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COST-BENEFIT ANALYSIS OF ANAEROBIC BIODIGESTERS IN NORTHEAST WISCONSIN

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EXECUTIVE SUMMARY

This report reviews the social and economic costs and benefits of anaerobic digester facilities located on dairy farms in Northeast Wisconsin. Digesters enable renewable energy production, increase revenue for farm operators, and reduce agricultural nuisances. In this report, we explore three models of ownership and energy production at various dairy herd sizes through a 20-year time horizon. We estimate and monetize the present value of costs and benefits to the private farmer and to society under each of these models. We also perform a Monte Carlo simulation to assess the robustness of our results given uncertainty in our estimates.

Net benefits of digesters vary significantly among our three models and by herd size. Farmers experience the largest net benefits when a third-party firm constructs and operates a digester on their farm. In this scenario, we expect a gradation of net farmer benefits from $0.8 million for a 500-cow herd and $7.6 million for a 5,000-cow herd over a 20-year time horizon. Therefore, we provide the following recommendations:

I. Farm operators at any herd size should seek third-party firms or government entities to construct and operate a digester on their farm.
II. Farms with herd sizes of more than 1,000 cows should see positive net benefits without a third-party operator, but only farms with herd sizes of 2,000 cows or more are likely to realize those benefits in the first decade of operating a digester.
III. Digester operators should sell biogas for pipeline injection as part of renewable energy credit trading programs, such as the California Low Carbon Fuel Standard, to realize the greatest benefits from energy production.

Herd size is directly and positively correlated with revenue potential, so we expect larger farms will realize greater benefits, although it should be noted that these benefits do not differ greatly amongst farms with a herd size greater than 2,500. Digesters mitigate many existing social costs associated with large farms; therefore, social benefits scale up with farm size in our analysis as well. However, social benefits are positive in all models and at all herd sizes, and often exceed benefits to farmers, potentially providing a rationale for subsidizing the technology through grants or tax credits. Social net benefits range from approximately $0.3 million for a 500-cow herd to approximately $3.3 million for a herd size of 5,000 cows.

We estimate 11 cost and benefit categories in each model. Costs are primarily capital costs associated with the construction of the facility. Farmer benefits are primarily realized through the sale of gas and electricity produced by the digester and in the form of reduced costs to farmers. Social benefits are primarily realized through reduction in greenhouse gas emissions and reduction in noxious odors from dairy farms.

Our analysis makes a number of assumptions in all models:

- We do not consider nascent technologies to further process digested material.
- We do not consider co-digestion opportunities with other substrates like food waste, creamery waste, or wastewater.
- We tailor our analysis to the Northeast region of Wisconsin given the region's high concentration of dairy farms and ecologically sensitive topography.
- We do not analyze any models in which a farmer uses biogas from a digester on-site for heat or electricity.
- We use data that aims to generalize the impacts of anaerobic digestion on the relevant impact categories, rather than analyzing a specific digester operation.
- We assume that digesters in our models are constructed and operated without funding from USDA grants, tax credits, or other government programs.

Modification of any of these assumptions provides an opportunity for further analysis of digesters and their potential to provide economic and social benefits to farmers and to society.

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GLOSSARY

Anaerobic digestion (AD): The biochemical decomposition of organic matter into methane gas and carbon dioxide by microorganisms in the absence of oxygen (Costa et al., 2005).

Biogas: One of the naturally produced by-products from the decomposition of organic waste during anaerobic digestion. It is a mixture of carbon dioxide and hydrocarbons, primarily methane gas. Until biogas is processed to state pipeline standards, it is not considered renewable gas.

Biomethane: Biogas that has been converted and cleaned to state standards, which is renewable gas.

Buyback Rate: The rate paid by a local utility to producers of energy for use on the electricity grid (measured in Kilowatt-Hours (kWh)).

Compressed Natural Gas (CNG): The result of compressing natural gas to less than one percent of its volume at standard atmospheric pressure (USDOE, 2019).

Concentrated Animal Feeding Operation (CAFO): An animal feeding operation with more than 1,000 animal units confined on-site for more than 45 days during the year.

Digestate/Effluent: The organic liquid and solid material that leaves a digester. The terms are interchangeable.

Digester: The sealed container or tank where anaerobic digestion occurs. Also referred to as a reactor tank, biodigester, or anaerobic digester.

Engine-Generator Set (GenSet): The combination of an electrical generator and an engine mounted together to form a single piece of equipment that produces electrical power that can be used on-site or sold (MSU, 2019).

Influent: The waste material that enters the digester.

Karst region: A type of landscape where the dissolving of the bedrock has created sinkholes, sinking streams, caves, springs, and other characteristic features. Karst is associated with soluble rock types such as limestone, marble, and gypsum (NPS, 2019).

Mesophilic Digester: The most common type of digester that operates within the temperature range of 95 to 105 degrees Fahrenheit.

Methane: The combustible gas produced by anaerobic digestion. It is also the principal component of natural gas.

Organic Material: The matter composed of organic compounds that are from the remains of a once-living organism and their waste products.

Pipeline Natural Gas (PNG): An integrated pipeline network that transports natural gas across the country.

Reactor Tank: The sealed container or tank where anaerobic digestion occurs. Also referred to as the digester.

Renewable Natural Gas (RNG): methane produced from renewable sources like digested organic waste and gasified biomass.

Slurry: The mixture of solids and water processed in the digester.

Tariff: The rate charged by a local utility to purchase or sell energy as gas or electricity.

Wellhead Price: The price paid to producers of natural gas like biogas at the point of production, prior to refining.

INTRODUCTION

Anaerobic digestion of dairy manure is an increasingly prevalent method for producing energy, sustainably. Anaerobic digestion converts waste into various forms of energy, including electricity, compressed natural gas (CNG), and pipeline natural gas (PNG)—both of which are considered renewable natural gas (RNG) (Liebrand, 2009).

Dairy farms are among the primary sites for anaerobic digestion due to their high volume and concentration of waste. While the number of dairy farms has declined over time, the average herd size at each farm, measured by cows per farm, has grown (USDA, 2007). The increasing average size of dairy farms means the quantity and concentration of manure has also grown. This poses new challenges to traditional land application methods. Mismanagement of manure has several environmental and health consequences, including runoff that is harmful to water quality and greenhouse gas emissions from manure lagoons. However, in recent decades, dairy waste has provided new opportunities for farmers to leverage manure as an economic resource by using it for renewable energy and animal bedding.

Anaerobic digestion is the "natural process in which microorganisms break down organic materials" (EPA, 2019). The process creates a variety of products, such as biogas used for electricity generation or fuel, and digestates used for soil application, bedding, and compost (Scott, 2016). Anaerobic digestion primarily takes place in a reactor tank or container known as an anaerobic digester (referred to in this report as a digester), which uses different combinations of microbes, heat, water, and physical agitation to process animal waste. The use of digesters has grown across the country, with approximately 250 farms operating systems that process animal manure (AgSTAR, 2019). Wisconsin currently has 39 operating digesters, making it one of the largest biogas-producing states in the country (AgSTAR, 2019).

As a leader in the dairy industry, Wisconsin has taken steps to encourage waste-to-energy production in recent years. In 2016, Governor Scott Walker's administration approved plans for a new public-private initiative in northeastern Wisconsin to convert manure into energy. In 2017, the Wisconsin Public Service Commission approved a grant of $15 million to help finance a digester system in Brown County (WI PSC, 2017). Governor Tony Evers' administration recently released a scope statement outlining a potential administrative rule to impose additional restrictions on spreading manure in areas of the state with highly permeable soil (WI DNR, 2019). With the decline in the number of Wisconsin dairy farms, an excess of manure, and increasing water quality issues, digesters are a potentially beneficial way to mitigate these challenges while increasing economic growth.

The majority of current Wisconsin digesters are farm-scale, though Dane County has four regional digesters. Almost all Wisconsin digesters use either a plug-flow or complete mix digestion system, while more than half use products such as food waste, wastewater, or fats, oils, and grease for co-digestion. The average herd size for farms with digesters is 2,552 cows, and all except two digesters are located on farms with a herd size of at least 650 cows (AgSTAR, 2019). The average Wisconsin dairy farm has a herd size of 169 cows (WI Agricultural Statistics Service, 2019). The two smallest farms with digesters in Wisconsin, which have 120 and 200 cows, respectively, increase biogas production by co-digesting food waste. The size of the relevant farms indicates that most farms with digesters would be Concentrated Animal Feeding Operations (CAFOs). The growth of CAFOs in Wisconsin is the subject of ongoing political debate concerning their environmental, economic, and local impacts. For this reason, policymakers have shown interest in projects like digesters, which can mitigate negative impacts of CAFOs while enriching the Wisconsin energy industry.

Despite several barriers to entry into the dairy farm digester market, including high capital, operation, and maintenance costs, as well as economies of scale, farmers can still realize economic benefits. In this cost-benefit analysis, we analyze three models common in the biogas industry that

Wisconsin dairy farms could implement. This report assesses the economic feasibility of each of these models for a Wisconsin farmer (private analysis), as well as the overall costs and benefits to society on a national scale (social analysis). Because the economic and environmental effects of a digester are not limited to Wisconsin, we assume national standing for our social cost-benefit analysis. We assume conditions in the karst topographical region of Northeast Wisconsin, where digesters are most prevalent. Additionally, this region has shallow soil and carbonate bedrock. The implications of these features are discussed in Appendix E. While there are several types of digesters, this analysis assumes farmers use a mixed plug flow digester, as these are most common in the region (see Appendix C for a description of mixed plug flow digesters and Appendix D for an overview of other digester types).

Early adopters of anaerobic digestion technology burned the biogas produced by the digester directly to provide heat on-site, or to power a generator for electricity used on-site. Producers with excess electricity after generation sold that electricity to the local utility for distribution in their service area. Because of high costs associated with electricity storage, the variability of electricity needs, and state monopoly rules preventing anyone but a utility from selling electricity to customers, most Northeast Wisconsin farmers sell all the electricity they generate directly to the grid (Interview 3, 2019). Some farms sell their gas to private companies or utilities that clean the gas and inject it into pipelines for sale on the open market. Those third parties claim renewable energy credits from states with incentives for lower carbon-intensity vehicle fuel (see Appendix G). Currently, the most popular state program is California's Low Carbon Fuel Standard. In recent years, private investors and utilities have increasingly moved to lease land from farmers to build and operate digesters so they can participate in renewable energy offset markets. We consider each of these scenarios in our analysis.

Our analysis quantifies the costs and benefits of an additional mixed plug flow digester on a Northeast Wisconsin dairy farm, contingent on the size of the farm. Private costs to farmers include capital costs, operation and maintenance costs, and the opportunity costs of land use. Farmer benefits include income from the sale of electricity or biogas, and reduced costs for animal bedding and trucking of manure. Social costs include the opportunity cost of using otherwise productive agricultural land for a digester. Social benefits include reductions in greenhouse gas emissions from dairy farms, pathogens entering groundwater, and externalities from noxious odor emissions. Changes in trucking patterns as a result of digestion have both positive and negative social effects. Economic viability and social benefits differ based on the size of the farm. By performing our analysis on a per-cow basis, we can estimate these benefits for farmers with a wide range of operations. Because of prohibitively high capital costs and limited quantities of manure, we do not estimate net benefits for dairy farms smaller than 500 cows. We converted all inputs to 2019 USD using the Bureau of Labor Statistics' Consumer Price Index calculator (BLS, 2019).

In our analysis, we quantify and monetize most costs and benefits on a per-cow basis. We perform a Monte Carlo simulation, which accounts for the uncertainty in each parameter used in the calculations of net benefits. We use a twenty-year time horizon, the minimum estimated life of the digester, and discount net benefits using a 3.5 percent annual discount rate to obtain the net present value of costs and benefits. For each model outlined below, we report the net present value of private and social benefits for farms between 500 and 5,000 head of dairy cattle. We assess the resulting costs and benefits for the farmer and society at large, separately. We consider the costs and benefits incurred by other private actors, such as biogas investors and utility companies, to be transfers.

OVERVIEW OF ALTERNATIVES

The following section details three alternative proposals for on-site digesters for dairy farmers in Northeast Wisconsin. We anticipate approximately the same social benefits in each scenario – groundwater pathogen reductions, greenhouse gas emission reductions, and some reductions to trucking externalities – although the costs and benefits for farmers vary among the three models.

MODEL ONE: FARMER-OWNED DIGESTER WITH ELECTRICITY GENERATION

Our first alternative assumes that a dairy farmer in Northeast Wisconsin pays to construct, operate, and maintain an on-site digester, and that the farmer sells 100 percent of the electricity they generate back to their local utility. This requires installing, operating, and maintaining a generator set (genset), which needs to be replaced approximately every ten years. We assume farmers will finance 70 percent of construction with a four-year loan, at a loan rate of 3.1 percent. Farmers and society additionally incur small opportunity costs from using agricultural land for a digester, rather than using it for agricultural purposes.

This alternative assumes farmers will continue to spread and store the same volume of manure as they did prior to constructing a digester, and that digested manure has the same levels of nitrogen and phosphorous as undigested manure. Farmers would therefore continue to purchase the same volumes of fertilizer. Digested manure would, however, contain lower levels of pathogens than undigested manure. The risk of groundwater pollution from pathogens is especially high in karst topography. While we do not expect a digester to completely reverse these effects, we do expect pathogen reduction in the groundwater, which should reduce the risk of illness to the population. Like other models, this alternative results in reduced greenhouse gas emissions from the dairy farm.

In addition to electricity sales, the farmer sees benefits in the form of avoided costs for bedding. Farmers can dry some of their digestate and use it for bedding for their herds, thus avoiding the costs of purchasing bedding.

Farmers typically truck their excess manure to off-site fields. Based on conversations with farmers in the region, we expect trucking costs to be reduced by up to 20 percent from digester use due to pathogen reduction.

MODEL TWO: FARMER-OWNED DIGESTER WITH BIOGAS PRODUCTION

Our second alternative makes the same assumptions as the first, but rather than sell electricity to the utility, the farmer sells biogas to a private firm or utility, which processes the gas into biomethane and injects it into a pipeline that is connected to the national network of natural gas pipelines. Programs such as California's Low Carbon Fuel Standard program, which offer tradable credits for producers of renewable transportation fuel, provide a viable outlet for third parties in this model (see Appendix G). Rather than a genset, the farmer constructs, operates, and maintains a biogas storage tank.

While the farmer does not privately incur these costs, the social costs of trucking biogas to the pipeline injection site counteract the anticipated social benefits from reduced manure trucking. The social benefits of greenhouse gas emissions are mitigated in this model by the potential for methane leakage from natural gas pipelines.

MODEL THREE: INVESTOR-OWNED DIGESTER WITH BIOGAS PRODUCTION

Our third alternative proposes that a private investor or local utility leases land from the farmer and pays to construct, operate, and maintain the digester in order to fully capture profits in the carbon offset markets. In this model, the farmer incurs virtually no private costs from the digester, aside from minor opportunity costs from land use. We assume that the farmer provides raw manure for digestion without receiving payment from the third party. Benefit and cost categories are otherwise the same as in Model 2.

COSTS AND BENEFITS: MODEL 1

Model 1 assumes the farmer owns the digester, pays to construct, operate and maintain the digester, and sells the energy they generate back to their local utility.

COSTS

PRIVATE COSTS TO FARMERS

We define private costs as costs incurred by the farmer. We identify four private cost categories for this model: upfront capital, operations and maintenance, genset replacement, and the opportunity cost of land use. We assume 70 percent of upfront capital is financed at four years.

UPFRONT CAPITAL

The most significant cost of a digester is the upfront capital needed for its equipment. The capital costs, which are consistent across all three alternatives, are the physical structures (the reactor tank(s), pumps, piping, and solids separation and drying systems), engineering design fees, installation costs, and permitting for construction of the digester. A capital cost unique to Model 1 is the cost of an engine-generator set (or a genset) to generate electricity by using biogas as the fuel.

We estimated capital costs in Model 1 (C_{m1}) as a function of herd size (S_{OP}) using the following equation:

$$C_{M1} = \$728 * S_{op} + \$668{,}000$$

For information on how we derived this equation, see Appendix H.

FINANCING

In Models 1 and 2, due to the financial burden of the digester being transferred to the farmer, financing plays a key role in mitigating upfront capital costs. A private farm has many financial options including, but not limited to, direct investment from state and federal grant programs, negotiating longer-term loans given projected income increases, and direct investments from third-party sponsors (Baker Tilly, 2012). Although digester construction projects have frequently received USDA and other public funding, for our analysis, we assume that the costs of installing a digester are directly incurred by the farm, that no government programs were used to offset its costs, and that no special terms were granted for digester-specific loans. Therefore, the entirety of the upfront capital costs financed in Models 1 and 2 are under average loan lengths and interest rates.

Terms of agricultural loans vary greatly from lender to lender as well as across time. We use the Agricultural Finance Databook (Federal Reserve Bank, 2019) in determining the maturity length and the private borrowing rate for the financing of the upfront capital needed for a digester. We use the average of loan maturity term and interest rates for agricultural loans under the category of, "Loans over $250,000," because there is no specific category for digesters (Federal Reserve Bank, 2019). We take the resulting private borrowing rate of 5.1 percent and subtract the current estimated inflation of 2.0 percent (Federal Reserve Bank, 2019) to determine the real interest rate for upfront capital costs. The resulting financing model we apply to the upfront capital costs of Model 1 and Model 2 is a loan length of 4 years and a real interest rate of 3.1 percent. Table 1 summarizes the upfront capital costs for a digester under this model.

TABLE 1. PRIVATE UPFRONT CAPITAL COSTS, BY SAMPLE HERD SIZE (MODEL 1)

Herd Size	Total Upfront Capital	Down Payment	Annual Loan Payments, Years 1-4
500 cows	$1,032,000	$309,600	$197,400
1,000 cows	$1,396,000	$418,800	$267,000
2,500 cows	$2,488,000	$746,400	$475,900
5,000 cows	$4,308,000	$1,292,400	$824,000

OPERATIONS AND MAINTENANCE

We categorize the second set of costs as operating costs. Farmers incur these costs annually. They include electricity use during manure processing and digestion, routine maintenance on solids separation and drying equipment, and management and labor expenses. Most feasibility reports also account for a small portion of annual costs to be used toward miscellaneous expenses. Annual maintenance costs range between 2 percent and 11 percent of total upfront capital costs, with the most likely value at 5 percent (Peters, et al., 2003). We use a triangular distribution in our Monte Carlo simulation to approximate annual operations and maintenance costs for farms at various herd sizes, rounded to the nearest hundred dollars.

TABLE 2. PRIVATE OPERATING COSTS, BY SAMPLE HERD SIZE (MODEL 1)

Herd Size	Annual Operating Costs
500 cows	$58,900
1,000 cows	$79,700
2,500 cows	$142,000
5,000 cows	$246,000

For more information on our calculations, see Appendix H.

GENSET REPLACEMENT

In addition to the capital costs previously mentioned, Model 1 requires purchase of a genset. According to interviews with industry experts, gensets must be replaced approximately every 10 years. We identify $325 and $380 as the lower and upper bounds genset replacement costs per cow, apply a uniform distribution to the values, and multiply by herd size to determine the overall cost at each farm. We apply this cost in Year 11 in our calculations. Table 3 summarizes these costs as a function of herd size, rounded to the nearest hundred dollars.

TABLE 3. PRIVATE ENGINE-GENERATOR SET COSTS, BY SAMPLE HERD SIZE

Herd Size	Genset Costs (in Year 11)
500 cows	$14,200
1,000 cows	$27,800
2,500 cows	$68,900
5,000 cows	$138,700

For more information, see Appendix H.

LAND USE COSTS

Installing a digester on a private farm represents an opportunity cost to farmers who otherwise could use the required land productively for growing crops. This cost accrues annually each year the digester is in operation and the farmer does not use that land to grow crops. Based on the annual value of agricultural land in Northeast Wisconsin, and an approximate digester size of four acres, we estimate this cost as $572 per year (see Appendix N for more information).

SOCIAL COSTS

Because our analysis uses national standing, we consider all capital, operations, and maintenance costs to be transfers. The payment by the farm to the manufacturer of the digester is an exchange of money, capital, and labor which has no net social gain or loss. The capital cost to the farmer for purchasing the digester has a corresponding benefit to the manufacturer for selling the digester.

SOCIAL OPPORTUNITY COST OF LAND

We calculate the social opportunity cost of land similarly to the farmer cost. Digesters occupy approximately four acres of land (Lawson, 2010). Because this land could otherwise produce feed crops like corn, soybeans, and alfalfa, which contribute to the local and national economies, the value lost by installing a digester represents a cost to society. We calculate this opportunity cost using the rental cost for productive agricultural land in the U.S. Department of Agriculture's East Central region of Wisconsin, or $143 per acre (USDA, 2019). Therefore, the opportunity cost of four acres of land used for the digester is $572. For more information, see Appendix N.

BENEFITS

FARMER BENEFITS

In the first model, we assume that the farmer producing biogas generates electricity from digested manure. Under this model, all of the electricity is sold to the local utility under Wisconsin's utility monopoly rules. Some farms are able to utilize the electricity they generate from anaerobic digestion, however due to the prohibitive costs of electricity storage and the irregularity of on-farm electricity needs, Model 1 assumes that farmers will not use electricity directly on their farm. For this reason, the costs of electricity use for the farmer will not change.

ELECTRICITY GENERATION

The farmer accrues private benefits through the sale of electricity to a local utility. Utilities offer a buyback rate and capacity payment to private operators in their region who generate electricity (see Appendix F for information on utility operation in Wisconsin). Producers are also required to pay a daily charge to the utility for the sale of electricity.

To calculate the net benefits to the farmer under this model, we calculate a weighted average of the buyback rate and capacity payment that a farmer would receive, based on the percentage of farmers serviced by each utility in the region, and the percentage of time that each utility uses on-peak and off-peak rates (see Appendix I). We calculate that farmers would receive a weighted average of $0.033/kilowatt-hour generated. We apply the same weighted average calculations to utility customer charges, to estimate that farms of all scales would pay utilities an estimated $235 per year in fees.

The U.S. Environmental Protection Agency (EPA) AgSTAR program has compiled a database of operational digesters in the United States. Among mixed plug flow digesters on farm-scale dairy operations nationwide, electricity production averaged 2,002 kilowatt-hours per cow, per year. Applying our estimated buyback rate to this production capacity results in a gross annual benefit of $67 per cow, less the utility customer charge.

A digester's electricity production is uncertain: it may vary based on the rate and efficiency of electricity generation, how frequently the digester is run, whether material other than manure is added to the digester, and other factors. This uncertainty is reflected in the AgSTAR data, which take the form of a normal distribution centered on the mean. In order to account for uncertainty, we use this normal distribution to calculate the private benefits resulting from electricity generation in our Monte Carlo simulation. Table 4 summarizes the annual private energy benefits to producers under this model based on our simulation, rounded to the nearest hundred dollars.

TABLE 4. PRIVATE ENERGY BENEFITS TO FARMERS, BY SAMPLE HERD SIZE

Herd Size	Gross Annual Benefit	Customer Charge	Net Private Annual Energy Benefits
500 cows	$33,100	$235	$32,900
1,000 cows	$66,500	$235	$66,300
2,500 cows	$165,900	$235	$165,700
5,000 cows	$332,400	$235	$332,100

It is worth noting that some farmers may choose to use electricity generated on-site, which would reduce the benefits calculated above, but would also result in benefits from avoided electricity costs. We did not model this scenario in our analysis. For more information on electricity generation, see Appendix I.

