.38)	(0.49)	(372)	(0.015)
250–499	248	3,040	13.5%	16.4%	0.88	0.40	775	0.068
					(0.32)	(0.49)	(443)	(0.019)
<250	1,229	46,417	41.1%	26.2%	0.46	0.07	1,085	0.068
					(0.50)	(0.25)	(714)	(0.015)
Region								
West	304	6,095	33.3%	44.2%	0.79	0.38	893	0.058
					(0.40)	(0.49)	(608)	(0.022)
Midwest	647	28,438	36.4%	25.7%	0.46	0.06	1,102	0.064
					(0.50)	(0.23)	(698)	(0.006)
South	394	4,034	9.2%	15.0%	0.70	0.27	791	0.065
					(0.46)	(0.44)	(706)	(0.013)
Northeast	469	13,670	21.1%	15.1%	0.41	0.04	1,080	0.085
					(0.49)	(0.19)	(728)	(0.013)

Notes: Statistics are weighted values. All values are in 2009 dollars. Standard deviations are shown in parentheses.
Source: 2005 USDA Agricultural Resource Management Survey, Dairy Version.

the retail price. Over the billing period, the operation is only billed for its net electricity usage. Forty states have adopted net metering laws, although their specifics vary (Database for State Incentives for Renewable Energy [DSIRE], 2010). While many states' net metering laws have maximum generator sizes above those found in digester systems, in some states the maximum generator size is lower than what would be optimally used with a digester (DSIRE, 2010).[6] Operators in states facing a binding generator size limit may not obtain the full retail price for the electricity they generate but do not consume.

Net metering laws can allow a farm to receive the retail price for generated electricity used on-farm. However, excess electricity that is sold to the grid may only command the wholesale price (the price that utilities pay for electricity from large-scale generators). Since wholesale prices for electricity are below retail, electricity that is sold would be worth less than that used on-farm. However, since manure-derived electricity is from a renewable source, the selling price for surplus electricity could enjoy a substantial premium over wholesale. About 30 states require utilities to purchase a share of power from renewable sources, including from biogas systems (U.S. Department of Energy, 2009).

Climate change legislation that raises the price of carbon could also be expected to increase electricity prices. Regions where electricity is generated using more carbon-intensive methods would likely see the larger price increases.

Methane digesters can offer other benefits to livestock producers beyond carbon offset sales and electricity generation, which could affect their adoption decision. Covers and well-managed anaerobic digestion can substantially reduce odors from lagoon manure storage (Pain et al., 1990; Welsh et al., 1977; Wilkie et al., 1995). Digesters can reduce the potential for surface water contamination from pathogens which can be hazardous to animal and human health (Demuynck, Nyns, and Naveau, 1985). By excluding rainwater, a lagoon cover can substantially increase a lagoon's storage capacity and thereby reduce the size or number of lagoons required per operation (Shepherd et al., 2010). An anaerobic digester can also be designed to accept food waste from local food processors or manure from local operations, which can provide additional "fuel" for the digester and a potential source of revenue from "tipping fees" charged to the waste depositors (Bishop and Shumway, 2009).[7] Farms that use a solids separator can sell the collected solids as bedding material or use them on-farm for bedding. Separated solids can be sold as a soil amendment, which can provide a significant source of income (Leuer, Hyde, and Richard, 2008).

Empirical Framework

We use a model of digester profitability to predict adoption rates and revenue by size and region. Our approach is similar to Gloy (2011), but we extend his analysis by allowing the adoption decision to be based on the digester project's net present value (NPV) instead of annual profits, estimating parameters using case study data, setting electricity prices to be a function of the carbon offset price, adding transactions costs associated with carbon offset market participation, and incorporating electricity production variation by state for lagoon-based digesters.

Investment Model

We use the net present value to assess the profitability of a digester project. The NPV is the sum of future net revenues (e.g., revenues from electricity and carbon offsets minus capital and variable costs) over the life of the project,

---

[6] In two compilations of digester case studies for dairies, generator capacities ranged from 75kW to 775kW (Dairy Power Production Program, 2006; Kramer, 2004). Maximum generator sizes for net metering in the states in our sample range from 10kW in Indiana to no specified limit in Arizona and Ohio (DSIRE, 2010).

[7] In the case study analyzed by Bishop and Shumway (2009), accepting food waste was found to be profitable for the digester owner, while transportation costs made accepting manure from local farms unprofitable. A potential downside to using food waste is that it can elevate the nutrient content of the manure spread on fields. In some regions, land available for manure spreading is limited so extra manure nutrients can increase manure spreading costs or the risk of water pollution.

discounted to their present values. An operator who is considering investing in a methane digester has two related decisions: the decision to construct a digester that will produce electricity and the decision to sell carbon offsets. An operator with a digester will also sell offsets if the discounted stream of offset revenues exceeds the expected discounted transaction costs of participating in the market. Hence, there are three possible outcomes:

$$(1)\qquad \begin{array}{l} NPV_D \leq 0 \text{ and } NPV_D + NPV_M \leq 0\text{:} \\ \quad \text{no investment} \\ NPV_D > 0 \text{ and } NPV_M \leq 0\text{: construct digester} \\ \quad \text{but do not sell offsets} \\ NPV_D + NPV_M > 0\text{: construct digester and} \\ \quad \text{sell offsets} \end{array}$$

where NPV_D is the net present value of the digester and NPV_M is the net present value of participating in a carbon offset market. A fourth possibility would be to construct a digester without an electricity generator and to flare the methane and sell offsets. This scenario is not considered in this study.

The NPV of the digester enterprise for operation *i*, located in state *s*, using manure management facility type *f* is:

$$(2)\qquad NPV_D = \sum_{t=0}^{T} \left[\frac{R_{isft} - C_{ift}}{(1+d)^t} \right],$$

where *T* represents the lifespan of the digester, *t* indexes time, *d* is the discount rate, R_{isft} is the value of generated electricity (used on-farm and/or sold), and C_{ift} is the cost of constructing and maintaining the digester.

The value of electricity generated by the digester R_{isft} depends on time and on whether the quantity generated on-farm E_{if}^G is less than or greater than the quantity used on-farm E_i^U:

$$(3)\qquad R_{isft} = \begin{cases} 0 & \text{if} \qquad\qquad\qquad\quad t = 0 \\ P_s^{ER} \cdot E_{if}^G & \text{if} \quad 1 \leq t \leq T \quad \text{and} \quad E_{if}^G \leq E_i^U \\ P_s^{ER} \cdot E_i^U + P_s^{EW} \cdot (E_{if}^G - E_i^U) & \text{if} \quad 1 \leq t \leq T \quad \text{and} \quad E_{if}^G > E_i^U \end{cases}.$$

If the quantity generated is less than or equal to what is used on-farm, then the generated electricity is valued at the buying ("retail") price P_s^{ER}. If more electricity is generated than is used on-farm, then this surplus electricity ($E_{if}^G - E_i^U$) is valued at the selling ("wholesale") price P_s^{EW}.

Since the power generation sector is likely to be affected by climate change legislation, we allow the retail and wholesale electricity prices to depend on the carbon intensity of the state energy sources and the price of carbon. Specifically, the retail price of electricity is a function of the observed current retail price P_s^E plus an increase that is proportional to the average carbon dioxide equivalent emissions rate from power plants ϕ_s (in pounds per kW/h) times the carbon price P^M:

$$(4)\qquad P_s^{ER} = P_s^E + 0.00045 \cdot \phi_s \cdot P^M,$$

where we multiply by 0.00045 to convert pounds to metric tons.

The selling price of farm-generated electricity will likely also increase with the carbon price. For simplicity, the selling price of electricity is assumed to be less than the retail price by a fixed amount θ^W:

$$(5)\qquad P_s^{EW} = P_s^{ER} - \theta^W.$$

Electricity generation depends on the type of manure storage and the quantity of manure produced. Since the quantity of manure produced is a linear function of the number of head, the quantity of electricity generated can be expressed as:

$$(6)\qquad E_{if}^G = e_{sf} \cdot N_i.$$

Pit systems generate substantially more electricity per head than lagoon systems. This is mainly because pit systems are heated in the cooler months to optimize methane production, and therefore electricity output. Since covered lagoon digesters cannot be heated, the amount of electricity generated per head will depend on the climate. To account for differences in generation capacity in lagoon systems, we adjust e_{sf} for lagoons by the methane emissions in the state where the operation is located:

$$(7)\quad e_{sf} = \overline{e_{sf}} \cdot \frac{m_{sf}}{\bar{m}}, \quad for \quad f = \text{lagoon},$$

where $\bar{m}$ and $\overline{e_{sf}}$ are the average methane emission factor and electricity generation for the lagoon operations in the case study sample (described below). Electricity generation per head for operations with pits (having complete mix or plug flow digesters) is assumed not to vary across states, because methane production can be maintained year-round by heating.

The costs of the biogas system consist of the capital investment K_{if} at the beginning of the project ($t = 0$) plus maintenance and operating costs V_{if} for years 1 through T:[8]

$$(8)\quad C_{ift} = \begin{cases} \lambda K_{if} & \text{if} \quad t = 0 \\ V_{if} & \text{if} \quad 1 \leq t \leq T \end{cases}$$

Capital investment includes costs of the constructing and designing the pump, pit, heating, building, solids separator, effluent holder, generator, and power lines. A share of capital investment $1 - \lambda$ is born by a government cost-share program. The capital investment increases with the scale of the operation at a decreasing rate that depends on parameters a_f and b_f. The cost of this investment is:

$$(9)\quad K_{if} = a_f \cdot (N_i)^{b_f}$$

Annual variable costs V_{if} include costs of maintenance and repairs. Following past studies, we assume that variable costs are proportional to the quantity of electricity generated (which depends on farm size and type of manure handling facility):

$$(10)\quad V_{if} = v \cdot E^G_{if} = v \cdot e_f \cdot N_i.$$

The NPV of participating in a carbon offset market is given:

$$(11)\quad NPV_M = \sum_{t=0}^{T} \left[\frac{P^M \cdot M_{isft} - Z_t}{(1 + d)^t} \right],$$

where P^M is the price of carbon offsets (\$/t CO_2e), M_{isft} is the quantity of methane that could be sold in the offset market, and Z_t represents transaction costs associated with selling carbon offsets.

The quantity of methane produced and burned that would qualify for offset sales is:

$$(12)\quad M_{isft} = \begin{cases} 0 & \text{if } t = 0 \\ N_i \cdot m_{sf} \cdot 24 \cdot 365 \cdot 0.001 & \text{if } 1 \leq \text{t} \leq \text{T} \end{cases}$$

where N_i is the number of head and m_{sf} is the state methane emission factor (kg CH4 per head per day), which is multiplied by 24 (t CO_2e/t CH_4), 365 (days per year), and 0.001 (tons per kg) in order to express M_{isft} in tons of carbon dioxide equivalents (t CO_2e).

Transaction costs associated with selling carbon offsets include the initial one-time fixed start-up cost for entering the offset market (Z^E) plus on-going annual costs of monitoring and verification (Z^V):

$$(13)\quad Z_t = \begin{cases} Z^E & \text{if} \quad t = 0 \\ Z^V & \text{if} \quad 1 \leq t \leq T. \end{cases}$$

The NPV approach used in this analysis is deterministic in the sense that real prices are assumed to be known and constant by the operator throughout the economic life of the digester. In fact, many of the benefits and costs associated with a digester are uncertain and variable. For example, the price of electricity – both the retail and selling price – is likely to fluctuate depending on global economic conditions and policy changes that are difficult to predict. There is also uncertainty about digester variable costs and methane and electrical output, which could fluctuate from year to year depending on system reliability and unexpected weather or mechanical failures. Although we do not explicitly account for the stochastic nature of the determinants of digester benefits and costs, we characterize the range of possible outcomes using sensitivity analyses for the key variables.

If we had information about the probability distribution of prices and other model parameters, then it would be possible to estimate the distribution of the NPV, which would provide a more accurate representation of a digester project's value (Leuer, Hyde, and Richard, 2008). A further extension could also take into account the irreversible nature of a digester investment. Stokes, Rajagopalan, and Stefanou (2008) use a real option framework to estimate the value to a producer of the option to delay investment in

---

[8] This study does not explicitly consider costs associated with obtaining air quality permits or costs associated with installing equipment to comply with air quality standards. Recent news accounts suggest that in some regions or states (such as California) these costs could be substantial (Huffstutter, 2010).

a digester. The authors find that producers would require significant financial compensation – perhaps in the form of assured grant funding or greater electricity prices to immediately adopt the technology, rather than delay investment even if the NPV is positive.

By not accounting for the stochastic nature of a digester's benefits and costs or the option value of delaying investment, we may overestimate the value of digester systems and consequently overestimate digester adoption. However, as noted in the text, we do not account for some possible benefits from a digester such as from "tipping fees" or bedding sales, which reduces our estimate of the project's value. In addition, the study does not account for non-market benefits from a digester such as odor control, or reduced water or air pollution, which also causes us to underestimate the private and social benefits of the project. The model used in this study does not account for the value of these additional benefits because they can vary widely across farms and regions, and we do not have sufficient data to estimate values of these benefits for individual farms used in the policy simulations.