REDUCED BEDDING COSTS

The anaerobic digestion process produces digestate that can be separated into solids and liquids. The separated solids can be used as animal bedding. Bedding provides cows comfort, which is crucial because cows spend most of the day lying down processing feed into milk (Center for Agriculture, Food, and the Environment, 2019). The ability to use bedding produced on-site by the digester provides a significant benefit to dairy farms. We assume that the bedding produced by the digester completely covers the farm’s bedding expenses. Rather than purchasing sand, sawdust, or some other type of bedding, the farmer substitutes the digestate solids, a byproduct of anaerobic digestion, for their bedding. To calculate the benefit, we apply the market price of bedding ($0.41/cwt) to the average hundredweight (cwt) of milk produced per cow and multiply our estimate by the herd size. The expected annual benefits by herd size are detailed in Table 5, rounded to the nearest hundred dollars.

TABLE 5. PRIVATE BEDDING BENEFITS TO FARMERS, BY SAMPLE HERD SIZE

Herd Size	Net Private Annual Bedding Benefits
500 cows	$44,500
1,000 cows	$89,100
2,500 cows	$222,600
5,000 cows	$445,300

For more information, see Appendix K.

REDUCED TRANSPORTATION COSTS

All three models provide farmers benefits in the form of reduced transportation costs. A study conducted by Michigan State University estimates the average farm spends $100 to $160 per cow annually on trucking and transportation (Harrigan, 2011). These estimates include the cost accrued from manure agitation, pumping, transport, and land application of nutrients.

As mandated in Wisconsin Rule NR 151, manure spreading and application processes are restricted in areas of the state with permeable soils and shallow bedrock. These areas, including much of the Northeast region of Wisconsin, are more susceptible to groundwater contamination. Wisconsin NR 151 establishes the performance standards for manure spreading in our region of interest. Pathogen reduction benefits resulting from digested manure allow farmers to more easily meet these established manure-spreading standards, thus increasing the amount of manure that can be spread on a given field and decreasing the cost to farmers of transportation to fields further from the primary farm site (see Appendix L).

Interviews with farmers in Northeast Wisconsin suggest that a digester can reduce trucking costs by as much as 20 percent. In our Monte Carlo simulation, we use this estimate as an upper bound of a uniform distribution, with no cost reduction as a lower bound. We estimate average benefits through avoided trucking costs of approximately $15 per cow, per year. The estimated annual benefits to farmers are summarized in Table 6, rounded to the nearest hundred dollars.

TABLE 6. ANNUAL AVOIDED TRANSPORTATION COSTS, BY SAMPLE HERD SIZE

Herd Size	Farmer Savings
500 cows	$7,600
1,000 cows	$15,200
2,500 cows	$22,800
5,000 cows	$30,400

For more information, see Appendix J.

SOCIAL BENEFITS

Digesters decrease the levels of methane, nitrous oxide, pathogens, and noxious odor released by manure. This produces social benefits in the form of greenhouse gas emission reductions, improved local water supply, and improved quality of life for local residents. We also expect social benefits from reduced manure trucking in this model.

GREENHOUSE GAS EMISSION REDUCTIONS

Dairy farms are major producers of methane (CH_4) and nitrous oxide (N_2O), primarily through enteric fermentation in animals, but also through manure storage and management. Without a digester, manure is most often stored in lagoons. Chemical reactions in these lagoons result in significant emissions of methane, nitrous oxide, and ammonia. These are greenhouse gases that, when released into the atmosphere, contribute to global climate change. Continued greenhouse gas emissions have significant negative implications for the United States: rising temperatures cause increased weather volatility, contributing to disaster prevention and cleanup costs; rapidly changing water levels in oceans and water bodies, including the Great Lakes, imperil coastal communities; displacement of communities from affected areas imposes significant costs on local, state, and federal taxpayers (IPCC Climate Report, 2018). Insofar as anaerobic digestion reduces the emissions of greenhouse gases from a dairy farm, the process can reduce the costs to society of climate change.

Climate change impacts are typically measured in carbon dioxide (CO_2) equivalents. This measure tells us how much CO_2 would be removed from the atmosphere if emissions of another greenhouse gas were reduced by one ton. For example, one ton of methane accounts for 25 CO_2 equivalents, and one ton of nitrous oxide accounts for 298 CO_2 equivalents (EPA Greenhouse Gas Overview, 2019). Anaerobic digestion virtually eliminates nitrous oxide and ammonia emissions from manure and significantly reduces methane emissions (Lawson, 2010). Data from AgSTAR indicates that digestion on dairy farms accounts for an average of 6.1 metric tons of CO_2 equivalents (MT CO_2eq) reduced per cow, per year. To value this reduction, we apply the median $7 value for the domestic social cost of carbon currently used by the EPA (EPA Regulatory Impact Analysis, 2019).

These estimates are uncertain: the rate of biogas production per-cow depends on the efficiency of the digester, whether materials other than manure are added to the digester, and how frequently the digester operates. All of these variables are uncertain in our models and vary across the AgSTAR data. To account for this uncertainty, we apply a uniform distribution to the data on greenhouse gas reduction and use the EPA's seven dollar CO_2 equivalent shadow price to value this reduction in our Monte Carlo simulation. Table 7 summarizes the annual social energy benefits from greenhouse gas reduction based on that simulation, rounded to the nearest hundred dollars.

TABLE 7. ANNUAL SOCIAL BENEFITS OF GREENHOUSE GAS REDUCTION, BY SAMPLE HERD SIZE

Herd Size	CO_2 equivalent Reduction (MT CO_2eq)	Social Annual Energy Benefits
500 cows	3,062	$21,100
1,000 cows	6,124	$42,200
2,500 cows	15,310	$105,400
5,000 cows	30,620	$210,800

For more information, see Appendix I.

WATER QUALITY

Improvements in water quality represent a potential social benefit of anaerobic digestion. Society realizes these improvements in water quality through better health outcomes. We expect digesters to improve local water quality by reducing the presence of pathogens in groundwater. However, digesters do not alter the nitrogen and phosphorus content of manure, and thus we do not anticipate improvements to surface and groundwater quality through nutrient reduction (see Appendix O).

Through monetizing the cost of illnesses likely to be borne from common pathogens, and accounting for both the affected population and the probability of manure runoff contaminating domestic water sources with pathogens, we anticipate an average benefit in avoided costs associated with illness to be approximately $2,000 annually. For more information, see Appendix L.

REDUCED TRANSPORTATION EXTERNALITIES

Farmers are able to spread more digested manure than undigested manure due to its lower pathogen levels, and thus truck less to other fields (Wis. Stat. § 151.075). This in turn reduces the social costs of trucking manure. Unpriced external costs of transportation by truck freight contribute to the deterioration of public roads, traffic congestion, loss of income, injuries, fatalities, property damage, and adverse environmental impacts caused by exhaust emissions (CBO, 2015). These externalities are not fully captured through taxation, licensure, or permits. The CBO estimates that the social cost of trucking is between $0.028 and $0.063 per ton, per mile trucked. We apply a uniform distribution of these prices in calculating the social benefits from reduced manure trucking, given the presence of a digester.

A typical dairy farm uses a hauler to apply manure near the primary farm site, a distance of approximately 5 miles per trip. Assuming that farmers use their haulers at full capacity each trip, we calculate the trips (*Trip*) as a function of herd size (S_{op}), and multiply the number of trips by the average distance (*5 miles*) and the social costs of trucking per mile (SCT_m) to determine the social costs of trucking at baseline (*SCTB*).

$$SCTB = Trip * S_{op} * 5miles * SCT_m$$

We assume these trips reduce by 0 to 20 percent in the presence of a digester (*RT*). We apply this distribution to our baseline calculation to estimate the social benefits from trucking reduction (*SBT*).

$$SBT = RT * SCTB$$

This results in an expected social benefit of about $0.03 per cow. Table 8 summarizes these benefits annually by herd size, rounded to the nearest dollar.

TABLE 8. ANNUAL SOCIAL BENEFITS OF TRUCKING REDUCTION, BY SAMPLE HERD SIZE

Herd Size	Annual Social Transportation Benefits
500 cows	$14
1,000 cows	$43
2,500 cows	$71
5,000 cows	$143

For more information, see Appendix J.

ODOR REDUCTION

Raw, untreated manure emits noxious odors that can reduce the quality of life in nearby communities. We monetize the benefits of odor reduction using the estimated impacts on property values in northeast Wisconsin.

Research has shown there is potential for up to a 13 percent decrease in residential home value for parcels within one mile of a CAFO. However, this reduction is not entirely due to odor. We therefore use as an upper bound an 8 percent reduction in home value as a proxy for the cost of reductions in quality of life due to odor. With approximately 56 homes within a one-mile radius of CAFOs and a median home value of $150,000 in the region of analysis, the potential benefits of odor reduction proxied through eliminating this reduction in home prices range between $0 and $672,000, with an average value of approximately $250,000, realized in the first year of digester operation. Because home values will reflect the reduced odor from the nearby CAFO after this first year, we count these benefits only once in our Monte Carlo simulation.

For more information, see Appendix M.

NET SOCIAL AND FARMER BENEFITS

Table 9 details the expected private, social, and total net benefits given different herd sizes under Model 1.

TABLE 9. MODEL 1 NET PRESENT VALUE OF BENEFITS, BY SAMPLE HERD SIZE (IN MILLION USD)

Herd Size	Farmer Benefits	Social Benefits	Total Benefits
500 cows	-1.0	0.3	-0.7
1,000 cows	-0.6	0.6	0.0
2,500 cows	0.5	1.8	2.3
5,000 cows	2.4	3.3	5.7

COSTS AND BENEFITS: MODEL 2

Model 2 assumes the farmer sells their minimally processed biogas to a private investor, rather than selling electricity to a utility.

COSTS

PRIVATE COSTS TO FARMERS

In Model 2, no genset is needed. Rather, the farmer must purchase a pressure tank to store raw biogas. The pressure tank must be large enough to store three days-worth of biogas to be transported to a cleaning site and injected into the natural gas pipeline.

UPFRONT CAPITAL

We estimate no additional capital investment in major equipment for the purposes of natural gas processing. In Model 1, the biogas collected directly from the reactor tank needs moisture and hydrogen sulfide removal before being used as fuel for electricity generation. Therefore, we assume the biogas quality produced by the farm in Model 1 is no different than the quality of biogas produced in Model 2. Because of these factors, no additional biogas processing equipment is needed for purchase by the farm, only the pressure vessel for biogas storage.

Gensets are expensive and replacing them with pressure tanks reduces equipment costs considerably. Accounting for the subtraction of the genset and the addition of the pressure tank, we calculated total upfront capital costs for Model 2 (*Cm2*) as a function of herd size (S_{op}):

$$Costs_{M2} = \$678 * S_{op} + \$622{,}309$$

For more detail on our assumptions and calculations, see Appendix H.

OPERATING COSTS

Without a genset, the operating costs of Model 2 increase. In Model 1, the genset provides the necessary heat for the digestate in the reactor tank to reach temperatures required for anaerobic digestion. Therefore, without the genset, the digester requires significantly more energy. Consequently, operating costs in Model 2 rise.

We obtained anecdotal data suggesting an increase in operating costs without a genset (Interview 5, 2019). However, we are unable to estimate any exact increase in operating costs due to lack of data. Therefore, we adjust operating costs at all values by 1 percent, moving the center of the distribution of values from 5 percent of capital costs in Model 1, to 6 percent of capitals costs in Model 2. We again use a triangular distribution to estimate annual operating costs at specified herd sizes in our Monte Carlo simulations.

These increased operating costs are not large, but must be taken into account because these costs occur annually and slightly offset the reduction in capital costs when the digester is not using methane biogas for on-site electricity generation. For more information, see Appendix H.

LAND USE COSTS

As in Model 1, our estimation for land use costs is $572 per year (see Appendix N).

SOCIAL COSTS

Compared to Model 1, there are minor changes in the social costs associated with Model 2.

GAS TRANSPORTATION EXTERNALITIES

Models 2 and 3 involve social costs from transportation externalities associated with moving raw methane biogas from the biogas storage vessel on the farm to the natural gas processing facility. As of September 2019, there is one natural gas injection facility in the region located in Newton, Wisconsin (DTE Energy, 2019).

We estimate the distance from farms in two counties within the Northeast region of Wisconsin to the injection site in Newton, WI. Brown and Kewaunee counties both have digester sites located near a high concentration of CAFOs. We applied a uniform distribution to those distances to generate our expected miles traveled to an injection site. We then multiply that distance by our estimated social cost of trucking per cow per mile, which is uniformly distributed from $0.03 to $0.06, and subtract this from our estimated social benefits per cow, per year from reduced manure trucking (see Model 1) to calculate the total social costs of gas transportation per cow, per year in Models 2 and 3. Table x summarizes the net annual social costs of gas transportation in Models 2 and 3, including benefits from reduced manure trucking. Values are rounded to the nearest hundred dollars.

TABLE 10. ANNUAL SOCIAL COSTS OF TRANSPORTATION, BY HERD SIZE (MODELS 2 AND 3)

Herd Size	**Annual Operating Costs**
500 cows	$1,100
1,000 cows	$2,200
2,500 cows	$5,600
5,000 cows	$11,100

For more information on these calculations, see Appendix J.

LAND USE COSTS

As in Model 1, our estimation for land use costs is $572 per year (see Appendix N).

BENEFITS

FARMER BENEFITS

In the second model, we assume that the farmer will sell the biogas generated to a third party for sale on the private market. The third party would receive renewable energy credits from California or other states with tradable credit incentive programs for renewable energy use in transportation fuel (see Appendix G). In this model, farmer-owned digesters produce biogas that will be stored, transported, processed, and sold by a third-party private entity or utility. The farmer will receive income from the sale of minimally processed biogas which will later be converted into pipeline quality biomethane, a renewable resource for blended transportation fuel.

BIOGAS SALES

We calculate farmer benefits in this model by determining the income received by the farmer for each cubic meter (m^3) of biogas sold. To determine this income, we calculate the quantity of biogas generated per cow according to AgSTAR data and apply the wellhead price of natural gas to that quantity.

The average quantity of gas produced annually by mixed plug flow digesters on dairy farms in the AgSTAR database was 1,084 cubic meters (m^3) per cow. The Energy Information Administration no longer tracks the wellhead price of natural gas; therefore, we calculate a ratio of historic wellhead prices to historic commercial prices. We then apply that ratio to the current commercial price for natural gas in Wisconsin to determine an estimated price the dairy farm would receive for their minimally processed biogas. This price, \$0.11 per cubic meter, gives us an average annual private benefit of \$114 per cow for farmers. To account for uncertainty in the quantity of biogas produced, the efficiency of the digester, and fluctuation in the wellhead price of gas, we apply a triangular distribution centered at these estimates to this variable in our Monte Carlo simulation. The private annual benefit found in that simulation is summarized in Table 11, rounded to the nearest hundred dollars.

TABLE 11. PRIVATE BIOGAS SALE BENEFITS TO FARMERS, BY SAMPLE HERD SIZE

Herd Size	Biogas Produced (m^3)	Private Annual Benefit
500 cows	555,377	$58,300
1,000 cows	1,110,754	$116,600
2,500 cows	2,776,886	$291,600
5,000 cows	5,553,771	$583,100

For more information on these calculations, see Appendix I.

REDUCED BEDDING COSTS

Bedding benefits in Model 2 are the same as in Model 1. We apply the market price of bedding ($0.41/cwt) to the average hundredweight (cwt) of milk produced per cow and adjust our estimate based on the herd size. The expected annual benefits given herd size are detailed under Model 1.

REDUCED TRANSPORTATION COSTS

Reduction in the quantity of trucked manure for application on fields is unchanged from Model 1. We estimate an average farmer benefit of approximately $15 per cow, per year.

SOCIAL BENEFITS

Social benefits change slightly from Model 1 to Model 2. Due to the potential for methane leakage from natural gas pipelines, the social benefits of greenhouse gas emission reductions in Model 2 are slightly lower than in Model 1. Our estimates for the social benefits of reduced trucking are also slightly smaller in this model compared to Model 1 because of the added costs of biogas transportation discussed above.

EMISSIONS REDUCTIONS

Our base calculation of the social benefits from energy production in this model is unchanged from Model 1. However, because this model assumes that biomethane will be injected into a natural gas pipeline after it is cleaned and processed, we must account for the potential of methane to leak into the atmosphere. The EPA currently estimates that, from the point of production to the point of use, 1.4 percent of all natural gas is leaked into the atmosphere (EPA Inventory of Greenhouse Gas Emissions and Sinks, 2017). We apply this leakage rate to the distribution of tons of CO_2 equivalents reduced by digester use found in Model 1. The average reduction in greenhouse gas emissions accounting for leakage is therefore calculated as 6.04 tons CO_2 equivalents reduced per cow, per year.

As in Model 1, we apply a uniform distribution to the AgSTAR data in order to account for the uncertainty of biogas production, and value the reduction in greenhouse gas emissions using the $7 EPA shadow price per ton of CO_2 equivalents reduced. Table 12 details the results from our Monte Carlo simulation for the annual social benefits of emission reduction in Model 2, rounded to the nearest hundred dollars.

TABLE 12. ANNUAL SOCIAL BENEFITS OF EMISSION REDUCTION ACCOUNTING FOR LEAKAGE, BY SAMPLE HERD SIZE

Herd Size	CO_2 equivalent Reduction (MT CO_2eq)	Social Annual Energy Benefits
500 cows	3,019	$21,000
1,000 cows	6,038	$42,100
2,500 cows	15,096	$105,200
5,000 cows	30,191	$210,300

All sales of biogas beyond its production are viewed as transfers in our social cost-benefit analysis, and therefore producer surplus accruing to third parties is not monetized. We assume that the value of renewable energy credits internalizes the social benefit of using renewable biomethane in transportation fuel, and therefore do not monetize these benefits. For more information on the social benefits of biogas production, see Appendix I. For more information on non-monetized values, see Appendix O.

WATER QUALITY

Regardless of the type of energy produced or ownership of the facility, digestion of the manure will still destroy pathogens. Therefore, we expect the same value of benefits in Model 1 by way of avoided cost of illness. The average benefit given pathogen destruction will be approximately $2,000 annually.

ODOR REDUCTION

Regardless of the type of energy produced or ownership of the facility, digestion of the manure will still reduce odors. Therefore, we expect the same value of benefits in Model 1 using avoided reduction in property values as a proxy for odor costs. The average benefit of odor reduction is approximately $250,000.

REDUCED TRANSPORTATION EXTERNALITIES

Because the pathogen reductions are the same as in Model 1, the reduced annual transportation externalities are in the same range of $0.53 to $1.20 per cow. Our net estimates, however, account for the social costs of trucking untreated methane, discussed above.

NET SOCIAL AND FARMER BENEFITS

Table 13 details the expected private, social, and total net benefits given herd size under Model 2.

TABLE 13. MODEL 2 NET PRESENT VALUE OF BENEFITS, BY SAMPLE HERD SIZE (IN MILLION USD)

Herd Size	Farmer Benefits	Social Benefits	Total Benefits
500 cows	-0.5	0.3	-0.2
1,000 cows	0.4	0.6	1.0
2,500 cows	3.0	1.7	4.7
5,000 cows	7.3	3.1	10.4

Farmers with herd sizes of 1,000 cows or more should now expect to see positive net benefits. Social benefits are positive at all herd sizes. For full analysis, see Results.

COSTS AND BENEFITS: MODEL 3

Model 3 assumes that a private investor or utility pays to construct and operate the digester. The farmer leases land to the investor and continues to use digestate for bedding and spreading. As in Model 2, the farmer does not sell electricity to a utility. We assume that the farmer will provide raw manure for use in the digester without receiving a payment from the third party.

COSTS

PRIVATE COSTS TO FARMERS

In Model 3, aside from the opportunity cost of land there are no costs to the farm; all upfront capital and operational costs are incurred by another party. The other party would likely be a utility or investment company constructing and operating anaerobic digestion systems. Firms are incentivized to participate in such a market because of the private market for natural gas and the value of renewable energy credits available in California and in other states where tradable credits are available for renewable energy resources (see Appendix G).

LAND USE COSTS

As in Models 1 and 2, our estimation for land use costs is $572 per year (see Appendix N).

SOCIAL COSTS

The social costs of Model 3 are the same as Model 2. The only difference between Model 2 and Model 3 is the private ownership of the digester on the farm.

BENEFITS

FARMER BENEFITS

In this model, we assume that an independent firm or utility company owns and operates the digester on land owned by a Wisconsin dairy farmer. The farmer will provide manure to the digester operator and receive the digested material after processing for on-farm use. We assume that the farmer will provide manure to the third-party operator without receiving payment for their manure. This is a conservative assumption: although other benefits to the farmer may provide enough incentive for the farmer to enter into such an agreement, it is possible that some third-party operators would offer payment for the use of manure for digestion (Interview 2). Our model provides a baseline in terms of the benefits that farmers could expect from an arrangement with a third-party digester operator without receiving payment for raw manure.

REDUCED TRANSPORTATION COSTS

Because the pathogen reductions are the same as in model one, the reduced annual transportation costs are in the same range of $0.53 to $1.20 per cow as the other models.

LEASE BENEFITS

Under third-party ownership, a farm would likely lease the land on-site needed for the digester to the third party as part of a long-term contract (see Appendix N). We expect the benefit to the farm through this one-time lease payment to be $22,704.

SOCIAL BENEFITS

The social benefits in Model 3 are assumed to be the same as Model 2.

NET SOCIAL AND FARMER BENEFITS

Table 14 details the expected private, social, and total net benefits given herd size in Model 2.

TABLE 14. MODEL 3 NET PRESENT VALUE OF BENEFITS, BY SAMPLE HERD SIZE

Herd Size	Farmer Benefits	Social Benefits	Total Benefits
500 cows	0.8	0.3	1.1
1,000 cows	1.5	0.6	2.1
2,500 cows	3.8	1.7	5.5
5,000 cows	7.6	3.1	10.7

Farmer and social benefits are now positive at all herd sizes. Farmer benefits are estimated to be larger at all herd sizes than in any other model.

NON-MONETIZED VALUES

There are various benefits and costs that we do not monetize in our analysis:

- **Impacts of large farms on communities**: Because anaerobic digestion provides an additional revenue stream for large farm operators, there may be an incentive to grow these types of operations. We do not monetize the impacts that large farms may have on communities.
- **Water quality benefits through nutrient reduction**: Our analysis does not consider potential benefits to water quality due to changes in nutrient loading of phosphorus and nitrogen because standard anaerobic digestion does not alter the nutrient content of the digestate. Without an alteration (such as a tertiary water filtration system or phosphorus capture), we anticipate there will be no reduction in the nutrient loading that impacts water quality.
- **Fertilizer costs**: We do not consider changes to fertilizer costs for farmers. We assume that the farm will still purchase the same amount of fertilizer to supplement nutritional needs, meaning there will be no reduction in costs of fertilizer.
- **Construction emission**s: We do not consider the greenhouse gas or particulate emission impacts of constructing the digester facility. Transportation and raw materials associated with construction of the facility would generate some emissions that would offset some of the emissions benefits.
- **Indirect and secondary markets**: Because of the uncertainty in natural gas markets nationally and the fact that many of the social benefits of biogas use are internalized by Renewable Energy Credit programs, we do not monetize producer surplus that might accrue to third parties selling biogas in Models 2 and 3. We also do not account for impacts to indirect and secondary markets.

These categories are further detailed in Appendix O.

RESULTS

NET PRESENT BENEFITS OF A DIGESTER OVER ITS LIFESPAN

We calculate the net present value for dairy farms adopting a digester, assuming a 20-year lifespan for a digester, and find positive social benefits at all herd sizes and in each model. We find that positive farmer benefits are conditional on herd size for Models 1 and 2, but farmer benefits are positive for all herd sizes in Model 3.