Case Studies and Parameter Values

The model parameters, units, and data sources used are shown in Table 2. We estimate electricity generation and cost parameters using information from multiple case studies drawn from compilations (Dairy Power Production Program, 2006; Kramer, 2004), individual project descriptions (Bishop and Shumway, 2009), and a dataset of vendor quotes for prospective digester projects (described in USEPA, 2010c).[9] Other case studies and certain vendor quotes were excluded from consideration if they did *not* meet the following conditions:

1) The digester was built in 2000 or later to reflect current technology. (This excluded certain operations listed in Kramer, 2004; Lazarus and Rudstrom, 2007; Lusk, 1998; and Wright and Perschke, 1998.)
2) The case study farm or vendor quote included a generator for electricity production. This excluded digesters that were constructed solely for odor control and those to be used just to flare methane.
3) The digester was located on an individual farm operation. This excluded digesters at research stations and those that combined manure or other byproducts from multiple sources. This also excluded data collected and synthesized by other researchers or generated by economic models (e.g., Crenshaw, 2009; Gloy, 2011; Leuer, Hyde, and Richard, 2008; Stokes, Rajagopalan, and Stefanou, 2008).
4) The case study provided information on the type of digester, specifically whether it was a lagoon- or pit-based system.
5) The case study or vendor quote provided start-up cost estimates.
6) For case studies, the name of the farm was provided or the farm could be uniquely distinguished in another fashion (e.g., it was in a state with no other case studies). This was required to avoid double-counting, as several digesters were the subjects of multiple case studies.

We identified 14 case studies and 31 vendor quotes that satisfied the above conditions. The average farm size, capital and variable costs, and per-head electricity output for the farms used in the analysis are displayed in the Appendix A, Table A1. We update all digester costs to 2009 dollars using *Chemical Engineering's* Plant Cost Index (see www.che.com/pci). For the 37 case studies or vendor quotes for pit-based digesters, investment costs average \$958/cow and range from \$274/cow to \$1,672/cow; for the eight lagoon-based digester case studies or vendor quotes, investment costs average \$863/cow and range from \$238/cow to \$1,564/cow.

Construction costs per head for the case study or vendor quote operations decline with farm size (see Appendix A, Table A1). To estimate the cost model parameters (a_f and b_f from Equation [9]) we use ordinary least squares and a log-log functional form:

$$\text{(14)} \qquad \ln\left(K_{if}\right) = \alpha_f + \beta_f \ln\left(N_{if}\right) + \varepsilon_{if},$$

where K_{if} is total observed capital construction costs for case study operation i using manure

---

[9] In earlier work, we used a different set of case studies to estimate capital and variable cost parameters and electricity generation parameters (Key and Sneeringer, 2011).

Table 2. Model Parameters, Values, Description, and Sources

	Value	Units	Description	Source
Estimated Parameters				
$e_{f\,=\,pi}$	729	kWh/cow	Electricity produced per cow at an operation utilizing a pit-based digester	Averages based on case studies
$e_{f\,=\,lagoon}$	$450 \times \frac{m_{sf\,=\,lagoon}}{\bar{m}}$	kWh/cow	Electricity produced per cow at an operation utilizing a lagoon-based digester	
$v_{f\,=\,pit}$	0.046	\$/kWh	Variable cost for pit-based digester	
$v_{f\,=\,lagoon}$	0.037	\$/kWh	Variable cost for lagoon-based digester	
$\bar{m}$	0.645	kg CH4 per cow per day	Average state methane emission factor for lagoon digesters in case studies	
$a_{f\,=\,pit}$	17,654	No unit	Capital investment cost parameter for pit-based digesters	Regression estimates based on case studies
$b_{f\,=\,pi}$	0.596	No unit		
$a_{f\,=\,lagoon}$	39,020	No unit	Capital investment cost parameter for lagoon-based digesters	
$b_{f\,=\,lagoon}$	0.454	No unit		
P_s^E	Varies by state	\$/kWh	State retail electricity price for industrial sector	U.S. Energy Information Administration, 2010, Table 5.6B
m_{sf}	Varies by state and manure management method	kg CH4 per cow per day	State methane emission factors by manure management method	Chicago Climate Exchange, 2009, Tables 3–4
ϕ_s	Varies by state	lbs/kWh	Carbon emissions factor	U.S. Department of Energy, 2000, Table 4
θ^W	0.031	\$	Difference between wholesale and retail prices	U.S. Energy Information Administration, 2010
Assumed Parameters				
d	0.05	rate	Discount rate	
t	15	years	Economic life of a digester	
Z^E	10,000	\$	Initial offset market transaction costs	
Z^V	3,000	\$	Annual offset market transaction costs	
P_M	Varies by policy	\$/t CO_2e	Price per ton of CO_2e	
λ	Varies by policy	%	Percentage of capital investment paid by operator after cost-share program; $(1 - \lambda)$ is the portion paid by the program.	

facility type f. The parameters in Equation (9) are computed from the estimated parameters as follows: $\alpha_f = \exp(\hat{\alpha}_f)$ and $b_f = \hat{\beta}_f$. We estimate separate regressions for the pit and lagoon operations (shown in the Appendix A, Table A2). The coefficients are plausible and statistically significant at the 10% level.[10]

For the variable cost parameter v from Equation (10) we use simple averages for the nine case studies for which variable costs are reported (Appendix A, Table A1). For pit systems, the parameter value is \$0.046/kWh; for lagoon systems it is \$0.037/kWh.

We estimate the electricity generation parameter e_{sf} separately for lagoon and pit systems as the average values from eight pit operations and four lagoon case studies (Appendix A, Table A1). Since the lagoon case studies are all located in California, we adjust the electricity generation parameter for lagoons by multiplying by the ratio of the individual observation's state emission factor and the California emissions factor. This accounts for state-level differences in methane emissions, and consequently, in electricity generation.

For state electricity prices, we use the 2009 retail electricity prices for the industrial sector, which includes agriculture (U.S. Energy Information Administration, 2010a, Table 5.6.B).[11] In the "Sensitivity Analyses" section, we illustrate the implications of relaxing the assumption that operations receive the full retail value for the electricity they generate. Examining the effects of a 25% lower rate allows us to consider what may happen if operations are in states without net metering laws, are in states with net metering laws but with low maximum generator sizes, or receive less than the retail rate for the electricity generated for other reasons.[12] We also examine the effect of a 25% higher retail rate to consider the case where operations instead pay residential rates for electricity (rather than industrial), which are generally higher.

The average retail price of electricity in the United States (all end uses) in 2008 was 9.8 cents per kilowatt-hour (kWh), with distribution and transmission costs comprising 3.1 cents per kWh (generation comprises the remaining 6.7 cents) (U.S. Energy Information Administration, 2010b). Accordingly, we define the difference between the retail and wholesale prices as 3.1 cents, which is assumed not to vary across states. The case studies indicate that electricity selling prices range widely, even within an individual state.[13] In the "Sensitivity Analyses" section we illustrate scenarios in which the selling price is substantially lower and higher than \$0.031 below the retail price to reflect potential experiences with renewable energy policies (higher prices) and difficulty selling electricity to the grid (lower prices).

The methane emission factors for manure management m_{sf} are based on Intergovernmental Panel on Climate Change tier 2 standards (Chicago Climate Exchange, 2009, Tables 3–4). The carbon emissions factors ϕ_s for electricity use by region are from the Department of Energy's publication "Carbon Dioxide Emissions from the Generation of Electric Power" (U.S. Department of Energy, 2000). We assign the same carbon emissions factor to each state within the region.

We begin by assuming that farmers pay 75% of the full capital investment for digester projects, with government cost-sharing programs

---

[10] One potential concern with the lagoon parameter estimates stems from the fact that all the lagoon case studies were located in California. It is possible that lagoon size (and consequently costs) will vary with climate – with lagoons in cooler climates being larger to allow for sufficient manure decomposition over the year. We were unable to account for this possibility because we lack information on how the costs of constructing a lagoon digester vary based on location or climate.

[11] The U.S. Energy Information Agency defines the industrial sector "encompasses the following types of activity manufacturing (NAICS codes 31–33); agriculture, forestry, fishing and hunting (NAICS code 11); mining, including oil and gas extraction (NAICS code 21); and construction (NAICS code 23). Overall energy use in this sector is largely for process heat and cooling and powering machinery, with lesser amounts used for facility heating, air conditioning, and lighting."

[12] Because state net metering laws are in flux (there has been a rapid movement toward more states adopting net metering laws) we do not attempt to model specific policies at the state level.

[13] For example, the Dairy Power Production Program (2006) notes that individual digester projects within the state of California received between \$0.03 and \$0.10/kWh for net electricity generation. In 2006 the California industrial price for electricity was \$0.109/kWh.

covering 25%. In our sensitivity analysis we examine the effect of modifying this assumption to show effects of reducing the government cost-sharing rate to 0% and raising it to 50%.

We apply the model to each farm included in the 2005 Dairy Production Practices and Costs and Returns Report, which is part of the Agricultural Resource Management Survey (ARMS). The ARMS is a restricted-use dataset compiled by the National Agricultural Statistics Service in conjunction with the Economic Research Service of the U.S. Department of Agriculture. The ARMS contains information on the number and type of animals, type of manure management system, and costs of electricity consumed. More information about the ARMS data and variables is given in Appendix B.

Results

Table 3 displays the potential digester adoption rates and estimated revenues by size and region for dairies when the offset price is \$13/tCO_2e and \$26/tCO_2e.[14] Results indicate that even at the moderate carbon price of \$13/tCO_2e, offset sales could provide a substantial new source of revenues for farms with digesters. At this price, the revenue from offset sales represents 62% of the gross present value of the digester for dairies (electricity generation is responsible for the remaining 38%). At the higher carbon price of \$26/tCO_2e, offset sales represent 72% of the present value of gross returns.

There is a positive relationship between farm size and digester adoption rates. With an offset price of \$13/tCO_2e, no dairies with fewer than 500 head would find it profitable to adopt a digester, compared with 23.6% of dairies with 500–999 head, 42.5% of operations with 1,000–2,499 head, and 65.6% of operations with more than 2,500 head. A higher carbon price lowers the size threshold above which farms find it profitable to operate a digester, and increases the number of farms that would adopt a digester. At a carbon price of \$26 per ton, 0.1% of dairies with fewer than 250 head, 33.4% of dairies with 250–499 head, 48.9% of dairies with 500–999 head, and over 70% of dairies with over 1,000 head would find it profitable to adopt a digester.

Net revenues from digesters flow mainly to large-scale operations. With a carbon price of \$13, the NPV of digesters on dairies with at least 2,500 head is \$361 million or 63% of total value of digesters in the dairy sector. Dairies with at least 1,000 head would earn 93% of the NPV, while no dairies with fewer than 500 head would find a digester profitable. While digester profits accrue predominantly to large farms over a range of carbon prices, higher prices increase the number of smaller farms that could benefit from an offset program, and cause the distribution of benefits to become somewhat less skewed toward the largest operations. For example, dairies with at least 2,500 head earn 100% of digester profits with no offset market compared with 63% when the offset price is \$13/tCO_2e and 42% when the price is \$26/tCO_2e.

Regional Variation

Figure 1 illustrates, for each state in the sample, the number of operations on which digesters are predicted to have a positive NPV when carbon offsets are priced at \$13/tCO_2e and \$26/tCO_2e. The data used to construct the figures are drawn from the USDA ARMS 2005 survey of dairy producers, which was conducted only in the states accounting for most dairy production.

Digester adoption rates would be highest in the states in the West, reflecting the region's prevalence of anaerobic systems, particularly lagoons. At a carbon price of \$13/tCO_2e, dairies in the West receive 60.6% of total digester value, despite producing only 33% of total dairy production. The higher income from digesters in the West mainly reflects the larger scale of production in that region, but also reflects the region's large share of anaerobic systems (the West produces 44% of total methane emissions, as shown in Table 1).

The figure shows that with an offset price of \$13/tCO_2e, there would be over 400 dairies in California, and between 50 and 100 dairies in Arizona, Florida, New Mexico, New York, and Texas that would find it profitable to adopt

---

[14] With no market for carbon offsets (a carbon price of zero) we estimate that digesters would have a positive NPV on 18 dairies.

Table 3. Methane Digester Adoption and Revenues for Dairies

			For those who adopt. . .				
	Number of Farms that Adopt	% of Farms in Category that Adopt	Revenues from Offset Sales (million $)	Value of Generated Electricity (million $)	Net Revenues from Digester (million $)	Average Net Revenues from Digester per Farm ($)	Average Net Revenues from Digester per Head ($)
				(Carbon Price = $13/tCO2e)			
All farms	934	1.8%	$1,083	$669	$574	$615,361	$252
Number of Head							
>2500	163	65.6%	$471	$300	$361	$2,219,935	$443
1,000–2,499	390	42.5%	$401	$252	$172	$440,541	$281
500–999	381	23.6%	$211	$117	$42	$109,363	$141
250–499	0	0.0%	$0	$0	$0	$0	$0
<250	0	0.0%	$0	$0	$0	$0	$0
Region							
West	556	9.1%	$642	$403	$348	$625,977	$228
Midwest	84	0.3%	$102	$54	$48	$573,410	$283
South	176	4.4%	$176	$129	$89	$506,676	$274
Northeast	118	0.9%	$163	$82	$90	$756,203	$310
				(Carbon Price = $26/tCO2e)			
All farms	2,717	5.2%	$3,314	$1,285	$2,045	$752,716	$558
Number of Head							
>2500	181	73.0%	$978	$353	$866	$4,785,184	$1,021
1,000–2,499	678	74.0%	$1,083	$541	$689	$1,016,404	$668
500–999	790	48.9%	$710	$250	$362	$458,020	$669
250–499	1,015	33.4%	$524	$136	$126	$123,821	$335
<250	54	0.1%	$19	$6	$2	$46,152	$200
Region							
West	1,460	24.0%	$1,884	$710	$1,196	$819,513	$591
Midwest	459	1.6%	$435	$177	$213	$464,181	$381
South	511	12.7%	$533	$215	$332	$650,470	$616
Northeast	287	2.1%	$461	$184	$304	$1,056,104	$574

Note: All values are in 2009 dollars.