In the calculation of the present value of upfront costs, odor reduction, and were assumed to occur at the beginning of the first year. Odor reduction was only included in calculations for farms of herd sizes of 2,500 cows or more. All other annual costs and benefits were discounted mid-year using a 3.5 percent discount rate over a 20-year time horizon.

Many of our variables have highly uncertain parameters, so we simulate 10,000 trials across the potential values of each variable to generate the expected net present benefits from farm-level digesters after 20 years of operation, to both the farmer and to society, for farms with 500 to 5,000 cows. Those simulations are summarized in Table 15 for each model at herd sizes of 500, 1,000, 2,500 and 5,000 cows. We show both the mean value of those 10,000 trials, as well as the 5th (P5) and 95th (P95) percentile values to give a sense of the range of possible benefits.

TABLE 15. NET PRESENT BENEFIT ESTIMATES FOR DIGESTERS OVER 20 YEARS (IN $ MILLIONS)

	Farmer Benefits			**Social Benefits**			**Total Benefits**		
Herd Size	Mean	P5	P95	Mean	P5	P95	Mean	P5	P95
MODEL 1									
500 cows	-1.0	-1.7	-0.3	0.3	0.1	0.5	-0.7	-1.6	0.2
1,000 cows	-0.6	-1.8	0.6	0.6	0.2	1.0	0.0	-1.6	1.6
2,500 cows	0.5	-2.2	3.2	1.8	0.8	2.8	2.3	-1.4	6.0
5,000 cows	2.4	-2.9	7.6	3.3	1.3	5.3	5.7	-1.5	12.9
MODEL 2									
500 cows	-0.5	-0.7	-0.3	0.3	0.1	0.5	-0.2	-0.6	0.2
1,000 cows	0.4	-0.2	0.9	0.6	0.2	1.0	1.0	0.0	1.9
2,500 cows	3.0	1.3	4.8	1.7	0.7	2.7	4.7	2.0	7.5
5,000 cows	7.3	3.8	11.3	3.1	1.2	5.1	10.4	5.0	16.4
MODEL 3									
500 cows	0.8	0.7	0.9	0.3	0.1	0.5	1.1	0.8	1.4
1,000 cows	1.5	1.3	1.7	0.6	0.2	1.0	2.1	1.5	2.7
2,500 cows	3.8	3.3	4.3	1.7	0.7	2.7	5.5	4.0	7.0
5,000 cows	7.6	6.6	8.6	3.1	1.2	5.1	10.7	7.7	13.7

Total benefits are positive for all values in Model 3 and social benefits are positive for all herd sizes and all models, but herd size affects outcomes for the other models. In Model 1, there is some possibility costs still outweigh benefits for farmers after 20 years at all herd sizes.

To further illustrate the differences in possible benefits to farmers by model and herd size, we additionally calculate the percent of trials with positive present value of benefits after 20 years in each model. Table 16 shows those results for herd sizes of 500, 1,000, 2,500, and 5,000 cows.

TABLE 16. PERCENT OF TRIALS WITH POSITIVE FARMER NET BENEFITS

Herd Size	**Model 1**	**Model 2**	**Model 3**
500 cows	0.6	0.0	100.0
1,000 cows	20.7	81.3	100.0
2,500 cows	62.3	100.0	100.0
5,000 cows	77.2	100.0	100.0

Based on these results, it is highly unlikely farmers with a herd size under 1,000 cows will see profit with a digester in Model 1. It is nearly impossible that benefits outweigh costs for farms with 500 cows or less. This reinforces our decision to limit our analysis to large farms. One hundred percent of trials show positive net benefits in Model 2 for herd sizes above 1,500 cows. In Model 3, where farmers incur very few costs, 100 percent of trials show positive benefits after 20 years, though it is important to note that benefits to digester owners in Model 3 would likely vary substantially by herd size.

All models found positive social benefits in 100 percent of trials.

For additional information on our calculation methods, variable parameters and estimates, and benefit estimate distributions, see Appendix P. We perform our simulations in Stata. Our full code is available in Appendix Q.

In light of the high level of uncertainty in our parameters, we conduct several sensitivity analyses to verify the robustness of our results, finding positive social benefits at all herd sizes and in each model, even under the least generous assumptions, although private and total benefits are more variable in these conditions. These results are described in Appendix P.

BENEFIT AND COST CATEGORIES

Breaking out costs and benefits by category allows us to identify the main forces driving the results observed above. Tables x and y show the mean value for our central benefit and cost variables across 10,000 simulations by model, at a herd size of 1,000 and 2,500 cows, for farmers (Table 17) and society as a whole (Table 18).

TABLE 17. PRESENT VALUE OF FARMER BENEFITS AND COSTS OF DIGESTERS AFTER 20 YEARS (IN MILLION USD)

Herd Size	**Model 1**	**Model 2**	**Model 3**
	Energy Sales[a]		
1,000 cows	1.0	1.7	0
2,500 cows	2.4	4.2	0
	Avoided Bedding Costs		
1,000 cows	1.3	1.3	1.3
2,500 cows	3.2	3.2	3.2
	Reduced Manure Transportation		
1,000 cows	0.2	0.2	0.2
2,500 cows	0.5	0.5	0.5
	Capital[b]		
1,000 cows	-1.4	-1.3	0
2,500 cows	-2.5	-2.3	0
	Operations and Maintenance		
1,000 cows	1.2	1.3	0
2,500 cows	2.1	2.2	0

[a]Energy sales in Model 1 come from electricity sales to the local utility; energy sales in Model 2 come from biogas sales to the third party.
[b]Due to financing, capital costs would actually be higher (by an estimated $0.3 million for herd size 500 and $0.5 million for herd size 1,000)

Table 17 illustrates the fiscal burden of building and operating a digester for farmers. Although benefits to farmers are lower in Model 3, avoided capital and operations costs are enough to make digesters more profitable. Table 11 also shows that biogas sales (Model 2) are more cost effective for farmers than electricity sales to utilities (Model 3). In addition to the variables in the table, the present value of agricultural land loss over 20 years comes to approximately $8,300 in each model.

Table 18 details the net social costs and benefits from one digester after 20 years of operation, for herd sizes of 1,000 and 2,500 cows. Models 2 and 3 have the same estimated social benefits, and are shown together. Social cost and benefit categories include transportation externalities, pathogen reduction, noxious odor reduction, greenhouse gas emission reduction, and agricultural rents. Transportation externalities in Models 2 and 3 generate the most substantial social costs from digesters. These costs are far outweighed by the benefits, particularly greenhouse gas emission reductions.

TABLE 18. PRESENT VALUE OF SOCIAL BENEFITS AND COSTS OF DIGESTERS AFTER 20 YEARS (IN THOUSAND USD)

Herd Size	Model 1	Models 2 and 3
	Transportation Externalities	
1,000 cows	0.4	-32.2
2,500 cows	1.0	-80.4
	Pathogen Reduction	
1,000 cows	29.9	29.9
2,500 cows	29.9	29.9
	Noxious Odor Reduction	
1,000 cows	-	-
2,500 cows	242.5	242.5
	Greenhouse Gas Emission Reduction	
1,000 cows	609.7	608.2
2,500 cows	1,524.3	1,520.4
	Agricultural Rents	
1,000 cows	-8.3	-8.3
2,500 cows	-8.3	-8.3

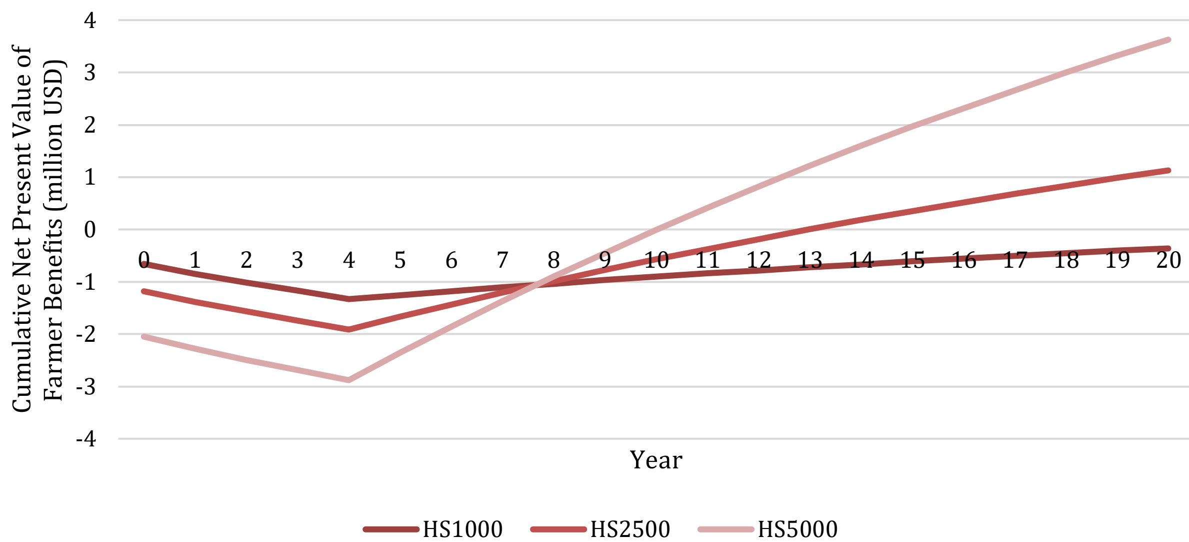
While we do predict digesters to produce some social costs, most social impacts are positive across each category and model. Greenhouse gas emission reductions generate the largest benefits to society. It is important to note, in comparing benefits by herd size, that these estimates are relative to a baseline where farms do not use a digester. Farms with fewer cows have lower social costs at baseline than bigger farms, and thus a digester would have a smaller social impact.

FARMER BENEFIT TRAJECTORIES

While we assume a 20-year time horizon in calculating the net present benefits of a digester, many farms may need to see returns on investment earlier in order to remain operational. We therefore estimated the present value of net benefits in each year of the project to identify the point at which a farm would "break even" in each model.

Figure 1 tracks the farmer's cumulative benefits over time in Model 1, at herd sizes of 1,000, 2,500, and 5,000 cows. They are labeled HS1000, HS2500, and HS5000, respectively.

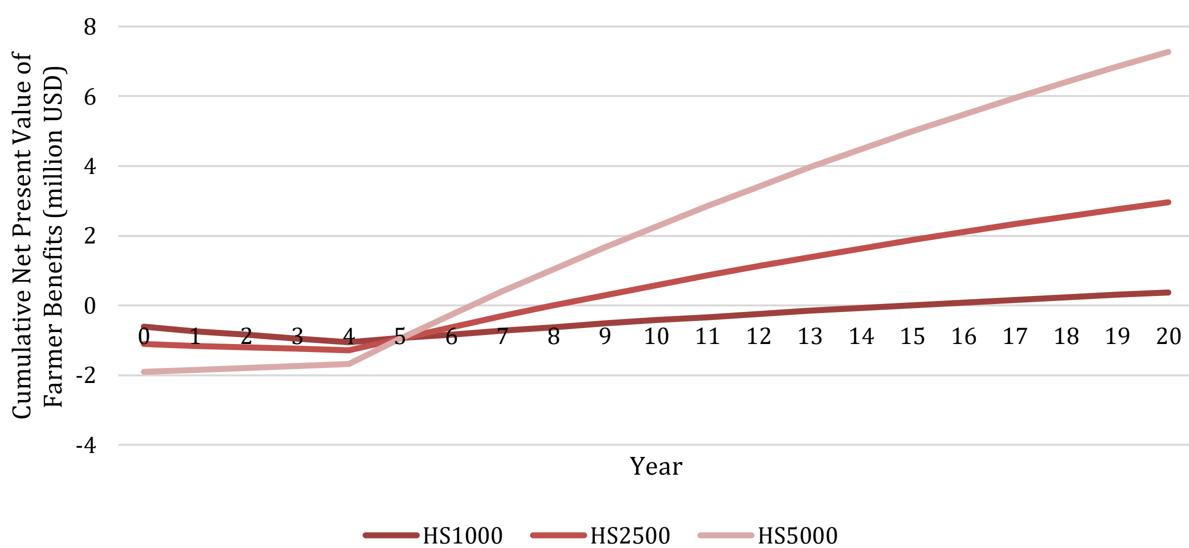
FIGURE 1. CUMULATIVE BENEFITS TO FARMERS OVER 20 YEARS IN MODEL 1



Farmers with 1,000 cows never break-even in our estimation. At herd size 2,500, a farmer would break-even between Year 13 and Year 14. Even on the largest farm in our calculations, farmers do not break-even until Year 11.

Model 2 shows much more promising results for farmers at all herd sizes (Figure 2).

FIGURE 2. CUMULATIVE BENEFITS TO FARMERS OVER 20 YEARS IN MODEL 2



Break-even points are now much earlier, and closer together. Farmers with 2,500 and 5,000 cows both start seeing their investment pay off around Year 7. Unlike Model 1, farmers with 1,000 cows can now break-even, but still not until Year 15. Our analysis suggests the farms with herd sizes of 1,500 cows and 2,000 cows should break even in Years 11 and 9, respectively.

This section does not discuss Model 3 because Model 3 shows positive benefits to the farmer in each year of the project life.

ASSUMPTIONS, LIMITATIONS, AND CONSIDERATIONS

As outlined in the discussion of our results, our analysis contains a high degree of uncertainty in relation to the net benefits of anaerobic digestion projects. Much of this uncertainty results from unquantified variables that determine the rate of biogas production, including: the efficiency of digester operation, the frequency of digester operation, and whether substrates other than cattle manure are added to the digester slurry. Codigestion could potentially yield higher profits for digester operators through additional revenue incurred through tipping fees, which are imposed by operators to accept other substrates such as food waste, oil, fats, or wastewater (Liebrand, 2009). These variables are reflected in the uncertainty for our parameters in maintenance cost and biogas production benefits. Future research with larger datasets may more closely approximate the true parameters of these variables, and thus generate less variable estimates for digester costs and benefits.

Our findings for water quality benefits are limited in this analysis; however, many Wisconsin policymakers are interested in the benefits that anaerobic digestion could have to reduce farm runoff and improve surface and groundwater quality. The Dane County Community Digester uses a tertiary wastewater filtration system, also known as a Nutrient Concentration System, that may remove up to 60 percent of phosphorous from the digested manure (AgSTAR, 2019). Further analyses should examine the extent to which filtration systems would be useful in privately-owned digesters, and their impact on costs and benefits to society and digester operators.

Models 2 and 3 in our analysis depend on markets for renewable energy credits that are currently promoted by the state of California and, more recently, other western states. This is an emerging and growing market, and as more states adopt policies to promote the use of lower carbon-intensity resources in fuel, the market for biogas may grow as well (Interview 2). However, recent rollbacks of federal fuel standards have left uncertainty in this market on a national scale. Producers of biogas and other renewable fuel resources will have to be conscious of changing state and national policies as they develop plans for increased operation.

Additionally, we only calculate private benefits to farmers. We assume that the sales of biomethane by third parties do not alter the social surplus in the nationwide natural gas market, and we assume that Renewable Energy Credits internalize the social benefits of using biomethane as transportation fuel. Thus, we consider these cost and benefit categories to be transfers.

Finally, both state and national policy affect the construction of digesters directly through the potential for grants, loans, and tax credits encouraging biogas production. Historical tariffs in Wisconsin, which expired in 2014, offered higher buyback rates from utilities for biogas producers (PSC Utility Tariffs, 2019). Many private Wisconsin digesters were constructed when these tariffs were in place, and future digester operators could benefit from the opportunity to sell digester-generated electricity at higher rates. At the federal level, according to AgSTAR data, more than half of operational digesters in Wisconsin received USDA funding to support their construction, including all but one constructed prior to 2012. The availability of these grants is limited today, but HR 3744, currently referred to the House Committee on Ways and Means, would offer tax credits to biogas producers to help offset construction costs. Implementation of any of these biogas-supporting policies would alter the results of this analysis.

RECOMMENDATION

Based on our analysis, we recommend farms adopt Model 3. With no capital or upfront cost, this model yields net benefits for the farmer at all herd sizes. Our research suggests this model not only elicits the highest return for farmers, but also reflects the burgeoning biogas production market trends statewide and nationwide. However, Model 3 requires an interested third-party developer for the farmer to fully realize the benefits.

The third-party requirement leads us to also recommend that, without a third-party developer, farmers should adopt Model 2. From a private perspective, if a farmer owns the digester, adoption of Model 2 would be preferential compared to Model 1. In Model 2, farmers with herd sizes over 1,000 cows should experience positive net benefits, but not until 15 years into operation. At herd sizes of 2,500 cows or more, however, farmers in Model 2 should start breaking even around the seventh year of operation. For this reason, digesters are likely a safer investment for farms with 2,500 cows or more. All or nearly all of our trials showed net positive farmer benefits for herd sizes above 1,500 cows, so farmers with 1,500-2,500 cows could likely still consider investing in a digester if they can afford to wait longer for the investment to pay off, or if they can identify funding sources to mitigate the capital costs

The market for raw dairy biogas that can be sold and cleaned into pipeline quality biomethane is expanding, while current utility tariffs make electricity generation and sale less profitable. Additionally, Wisconsin projects an increase in interstate injection sites throughout the state, which could potentially reduce the private and social costs of transporting biogas (Lillian, 2019). Growth in interstate biogas processing and biomethane injection sites would increase the economic viability of Model 2 for a farmer-owned manure digester. Lastly, as more states adopt credit-based incentive programs for the use of biomethane in transportation fuel, this market will continue to expand. If Wisconsin or other

Midwestern states adopted such a program, then the low costs of piping biomethane would improve farmers' prospects for realizing significant benefits.

Although Model 1 generates lower projected benefits at all herd sizes than Model 2, farms should still expect to see returns on investment in Model 1 at herd sizes of 2,000 cows or more. However, these results are more uncertain. Even at a herd size of 5,000 cows, only 77 percent of trials showed positive net benefits after 20 years. Additionally, farmers will have to wait far longer to see their investment pay off. If utilities adjust buyback rates in the future to better compensate renewable electricity producers, or use net-metering billing mechanisms to allow for easier on-site use of digester-generated electricity, smaller farms could realize positive net benefits.

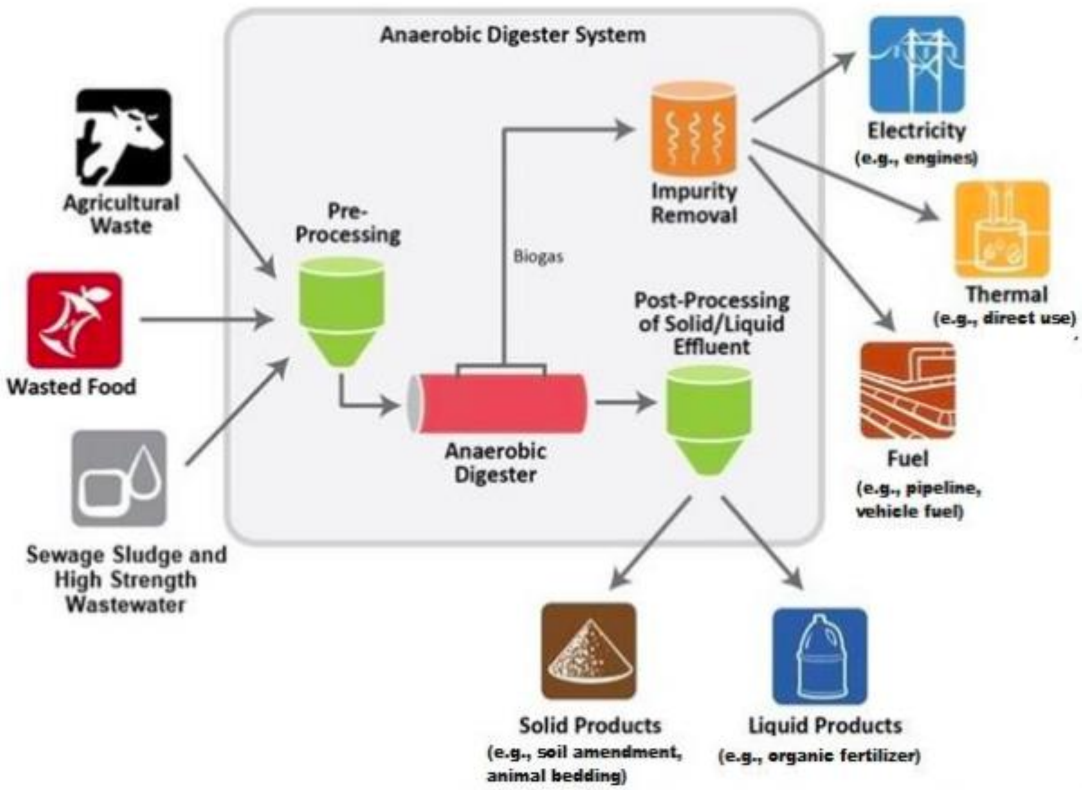
All three models result in significant positive social net benefits, even when accounting for uncertainty. For most farms in Wisconsin, however, social benefits exceed the benefits to the farmer. This leads us to conclude that digesters may be undersupplied by the current market, particularly for smaller farms. The reason for undersupply may be that high capital costs prevent farmers from realizing benefits for several years or more. In an environment where over 40% of dairy farms have shut down in Wisconsin in the past decade, making significant capital investments for uncertain monetary benefits is a challenging proposition for farmers (Quirmbach, 2019). To correct this market failure, policymakers at the state and national level could consider expanding grant programs for digesters or making tax credits available to offset capital costs for biogas producers, as HR 3744 proposes.

Based on the positive net benefits in most scenarios, all three models are feasible options for policymakers to consider when pursuing policies aimed at increasing economic benefits for Wisconsin dairy farms, encouraging the growth of the renewable energy industry, and promoting Wisconsin-based energy production markets.

APPENDIX A: THE ANAEROBIC DIGESTION PROCESS

Anaerobic digestion (AD) is the "biochemical decomposition of organic matter into methane gas and carbon dioxide by microorganisms in the absence of air" (Costa et al., 2015). Anaerobic digestion primarily takes place in a tank or container known as an anaerobic digester (also referred to as a biodigester or digester), which uses different combinations of microbes, heat, water, and physical agitation to process animal waste (Gordon, 2016). The result of anaerobic digestion is digestate and biogas.

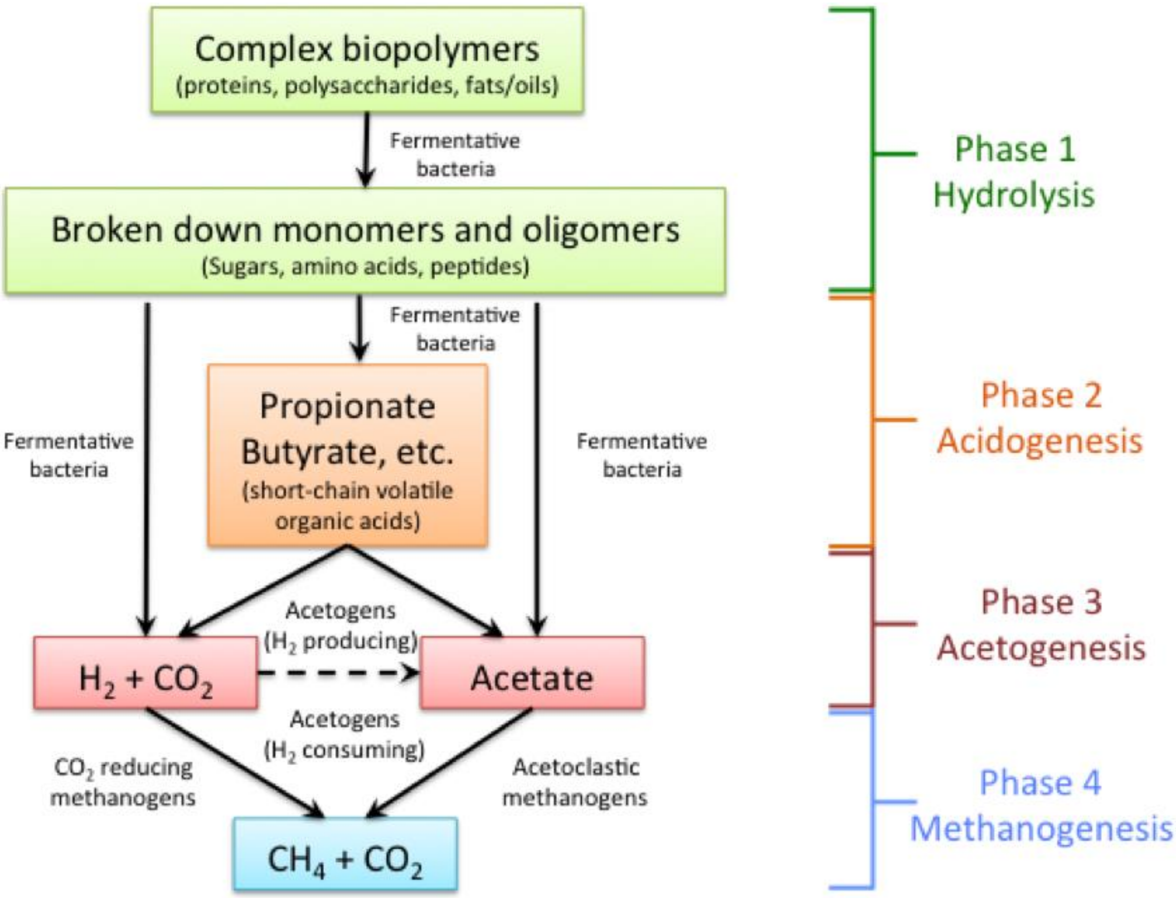
FIGURE 3. ANAEROBIC DIGESTER SYSTEM DIAGRAM



Source: Costa et al., 2015

AD begins with bacterial hydrolysis of manure to break down insoluble organic polymers and make them available for other bacteria. Acidogenic bacteria convert the sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids. Acetogenic bacteria converts the resulting organic acids into acetic acid and additional ammonia, hydrogen, and carbon dioxide. Finally, methanogens convert these products to methane and carbon dioxide (American Biogas Council, 2019).

FIGURE 4. PHASES OF BIODIGESTION



Source: Clifford, 2019

APPENDIX B: DIGESTERS OPERATING IN WISCONSIN

As of October 2019, Wisconsin has 39 operating livestock digesters. All digesters process dairy waste, while some process additional waste streams such as swine waste, food waste, and wastewater. Herd sizes range from 120 cows to 8,500 cows. There is a digester currently under construction in Adams County that will have a herd size of 9,100 cows. Six out of nine digesters with fewer than 1,000 cows process additional waste streams.

The following table lists all 39 operational livestock digesters in Wisconsin, including their project type (for a single farm or a regional system), county, digester type, year constructed, herd size, and emissions reduction. Data for the estimated biogas and electricity production for each digester is limited, but is available at the EPA's AgSTAR website.

TABLE 19. OPERATIONAL LIVESTOCK BIODIGESTERS IN WISCONSIN (AS OF JANUARY 2019)

Project Name	Project Type	County	Digester Type	Year Built	Herd Size	Emissions Reduction (MTCO2e/yr)
Four Cubs Farm Digester	Farm Scale	Burnett	Covered Lagoon	2008	800	5,809
Dallmann Digester	Farm Scale	Calumet	Mixed Plug Flow	2012	2,400	9,074
Holsum Dairy - Elm Road Digester	Farm Scale	Calumet	Mixed Plug Flow	2007	4,000	13,958
Holsum Dairy - Irish Road Digester	Farm Scale	Calumet	Mixed Plug Flow	2004	4,000	10,936
Bach Digester, LLC Digester	Farm Scale	Clark	Mixed Plug Flow	2010	1,250	10,642
Bach Digester, LLC II Digester	Farm Scale	Clark	Mixed Plug Flow	2013	1,250	10,642
Norm-E-Lane, Inc. (NEL) Digester	Farm Scale	Clark	Mixed Plug Flow	2008	2,000	17,121
Dane County Digester - Springfield Digester	Centralized/ Regional	Dane	Complete Mix	2014	2,000	25,890
Dane County Digester - Vienna Digester	Centralized/ Regional	Dane	Complete Mix	2011	2,500	30,593
Maunesha River Dairy Digester	Centralized/ Regional	Dane	Complete Mix	2014	1,300	6,627

Project Name	Project Type	County	Digester Type	Year Built	Herd Size	Emissions Reduction (MTCO2e/yr)
Statz Brothers, Inc. 2 Digester	Centralized/ Regional	Dane	Mixed Plug Flow	2015	2,500	9,335
Statz Brothers, Inc. Digester	Multiple Farm/Facility	Dane	Mixed Plug Flow	2009	2,100	7,079
Crave Brothers Farm Digester	Farm Scale	Dodge	Complete Mix	2007	2,450	5,847
S & S Dairy (WI) Digester	Farm Scale	Door	Mixed Plug Flow	2012	4,000	6,756
Five Star Dairy Farm Digester	Farm Scale	Dunn	Complete Mix	2005	850	6,153
Clover Hill Dairy, LLC Digester	Farm Scale	Fond du Lac	Mixed Plug Flow	2007	1,750	13,821
Vir-Clar Farm Power LLC Digester	Farm Scale	Fond du Lac	Complete Mix	2013	1,450	15,276
Volm Farms Digester	Farm Scale	Fond du Lac	Mixed Plug Flow	2009	825	3,137
Heller Farms / Cow Poo, LLC Digester	Farm Scale	Jackson	Complete Mix	2012	1,900	6,095
Dairy Dreams Digester - pipeline injection	Farm Scale	Kewaunee	Mixed Plug Flow	2010	3,000	25,966
Dairyland Digester	Farm Scale	Kewaunee	Mixed Plug Flow	2012	3,000	10,225
Deer Run Digester	Farm Scale	Kewaunee	Mixed Plug Flow	2008	2,100	7,962
Pagels Ponderosa Dairy Digester 1	Farm Scale	Kewaunee	Mixed Plug Flow	2009	4,600	39,830
Pagels Ponderosa Dairy Digester 2	Farm Scale	Kewaunee	Unknown	2019	N/A	N/A
Wakker Dairy Digester	Farm Scale	Kewaunee	Mixed Plug Flow	2012	2,100	8,131
Maple Leaf Dairy East Digester	Farm Scale	Manitowoc	Mixed Plug Flow	2010	2,000	20,414
Maple Leaf Dairy West Digester	Farm Scale	Manitowoc	Mixed Plug Flow	2010	4,000	32,162
Grotegut Dairy Farm, Inc. Digester	Farm Scale	Mantiowoc	Mixed Plug Flow	2009	2,400	13,236
Sunrise Dairy Digester	Farm Scale	Oronto	Complete Mix	2005	810	7,290
Gordondale Farms - Deer Ridge Digester	Farm Scale	Portage	Mixed Plug Flow	2002	850	2,626

Project Name	Project Type	County	Digester Type	Year Built	Herd Size	Emissions Reduction (MTCO2e/yr)
Baldwin Dairy Digester	Farm Scale	Saint Croix	Mixed Plug Flow	2006	1,050	9,027
Green Valley Dairy Digester	Farm Scale	Shawano	Complete Mix	2006	3,900	32,513
Majestic Crossing Dairy, LLC Digester	Farm Scale	Sheboygan	Plug Flow	2016	650	1,530
USEMCO - Peters Farm Digester	Farm Scale	Vernon	Complete Mix	2011	200	886
Wild Rose Dairy Digester	Farm Scale	Vernon	Complete Mix	2005	880	2,072
UW Oshkosh Foundation-Witzel, LLC Digester	Research	Winnebago	Dry Digester	2011		1,655
UW Oshkosh Foundation, Rosendale Biodigester, LLC Digester	Farm Scale	Winnebago	Complete Mix	2013	8,500	70,443
Allen Farms/Titan 55 Digester	Farm Scale	Winnebago County	Mixed Plug Flow	2013	120	626
Central Sands Dairy, LLC Digester	Farm Scale	Wood	Mixed Plug Flow	2008	3,900	32,732

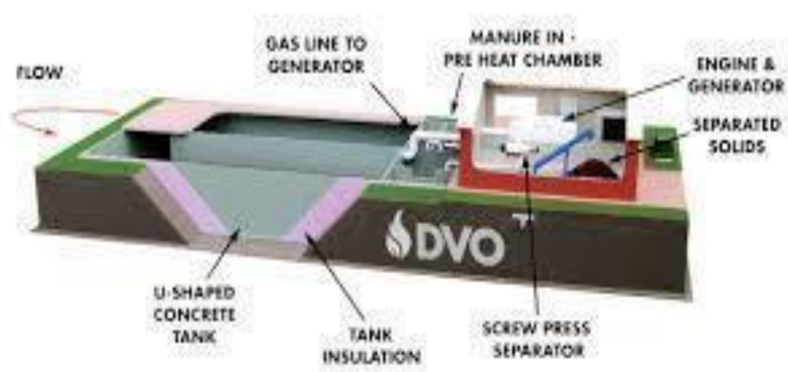
Source: AgSTAR: Biogas Recovery in the Agriculture Sector database, October 2019

APPENDIX C: OPERATION OF A MIXED PLUG FLOW DIGESTER

A plug flow digester vessel is a long, narrow, insulated, and heated tank used to process manure. It is typically reinforced with either concrete, steel, or fiberglass. A cover or top is used to capture the biogas. Plug flow digesters are primarily used at dairy operations that collect manure by scraping.

A mixed plug flow digester is a modified form of a plug flow digester that has a vertical gas mixer. DVO, Inc. patented the two-stage mixed plug flow system and is based in Wisconsin. A 2016 case study of the DVO Two-Stage Linear Vortex Anaerobic Digester explained that the digester is designed as a U and operates at 100 degrees Fahrenheit and their patented first-in/first-out plug flow design mixes gas axially to “accentuate manure/bacteria reaction while allowing for a range of manure solids concentrations” (Frear et al., 2016).

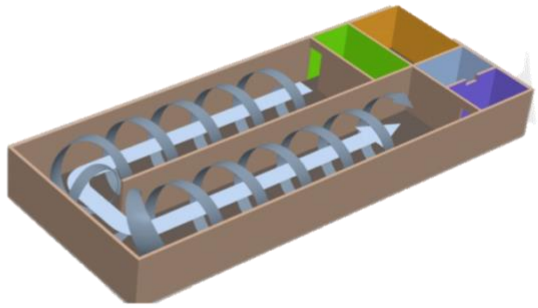
FIGURE 5. ILLUSTRATION OF THE DVO SYSTEM



Source: DVO, Inc. 2016

In the mixed plug flow digester, manure flows through the channel. The manure enters one end and processed waste exits out the other as it slowly “corkscrews” its way through the digester. Mixed plug flow systems can tolerate a broader range of solids concentrations (EPA, 2019).

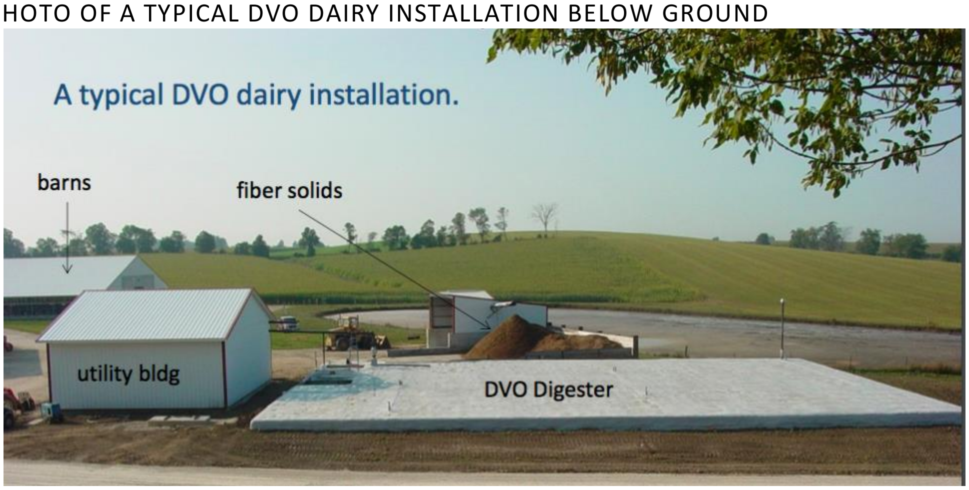
FIGURE 6. ILLUSTRATION OF HOW MANURE CORKSCREWS THROUGH THE DIGESTER



Source: DVO, Inc. 2016

The mixed-plug flow digester can be poured in-place and sealed with reinforced concrete panels. The digester can be partially below grade and insulated to more easily maintain mesophilic conditions during cold weather (Martin, 2005). This optimizes bacteria growth because temperature fluctuations are moderated.

FIGURE 7. PHOTO OF A TYPICAL DVO DAIRY INSTALLATION BELOW GROUND



Source: DVO, Inc. 2016

APPENDIX D: OTHER TYPES OF ANAEROBIC DIGESTER SYSTEM DESIGNS

There are various designs for anaerobic digester systems. Farmers or investors must select the appropriate system for their needs. Descriptions are taken directly from the EPA (2011). For our purposes, we assume a mixed plug flow digester system. EPA does not provide information on mixed plug flow digesters. That information is summarized separately in Appendix C.

TABLE 20. DESCRIPTION OF DIGESTER DESIGNS

Type	Description	Percent Solids	Hydraulic retention time
Plug Flow	Long, narrow tank, typically heated and below ground, with impermeable gas-collecting cover. Contents move through the digester as new manure is added. Modified plug flow systems can use vertical mixing techniques. These systems work best with dairy manure, handled by scraping, with minimal bedding.	11-13	15+ days
Complete Mix	Above- or below-ground heated or unheated tank with impermeable gas-collecting cover. Contents mixed by motor or pump. Complete mix digesters work best when there is some dilution of the excreted manure with water manure should be handled via slurry.	3-10	15+ days
Covered Lagoon	In-ground earthen or lined lagoon with impermeable gas-collecting cover. Contents can be heated or mixed but are not typically due to volume. Covered lagoons work best with manure handled via flush or pit recharge collection systems in warmer climates.	0.5-3	40 to 60 days
Up-flow Anaerobic Sludge Blanket (UASB)/Induced Blanket Reactor (IBR)	High-rate, above-ground, heated vertical tanks where the influent is added continuously to the bottom of the reactor. Bacteria are suspended in the reactor due to the flow of the influent. These systems are best suited for consistent, homogenous waste streams.	< 3 (UASB) 6-12 (IBR)	~5 days or less
Fixed Film/Attached Media Digester/ Anaerobic Filters	Above-ground, heated tank containing media such as plastic or wood chips on which bacteria attach and grow. Manure waste is passed through the media and is digested as it comes into contact with the bacteria attached to the media. These digesters work best with manure in temperate.	1-5	~5 days or less
Anaerobic Sequencing Batch Reactors (ASBR)	Typically an above-ground, heated tank with an impermeable roof that collects gas. Manure is added and removed from the reactor in batches. There are four phases in the ASBR cycle: fill, react, settle, and decant. An ASBR is best suited for treating dilute wastes (i.e., manure handled via slurry).	2.5-8	~5 days or less

Type	Description	Percent Solids	Hydraulic retention time
High-Solids Fermentation	Heated aboveground, airtight container. Designed for high solids manure and other organic substrates (e.g., silages such as corn, grass, or rye; food waste; ethanol and biodiesel production byproducts such as distillers grains or glycerin).	18+	2 to 3 days

Source: AgSTAR, 2019

APPENDIX E: KARST TOPOGRAPHY

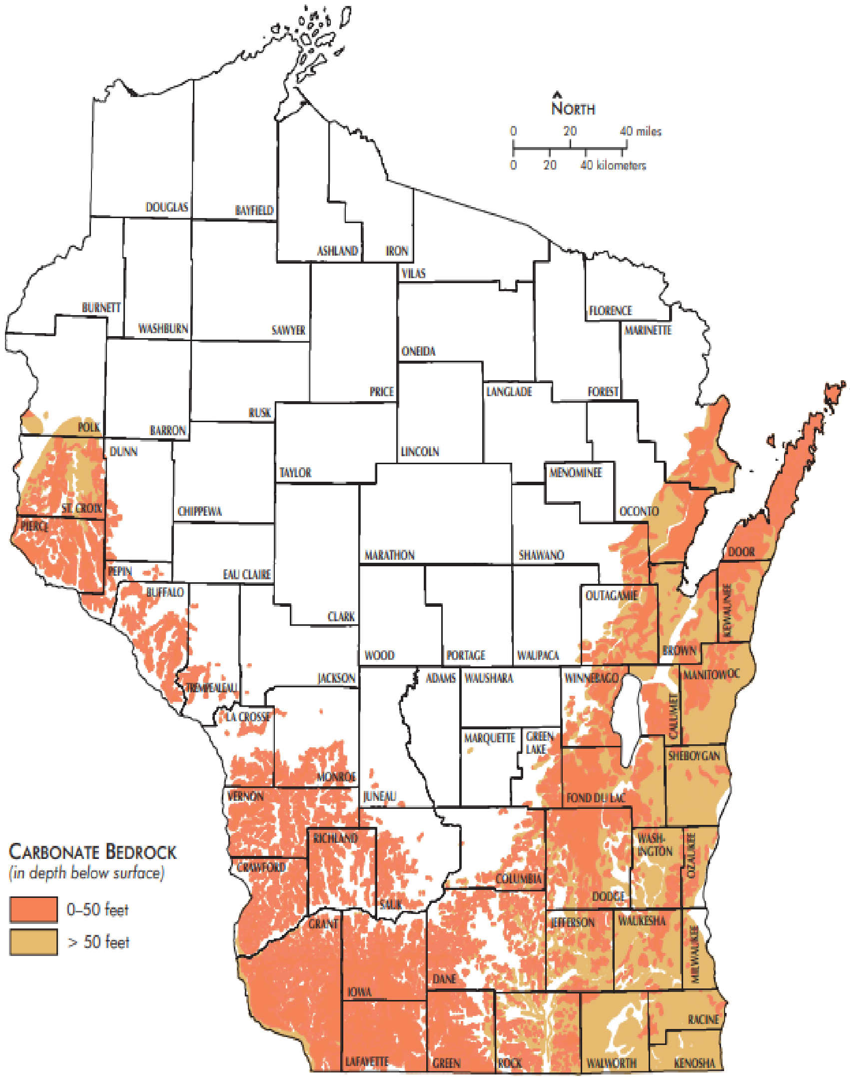
Karst topography, also known as carbonate bedrock, are formations primarily composed of limestone or dolomite. These areas are particularly sensitive to groundwater contamination due to the ratio of fractured bedrock to soil. Karst landscapes have surface and underground features like caves, sinkholes, disappearing streams, and subsurface drainage. These features result when the limestone or dolomite bedrock is easily dissolved by water. When the rock is dissolved, cracks and solution channels in the rock can form an underground drainage network. These cracks and channels can rapidly transport surface water and pollutants to groundwater.

Soil depths to bedrock of less than 50 feet increase the likelihood of groundwater contamination due to an absence of natural filtration processes. Soil acts as a natural water filter, pulling contaminants out of the water as it filters below the surface and into the groundwater. The deeper the soil, the more opportunity to remove pathogens and nutrients that can impact ground and surface water quality.

Southwest and northeast Wisconsin are in karst regions and, thus, are more vulnerable to water pollution. Certain agricultural practices related to manure storage and liquid manure spreading can exacerbate groundwater contamination, which impacts public health.

See Figure 8 for a map of carbonate bedrock and associated soil depths.

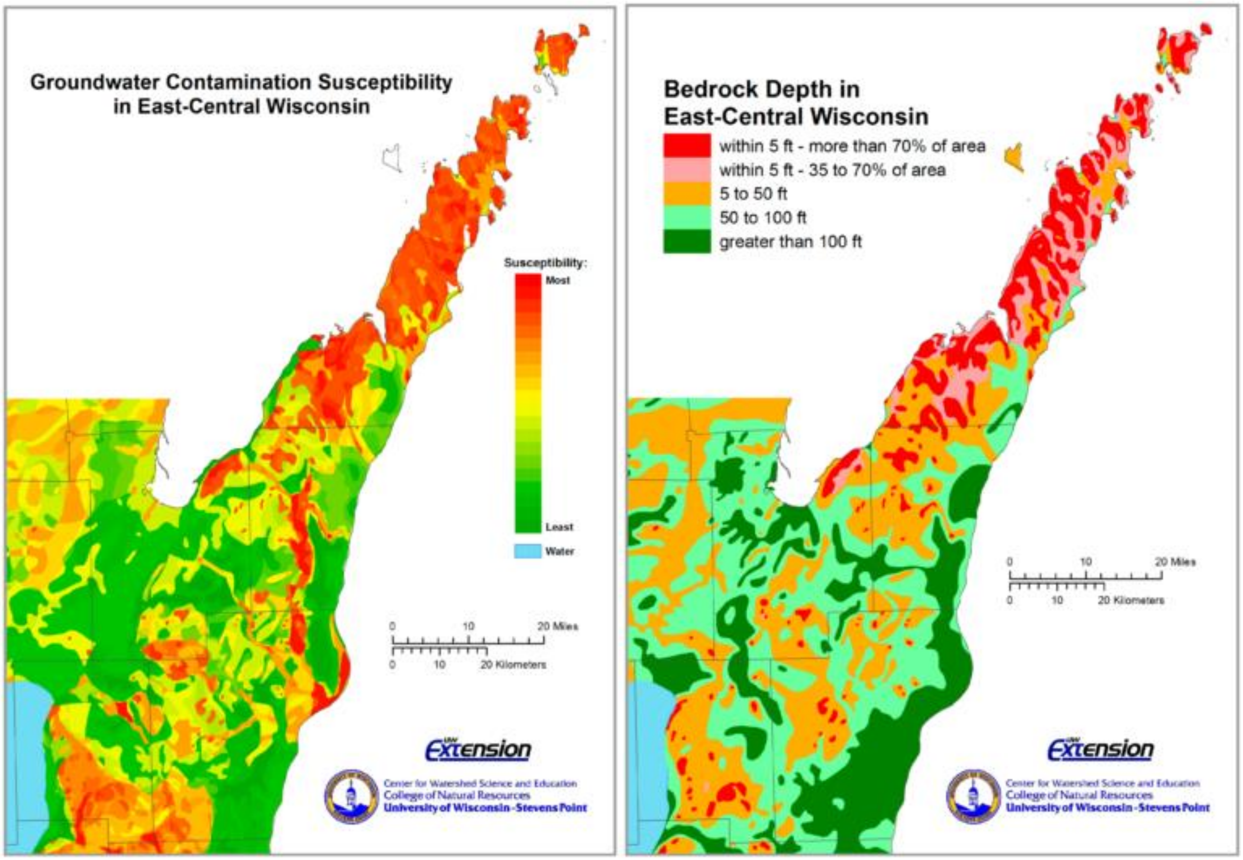
FIGURE 8. CARBONATE BEDROCK MAP OF WISCONSIN



Source: Wisconsin Geological & History Survey. Regions in white indicate areas where bedrock is not carbonate.