Source: Authors' calculations.

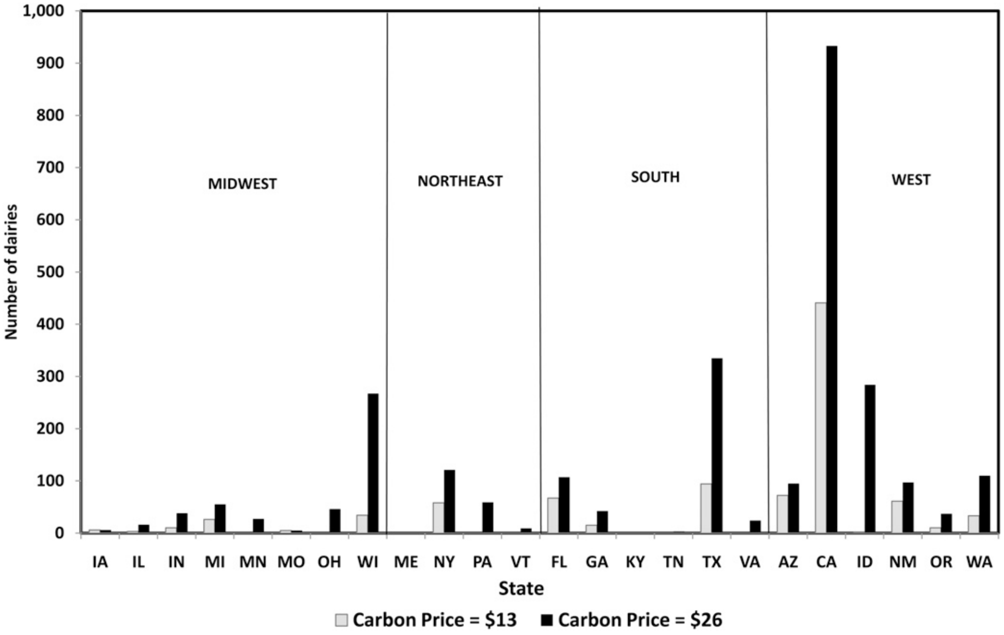

Figure 1. Number of Dairies Predicted to Adopt Methane Digesters, by State; Carbon Price per Ton of $13 and $26

a digester. At a price of $26/tCO_2e$, all of the dairy states see an increase in the number of potential digester adopters. At the higher price, over 200 producers in Idaho, Texas, and Wisconsin, and nearly 1,000 producers in California would find it profitable to adopt a digester.

A clearer geographic pattern emerges when we examine the share of operations in each state that would earn a positive NPV from a digester project (Figure 2). In the Midwest and Northeast, fewer than 4% of operations in each state would find a digester profitable, even with a carbon price of $26/tCO_2e$. In contrast, at $26/tCO_2e$ over 50% of operations in Florida and Texas in the South, and Arizona, California, and New Mexico in the West would find a digester profitable.

Sensitivity Analyses

To illustrate how sensitive the model results are to the parametric assumptions, we perform three sensitivity analyses of key variables. All the analyses are performed using the same parameters as in the above analyses and a carbon price of $13/tCO2e. First, we consider a range of assumptions about the share of digester construction costs borne by the operator. Specifically we consider the effects of policies or programs that pay for 0% and 50% of construction costs (Table 4). Cost share programs could take a variety of forms, including grants (e.g., the U.S. Department of Agriculture Rural Energy for America Program Grants), tax credits (e.g., the Renewable Electricity Production Tax Credit), accelerated depreciation (Accelerated Cost Recovery System, which allows qualifying renewable energy systems to be depreciated using an accelerated schedule), and property and sales tax exemptions (usually at the state level).[15] We estimate that the number of operations on which a digester would be profitable would decline by almost 50% with no cost share, and would more than double with a 50% cost share. Notably, most of the dairies affected by this change in cost sharing rate are in the smaller size range (less than 1,000 head), as

---

[15] The USDA Rural Energy for America Program provides grants for up to 25% of total eligible project costs up to $500,000. Combined with other grants, incentives, and tax savings, it is possible that growers could reduce construction costs by as much as 50%.

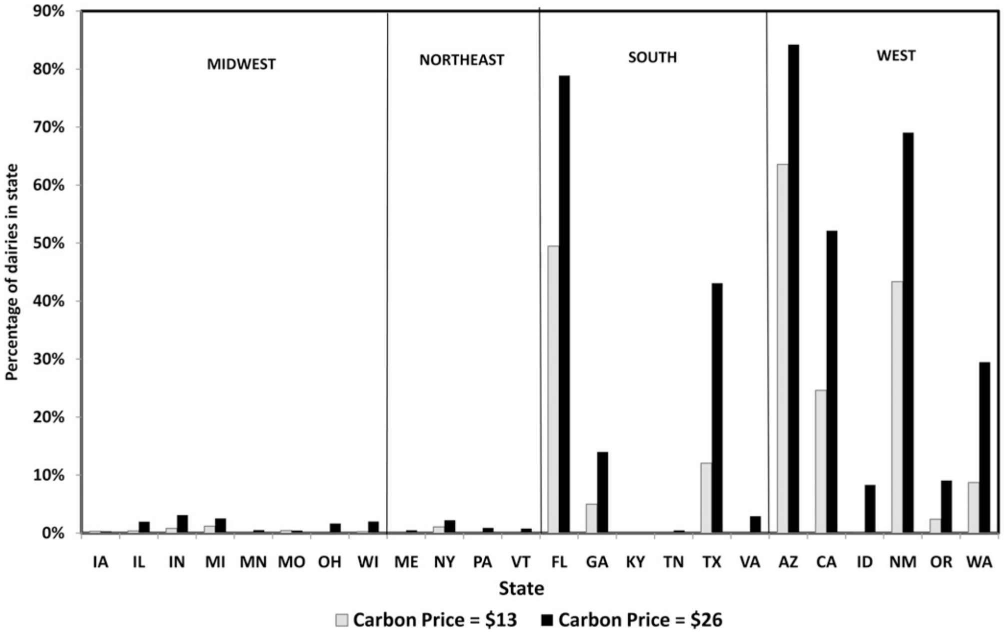

Figure 2. Percentage of Dairies Predicted to Adopt Methane Digesters, by State; Carbon Price per Ton of $13 and $26

almost all of the larger farms that could feasibly adopt a digester would have done so without the cost share benefit.