In 2017, the Wisconsin State Legislature adopted changes to NR 151, which governs the spreading of manure on agricultural land. The changes specifically targeted karst regions with uniquely low levels of soil to bedrock found in northeast Wisconsin where our analysis is focused. Figure 9 depicts varying soil depths in northeast Wisconsin, and groundwater contaminations susceptibility.

FIGURE 9. GROUNDWATER CONTAMINATION RISK AND BEDROCK DEPTH MAP OF NORTHEAST WISCONSIN



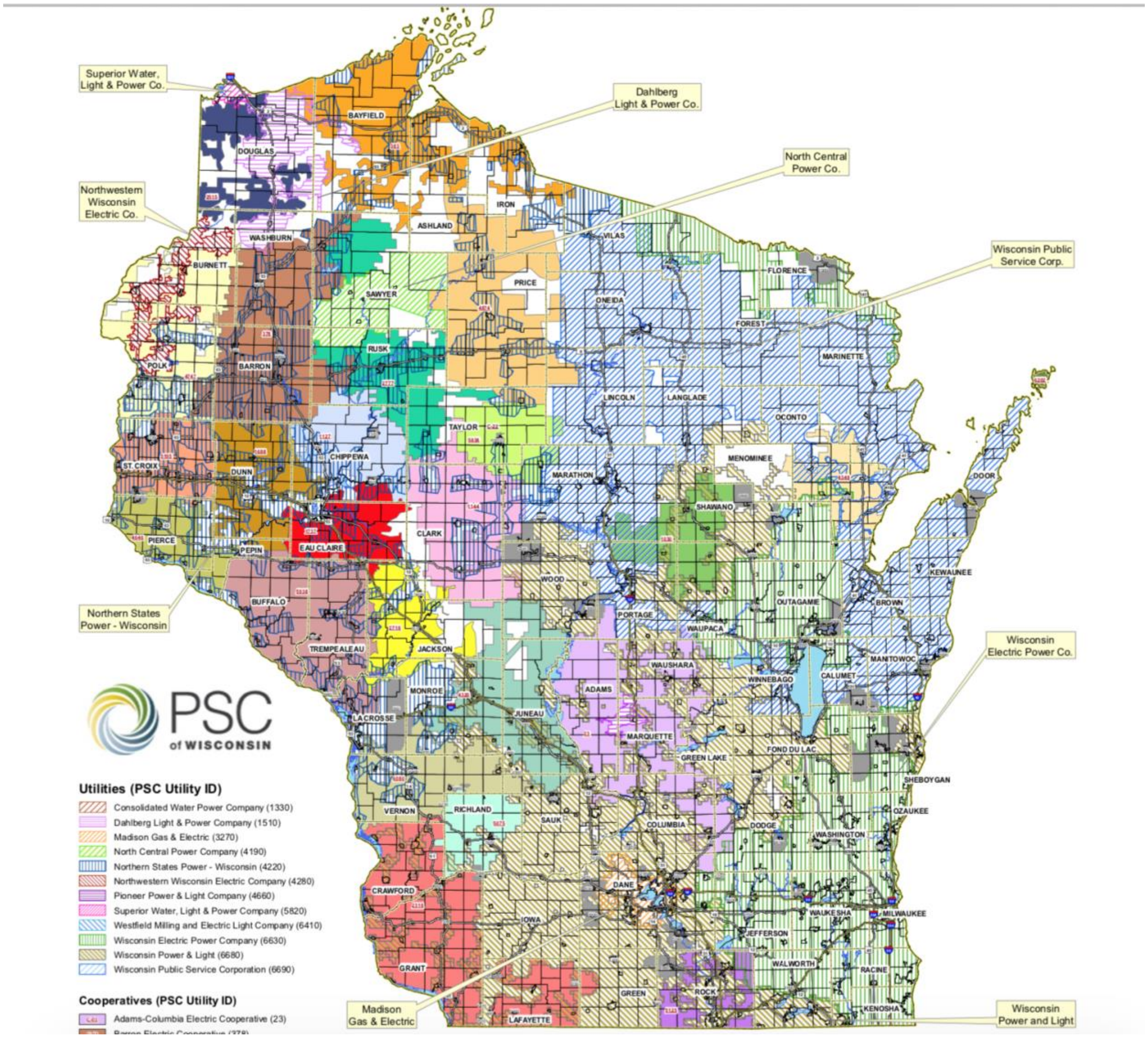
Source: Dukehart 2017

Many regions in the counties we consider in this analysis have soil depths of less than 20 feet, making them particularly susceptible to pathogen and nutrient infiltration. The presence of this topography and its susceptibility to water contamination from agricultural activity in conjunction with the high concentration of large dairy operations in the region informed our decision to center our analysis on this region. While the financial feasibility of a digester at a farm is largely a function of herd size regardless of underlying topography, the reduction in pathogens and potential improvement of nutrient management provided by digesters would have significant social benefits to the region relative to other parts of the state.

APPENDIX F: ELECTRICITY TARIFFS AND MARKETS (MODEL 1)

Wisconsin is a "local monopoly" state for energy and electricity. This means that producers of renewable energy like biogas are prohibited from making private sales of the energy they produce. Instead, they can use their production on-site as electricity or heating fuel, or they can sell their production to the local utility for distribution to ratepayers. Utilities, whether public, private, or cooperative, operate in a defined service area without competition. Figure 10 contains a map of Wisconsin utility service areas.

FIGURE 10. UTILITY MAP OF WISCONSIN



Source: Wisconsin Public Service Commission

The dominant electric utilities in our region of interest are Wisconsin Public Service Corporation, Wisconsin Power and Light, and Wisconsin Electric Power Company.

Utilities set rates by issuing tariffs, which are reviewed by the Wisconsin Public Service Commission. These tariffs set the rates at which customers in the service area can buy electricity, as well as the rate at which the company will purchase electricity from producers (buyback rate). The tariff rates vary based on peak and off-peak hours, as well as the generation capacity of the producer. To calculate farmer benefits in Model 1, we took a weighted average of the rates that producers in our region of interest would receive based on calculations of peak hours annually, and a weighted average of the approximate number of dairy farms who would be served by each utility (see Appendix I).

Producers who use energy on-site could calculate their avoided costs and the resulting Farmer Benefit by accessing the relevant tariff through the Public Service Commission. Further, they could apply the rate for which they are eligible for buyback directly into our model, rather than using the weighted average calculation.

Based on conversations with several Northeast Wisconsin farmers, we chose to model only a scenario where farmers sell all of their electricity directly to the utility, and not a scenario where farmers use electricity on-site. We did so because of the logistical challenges associated with on-site electricity generation and use. The time at which the most electricity is generated often does not align with the time at which farmers use the most electricity. Therefore, effective use of such a system would require biogas storage in addition to a generator set, so that biogas could be stored until it is needed to be used as fuel for on-site electricity generation. We believe the costs of such a system would be prohibitive for many dairy farmers in our region of interest.

Similarly, farmers would likely see greater benefits from generating electricity if net-metering billing mechanisms were used in Wisconsin. Net-metering billing is where a private generator of electricity is only billed for the net amount of electricity they use. Hypothetically, the amount of electricity produced and supplied to the grid is directly subtracted from the amount of electricity used from the grid. Currently, for anaerobic digesters, net-metering is not used by utility providers in Wisconsin which is another reason we choose a model whereby the farmer sells 100 percent of their generated electricity back to the utility.

APPENDIX G: CALIFORNIA RENEWABLE ENERGY MARKETS

Models 2 and 3 assume the sale of biomethane and the redemption of renewable energy credits as part of the California Low Carbon Fuel Standard program. As the largest economy in the United States and the equivalent of the fifth largest national economy in the world, California has considerable buying power in U.S. and international markets. California state policy has encouraged the production and use of renewable energy, particularly for transportation fuel, and producers of renewable fuel sources like biomethane are able to take advantage of these markets.

In 2009, California instituted a Low Carbon Fuel Standard (LCFS) regulation intended to reduce the carbon intensity of vehicle fuel. The LCFS standard incorporates the entire lifecycle of a fuel's production into its calculation of carbon intensity, and requires that the carbon intensity of vehicle fuel in California be reduced by 20 percent by 2030 from a 2010 baseline (CA Air Resources Board, 2019). Fuel distributors in California can purchase fuels from anywhere in the United States.

Biomethane is an eligible fuel for participation in the California market because its carbon intensity, given the carbon costs of production, transportation, and distribution, is significantly below the benchmark fossil fuel. The benchmark gasoline carbon intensity for 2019 in California was 93.23 gallons in CO_2 equivalents/Megajoule. Landfill biogas, to which digested dairy biogas is comparable, had a carbon intensity of 57gCO_2e/MJ (CA Air Resources Board, 2019). This suggests a potential market for biomethane producers to sell their product in California and beyond, as other states continue to institute policies like the LCFS. Biomethane is eligible for credits on the California marketplace even if it does not directly reach transportation fuel producers in California: by injecting the gas into a national network of pipelines, biomethane producers contribute to the reduction in carbon intensity of the gas that is ultimately mixed into transportation fuel. They therefore can claim these credits even though the biomethane is produced and injected in Wisconsin.

When sold, biomethane can be blended with other fuels to reduce the carbon intensity of transportation fuel. This would generate not only private benefit to a producer from the sale of biomethane, but also would generate a Renewable Identification Number (RIN) for the producer: A RIN is a federally identifiable marker of renewable fuel, which can be sold for further benefit to its owner (EPA RINS, 2019).

Between the sale of biomethane and the designation of RINs, we expect the secondary markets in Models 2 and 3 to be robust. Although our analysis does not go beyond the level of the Wisconsin dairy farmer, we expect that as states continue to implement carbon intensity-reducing policies, the market will expand for the owners of biogas generated from digesters (See Appendix O: Non-Monetized Values). This market, while not monetized in our models, provides incentive for the third-party operators described in Models 2 and 3.

APPENDIX H: CAPITAL & OPERATING COSTS

Capital and operating costs are primarily relevant for Models 1 and 2. We consider these costs transfers from a social perspective in all models.

MODEL 1

UPFRONT CAPITAL

The most significant cost of anaerobic digesters is the upfront capital needed for the equipment. The capital costs are the physical structures (the reactor tank(s), pumps, piping, and solids separation and drying systems), engineering design fees, installation costs, and permitting for the construction of the digester.

According to multiple interviews with industry experts, the price of the entire digester system is determined by many different factors that are specific to the individual farm. The most influential of those factors is the size or capacity of the digester. The capacity of the digester is directly determined by the number of cows producing manure. Despite being confident in the most influential variable, herd size, each digester system is built to the specifications to the individual farm, thus making estimating the capital costs difficult.

Corroborating industry experts with estimates from the academic literature, we calculate total estimated upfront capital in Model 1 (C_{M1}) as a function of herd size (S_{op}) by a standard linear equation and adjusted for inflation.

$$C_{M1} = \$728 * S_{op} + \$668{,}000$$

Faulhaber, Raman, and Burns refer to EPA AgSTAR's analysis of anaerobic digesters on dairy farms from 2005-2008 (2012).

OPERATING COSTS

Operating costs are incurred annually and include the electricity used during manure processing and digestion, the routine maintenance of the solids separation and drying equipment, and management and labor expenses. Most feasibility reports also account for a small portion of annual costs due to miscellaneous expenses. According to Peters et al., annual maintenance costs range between 2 and 11 percent of total upfront capital costs (2003).

As this calculation was determined in 2003, we validate these from Klavon et al. (2012), which contain data from nine existing anaerobic digesters on 100 to 250-cow farms. These data points are not used in our upfront capital cost estimation because they do not meet the 500 cow herd threshold. However, these data are still useful for validating annual operating expenses as a fraction of total upfront capital. We are able to verify the actual and estimated annual operating expenses from Klavon et al. (2012) is indeed between 2 and 10 percent of total upfront capital.

For our analysis, we assume a triangular distribution for operational cost rates (R_{OC}), using 2 percent as a minimum, 11 percent as a maximum. We center the distribution around 5 percent. We then apply this rate to our capital cost equation (C_{M1}) to estimate annual operational costs as a function of herd size (S_{OP}).

$$OC = R_{OC} * C_{M1} = R_{OC}(\$728 * S_{op} + \$668{,}000)$$

This provides a triangularly distributed estimate for operational costs.

GENSET REPLACEMENT

The genset uses the methane biogas as fuel to generate electricity. Even though the hydrogen sulfide, a corrosive acidic compound, is removed prior to being used as fuel in the genset, the quality of biogas without additional cleaning equipment requires replacement of the genset at an estimated 10 years (Interview 5). Because the time horizon for our analysis is 20 years, we add the cost of the genset as a one-time expense in Year 11. We consider this a separate category of costs because it is only realized in Model 1.

We use two data points for the costs of gensets on farms with anaerobic digesters. USEMCO did an analysis of a possible digester on a 400-cow dairy farm and determined a genset cost of $142,000 (2014). The 2002 Gordondale Farms study determined a genset cost of $198,000. The present values of the costs of the respective gensets are $152,000 and $279,000. Again, in our analysis we calculate costs in relation to herd size: this gives us values of $380 per cow and $325 per cow. Therefore, we use a uniform distribution between these two values to determine the one-time cost of replacing a genset during a twenty-year period.

As the time horizon in our analysis is 20 years, and the estimated useful life of a genset is ten years, we add this cost of replacement once at Year 11.

MODEL 2

UPFRONT CAPITAL

Gensets are expensive and replacing them with a storage unit reduces equipment costs for the private farm considerably. According to a manufacturer of anaerobic digesters, an appropriately sized pressure tank to replace a genset using a comparable amount of biogas as fuel would cost approximately 17 percent of the genset's cost (Interview 5). Faulhaber, Raman & Burns estimate that a genset is approximately 36 percent of total capital costs (2012). Accounting for the subtraction of the genset and the addition of the pressure tank, we calculate total upfront capital costs for Model 2 (*Cm2*):

First we calculate the tank's overall cost in relation to capital costs in Model 1 (C_{M1}):

$$PressureTank = 0.17 * 0.36 * C_{M1} = 0.061C_{M1}$$

The new total capital cost for Model 2 (C_{M2}) is therefore:

$$C_{M2} = C_{M1} - PressureTank = C_{M1} - 0.061C_{M1}$$

We calculate capital costs in Model 2 (C_{M2}) in relation to the herd size (S_{op}) using the capital cost equation for Model 1 (C_{M1}):

$$C_{M2} = (\$728 * S_{op} + \$668{,}000) - 0.061C_{M1} = \$678 * S_{op} + \$622{,}309$$

We use this estimate for total upfront capital in Model 2. This clearly reduces the upfront capital needed for a digester.

OPERATING COSTS

Without a genset, the operating costs for Model 2 increase. In Model 1, the genset provides the necessary heat for the digestate in the reactor tank to reach temperatures required for mesophilic anaerobic digestion. Therefore, without the genset, the digester requires significantly more energy. Consequently, operating costs in Model 2 are higher than in Model 1.

In a 2004 study, a digester on an 800-cow dairy farm that included an engine-generator set to produce electricity, “the total BTUs recovered [from the genset] represent approximately 34 percent of the biogas energy being produced” (Martin, 2005, p.15). The study also notes that it is nearly impossible to measure the amount of heat put to use by the genset accurately and to subsequently monetize it. However, Martin placed a value of $5,600 annually on the heat value provided by the genset.

The analysis done by USEMCO on the digester operating on a 200-cow dairy farm suggested the heat value captured and utilized was between approximately $4,500 and $10,000 per year (2014). This was calculated by measuring the amount of energy needed to heat the farm’s hot water tank and to heat the milking parlor during the winter months. The energy approximation was then converted into a cost reduction approximation resulting in the aforementioned values. The energy needed to heat the reactor tank for proper anaerobic digestion was never realized.

Removing the cost of the genset from total capital, the new percentage of estimated operating costs without a genset to total capital is a range of 3.3 percent to 3.7 percent. The percentage of operating costs with a genset was 2.5 percent, thus an increase in operating costs as a percentage of total capital costs of 0.8 to 1.2 percentage points. As we anticipate operating costs to increase without a genset due to the loss of heat value, but are unable to estimate any other exact increase in operating costs due to lack of data, we adjust operating costs at all values by 1 percentage point, including moving the center of the distribution of values from 5 percent of capital costs in Model 1 (C_{M1}) to 6 percent of capital costs in Model 2 (C_{M2}). This gives us a minimum rate of 0.03 percent, a maximum rate of 0.12 percent, and a modal rate of 0.06 percent. We apply a triangular distribution to these rates to generate our estimated operational cost rate (R_{OC})

Similar to Model 1, in Model 2 we calculate the operational costs (*OC*) in relation to the herd size (S_{op}) by replacing the total upfront capital (C_{M2}) with its formula according to herd size.

$$OC = R_{OC} * C_{M1} = R_{OC}(\$678 * S_{op} + \$622{,}309)$$

This generates our expected range of annual operating costs per cow.

MODEL 3

All costs to farmers in Model 3 would be incurred by a third party or an outside owner of the digester other than the farm. Because our analysis only examines the costs for the individual farmer, we do not analyze costs from the perspective of an outside entity purchasing a digester on a farm. Likely, the upfront capital costs for a third party would be similar to Model 2, however if the third party is a public entity the financing for the digester would look different than that of a private investor. Similarly, an outside investor would have other cost considerations like the farm's vicinity to the interstate natural gas pipeline. If within close range of an interstate pipeline, an outside investor will conduct a separate fiscal analysis of adding pipelines versus trucking costs and the costs of additional biogas cleaning facilities. These considerations would have an impact on whether Model 3 is a reasonable option for the individual farmer. However, these considerations are outside the scope of our analysis.

APPENDIX I: ENERGY BENEFITS

FARMER BENEFITS

MODEL 1

Under this model, benefits to the farmer for producing biogas result from the sale of electricity to the local utility. Three utilities operate in our region of interest: Wisconsin Public Service Corporation (WPS), Wisconsin Power and Light (WPL), and Wisconsin Electric Power Company (WEP). Each of these utilities offers buyback rates to private operators in their service region who generate electricity (WI Public Service Commission, 2019). In addition, utilities offer a capacity payment based on the most recent Midcontinent Independent System Operator (MISO) auction rates in the region (WI Public Service Commission, 2019). Producers are also required to pay the utility a daily charge for the sale of electricity.

In order to calculate net farmer benefits, we first calculate benefits per kilowatt-hour from each utility's payments. This involves taking a weighted average of peak and off-peak buyback rates based on the timeframe each utility treats as peak hours, and then adding the capacity payment. That calculation gives us the gross benefit calculations specified in Table 12, without deducting the customer charge.

TABLE 21. WISCONSIN UTILITY BUY-BACK RATES

Utility	Generation Capacity (kW)	On-Peak Buyback Rate (per kWh)	Off-Peak Buyback Rate (per kWh)	Capacity Payment (per kWh)	Weighted average gross benefits with capacity payment (per kWh)	Daily Customer Charge
WPS	< 2,000	$0.03708 (63.89 percent of the year)	$0.02745 (36.11 percent of the year)	$0.00028	$0.0338825	$0.6575
WPS[a]	2,000 - 5,000	$0.02171	$0.02171	$0.00028	$0.02199	$0.6575
WPL	20 - 200	$0.0415[c] (12.5 percent of the year)[d]	$0.0247[c] (29.16 percent of the year)[d]	$0.001	$0.03170834	$0.3205

Utility	Generation Capacity (kW)	On-Peak Buyback Rate (per kWh)	Off-Peak Buyback Rate (per kWh)	Capacity Payment (per kWh)	Weighted average gross benefits with capacity payment (per kWh)	Daily Customer Charge
WPL	> 200	$0.0415[c] (12.5 percent of the year)[d]	$0.0247[c] (29.16 percent of the year)[d]	$0.001	$0.03170834	$0.6411
WEP[b]	< 20	$0	$0	$0	$0	$0
WEP	20 - 300	$0.022	$0.022	$0	$0.022	$0.5951

[a]It is highly unlikely that an on-farm digester would have an electricity generation capacity higher than 2,000 kilowatts, therefore this rate is excluded from our simulation.
[b]Producers at this low energy level are simply not billed for their energy use they would otherwise draw from the grid -- this is not relevant to any of the farms in our models and is therefore not included in our calculation.
[c]Rates as of 11/23/2019. WPL uses the MISO day-ahead Locational Marginal Price (LMP), which varies day-to-day but remains relatively consistent over a longer time horizon, with annual summer peaks. This uncertainty is incorporated into our Monte Carlo simulation.
[d]WPL also uses a “regular” rate of $0.0314 / kWh that applies to 58.33 percent of the year.

To obtain an estimate for the buyback rate that a farmer in our region of interest would receive, we need to account for differential rates both in terms of time (peak and off-peak rates) and differential rates between utilities. As noted in the table above, we use the utilities’ designations of peak and off-peak time periods to obtain a weighted average of the gross benefits to the electricity producer for each utility (column 6). The capacity payment (column 5) is added to each weighted average to give us our value.

We then need to account for the differential buyback rates that utilities pay in order to obtain a regional estimate. Based on AgSTAR data, all of the existing digesters in the Karst region are WPS customers with generation capacity of below 2,000 kilowatts. Therefore, we weight this dollar value ($0.0338825 / kWh) at an estimated 90 percent of market share, and the dollar values for the other utilities at 6.6 percent and 3.3 percent of market share, in order to develop a point estimate for buyback rate that we use in our Monte Carlo simulation. We calculate the average buyback rate for each utility, and weight those averages accordingly. Our point estimate for this parameter is calculated as:

$$BuybackRate = 0.9 * WPS_{avg} + 0.066 * WPL_{avg} + 0.033 * WEP_{avg}$$

Next, we calculate electricity generation per cow, per year. An analysis of national AgSTAR data for operational mixed plug flow digesters on farm-scale dairy operations (n=57) provides the following data points for electricity generation per-cow, per-year (EPA AgSTAR, 2019):

TABLE 22. ELECTRICITY GENERATION ESTIMATES FOR MIXED PLUG FLOW DIGESTERS

Statistic	**Value**
Maximum	8,123 kWh
Minimum	232 kWh
Mean	2,002 kWh
Median	1,804 kWh
Standard Deviation	1,166 kWh

This wide range of values is due to variation in a number of factors, most importantly whether products other than manure are added to the digester, and how frequently the producer runs their generator. However, electricity generation is not likely to be dependent on any local or environmental factors. A brief analysis of AgSTAR data indicated that we can observe the electricity generated per cow, per year as a normal distribution of the form:

$$\text{Electricity/Cow-Year}_{\text{kWh}} \sim N(2{,}002, 1166^2)$$

Multiplying each point in the data set by our point estimate for the buyback rate gives us a formula for the gross benefit to biogas producers from electricity generation per-cow, per-year, of the form:

$$\text{Gross Benefit}_{\$/\text{Cow-year}} \sim N(66.6, 38.8^2)$$

We use this normal distribution in our Monte Carlo simulation to calculate the private benefits to farmers from the sale of electricity to the utility.

From this result, we subtract a weighted average of the utility customer charges, calculated using the same ratios as the buyback rate according to the following formula. We applied those ratios to the daily producer charges at each utility. We weight the small and large producer daily charges at WPL separately, dividing the general WPL weight in half for each.

$$CustomerCharge = 365\left(0.9 * WPS_{daily} + 0.033 * WPL_{SPdaily} + 0.033 * WPL_{LPdaily} + 0.033 * WEP_{daily}\right) = \$234.74$$

The annual net private energy benefits to producers of herd sizes 500, 1,000, and 2,500 under Model 1 are summarized in the main report.