Next, consider the effect of varying the electricity retail price (Table 5). In the base scenario, the retail electricity price is defined as the annual average for the industrial sector for the state. The table shows the effect of a 25% increase and decrease in the price relative to the base price. If retail prices were 25% lower, the number of operations that would find digesters profitable declines by about 30%, while at a higher price

Table 4. Sensitivity Analysis for Rate of Government Cost Share

	25% Government Cost Share		No Government Cost Share		50% Government Cost Share	
	Number of Farms that Adopt	Net Revenues from Digester (million $)	Number of Farms that Adopt	Net Revenues from Digester (million $)	Number of Farms that Adopt	Net Revenues from Digester (million $)
All farms	934	$574	473	$367	1,953	$929
Number of Head						
>2500	163	$361	131	$283	176	$443
1,000–2,499	390	$172	278	$81	622	$325
500–999	381	$42	64	$3	743	$145
250–499	0	$0	0	$0	412	$16
<250	0	$0	0	$0	0	$0
Region						
West	556	$348	235	$233	1,155	$560
Midwest	84	$48	78	$23	230	$83
South	176	$89	78	$53	350	$151
Northeast	118	$90	81	$59	218	$135

Notes: Carbon price = $13/ton. All values are in 2009 dollars.
Source: Authors' calculations.

Table 5. Sensitivity Analysis for Retail Electricity Price

	Electricity Price = Industrial		Electricity Price = 25% Less		Electricity Price = 25% More	
	Number of Farms that Adopt	Net Revenues from Digester (million $)	Number of Farms that Adopt	Net Revenues from Digester (million $)	Number of Farms that Adopt	Net Revenues from Digester (million $)
All farms	934	$574	656	$423	1,251	$768
Number of Head						
>2500	163	$361	137	$285	166	$441
1,000–2,499	390	$172	309	$121	567	$254
500–999	381	$42	210	$18	482	$73
250–499	0	$0	0	$0	36	$0
<250	0	$0	0	$0	0	$0
Region						
West	556	$348	357	$255	780	$475
Midwest	84	$48	81	$36	95	$60
South	176	$89	128	$63	217	$120
Northeast	118	$90	90	$70	159	$113

Notes: Carbon price = $13/ton. All values are in 2009 dollars.
Source: Authors' calculations.

the number of operations increases by about 34%. Digester net revenues respond in similar proportions. Again, most of the response to price occurs amongst operations with fewer than 1,000 head.

The third sensitivity analysis considers variations in the selling price of electricity for the farm (Table 6). In the baseline scenario we assumed that operations could sell surplus electricity at the "wholesale" price – i.e., the price that the utility pays for electricity, which is assumed to be $0.031/kWh below the retail price. In reality, the selling price could be higher or lower than the wholesale price. In some regions, operators incur connection fees and standby charges (to provide electricity in the case that a farm's generator goes out of service) if they sell electricity. Alternatively, digester-generated electricity could be a substantial premium earned above the wholesale price, because it is generated from a "renewable" source. The premium for renewable energy certificates varies between about 0.5 and 5.5 cents/kWh and averages about 2 cents per kilowatt hour (U.S. Department of Energy, 2011). Table 6 shows how the number of operations and profits change if the selling price is zero or equal to the retail price. The results indicate that the number of operations and profits are not very sensitive to the selling price of electricity. This is likely because at a carbon price of $13/tCO2, electricity sales comprise only 5.4% of gross revenues from the digester.

Conclusion

Model simulations show that a national carbon offset market could substantially increase the number of U.S. dairy producers who would find it profitable to install a methane digester. With a carbon price of $13/tCO$_2$e, we estimate that 934 dairy operations would find it profitable to adopt a digester and the total NPV of digesters having a 15-year lifetime is about $574 million. At this carbon price, carbon offset sales would represent 62% of the present value of gross returns from the digester.

Results indicate total digester profits and profits per-head from digesters both generally increase with farm size over a range of carbon offset prices. We found that with a carbon price of $13/tCO$_2$e, dairies with at least 1,000 head earn 93% of dairy-sector digester profits. Larger-scale operations benefit more because the costs of constructing and maintaining a digester do not increase in proportion with digester size and because these larger operations are more likely to use manure management methods that emit more methane.

Table 6. Sensitivity Analysis for Electricity Selling Price

	Selling Price = Wholesale Price		Selling Price = 50% of Wholesale		Selling Price = 150% of Wholesale	
	Number of Farms that Adopt	Net Revenues from Digester (million $)	Number of Farms that Adopt	Net Revenues from Digester (million $)	Number of Farms that Adopt	Net Revenues from Digester (million $)
All farms	934	$574	846	$487	1,040	$636
Number of Head						
>2500	163	$361	144	$300	171	$400
1,000–2,499	390	$172	343	$148	470	$192
500–999	381	$42	359	$39	399	$44
250–499	0	$0	0	$0	0	$0
<250	0	$0	0	$0	0	$0
Region						
West	556	$348	493	$285	648	$389
Midwest	84	$48	84	$48	84	$48
South	176	$89	164	$82	178	$95
Northeast	118	$90	105	$73	130	$105

Notes: Carbon price = $13/ton. All values are in 2009 dollars.
Source: Authors' calculations.

Recent decades have seen dramatic increases in the scale of production in the dairy sector. Dairies with at least 1,000 head now produce almost a third of output, despite comprising only about 2% of all operations. Studies indicate that there are substantial economies of scale in dairy production (MacDonald et al., 2007; Mosheim and Knox Lovell, 2009). The additional profits that large farms could earn from digesters could enhance these existing scale economies and thereby contribute to further consolidation of production over time.

There are several avenues by which private actions and public sector investments and policies could promote the adoption of biogas systems by smaller-scale operations. Smaller-scale livestock operations could achieve a more efficient digester size by supplementing manure with food waste products from nearby crop or meat processing facilities, breweries, bakeries, or restaurants (Minnesota Department of Agriculture, 2005). When mixed with manure, food waste can provide an efficient feedstock for biogas production and livestock operators can charge "tipping fees" for receiving the waste. However, the availability and suitability of food waste for digestion may limit the economic and practical feasibility of co-digestion to certain locations.

A centralized digester is another way that smaller-scale operations could take advantage of a more efficient digester size. With a centralized system, several nearby farms share a single large digester. In addition to construction and maintenance cost efficiencies, centralized systems could increase marketing leverage in negotiating electricity sales; improve access to financing, tax credits, or grants; and could permit a manager to develop specialized skill in digester maintenance and operation (USEPA, 2002). The main disadvantage to centralized digesters is the additional costs of transporting manure to and from the central facility (Ghafoori and Flynn, 2006).

If carbon offset prices are sufficiently high, a lower-cost biogas system that flares methane rather than using it to generate electricity may become profitable. This approach removes electricity generation from the biogas system, which eliminates the costs of the generator, electrical connections, and related maintenance. This approach might be economically viable for smaller-scale operations that would otherwise find it difficult to finance or maintain an electricity generator. This option has the greatest potential for operations with lagoons, as covers can be installed relatively inexpensively and can provide other benefits to producers such as odor control and rain exclusion.