Some farms may choose to store and then utilize generated electricity on-site. If they did so, this would likely increase private net benefit calculations because a portion of the energy produced would go toward avoiding retail electricity costs, which have a higher price than the buyback rate. Based on conversations with several Northeast Wisconsin farmers about their practices, we have chosen to model a system where all electricity produced is sold directly to the utility (see Appendix F)

MODEL 2

Estimates vary in terms of the biogas generation potential for dairy manure (PSU Extension, 2012). AgSTAR data delivers an estimated average of 1,084 m^3 of biogas produced per-cow, per-year, with a range from 267.5 m^3 to 2,230 m^3. To calculate the monetized value of the biogas produced, we apply the wellhead price of natural gas (EIA, 2012-2019). This price, which is paid to producers prior to the processing and transportation of natural gas for fuel and energy use, is no longer tracked by the U.S. Energy Information Association. Therefore, we use an average of the historical ratios of wellhead price to commercial price, and apply this ratio to the current commercial natural gas price in Wisconsin.

The average ratio of wellhead to commercial price, from January 1989 to December 2012, when data was available, is 0.494. The current commercial natural gas price in Wisconsin, as of August 2019, was $6.02 per 1000 cubic feet, or $0.17 per cubic meter. Applying the wellhead to commercial price ratio to the current commercial gas price in Wisconsin, we calculate a wellhead natural gas price of $2.97 per 1000 cubic feet, or $0.105 per cubic meter.

We apply this price to the minimum, maximum, and mean values for biogas production per cow. In order to account for uncertainty in biogas production, we apply a triangular distribution to these values and use that distribution in our Monte Carlo simulation. The distribution for farmer benefits from biogas production in Model 2 has a central point of $113.74/cow-year, a minimum of $28.07/cow-year, and a maximum of $233.99/cow-year.

MODEL 3

Because manure is provided to the third-party digester operator at no cost, farmers do not receive private benefits in this model.

SOCIAL BENEFITS

MODEL 1

An anaerobic digester can reduce emissions by converting the methane contained in manure into energy; when this methane is eventually burned for heat or electricity, it releases carbon dioxide, a greenhouse gas with 25 times less of a climate change impact than methane (EPA Overview of Greenhouse Gases, 2019). The anaerobic digestion process also eliminates significant emissions of nitrous oxide by reducing the volatility of liquid slurry. N_2O emissions are measured as accounting for 298 times the climate change impact as CO_2 (EPA Overview, 2019). In addition, each ton of biogas produced and used for energy replaces a ton of natural gas that would otherwise be extracted from a fossil source. Therefore, for each kilogram of biogas produced by an anaerobic digester, we see the equivalent of a 26-fold reduction in CO_2 equivalents based on methane reduction. In addition, for every kilogram of N_2O emissions eliminated by the digester, we reduce CO_2 equivalents by 298.

We use AgSTAR data to estimate the reductions in greenhouse gas emissions. Based on a sample of 64 dairy farms, the descriptive statistics in Table 23 result.

TABLE 23. STATISTICAL ESTIMATES OF GREENHOUSE GAS EMISSIONS REDUCED BY ANAEROBIC DIGESTION

Statistic	**Estimate (metric tons CO_2 eq./cow-year)**
Mean	6.124
Maximum	10.363
Minimum	1.70

Because of the uncertainty relating to gas production, we apply a uniform distribution to this range of data for our Monte Carlo simulation. We then apply the median shadow price of $7 per ton of CO_2 equivalents reduced to each draw in our Monte Carlo simulation in order to come to our conclusions on the social benefits of greenhouse gas reduction from anaerobic digestion (EPA RIA, 2019).

MODELS 2 AND 3

Models 2 and 3 assume that a third party will clean and process the biogas into biomethane and inject it into a national network of natural gas pipelines. As with all pipeline transport, this process carries the inherent risk of leakage. When methane is leaked from a pipeline, it is emitted directly into the atmosphere without producing any benefit to society. This leakage is the equivalent in emissions of methane entering the atmosphere directly from an undigested manure lagoon. Therefore, we need to account for the leakage of methane from pipelines in our calculations of the social benefits of emission reduction in models 2 and 3.

The EPA currently estimates that approximately 1.4 percent of natural gas is leaked into the atmosphere, from the point of production to the point of use (EPA Inventory of Greenhouse Gas Emissions and Sinks, 2017). Applying this leakage rate to our previous estimates for emissions reductions gives us the following statistics for emission reduction per cow, per year:

TABLE 24. STATISTICAL ESTIMATES OF GREENHOUSE GAS EMISSIONS REDUCED BY ANAEROBIC DIGESTION, ACCOUNTING FOR PIPELINE LEAKAGE

Statistic	Estimate (metric tons CO_2 eq/cow-year)
Mean	6.038
Maximum	10.22
Minimum	1.68

As in Model 1, we accounted for the uncertainty in biogas production by applying a uniform distribution to the data above, and valuing that production using the EPA shadow price of $7 per metric ton of CO_2 equivalents reduced. We use these values to calculate the social benefits of emissions reduction and energy production in Models 2 and 3.

APPENDIX J: TRUCKING AND TRANSPORTATION

FARMER BENEFITS

According to a Michigan State University Extension study the typical Michigan farm spends approximately $117 to $187 (2019 USD) per cow annually to transport manure. This cost to the farmer includes manure agitation, pumping, transport, and land application processes (Harrigan, 2011). Labor, machinery, and average gas consumption is internalized in these estimates. We apply a uniform distribution to these figures to estimate baseline transportation costs (*FCT*)

According to farmers currently operating digesters in northeast Wisconsin, installing a digester reduced private transportation costs by 20 percent (Interview 3). We consider the reduction of transportation as benefits to the farmer in the form of avoided costs. For the sake of our analysis, we assume a range of 0 to 20 percent reduction in the associated farmer benefits, and apply a uniform distribution to generate our estimated trucking reduction rate (*RT*). We calculate the farmer benefits of reduced trucking according to the baseline farmer's cost of trucking (*FCT*) and the estimated reduction in trucking (*RT*):

$$FBT = FCT * RT$$

Annually, this equates to an average farmer benefit of approximately $15 per cow.

SOCIAL BENEFITS

Using an average of 5 miles per truck per trip (Interview 3), at the rate of 2.62 to 5.86 cents per ton-mile adjusted with inflation, the social cost of trucking has a lower bound of $0.028 per ton-mile and an upper bound of $0.063 per ton-mile (Austin CBO, 2015). The factors contributing to the social costs of trucking are outlined in Table 25.

TABLE 25. UNPRICED EXTERNAL COSTS (2014 CENTS PER TON-MILE)

Type of Cost	Trucking Cost
Pavement Damage	0.74 - 0.96
Traffic Congestion	0.42 - 0.90
Accident Risk	0.85 - 2.28
Emissions: PM and NOx	0.59 - 0.80
Emissions: CO_2	0.02 - 0.92
Total	**2.62 - 5.86**
Inflation-adjusted total	*2.80-6.30*

Source: Congressional Budget Office, 2015.

A cow produces 37,960 lbs/year of manure, which we convert to an annual manure volume of 18.98 tons/cow annually. An average manure hauler has approximately the capacity to carry 5,800 gallons of manure per trip, or 23.78 tons. We divide estimated cow tonnage by truck tonnage, and estimate that a manure hauler carries the equivalent of 0.798 "cows" per truck. We then estimate the annual social benefits of trucking reductions per cow (*SBT*) as the cow tonnage per truckload (*0.798*) multiplied by the social costs of trucking (*SCT*), the expected trucking mileage per trip (*5 miles*), and the expected reduction in trucking for a farm with a digester (*RT*).

$$SBT = 0.798 * SCT * 5\, miles * RT$$

Where reduced trucking is uniformly distributed between 0 and 20 percent.

Social Costs

In Models 2 and 3, we assume biogas trucking to pipeline insertion sites. We expect this trucking to undermine the social benefits from reduced manure trucking described above.

As stated in Appendix I, we assume a dairy cow produces 267.5 to 2230 cubic meters (m^3) of biogas per year. Using the following conversion formula, we calculate the mass of biogas (*MB*) as a function of biogas volume (*BV*).

$$MB = BV * 0.75kg/m3 * \frac{1ton}{907kg}$$

This gives us a lower bound biogas produced per cow, per year of 0.22 tons and an upper bound of 1.84 tons. We take the mean of 0.9 tons/cow-year as our point estimate, and multiply it to the upper and lower bound social cost of trucking estimates. This produces a range of $0.0252-$0.0567 as our estimated social costs of trucking biogas, per cow per mile, uniformly distributed.

Next, we applied a uniform distribution to the range of potential distances from a farm to an injection site in the region. The only injection site in Northeast Wisconsin is in Newton, WI. We chose farms with digesters in two Northeast Wisconsin counties with significant proliferation of large dairy operations and digester use to represent the distance that a biogas producer in the region would need to transport gas in order to process and inject it. The representative Brown County digester location is located close to the injection site (39 miles) while the representative Kewaunee county location is located further away (71 miles). We apply a uniform distribution to these distances, and multiply the resulting distance estimate by the uniformly distributed social cost of trucking per-cow, per-mile estimate ($0.0252-$0.0567) to calculate expected social costs of trucking biogas in Models 2 and 3.

APPENDIX K: BEDDING

Digestate created from the anaerobic digestion process can be dewatered to produce animal bedding. Animal bedding presents a financial opportunity to farmers; however, it requires farmers to capture the digested solids and reach a moisture content that is suitable for use. The benefits of the digested solids as bedding may vary widely, depending on the farm's existing bedding system and management of the bedding. There are a variety of types of bedding that farmers use, such as sand, sawdust, and paper-based bedding. Therefore, not all farmers are willing to use bedding created from anaerobic digestion because many prefer other types of bedding. In each model, we assume that the bedding produced by the digester completely covers the farm's bedding needs and expenses.

We build in uncertainties for the market price of animal bedding because there are a range of bedding options. In the Monte Carlo simulation, we assume zero as the lower bound, $0.41/cwt as the upper bound, and a uniform distribution (National Agricultural Statistics Service, 2017). Next, we determined the average weight (lbs.) of milk produced per cow per month, which is 2,025 lbs., and converted our pound estimate to hundredweight, which is 18.1 cwt (National Agricultural Statistics Service, 2019). This estimate provides Wisconsin-specific estimates for bedding for milk production costs and returns in terms of hundredweight rather than the cost per cow, as cow size varies. Therefore, the annual benefit of bedding as a function of herd size (S_{OP}):

$$Bedding = \$0.41/cwt \ * 18.1cwt * 12months * S_{op} = \$89.052 * S_{op}$$

APPENDIX L: WATER QUALITY

Improvements in water quality represent a potential social benefit of anaerobic digestion. Society realizes these improvements in water quality through better health outcomes due to reduced presence of pathogens.

The pathogens present in dairy cow waste include bacteria (*E. coli, Campylobacter*, and *Salmonella*), protozoa (*Cryptosporidium, Giardia, Eimeria*) and viruses (*adenovirus, enterovirus, rotavirus*) (Borchardt et al., 2013). Anaerobic digestion destroys pathogens due to the heat used in the digestion process (Simpkins, 2005). Digesters are expected to reduce pathogens by 99.9 percent (Borchardt et al., 2013, Martin, 2005).

We monetize the benefits of avoided illness through reduction of pathogens by first determining the annual cost of the illness associated with ingestion of the pathogen, including treatment costs, the purchase of bottled water, and loss of wages. Then we determine the population likely to be affected by pathogens entering the waterway annually due to manure spreading. Finally, we determine the annual probability of runoff events that pose a human health risk. The product of these three values provides the current annual cost of illness due to pathogen contamination from manure. This value represents the potential benefit given pathogen destruction following digestion.

The negative health outcomes due to the pathogen presence are diarrhea and gastrointestinal distress. These ailments typically last between three and five days (Mayo Clinic, 2019). We will use a value of four days for the length of illness.

According to the Bureau of Labor Statistics for the Northeast Wisconsin nonmetropolitan region, the mean hourly wage for the region is $20.37 (BLS, 2018). Assuming an eight-hour workday, the cost per person for a missed day of work is:

$$MissedWork = \$20.37 * 8\ hours = \$162.96/day$$

This will serve as our shadow price for a lost workday due to illness.

Additionally, diarrhea- and rotavirus-associated outpatient costs are $69.08 and $83.77, respectively, adjusting for inflation (Zimmerman, 2001). We take the mean value of these costs, $76.42, as the cost of treatment.

In addition, we assume that a person who has a well contaminated with pathogens is purchasing their water from another source. The Wisconsin Department of Health and Family Services (now separated into the Department of Health Services and the Department of Children and Families) determined the cost for annual purchase of bottled water due to well contamination from nitrates to be $311 in 2019 USD (Chern, 1999).

Therefore, the cost per person for illness due to pathogens (PIC_{pp}) is:

$$PIC_{pp} = \$162.96 * 4 + \$76.42 + \$311$$

We then determine the number of people currently affected by pathogen contamination. A 2017 study of contaminated wells in Kewaunee County found that there are 380 people exposed to pathogens in their private wells (Borchardt, 2017). Of those affected by pathogens, 57 percent came from bovine sources. Therefore, we will assume the population affected by bovine pathogens is 216 people per year.

There is very little lag time for pathogens entering the waterway following a runoff event (Meals, 2010). In other words, pathogens can be expected to be active in waterways as soon as they are spread on a field and run off. If we assume the use of digestion for the life of the digester, net benefits of pathogen reduction will be calculated for each year of life of the digester beginning in the present period.

Finally, we must also account for the uncertainty of runoff. Runoff is inherently uncertain even between adjacent fields, being affected by meteorological events such as rainfall intensity and direction of storm movement as well as land use, field slope, vegetation, orientation of crops and more (USGS, 2019). The Wisconsin Department of Natural Resources maintains a hotline to report spills of hazardous substances. The Department defines a spill as a discharge of hazardous substances that adversely impact or threaten to adversely impact, human health, welfare or the environment and require an immediate response.

Table 26 shows the number of calls into the DNR spill hotline for manure spill events in seven northeast Wisconsin counties with a high proportion of dairy operations from 2008 to 2018 (WDNR, 2019).

TABLE 26. MANURE SPILLS IN NORTHEAST WISCONSIN, BY YEAR AND COUNTY

COUNTY	2018	2017	2016	2015	2014	2013	2012	2011	2010	2009	2008
Brown	6	2	1	3	10	1	1	2	4	3	6
Calumet	5	1	4	0	3	3	2	4	0	0	4
Door	1	2	3	0	2	1	1	2	0	1	0
Kewaunee	12	10	10	8	7	4	6	6	11	4	5
Manitowoc	5	8	7	4	4	6	4	7	5	5	3
Outagamie	3	3	0	2	2	4	0	2	2	3	2
Sheboygan	1	1	1	0	0	3	0	0	1	1	5
AVERAGE	**4.7**	**3.9**	**3.7**	**2.4**	**4.0**	**3.1**	**2.0**	**3.3**	**3.3**	**2.4**	**3.6**

Source: WDNR 2019

The average annual days where a runoff event was reported to the DNR is 3.31 days, with a range of between 2 days and 4.7 days. Therefore, the probability of runoff will be calculated by drawing from a triangular distribution between 2 days and 4.7 days, centered on 3.31 days. That value will then be divided by 365 days to determine the annual probability of hazardous manure runoff.

Due to the probability that some runoff events affecting waterways go unreported, and that pathogens may still be able to enter the waterway outside of a catastrophic runoff event, this estimate should be viewed as conservative.

Therefore, the benefits of pathogen reduction (*PRB*) are:

$$PRB = PIC_{pp} * Population * Runoff = (\$162.94 * 4 + \$76.42 + \$311) * 216 * Runoff$$

Where *Runoff* is drawn from a triangular distribution between 2 days and 4.7 days, centered on 3.31 days, and divided by 365. The projected benefits of pathogen reduction summed over the 20-year period are nearly $30,000.

APPENDIX M: ODOR REDUCTION

Raw, untreated manure emits noxious odors that can reduce the quality of life for people nearby. As anaerobic organisms degrade the organic waste in manure, they produce hydrogen sulfide, ammonia, volatile fatty acids and more (Levey, 2016). Hydrogen sulfide, commonly equated with a rotten egg smell, is thought to be the most noxious.

Odor reduction occurs when acid-forming bacteria converts soluble organic matter in the manure into odorus volatile acids. Methane-forming bacteria then convert the volatile acids into biogas (PSU, 2012). Therefore, the compounds that create most of the noxious odor are neutralized, and the digestate is significantly less odorous.

The extent to which odors cause a nuisance is highly subjective. Therefore, we monetize the benefits of odor reduction using estimated impacts on property values in northeast Wisconsin drawn from literature related hedonic pricing models for home values due to noxious agricultural odors. In theory, the present value cost of noxious odors into the future should be capitalized within the reduced property values for parcels affected by the odors.

Literature on the effects of animal feeding operations on nearby property values is mixed. A literature summary by Ulmer and Massey found that five out of eight studies analyzed showed a reduction in nearby residential property values, while some studies showed an increase in nearby property values (2006). Notably, beef and dairy operations had the smallest negative effect on values relative to poultry and hog operations. In addition, there were typically no reductions in property values at a distance of greater than one mile from the facility. Another study found that the economic activity generated by animal feeding operations outweighed their negative impacts on the local community (Aebles-Allison & Connor, 1997).

In 2017, a Kewaunee County resident successfully appealed to have his or her home's assessed value lowered due to its proximity to a CAFO (WI DOR, 2017). In validating the reduced assessment, the Department of Revenue analyzed residential property sale prices that took place in Kewaunee County near CAFOs. The report determined:

- The value of property located more than one mile away from a CAFO is not impacted
- The value of property located within any distance from a CAFO that is smaller than 4,000 units is not impacted
- The value of property located within one-quarter mile of a large CAFO (greater than 4,000 animal units) is reduced by 13 percent
- The value of property located between one-quarter mile and one mile of a large CAFO is reduced by 8 percent

There are potentially several adverse effects of living near a CAFO, including odor, impacts on water quality, truck frequency, and other nuisances (Hribar & Schultz, 2010). It is impossible to disaggregate what proportion of the impact to property values is due to odor.

We assume that noxious odors will never increase property values. The studies showing a potential increase in residential property values near animal feeding operations hypothesize it is the agglomeration of agriculture employees near their place of employment that drives prices upward, irrespective of odor (Taff et al., 1996).

Therefore, we use an 8 percent reduction in property values as an upper bound and no reduction in property values as a lower bound, drawing from a triangular distribution weighted toward no reduction in property values (zero percent) given the uncertainty in how much property values will be decreased.

To determine the value of properties within a one-mile radius of a CAFO in northeast Wisconsin, we used county land use records and GIS software from three northeast Wisconsin counties that are included in our analysis: Kewaunee (Ruekert-Mielke, 2019), Calumet (WG Extreme, 2019) and

Manitowoc (Headwaters Resources, 2019). Across these three counties, there are 32 active CAFOs that do not currently have a digester.

The DOR report and existing literature on agricultural odor is in relative agreement that property values are not impacted unless they are within one-mile of a CAFO. Therefore, we will restrict our impacts to surrounding property to those within one mile of the primary farm site.

In determining relevant properties for a potential reduction of property values, we looked at the parcels within a one-mile radius of the 32 CAFO operations and filtered for only those parcels that are zoned residential or commercial and contain an improvement value of greater than $50,000. We do not expect property value reductions to vacant, agricultural or manufacturing land (Hamed et al,. 1999). We also assume that improvement values of less than $50,000 indicate a structure that is not a primary residence, and thus not affected by our proxy for odor costs.

On average, there are 56 residential properties within a one-mile radius of CAFOs where we can expect to see reductions in property value. Assuming a median home value of $150,000 for the three selected counties (Delloite et al., 2017), the following represents the impact of CAFO odors on property values:

$$OdorCost = (56 * \$150{,}000) * PercentReduction$$

Where *PercentReduction* is drawn from a triangular distribution between 0 and 8 percent, with the most likely value being 0 percent. Therefore, the range of odor costs ranges from $0 to $672,000, with an average value of approximately $250,000. In agreement with the DOR report on the size of a farm necessary to affect property values, we will also apply the benefit of odor reduction only to herd sizes greater than 2,500. Our calculation is applied as a social benefit, assuming that the presence of a digester on the farm in question eliminates this reduction in property values.

APPENDIX N: LAND USE COSTS AND LAND LEASE BENEFITS

LAND USE COSTS

In all three of our models, digester installation represents an opportunity cost to both the farmer and society for the value of otherwise productive agricultural land that is occupied by the digester. To monetize this cost, we apply the average agricultural land rent rate for non-irrigated cropland for our region of interest in Northeast Wisconsin. Land rents are aggregates of a private marketplace for using land and producing crops (usually feed crops like corn, alfalfa, and soybeans). We assume that this market value, which in 2019 is $143 per acre, is a reasonable approximation of the annual value of the land, both for the farmer who could receive that rent and for society, which would use the crops produced on that land (USDA County Cash Rent, 2019).

A plug flow digester occupies between 2 to 4 acres if it is a single-tank system, and 4 to 6 acres if it has two tanks (Lawson, 2010). The two-tank system is typical for farms of more than 3,500 cows. We assume the middle value of 4 acres. Therefore, the private and social opportunity cost of land use, accruing annually in all three models, is:

$$OpportunityCost = AgRent * \ DigesterAcreage = \ \$143 * 4 = \$572$$

LAND LEASE BENEFITS

Model 3 offers an alternative where a third party enters into an agreement with the farmer to construct the digester on a farm. In this scenario, the farmer would not own or operate the digester; the farmer would only provide the manure needed to fill the reactor tank. Some experts anticipate this will become the primary way in which digesters proliferate as other states begin to adopt programs similar to the California Low Carbon Fuel Standard (Interview 2).

To limit costs associated with the transportation of manure from the animal to the digester, the facility will likely be located on the primary farm site in proximity to most of the cows. The firm is expected to lease the land from the farmer for the life of the digester, or 20 years. Therefore, the farmer will realize some monetary benefits from leasing the land.

Existing contracts between third parties who own the digester and farms are limited and proprietary. Therefore, we use existing agricultural land sale values as a proxy for the cost to lease the land for a 20-year period (Brannstrom, 2018). Due to the 20-year nature of the contract and construction of the facility that would functionally prohibit any other use of that land, we use the land sale prices rather than rental prices.

The weighted average cost of agricultural land in the east central district of Wisconsin is $5,676 per acre. Values are weighted to account for sales with uniquely high or low sale prices.

Assuming the same 4 acres we used to calculate the opportunity cost of land use, the benefit to a farmer for lease of the land is:

$$LeaseBenefit = AgLandPrice_{perAcre} * Digester\ Acreage = \$5{,}676 * 4 = \$22{,}704$$

We assume this is a one-time payment at the beginning of the contract period due to the inability of a farm to change the land use of the acreage after the facility is constructed.

APPENDIX O: NON-MONETIZED VALUES

IMPACTS OF CAFOS ON COMMUNITIES

As our analysis shows, the benefits of anaerobic digestion grow as herd size increases. Therefore, providing an additional revenue stream for farmers who operate large animal feeding operations may allow and incentivize these operations to grow.

Large animal feeding operations can have negative impacts on the surrounding community, including water quality impacts, nuisance odor, air quality, truck traffic and more (Hribar & Schultz, 2010). There may be a concern that the growth of CAFOs through the use of anaerobic digestion could exacerbate these negative impacts, representing an additional social cost of digesters.

We do not include this cost in our analysis for two reasons: 1) the uncertainty in the total social impact of CAFOs and 2) the fact that prohibiting renewable energy should not be a means to achieve environmental regulatory goals.

First, although CAFOs are believed to have negative environmental impacts on localities, some studies suggest they generate enough economic activity for the local community to offset these costs monetarily (Aebles-Allison & Connor, 1997). CAFOs can generate more jobs for a single community than smaller, sparse farms (Keeney, 2008).

The issue of standing complicates these costs and benefits. For example, the growth of CAFOs may bring more jobs that are taken from other nearby localities, possibly generating hyper-local benefits to that community but neutral benefits at the county or state level. In addition, negative environmental impacts may be primarily borne by people in the immediate vicinity of the operation, while the economic benefits may be realized by those outside the impacted area. Because our analysis is concerned with national standing, we do not consider decisions concerning the local impacts of the growth of CAFOs.

Second, we do not believe that restricting new technology that will help grow the renewable energy sector should be the regulatory mechanism to mitigate the broad negative impacts of CAFOs. In other words, environmental concerns, such as air and water quality, should be regulated through a different mechanism, such as stricter manure management standards, instead of restriction of renewable energy technology, particularly when digesters may help reduce negative externalities from CAFOs that are already in operation.

IMPACTS TO WATER QUALITY THROUGH NUTRIENT REDUCTION

This analysis does not consider potential benefits to water quality due to changes in nutrient loading of phosphorus and nitrogen.

Excess nitrogen and phosphorus can negatively impact ground and surface water (MPCA, 2008). Nitrogen and phosphorus are found in manure. The application of manure to fields therefore contributes to the deterioration of water quality if those nutrients enter ground or surface water. Manure is an important fertilizer for crop fields, but excess application or runoff events can create water quality concerns.

Standard anaerobic digestion does not alter the nutrient content of the digestate (Topper et al., 2012, Lauer, 2018). Put simply, phosphorus and nitrogen atoms go in and the same number of phosphorus and nitrogen atoms come out (Gordon, 2018). Without a reduction in the nutrient content of the digested material that is then spread on the field, we cannot reasonably expect a reduction in the amount of nutrients being applied, and thus there will be no reduction in the nutrient loading that implicates water quality.

All CAFOs in Wisconsin are required to implement a Nutrient Management Plan (NMP), which provides field-specific recommendations on nutrient applications to meet crop nutrient needs, while simultaneously reducing the potential for the nutrients to run off fields and into lakes, streams and groundwater (DATCP, 2019). Assuming farmers are adhering to their nutrient management plans, and given that digestion will not reduce the amount of nutrients that need to be managed, the digestion process will not reduce the amount of nutrient loading on a field. Reduction in nutrient loading can therefore be achieved through stricter nutrient management, but not through the use of digesters.

Some phosphorus and nitrogen is tied up in the separated solids used as bedding, which is not spread on the field. However, we still would not expect that to change the amount of phosphorus and nitrogen applied on the field. Assuming the implementation of a NMP, a farmer will apply the recommended phosphorus and nitrogen to a field regardless of whether it comes from raw manure, digestate, or imported fertilizer.

Digestate may be in a form that is easier for the farmer to manage given its nutrient concentration, consistency, and reduction of pathogens (Interview 3). The benefits of these management efficiencies are captured in reduced trucking costs for the farmer (see Appendix J). In fact, in some regions, the destruction of pathogens in manure through digestion allows for a greater volume of spreading (Wis. Stat. § 151.075), potentially increasing the likelihood of phosphorus and nitrogen runoff through greater nutrient application on fewer land acres.

In addition, we would expect impacts to water quality due to reduced phosphorus and nitrogen loading to be realized on a sufficiently distant time horizon that would significantly diminish the present value of those benefits. Research suggests that it takes between 15 and 50 years for water bodies to respond to changes in nitrogen management and greater than 20 years for phosphorus reductions (Meals, 2010). Combined with the conservation of phosphorus and nitrogen matter throughout anaerobic digestion and the relatively distant time horizons of benefits to nutrient reduction to be realized in water bodies, we are not incorporating changes to surface and groundwater quality in this analysis.

This analysis does not consider changes to fertilizer costs for the farm. Manure is a valuable fertilizer for livestock operations. Fertilizer is primarily considered in terms of phosphorus, nitrogen, and potassium, which are the three primary nutrients needed for traditional field crops (TFI, 2014). Of these, phosphorus and nitrogen are the most important for nutrient management in terms of environmental impacts.

The comparative models in this analysis assume a base case of an existing operational farm. The farm will already have a system in place to manage manure, informally or formally through use of a nutrient management plan, and supplement nutrient needs with commercial fertilizer. In the discussion of impacts to water quality immediately prior to this section, we argue that digestion does not change the nutrient content of the manure. Therefore, the farm will still have the same amount of phosphorus and nitrogen as they did before, and will still purchase the same amount of fertilizer to supplement nutritional needs, meaning there will be no reduction in costs of fertilizer.

Digestion does convert much of the nitrogen in raw manure into ammonium (Topper, 2014). When spread on a field, microorganisms convert ammonium into nitrate, which is more readily available or useful for plant uptake. Digested material's ammonium content can be up to two times higher than raw manure.

With a greater ammonium content that is more readily available for plant uptake, digested material should serve as a better fertilizer than raw manure. A farmer may see lower imported fertilizer costs due to this improvement.

Even so, the application of nitrogen and phosphorus is traditionally governed by a nutrient management plan. The specific nutrient needs for a field vary greatly, depending on soil type, crop history, topography, existing nutrient soil concentrations and more. Therefore, the value of readily available ammonium versus traditional raw manure varies with each field in a given area.

In keeping consistent with other areas of this analysis, we recommend a farmer develop a comprehensive nutrient management plan to determine the benefits they would realize through greater levels of crop-available ammonium rather than using a digester as a nutrient management tool.

CONSTRUCTION EMISSIONS

There are emissions associated with the construction of the digester facility due to transportation of raw materials to the farm site and the generation of raw materials to construct the facility. We do not include these emissions in our calculation of social impacts. We expect these emissions to be negligible relative to the benefits realized through emissions reductions using the digester. It is also unclear whether the emissions associated with construction of the digester represents additional emissions or a transfer that would otherwise go toward construction of a different industry, thus representing no change in emissions. In other words, if the materials were not being used to construct the digester, they would be used for a different purpose that would generate similar emissions.

FURTHER ECONOMIC IMPACTS, AND IMPACTS TO INDIRECT AND SECONDARY MARKETS

Anaerobic digestion and the production of biogas has impacts on the economy beyond the level of the individual farmer. Under models 2 and 3, the third-party sellers of natural gas may accrue additional producer surplus through their profits. We assume, however, that the prices for natural gas reflect equilibrium in supply and demand, and therefore no additional social surplus is created from these sales. Furthermore, we assume that the payments that third-party producers receive in Renewable Energy Credits accurately reflect the social value of replacing non-renewable transportation fuel with biogas. Therefore, these payments are viewed as transfers, and the reduction of methane emissions from dairy farms represents the only social benefit from greenhouse gas reduction in our models.

In terms of further environmental impacts, anaerobic digestion may eliminate externalities in air pollution and climate change impacts at the use end of the natural gas supply chain. As the marketplace for biogas grows, we may see increased demand for this product. We view these impacts as secondary markets, which we do not measure for our analysis. Because a single digester in northeast Wisconsin is not likely to alter the market price of goods in these markets, general benefit-cost practice suggests that impacts on them be left unmonetized (Boardman et al. 2018).

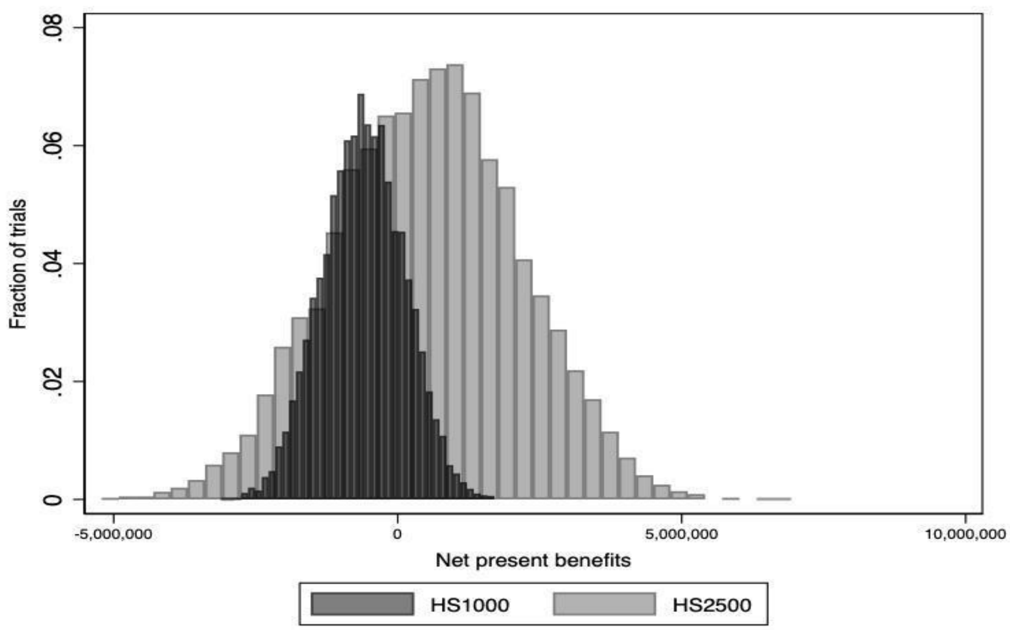
Furthermore, we might expect growth in the digester industry. That growth will inherently create impacts to other markets not directly associated with biogas production. Because this analysis is concerned with the costs and benefits of one additional digester at different scales, impacts to these indirect markets are outside the scope of this analysis but are an opportunity for additional research. For example, the development of hundreds of additional digesters generating tradable credits in California's Low Carbon Fuel Standard Program may create enough supply to drive the price of those credits down.

APPENDIX P: MONTE CARLO SIMULATIONS AND DISTRIBUTIONAL ASSUMPTIONS

Many of our parameters are highly uncertain. We account for this uncertainty by using a Monte Carlo simulation. A Monte Carlo simulation repeatedly draws random values from a specified distribution, rather than using a point estimate. We wrote a computer program (see Appendix Q) for this analysis that completed 10,000 of these random draws to generate 10,000 possible values for net benefits. The following figures show the distributions of those draws for farmer benefits in each model at herd sizes of 1,000 and 2,500 cows.

Figure 11 shows the distribution of net present farmer benefits for each model at herd sizes of 1,000 and 2,500 cows in Model 1.

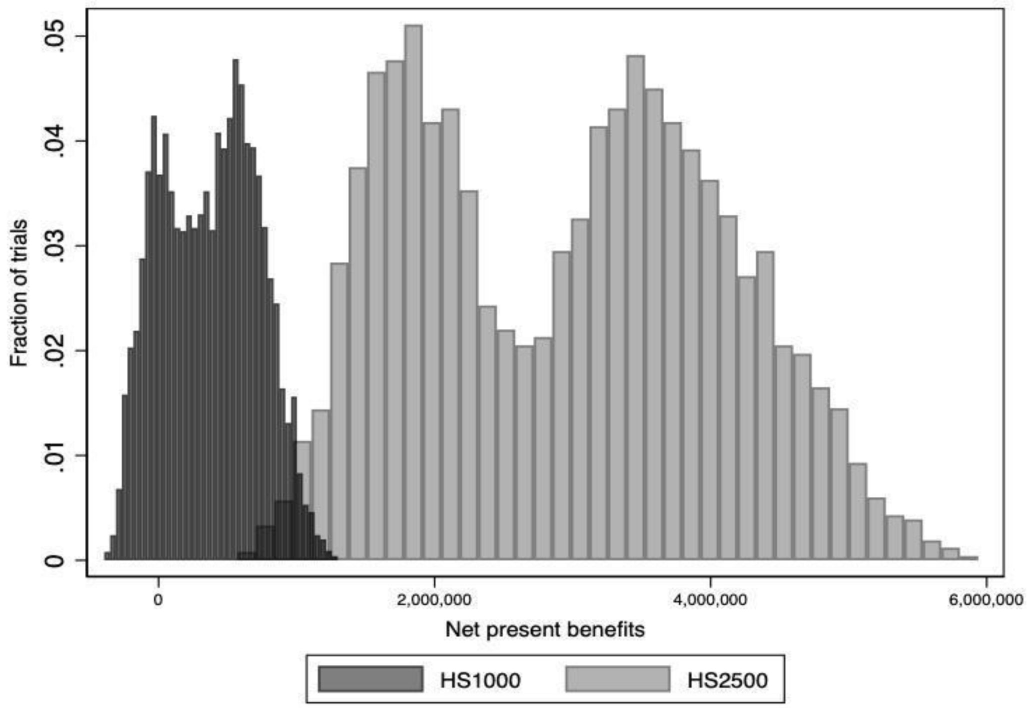
FIGURE 11. DISTRIBUTION OF PRESENT FARMER BENEFIT ESTIMATES IN MODEL 1, AT HERD SIZE 1,000 AND 2,500



Expected farmer benefits are more likely to be positive for the larger farm, but these estimates are also more widely distributed.

Figure 12 compares expected farmer benefits for herd sizes of 1,000 and 2,500 cows in Model 2.

FIGURE 12. DISTRIBUTION OF PRESENT FARMER BENEFIT ESTIMATES IN MODEL 2, AT HERD SIZE 1,000 AND 2,500



Farmer benefits are now much more likely to be positive in both models, but the estimates are less normal, wider, and further apart.

These wide variances largely reflect the high levels of uncertainty in our parameter estimates. Our parameter estimates and distributional assumptions for our variables are outlined in Table 27.

TABLE 27. PARAMETER DISTRIBUTIONS FOR MONTE CARLO ANALYSIS

Variable	Description	Point Estimate	Min	Max	Distribution
Bedding					
bedcost*	Monthly spending on bedding, per gallon of milk	0.41	Unknown	Unknown	Unknown
milk*	Average monthly gallons of milk produced per cow WI	18.1	Unknown	Unknown	Unknown
Capital					
finance	Percent of capital the farmer finances	0.7	Unknown	Unknown	Unknown
genrep	Cost to replace a genset (per cow)	-	325	380	Uniform
loanrate	Annual loan rate	0.031	Unknown	Unknown	Unknown
M1capital	Capital costs per cow (Model 1)	728*cow + 668000	Unknown	Unknown	Unknown
M1omrate	Operations and maintenance cost rate per cow, per year in Model 1 (percent of capital costs)	0.05	0.02	0.11	Triangular
M2capital	Capital costs per cow (Model 2)	678*cow + 622309	Unknown	Unknown	Unknown
M2omrate	Operations and maintenance cost rate per cow, per year in Model 2 (percent of capital costs)	0.06	0.03	0.12	Triangular
Energy					
M2wellhead	Wellhead natural gas sales, per cow, per year (Model 2)	113.74	28.07	233.99	Triangular
private_energy	Benefits to farmer from selling electricity back to the grid, per cow, per year	66.6	27.8	105.4	Normal
private_energy_cost	Annual cost to farmer to sell electricity to utility	234.74	Unknown	Unknown	Unknown
Lease					
lease	Land lease for digester (Model 3)	22,704	Unknown	Unknown	Unknown
Methane					
methc	Social cost of methane per ton of CO2 equivalents MAIN REPORT	7	Unknown	Unknown	Unknown
methcs	Social cost of methane per ton of CO2 equivalents SENSITIVITY ANALYSIS	64	Unknown	Unknown	Unknown
methq	Tons of CO2 equivalents emissions per cow reduced with a digester	-	1.7	10.4	Uniform
methq2	Tons of CO_2 equivalents emissions per cow reduced with a digester, accounting for pipeline leakage	-	1.67	10.25	Uniform

Variable	Description	Point Estimate	Min	Max	Distribution
Odor					
propred	Rate of reduction to property values near CAFOs due to noxious odor	0.01	0	0.08	Triangular
propval*	Median property values in NE WI	150000	Unknown	Unknown	Unknown
proxhome*	Number of households located near a CAFO in NE WI	56	Unknown	Unknown	Unknown
Opportunity Cost					
oppcost	Opportunity cost of using agricultural land for a digester	572	Unknown	Unknown	Unknown
Transportation					
distance	Estimated distance to truck biomethane in models 2 and 3	-	39	71	Uniform
M1truckdistance*	Average distance driven to spread manure, per ton of manure produced	5	Unknown	Unknown	Uniform
M1truckmile	Social costs of trucking, per ton of manure produced, per mile driven	-	0.028	0.063	Uniform
tonpercow*	Tons of milk produced, per cow, per year	18.98	Unknown	Unknown	Unknown
tonpertruck*	Tons of milk per truck	23.78	Unknown	Unknown	Unknown
truckcost	Trucking costs for farmers, per cow, per year	-	116.86	186.97	Uniform
truckmile	Social costs of trucking, per cow per mile driven (Models 2 and 3)	-	0.0252	0.0567	Uniform
truckrate	Rate of trucking cost reduction with a digester	-	0	0.20	Uniform
Water					
bottledwater*	Bottled water purchases from nitrate contamination	311	Unknown	Unknown	Normal
dayssick	Estimated number of days sick per person per year from pathogen	4	2	14	Normal
outpatient	Estimated diarrhea- and rotavirus-associated outpatient costs	76.42	69	84	Normal
pop	Estimated population living close enough to a CAFO to experience pathogen water infestation	216	Unknown	Unknown	Unknown
runoff	Estimated days per year with a pathogen runoff event	3.31	2	4.7	Uniform
wages*	Median day of wages	162.96	Unknown	Unknown	Unknown