Obtaining financing for the large capital investment associated with most biogas systems can be a particular barrier to adoption for smaller-scale operations (Gloy and Dressler, 2010). Digesters have little resale value, making their collateral value low. This problem could be addressed by loan guarantee programs such as the USDA's Rural Energy for America Program. The uncertainty surrounding digester systems' benefits and costs is another barrier to financing and adoption. Investors who are uncertain about the returns to a project are likely to delay investment or require substantial compensation for the uncertainty (Stokes, Rajagopolan, and Stefanou, 2008). Future climate legislation could increase energy prices and raise carbon offset prices far above current prices in regional carbon trading schemes. However, there is a great deal of uncertainty about the extent of these price increases. Stable and long-term government policies and programs can help reduce price uncertainty and encourage investment, as would the provision of long-term contracts for carbon offsets and electricity.

Finally, government policies and programs that raise returns to or lower costs of digesters can provide incentives for smaller-scale operations to adopt methane digester. Many of these policies can be targeted toward smaller-scale operations.

[Received December 2010; Accepted June 2011.]

References

Beddoes, J.C., Bracmort, K.S., Burns, R.T., and Lazarus, W.F. "An Analysis of Energy Production Costs from Anaerobic Digestion Systems on U.S. Livestock Production Facilities." Technical Note No. 1. U.S. Department of Agriculture, Natural Resources Conservation Service, October 2007.

Bishop, C., and C.R. Shumway. "The Economics of Dairy Anaerobic Digestion with Coproduct Marketing." *Review of Agricultural Economics* 31,3(2009):394–410.

California Environmental Protection Agency (CEPA). *Air Resources Board, Agricultural Activities, Manure Management.* Internet site: http://www.arb.ca.gov/ag/manuremgmt/manuremgmt.htm (Accessed May 5, 2011).

Chicago Climate Exchange. *Chicago Climate Exchange Offset Project Protocol: Agricultural Methane Collection and Combustion.* Internet site: https://www.theice.com/publicdocs/ccx/protocols/CCX_Protocol_Agricultural_Methane.pdf. Updated September 30, 2009.

———. *CXX Carbon Financial Instrument Contracts Daily Report*, Internet site: http://www.chicagoclimatex.com/market/data/summary.jsf (Accessed December 1, 2010).

Crenshaw, J. "What's a Digester Cost These Days?" Presented at the AgSTAR National Conference, Baltimore, MD, February 24–25, 2009.

Dairy Power Production Program. *Methane Digester System Program Evaluation Report.* A Report Prepared for California Energy Commission Public Interest Energy Research Program, 2006. Internet site: http://www.energy.ca.gov/2009publications/CEC-500-2009-009/CEC-500-2009-009.PDF.

Database of State Incentives for Renewable Energy. *Rules, Regulations, and Policies for Renewable Energy.* Internet site: http://www.dsireusa.org/summarytables/rrpre.cfm (Accessed June 7, 2010).

Demuynck, M., E.-J. Nyns, and H. Naveau. "A Review of the Effects of Anaerobic Digestion on Odour and on Disease Survival." *Composting of Agricultural and Other Wastes*. J.K.R. Gasser, ed. London: Elsevier Applied Science, 1985.

Ghafoori, E., and P. Flynn. "Optimizing the Size of Anaerobic Digesters." *Transactions Of The American Society of Agricultural and Biological Engineers* 50,3(2007):1029–36.

Global Methane Initiative. Internet site: http://www.globalmethane.org/ (Accessed June 1, 2011).

Gloy, B.A. "The Potential Supply of Carbon Dioxide Offsets from Anaerobic Digestion of Dairy Waste in the United States." *Applied Economic Perspectives and Policy* 33,1(2011):59–78.

Gloy, B.A., and J.B. Dressler. "Financial Barriers to the Adoption of Anaerobic Digestion on U.S. Livestock Operations." *Agricultural Finance Review* 70,2(2010):157–68.

Huffstutter, P. "A Stink in Central California over Converting Cow Manure to Electricity," *Los Angeles Times*, March 1, 2010.

Intergovernmental Panel on Climate Change. "Changes in Atmospheric Constituents and in Radiative Forcing." *Climate Change* 2007*: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of* *the Intergovernmental Panel on Climate Change*. S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller, eds. New York, NY: Cambridge University Press, 2007.

Key, N., and S. Sneeringer. *Climate Change Policy and the Adoption of Methane Digesters on Livestock Operations*. U.S. Department of Agriculture, Economic Research Service, Economic Research Report No. 111. February 2011. Internet site: http://www.ers.usda.gov/Publications/ERR111/.

Kramer, J. *Agricultural Biogas Casebook—2004 Update*. Internet site: http://www.michigan.gov/documents/CIS_EO_Agricultural_Biogas_Casebook_2004_Update_102421_7.pdf (Accessed May 5, 2011).

Lazarus, W., and M. Rudstrom. "The Economics of Anaerobic Digester Operation on a Minnesota Dairy Farm." *Review of Agricultural Economics* 29,2(2007):349–64.

Leuer, E., J. Hyde, and T. Richard. "Investing in Methane Digesters on Pennsylvania Dairy Farms: Implication of Scale Economies and Environmental Programs." *Agricultural and Resource Economics Review* 37,2(2008):188–203.

Lusk, P. "Methane Recovery from Animal Manures: The Current Opportunities Casebook." National Renewable Energy Laboratory ECG-8-17098-01, September 1998.

MacDonald, J.M., E. O'Donoghue, W. McBride, R. Nehring, C. Sandretto, and R. Mosheim. "Profits, Costs, and the Changing Structure of Dairy Farming." Economic Research Report No. 47. Economic Research Service, September 2007.

Minnesota Department of Agriculture. "Opportunities, Constraints, and Research Needs for Co-digestion of Alternative Waste Streams with Livestock Manure in Minnesota." Agricultural Resources Management and Development Division, November 23, 2005. Internet site: http://www.mnproject.org/pdf/CombinedWasteStreamsReport.pdf.

Mosheim, R., and C.A. Knox Lovell. "Scale Economies and Inefficiency of U.S. Dairy Farms." *American Journal of Agricultural Economics* 91,3(2009):777–94.

Pain, B.F., T.H. Misselbrook, C.R. Clarkson, and Y.J. Rees. "Odour and Ammonia Emissions Following the Spreading of Anaerobically-Digested Pig Slurry on Grassland." *Biological Wastes* 34(1990):259–67

Regional Greenhouse Gas Initiative. *Market Monitor Reports*. Internet site: http://www.rggi.org/market/market_monitor (Accessed June 1, 2011).

Shephard, T., P.E. Curt Gooch, K. Czymmek, and J. Karszes. *Covers for Long-term Dairy Manure Storages, Part 2: Estimating your Farm's Annual Cost and Benefit*. Internet site: http://www.ansci.cornell.edu/pdfs/pdFactSheetSC2PDv.pdf (Accessed December 1, 2010).

Stokes, J., R. Rajagopalan, and S. Stefanou. "Investment in a Methane Digester: An Application of Capital Budgeting and Real Options." *Review of Agricultural Economics* 30,4(2008): 664–76.