APPENDIX Q: STATA CODE

```
clear all
set more off
capture log close

cd "/Users/sarahosborn/Documents/School/Fall 2019/CBA/Stata"

log using "monte_carlo_rev_$S_DATE.log", replace

***************
*** PRESETS ***
***************
set obs 10000
set seed 867530999

gen u = runiform()

// Discount Rate //
gen d=0.035

****************
** ALL MODELS **
****************

*--COSTS--*

// Opportunity costs of a digester // (same for farmer and society)
	gen agrent = 143 //regional ag rent = $143
	gen oppcost = agrent*4 //assume 4 acres

*--SOCIAL BENEFITS--*

	// Water benefits per year //
	gen dayssick=4 //estimated days sick/year/person (from 2-14 days)
	gen outpatient = 76.42  //estimated associated costs (from $69-$84)
	gen pop = 216 // total population living near a CAFO

	gen savesick = (162.96*(dayssick) + outpatient+ 311)*pop

		*runoff*                                  *min = 2 days
		                                          *max = 4.7 days
		gen runoffdays =  2 + (4.7-2)*runiform()
		gen runoff = runoffdays/365

	gen pathogen = (runoff*savesick)  // total est pathogen reduction benefits/yr
```

```
	// Odor //

		* med prop values absent odor = $150,000
		* properties near a CAFO = 56
		* Expected property value loss from odor (triangular dist)		* min = 0.0
											* mode = 0.01
											* max = 0.08
	gen tri = (0.01)/(0.08)

	gen propred = sqrt(u*(.01*.01)) if u < tri
	replace propred = 0.08-sqrt((1-u)*(0.08-0.01)*0.08) if u >= tri

	drop tri

	gen propold = 150000*(1-propred) // expected current property values

	gen odor = 56*(150000-propold) /*	expected gains from odor reduction.
						assume 56 households near a CAFO */

*************
** MODEL 1 **
*************

*--COSTS--*


	// Construction and Financing //
		*financing rates come from Jack Links
		*assume same in Model 2

	gen finance = 0.7

	gen loanrate = 0.031
	gen time=4

	forval c=500(500)5000 {
		gen M1capital`c' = 728*`c' + 668000
		gen M1downpayment`c' = M1capital`c'*(1-finance) //downpayment
		gen M1principleY0C`c' = M1capital`c'*(finance) //interest on prev yr pmnt
		gen M1basepay`c' = M1principleY0C`c'/time

		local i = 1
		local j = 0

			while `i' <= time {
				gen M1principleY`i'C`c' = M1capital`c'*(finance) - M1basepay`c'
				gen M1loaninterestY`i'C`c' = M1principleY`j'C`c'*loanrate
				gen M1loanpayY`i'C`c' = M1basepay`c' + M1loaninterestY`i'C`c'
```

```
				local i = `i'+1
				local j = `j'+1
		}
	}

	// Operations and maintenance per cow, per year //	* min = 0.02
								* mode = 0.05
								* max = 0.11
	gen tri = (0.05-0.02)/(0.11-0.02)

	gen M1omrate = 0.02+sqrt(u*(0.05-0.02)*(0.05-.02)) if u < tri
	replace M1omrate = 0.11-sqrt((1-u)*(0.11-0.05)*(0.11-0.02)) if u >= tri

	drop tri

	// Genset replacement at year 11 (per cow) //		* min = 325
								* max = 380
	gen genrep = 325 + (380-325)*runiform()

*--PRIVATE BENEFITS--*

	// Avoided bedding costs per cow, per year //
	gen bedding = (.41*18.1*12)

	// Avoided trucking costs per cow, per year //		* min = 0%
								* max = 20%
	gen truckcost_low = 116.86
	gen truckcost_high = 186.97

	gen truckcost = truckcost_low+(truckcost_high-truckcost_low)*runiform()

	gen truckrate = 0.2*runiform()
	gen privatetruck = truckrate*truckcost

*--SOCIAL BENEFITS--*

	// Social benefits from reduced trucking //
		* Social costs per ton per mile			// min = 0.028
								// max = 0.063
		gen M1truckmile= 0.028+(0.063-0.028)*runiform()

	gen M1trucktotal = 5*M1truckmile*(23.78/18.98)		/*	gallons produced per cow.
									assume 5800 gal per truck. */
	gen M1socialtruck = truckrate*M1trucktotal

	// Greenhouse gas reduction per cow, per year //
```

```
		*Tons reduced per cow*								* min = 1.7
																* max = 10.4
		gen M1methq= 1.7+(10.4-1.7)*runiform()

	gen methc = 7
	gen M1methane = methc*M1methq

*--TOTALS--*

// Total Private Benefits to Farmer //

forval c = 500(500)5000{
	gen private_energy`c'=(rnormal(66.6,38.8)*`c')-234.74
	gen M1ompay`c' = M1omrate*M1capital`c' //annual operations & maintenance

	*annual costs*
		gen M1Y0`c' = M1downpayment`c' + M1basepay`c'
		gen M1farm_y1`c' = ((private_energy`c'+((bedding+privatetruck)*`c') ///
			-M1loanpayY1C`c'-M1ompay`c'-oppcost))/(1+d)^0.5
		gen M1farm_y2`c'=((private_energy`c'+((bedding+privatetruck)*`c') ///
			-M1loanpayY2C`c'-M1ompay`c'-oppcost))/(1+d)^1.5
		gen M1farm_y3`c' = (private_energy`c'+((bedding+privatetruck)*`c') ///
			-M1loanpayY3C`c'-M1ompay`c'-oppcost)/(1+d)^2.5
		gen M1farm_y4`c' = ((private_energy`c'+((bedding+privatetruck)*`c') ///
			-M1loanpayY4C`c'-M1ompay`c'-oppcost))/(1+d)^3.5

		gen M1farm_annual`c' = (private_energy`c'+((bedding+privatetruck)*`c') ///
			-M1ompay`c'-oppcost)

	*net present value - total*
	gen M1npv_farm`c' = -(M1downpayment`c' + M1basepay`c') ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1loanpayY1C`c'-M1ompay`c'-oppcost)/((1+d)^0.5) ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1loanpayY2C`c'-M1ompay`c'-oppcost)/((1+d)^1.5) ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1loanpayY3C`c'-M1ompay`c'-oppcost)/((1+d)^2.5) ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1loanpayY4C`c'-M1ompay`c'-oppcost)/((1+d)^3.5) ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/((1+d)^4.5) ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/((1+d)^5.5) ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^6.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^7.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
```

```
		-M1ompay`c'-oppcost)/(1+d)^8.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^9.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-genrep*`c'-oppcost)/(1+d)^10.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^11.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^12.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^13.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^14.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^15.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^16.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^17.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^18.5 ///
	+ (private_energy`c'+((bedding+privatetruck)*`c') ///
		-M1ompay`c'-oppcost)/(1+d)^19.5

	*trials with positive benefits*
	gen M1farmpos`c' = cond(M1npv_farm`c'>0,1,0)
}

set scheme  s1manual

twoway (hist M1npv_farm1000, fraction xtitle("Net present benefits") ///
		ytitle("Fraction of trials") color(grey%50)) ///
		(hist M1npv_farm2500, fraction color(black%30)), ///
		legend(order(1 "HS1000" 2 "HS2500"))

// Social Benefits //

forval c = 500(500)5000{

	*annual social cost est*
	gen M1soc_annual`c' = (pathogen+(M1socialtruck+M1methane)*`c')-oppcost

	*npv of social benefits*
	gen M1npv_soc`c' = ///
	((pathogen+(M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^0.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^1.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^2.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^3.5 ///
```

```
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^4.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^5.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^6.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^7.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^8.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^9.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^10.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^11.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^12.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^13.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^14.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^15.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^16.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^17.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^18.5 ///
	+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^19.5

	*Odor benefits at herd size >=2,500 cows*
	replace M1npv_soc`c'=cond(`c'>=2500,M1npv_soc`c'+(odor/(1+d)^0.5),M1npv_soc`c')

	*Trials with positive benefits*
	gen M1socpos`c' = cond(M1npv_soc`c'>0,1,0)
}

//Distribution of trials - HS1000 & HS2500 //
hist M1npv_soc1000, fraction xtitle("Net present benefits") ///
	subtitle("Model 1 Social Benefits, Herd Size 1,000") ///
	ytitle("Fraction of trials")

hist M1npv_soc2500, fraction xtitle("Net present benefits") ///
	subtitle("Model 1 Social Benefits, Herd Size 2,500") ///
	ytitle("Fraction of trials")

*************
** MODEL 2 **
*************

*--PRIVATE COSTS--*

	// Construction and Financing //

	forval c=500(500)5000 {
		gen M2capital`c' = 678*`c' + 622309
		gen M2downpayment`c' = M2capital`c'*(1-finance) //downpayment
		gen M2principleY0C`c' = M2capital`c'*(finance) //interest on prev. yr pmnt
		gen M2basepay`c' = M2principleY0C`c'/time

		local i = 1
```

```
		local j = 0

			while `i' <= time {
				gen M2principleY`i'C`c' = M2capital`c'*(finance)  - M2basepay`c'
				gen M2loaninterestY`i'C`c' = M2principleY`j'C`c'*loanrate
				gen M2loanpayY`i'C`c' = M2basepay`c' + M2loaninterestY`i'C`c'

				local i = `i'+1
				local j = `j'+1
		}
	}

	// Operations and maintenance per cow, per year //	* min = 0.03
								* mode = 0.06
								* max = 0.12

	gen tri = (0.06-0.03)/(0.12-0.03)

	gen M2omrate = 0.03+sqrt(u*(0.06-0.03)*(0.06-.03)) if u < tri
	replace M2omrate = 0.12-sqrt((1-u)*(0.12-0.06)*(0.12-0.03)) if u >= tri

	drop tri

*--SOCIAL COSTS--*

	// Social Cost of Trucking Gas Per Trip //

	* Social costs per cow per mile		* min = 0.0252
						* max = 0.0567
	gen truckmile= 0.0252+(0.0567-0.0252)*runiform()

	* Distance							* min = 39 miles
									* max = 71 miles
	gen distance = 39 + (71-39)*runiform()

	* Social costs per cow, per year
	gen socialtruckcost = truckmile*distance

	* Total social benefits from reduced trucking
	gen M2socialtruck = M1socialtruck-socialtruckcost

*--PRIVATE BENEFITS--*

	// Wellhead natural gas sales per cow, per year //	* min = $28.07
								* mode = $113.74
								* max = $233.99
	gen tri = (113.74-28.07)/(233.99-28.07)
```

```
	gen M2wellhead = 28.07 + sqrt(u*(113.74-28.07)*(113.74-28.07)) if u<tri
	replace M2wellhead = 233.99-sqrt((1-u)*(233.99-113.74)*(233.99-28.07)) if u>=tri

	drop tri

*--SOCIAL BENEFITS--*

	// Greenhouse gas reduction per cow, per year //

		*Tons reduced per cow*						* min = 1.67
										* max = 10.25
		gen M23methq= 1.67+(10.25-1.67)*runiform()

	gen M23methane = methc*M23methq

*--TOTALS--*

// Private benefits to farmer //

forval c = 500(500)5000{
	gen M2ompay`c' = M2omrate*M2capital`c' //annual operations & maintenance

	*annual estimates*
		gen M2Y0`c' = M2downpayment`c' + M2basepay`c'

		gen M2farm_Y1`c' = (((M2wellhead+bedding+privatetruck)*`c') ///
			-M2loanpayY1C`c'-M2ompay`c'-oppcost)/(1+d)^0.5

		gen M2farm_Y2`c' = (((M2wellhead+bedding+privatetruck)*`c') ///
			-M2loanpayY2C`c'-M2ompay`c'-oppcost)/(1+d)^1.5

		gen M2farm_Y3`c' = (((M2wellhead+bedding+privatetruck)*`c') ///
			-M2loanpayY3C`c'-M2ompay`c'-oppcost)/(1+d)^2.5

		gen M2farm_Y4`c' = (((M2wellhead+bedding+privatetruck)*`c') ///
			-M2loanpayY4C`c'-M2ompay`c'-oppcost)/(1+d)^3.5

		gen M2farm_annual`c' = ((M2wellhead+bedding+privatetruck)*`c') ///
			-M2ompay`c'-oppcost

	*Net present value of total benefits*
	gen M2npv_farm`c' = -(M2downpayment`c' + M2basepay`c') ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2loanpayY1C`c'-M2ompay`c'-oppcost)/(1+d)^0.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2loanpayY2C`c'-M2ompay`c'-oppcost)/(1+d)^1.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2loanpayY3C`c'-M2ompay`c'-oppcost)/(1+d)^2.5 ///
```

```
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2loanpayY4C`c'-M2ompay`c'-oppcost)/(1+d)^3.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^4.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^5.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^6.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^7.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^8.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^9.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^10.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^11.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^12.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^13.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^14.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^15.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^16.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^17.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^18.5 ///
	+ (((M2wellhead+bedding+privatetruck)*`c') ///
		-M2ompay`c'-oppcost)/(1+d)^19.5

	*trials with positive benefits*
	gen M2farmpos`c' = cond(M2npv_farm`c'>0,1,0)
}

//Distribution of trials - HS1000 & HS2500 //
twoway (hist M2npv_farm1000, fraction xtitle("Net present benefits") ///
		ytitle("Fraction of trials") color(grey%50)) ///
		(hist M2npv_farm2500, fraction color(black%30)), ///
		legend(order(1 "HS1000" 2 "HS2500"))

// Social Benefits //

forval c = 500(500)5000{
```

```
	*annual benefits*
	gen M23soc_annual`c' = pathogen+((M2socialtruck+M23methane)*`c')-oppcost

	*NPV of benefits*
	gen M23npv_soc`c' = ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^0.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^1.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^2.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^3.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^4.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^5.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^6.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^7.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^8.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^9.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^10.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^11.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^12.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^13.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^14.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^15.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^16.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^17.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^18.5 ///
	+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^19.5

	*odor benefits at herd size >=2,500 cows*
	replace M23npv_soc`c'=cond(`c'>=2500,M23npv_soc`c'+(odor/(1+d)^0.5),M23npv_soc`c')

	*trials with positive benefits*
	gen M23socpos`c' = cond(M23npv_soc`c'>0,1,0)

}

//Distribution of trials - HS1000 & HS2500 //
hist M23npv_soc1000, fraction xtitle("Net present benefits") ///
	subtitle("Model 2 and 3 Social Benefits, Herd Size 1,000") ///
	ytitle("Fraction of trials")

hist M23npv_soc2500, fraction xtitle("Net present benefits") ///
	subtitle("Model 2 and 3 Social Benefits, Herd Size 2,500") ///
	ytitle("Fraction of trials")

*************
** MODEL 3 **
*************
*--BENEFITS--*
```

```
	// Lease (assume one-time payment) //
	gen lease = 22704

*--TOTALS--*

forval c = 500(500)5000{

	*annual estimates*
	gen M3farm_annual`c' = ((bedding+privatetruck)*`c')-oppcost

	*NPV of benefits*
	gen M3npv_farm`c' = lease ///

	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^0.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^1.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^2.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^3.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^4.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^5.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^6.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^7.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^8.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^9.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^10.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^11.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^12.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^13.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^14.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^15.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^16.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^17.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^18.5 ///
	+ (((bedding+privatetruck)*`c')-oppcost)/(1+d)^19.5

	*trials with positive benefits*
	gen M3farmpos`c' = cond(M3npv_farm`c'>0,1,0)
}

//Distribution of trials - HS1000 & HS2500 //
hist M3npv_farm1000, fraction xtitle("Net present benefits") ///
	subtitle("Model 3 Farmer Benefits, Herd Size 1,000") ///
	ytitle("Fraction of trials")

hist M3npv_farm2500, fraction xtitle("Net present benefits") ///
	subtitle("Model 3 Farmer Benefits, Herd Size 2,500") ///
	ytitle("Fraction of trials")

// Export results tables //
```

```
	* NPV
	global list1 M1npv_farm* M1npv_soc* M2npv_farm* M23npv_soc* M3npv_farm*
	estpost sum $list1, detail
	esttab . using Table1.rtf, cell("mean p5 p95") nonumber nomtitle replace

	* Trials with positive benefits
	global list2 M1farmpos* M1socpos* M2farmpos* M23socpos* M3farmpos*
	estpost sum $list2
	esttab . using Table2.rtf, cell(sum) nonumber nomtitle replace

*****************************************************************************

*************************
** SENSITIVITY ANALYSES **
*************************

//--**--// SENSITIVITY 1: ASSUME NO BENEFITS FROM ODOR //--**--//

	// Model 1 Social Benefits Without Odor //
	forval c = 500(500)5000{
		gen S1M1npv_soc`c' = ((pathogen+(M1socialtruck+M1methane)*`c')-
oppcost)/(1+d)^0.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^1.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^2.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^3.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^4.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^5.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^6.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^7.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^8.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^9.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^10.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^11.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^12.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^13.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^14.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^15.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^16.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^17.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^18.5 ///
		+ ((pathogen + (M1socialtruck+M1methane)*`c')-oppcost)/(1+d)^19.5
	}

	// Models 2 and 3 Social Benefits Without Odor //

	forval c = 500(500)5000{
		gen S1M23npv_soc`c' = ((pathogen+(M2socialtruck+M23methane)*`c')-
oppcost)/(1+d)^0.5 ///
```

```
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^1.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^2.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^3.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^4.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^5.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^6.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^7.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^8.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^9.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^10.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^11.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^12.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^13.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^14.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^15.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^16.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^17.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^18.5 ///
+ ((pathogen+(M2socialtruck+M23methane)*`c')-oppcost)/(1+d)^19.5
}

global list3 S1M1npv_soc* S1M23npv_soc*
estpost sum $list3, detail
esttab . using Table3.rtf, cell("p5 mean p95") nonumber nomtitle replace


//--**--// SENSITIVITY 2: LOWEST POSSIBLE VALUES //--**--//

// Water benefits per year //
gen S2dayssick=2 //changed from point estimate (4) to lowest EV
gen S2outpatient = 69  //changed from point estimate (76.42) to lowest EV

gen S2savesick = (162.96*(S2dayssick) + S2outpatient + 311)*pop

gen S2runoff = (2/365) //lowest EV for runoff rate

gen S2pathogen = (S2runoff*S2savesick)  // total estimated pathogen reduction
benefits/year

// Greenhouse gas reduction per cow, per year //
*Tons reduced per cow*
gen S2methq= 1.67 // lowest EV

*Affiliated costs per ton reduced*
gen S2methc = 1 // lowest EV

gen S2methane = S2methc*S2methq
```

```
// Construction and Financing //

forval c=500(500)5000 {
	gen S2capital`c' = 2670*`c'
	gen S2downpayment`c' = S2capital`c'*(1-finance) //downpayment
	gen S2principleY0C`c' = S2capital`c'*(finance) //interest on previous year payment
	gen S2basepay`c' = S2principleY0C`c'/time

	local i = 1
	local j = 0

		while `i' <= time {
			gen S2principleY`i'C`c' = S2capital`c'*(finance) - S2basepay`c'
			gen S2loaninterestY`i'C`c' = S2principleY`j'C`c'*loanrate
			gen S2loanpayY`i'C`c' = S2basepay`c' + S2loaninterestY`i'C`c'

			local i = `i'+1
			local j = `j'+1
	}
}

** MODEL 1 **

	*-COSTS-*

		// Operations and maintenance per cow, per year //
		gen S2M1omrate = 0.11 // highest EV

		* Genset replacement at year 11 *
		gen S2genrep = 380 //highest EV

	*--TOTALS--*

	// Total Private Benefits to Farmer //

	forval c = 500(500)5000{
		gen S2M1ompay`c' = S2M1omrate*M1capital`c' //annual operations &
maintenance

		gen S2M1npv_farm`c' = -(S2downpayment`c' + S2basepay`c') ///
		+ (private_energy`c'+(bedding*`c') ///
			-S2loanpayY1C`c'-S2M1ompay`c'-oppcost)/((1+d)^0.5) ///
		+ (private_energy`c'+((bedding)*`c') ///
			-S2loanpayY2C`c'-S2M1ompay`c'-oppcost)/((1+d)^1.5) ///
		+ (private_energy`c'+((bedding)*`c') ///
			-S2loanpayY3C`c'-S2M1ompay`c'-oppcost)/((1+d)^2.5) ///
		+ (private_energy`c'+((bedding)*`c') ///
			-S2loanpayY4C`c'-S2M1ompay`c'-oppcost)/((1+d)^3.5) ///
```

```
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/((1+d)^4.5) ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/((1+d)^5.5) ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^6.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^7.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^8.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^9.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-S2genrep*`c'-oppcost)/(1+d)^10.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^11.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^12.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^13.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^14.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^15.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^16.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^17.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^18.5 ///
	+ (private_energy`c'+((bedding)*`c') ///
		-S2M1ompay`c'-oppcost)/(1+d)^19.5

	gen S2M1farmpos`c' = cond(S2M1npv_farm`c'>0,1,0)
}

// Social Benefits //

forval c = 500(500)5000{
	gen S2M1npv_soc`c' = ((S2pathogen+S2methane*`c')-oppcost)/(1+d)^0.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^1.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^2.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^3.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^4.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^5.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^6.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^7.5 ///
	+ ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^8.5 ///
```

```
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^9.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^10.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^11.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^12.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^13.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^14.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^15.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^16.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^17.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^18.5 ///
            + ((S2pathogen + S2methane*`c')-oppcost)/(1+d)^19.5
    }

** MODEL 2 **

    *--COSTS--*

    // Operations and maintenance per cow, per year //

    gen S2M2omrate = 0.12

    // Social Cost of Trucking Gas Per Trip //

            * Social costs per cow per mile         // min = 0.0252
                                                    // max = 0.0567
            gen S2truckmile= 0.0567

            * Distance                              // min = 39 miles
                                                    // max = 71 miles
            gen S2distance = 71

            * Social costs per cow, per year
            gen S2M2socialtruck = S2truckmile*S2distance

    *--BENEFITS--*

    // Wellhead natural gas sales per cow, per year //


    gen S2M2wellhead = 28.07

    // Private benefits to farmer //

    forval c = 500(500)5000{
            gen S2M2ompay`c' = S2M2omrate*M2capital`c' //annual O&M

            gen S2M2npv_farm`c' = -(S2downpayment`c' + S2basepay`c') ///
            + (((S2M2wellhead+bedding)*`c') ///
```

```
		-S2loanpayY1C`c'-S2M2ompay`c'-oppcost)/(1+d)^0.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2loanpayY2C`c'-S2M2ompay`c'-oppcost)/(1+d)^1.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2loanpayY3C`c'-S2M2ompay`c'-oppcost)/(1+d)^2.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2loanpayY4C`c'-S2M2ompay`c'-oppcost)/(1+d)^3.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^4.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^5.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^6.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^7.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^8.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^9.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^10.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^11.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^12.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^13.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^14.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^15.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^16.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^17.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^18.5 ///
	+ (((S2M2wellhead+bedding)*`c') ///
		-S2M2ompay`c'-oppcost)/(1+d)^19.5

	gen S2M2farmpos`c' = cond(S2M2npv_farm`c'>0,1,0)

}


// Social Benefits //

forval c = 500(500)5000{
```

```
		gen S2M23npv_soc`c' = ///
		((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^0.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^1.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^2.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^3.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^4.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^5.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^6.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^7.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^8.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^9.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^10.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^11.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^12.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^13.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^14.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^15.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^16.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^17.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^18.5 ///
		+ ((S2pathogen+(S2M2socialtruck+S2methane)*`c')-oppcost)/(1+d)^19.5
	}

** MODEL 3 **

	// Lease (assume one-time payment) //
	gen S2lease = 4000		//lowest EV

	forval c = 500(500)5000{
		gen S2M3npv_farm`c' = S2lease ///
		+ (bedding*`c'-oppcost)/(1+d)^0.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^1.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^2.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^3.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^4.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^5.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^6.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^7.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^8.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^9.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^10.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^11.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^12.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^13.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^14.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^15.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^16.5 ///
		+ (bedding*`c'-oppcost)/(1+d)^17.5 ///
```

```
			+ (bedding*`c'-oppcost)/(1+d)^18.5 ///
			+ (bedding*`c'-oppcost)/(1+d)^19.5

		gen S2M3farmpos`c' = cond(S2M3npv_farm`c'>0,1,0)
		}

	//Export results//
	global list4 S2M1npv_farm* S2M1npv_soc* S2M2npv_farm* S2M23npv_soc* S2M3npv_farm*
	estpost sum $list4, detail
	esttab . using Table4.rtf, cell("mean p5 p95") nonumber nomtitle replace

	global list5 S2M1farmpos* S2M2farmpos* S2M3farmpos*
	estpost sum $list5
	esttab . using Table5.rtf, cell(sum) nonumber nomtitle replace


//--**--// SENSITIVITY 3: HIGHER EST FOR SOCIAL COST OF METHANE //--**--//

	// New methane cost estimate //
	gen S3methc = 64
	gen S3M1methane = S3methc*M1methq

	// Totals //
	forval c = 500(500)5000{
		gen S3M1npv_soc`c' = ///
		((pathogen+(M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^0.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^1.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^2.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^3.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^4.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^5.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^6.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^7.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^8.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^9.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^10.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^11.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^12.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^13.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^14.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^15.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^16.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^17.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^18.5 ///
		+ ((pathogen + (M1socialtruck+S3M1methane)*`c')-oppcost)/(1+d)^19.5

	replace S3M1npv_soc`c' = cond(`c'>=2500,S3M1npv_soc`c'+odor/(1+d)^0.5,S3M1npv_soc`c')
	}
```

```
	gen S3M23methane = S3methc*M23methq

	forval c = 500(500)5000{
		gen S3M23npv_soc`c' = ///
		((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^0.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^1.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^2.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^3.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^4.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^5.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^6.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^7.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^8.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^9.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^10.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^11.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^12.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^13.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^14.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^15.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^16.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^17.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^18.5 ///
		+ ((pathogen+(M2socialtruck+S3M23methane)*`c')-oppcost)/(1+d)^19.5

	replace S3M23npv_soc`c' =
cond(`c'>=2500,S3M23npv_soc`c'+odor/(1+d)^0.5,S3M23npv_soc`c')
	}

	//Export results//
	global list6 S3M1npv_soc* S3M23npv_soc*
	estpost sum $list6, detail
	esttab . using Table6.rtf, cell("mean p5 p95") nonumber nomtitle replace

log close
```

APPENDIX R: SENSITIVITY ANALYSIS

Given the uncertainty in our parameters, we ran three sensitivity analyses to assess the strength of our findings.

SENSITIVITY 1: REMOVING ODOR REDUCTION BENEFITS

In our primary analysis, we used the difference between median housing prices in Northeast Wisconsin and estimated reductions to housing prices due to manure odor as a shadow price for quality of life benefits from odor reduction. This is a highly speculative assumption.

When we removed odor from our analysis, the net present value of social benefits decreased by over $3.5 million, or nearly $250,000 per year.

This difference is enough to make the estimated total benefits negative for herd sizes of 500 and 1,000 in Model 1 and herd size 500 in Model 2.

SENSITIVITY 2: LOWEST POSSIBLE ESTIMATE

Given the uncertainty in all of our parameters, we also estimated the lowest possible net present values for our models by using the lowest possible benefit values in each category. The net present value of social benefits is still positive for all herd sizes in each model, but farmer benefits and total benefits are only positive in Model 3, at each herd size.

SENSITIVITY 3: HIGHER SOCIAL PRICE OF EMISSION REDUCTION

The social cost of carbon is a hotly debated topic among environmental scientists, policymakers, and economists. In our analysis, we use the EPA's median value ($7) for the social price of reducing one ton of CO_2 emissions. This value reflects an approximation of the domestic price of one ton of CO_2 emission. We use this value in order to be conservative regarding the positive social benefits of reducing greenhouse gas emissions on dairy farms.

However, many estimates of the social cost of carbon are much higher than the current EPA value. Many scientists and economists believe that estimations of the social cost of carbon should be global in scale: although some emissions from the United States primarily affect other countries, the United States is also affected by emissions from other countries. In order to account for this effect, many economists use a global figure for the social cost of carbon (Howard and Sylvan, 2015).

Prior to a 2019 rule change, the EPA used a global estimate for the social cost of carbon in conducting benefit-cost and regulatory impact analyses. The 2019 value of this shadow price was $64 per ton of CO_2 equivalents (EPA, 2016). We conducted a sensitivity analysis using this figure as our shadow price for the social benefits of greenhouse gas emissions reductions. Using this shadow price, the net present value of social benefits remains positive but increases dramatically, indicating that the social benefits of anaerobic digestion may exceed the estimations in our model. This effect is summarized in Table 21 below for herd sizes of 500, 1,000, 2,500, and 5,000 cows.

TABLE 21. ESTIMATED PRESENT VALUE OF SOCIAL BENEFITS AT HIGHER CARBON PRICE (IN MILLION USD)

	Upper Bound Social Benefits			
Herd Size	**Mean**	**P5**	**P95**	**Difference in mean benefits**
Model 1				
500 cows	2.8	1.0	4.6	2.5
1,000 cows	5.6	2.0	9.3	5.0
2,500 cows	14.2	5.1	23.4	12.4
5,000 cows	28.1	9.9	46.4	24.8
Model 2				
500 cows	2.8	1.0	4.6	2.5
1,000 cows	5.5	2.0	9.1	5.0
2,500 cows	14.1	5.1	23.0	12.4
5,000 cows	27.9	9.9	45.7	24.8
Model 3				
500 cows	2.8	1.0	4.6	2.5
1,000 cows	5.5	2.0	9.1	5.0
2,500 cows	14.1	5.1	23.0	12.4
5,000 cows	27.9	9.9	45.7	24.8

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