U.S. Department of Energy. "Carbon Dioxide Emissions from the Generation of Electric Power in the United States." July 2000. Internet site: ftp://ftp.eia.doe.gov/environment/co2emiss00.pdf.

U.S. Department of Energy. *States with Renewable Portfolio Standards*. Internet site: http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm#chart (Accessed June 3, 2009).

U.S. Department of Energy. *Renewable Energy Certificates (RECs) Retail Products*. Internet site: http://apps3.eere.energy.gov/greenpower/markets/certificates.shtml?page=1 (Accessed June 1, 2011).

U.S. Energy Information Administration. Form EIA-826, *Monthly Electric Sales and Revenue Report with State Distributions Report*. Internet site: http://www.eia.doe.gov/electricity/epm/table5_6_b.html (Accessed May 23, 2010a).

———. *Annual Energy Outlook* 2010, Reference Case, Table A8: Electrical Supply, Disposition, Prices, and Emissions, p. 125, 2010b. Internet site: http://www.eia.gov/oiaf/archive/aeo10/index.html.

U.S. Environmental Protection Agency. *Managing Manure with Biogas Recovery Systems: Improved Performance at Competitive Costs*. The Agstar Program. EPA-430-F-02-004. Washington, DC: U.S. Environmental Protection Agency, 2002.

———. *Market Opportunities for Biogas Recovery Systems: A Guide to Indentifying Candidates for On-Farm and Centralized Systems*. AgStar Program. EPA-430-8-06-004. Washington, DC: U.S. Environmental Protection Agency, 2006.

———. *Climate Leaders Greenhouse Gas Inventory Protocol Offset Project Methodology for Project Type: Managing Manure with Biogas Recovery Systems.* Washington, DC: U.S. Environmental Protection Agency, Version 1.3, August 2008.

———. EPA Analysis of the American Clean Energy and Security Act of 2009 H.R. 2454 in the 111th Congress. June 23, 2009.

———. *Inventory of U.S. Greenhouse Gas Emissions and Sinks:* 1990–2008. EPA 430-R-10-006. Washington, DC: U.S. Environmental Protection Agency, April 15, 2010a.

———. "EPA Helps Launch Global Methane Initiative to Cut Greenhouse Gases/Countries to fight climate change while developing clean energy and stronger economies." 2010 News Release. Release date: October 1, 2010b.

———. *Anaerobic Digestion Capital Costs for Dairy Farms. May* 2010. Internet site: http://www.epa.gov/agstar/documents/digester_cost_fs.pdf (Accessed December 5, 2010c).

———. *AgStar Program Projects: Operating Anaerobic Digester Projects*. Internet site: http://www.epa.gov/agstar/projects/index.html (Accessed May 5, 2011).

Welsh, F., D. Schulte, E. Krocker, and H. Lapp. "The Effect of Anaerobic Digestion upon Swine Manure Odors." *Canadian Agricultural Engineering* 19,2(1977):122–26.

Western Climate Initiative. *Design for the WCI Regional Program*. Internet site: http://www.westernclimateinitiative.org/the-wci-cap-and-trade-program/program-design (Accessed May 3, 2010).

Wilkie, A.C., K.J. Riedesel, and K.R. Cubinski. "Anaerobic Digestion for Odor Control." *Nuisance Concerns in Animal Manure Management: Odors and Flies*. H.H. Van Horn, ed. Gainesville, FL: Florida Cooperative Extension Service, University of Florida, 1995.

Wright, P.E., and S.P. Perschke. "Anaerobic Digestion and Wetland Treatment Case Study: Comparing Two Manure Odor Control Systems for Dairy Farms." Presented at the American Society of Agricultural Engineers Annual International Meeting, Orlando, FL, 1998.

Appendix A. Case Study Information and Parameters

Appendix Table A1. Averages from Case Studies and Vendor Quotes

	Head	Capital Costs	Capital Costs per Head	Variable Costs ($/kWh)	Electricity (kWh/year/head)
Pit manure storage	1,786	$1,523,994	$958	$0.046	729
	(1,006)	(617,005)	(0.296)	(0.024)	(0.404)
N	37	37	37	5	8
Lagoon manure storage	2,458	$1,279,182	$863	$0.037	450
	(2,326)	(821,356)	(0.486)	(0.027)	(0.136)
N	8	8	8	4	4

Notes: Standard deviations shown in parentheses. An observation is a case study or vendor quote. The number of observations varies according to the number of studies providing information on the specific variable. All dollar values have been converted to 2009 real terms using the Chemical Engineering Plant Cost Index.
Source: See text for details.

Appendix Table A2. Regression Results, Dependent Variable: ln (Capital)

	Pit	Lagoon
Constant	9.779	10.572
	(0.578)	(0.946)
ln(Head)	0.596	0.454
	(0.078)	(0.128)
N	37	8
Adjusted R-squared	0.612	0.624

Note: Standard errors shown in parentheses.
Source: Authors' calculations.

Appendix B. ARMS Data Description

Farm level data are drawn from the 2005 Dairy Production Practices and Costs and Returns Report, a portion of the Agricultural Resource and Management Surveys (ARMS). The ARMS is a restricted-use dataset compiled by the National Agricultural Statistics Service in conjunction with the Economic Research Service of the U.S. Department of Agriculture. Farms must have sold $1,000 of agricultural products in the prior year to qualify for the sample.

Manure Management

The ARMS allows farmers to record up to four types of manure storage facilities. We classify the following systems as lagoons: “Single stage lagoon (for anaerobic or aerobic digestion)” and “Two stage lagoon (for anaerobic or aerobic digestion in 1st stage, storage in 2nd stage).” We characterize the following as pit-based manure management: “Manure pit (open),” “Manure pit (covered),” “Slurry or manure tank (open),” “Slurry or manure tank (covered),” and “Holding pond (for storage, not anaerobic or aerobic digestion).” The other types of manure storage systems that we do not characterize as either pit or lagoon are “Stacking slab or other open storage of manure” and “Manure barns or shed (covered storage of manure).”

Some farms have both manure and pit systems. In these cases, we discern the percentage of manure held in each type of system, and then use these percentages to weigh estimates dependant on the type of manure management (electricity produced, methane produced, and capital costs).

Number of Head

For dairies, ARMS provides the number of head in three categories: Milk cows, dry cows, and breeding bulls. We exclude breeding bulls and find the average number of milk and dry cows over the course of the year.

Electricity Use

ARMS records the total amount spent on electricity. We instead need the amount of electricity used. We therefore use the state electricity price from the U.S. Energy Information Administration to calculate electricity used in kWh.

State Methane Emissions Factors

The Chicago Climate Exchange provides methane emissions factors by livestock and manure management system, for the categories of “dairy cow” and “dairy heifer.” Since the ARMS data do not distinguish between dairy cows and dairy heifers (just between milk cows and dry cows), we only use the emission factor for “dairy cows.”