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Analysis

Anaerobic Digester Production and Cost Functions

Cortney Cowley*, B. Wade Brorsen

Department of Agricultural Economics, Oklahoma State University, Agricultural Hall, Stillwater, OK 74078-6026, United States of America

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ABSTRACT

Methane production from anaerobic digestion has long been technically feasible, but adoption has been limited by economic considerations. For the first time using survey data, methane production and cost functions for anaerobic digesters are estimated for U.S. dairy and swine operations. Farm size, digester inputs, digester design parameters, and construction materials all affect the productivity and profitability of an anaerobic digester. Economies of size were evident for plug flow and complete mix anaerobic digesters, which were more economically feasible on dairy farms than on swine operations. Methane production alone is not enough to provide positive net present values. On dairy farms, economic feasibility could be achieved by marketing co-products, but swine farms required government support to achieve positive NPVs.

1. Introduction

Anaerobic digestion of animal wastes is a promising source of bioenergy not only because methane can be produced, but the negative externalities reduced could justify government intervention to encourage its adoption. Runoff from livestock wastes can be a source of nutrient pollution, which is one of the top water quality issues in the U.S. (Carpenter et al., 1998). In addition to reducing water quality, enteric fermentation and manure decomposition account for almost 35% of methane emissions from anthropogenic activities in the United States (USEPA, 2014b; Lashof and Ahuja, 1990). With anaerobic digestion, solids and biosolids are stabilized by decomposing organic matter in the absence of molecular oxygen (Tchobanoglous et al., 2014). To alleviate greenhouse gas emissions, anaerobic digestion systems capture and combust methane. Anaerobic digesters can also produce value-added co-products such as soil amendments, livestock bedding, and liquid that can be used as fertilizer (Zaks et al., 2011; Bishop and Shumway, 2009). Anaerobic digestion systems are not common on U.S. farms. In 2014, only 238 of the almost 20,000 (~1%) confined animal feeding operations in the United States had anaerobic digestion systems (USEPA, 2012, 2014a).

The economics, and more specifically the capital costs, of these systems are often blamed for their limited adoption (Cowley and Brorsen, 2018; DeVuyst et al., 2011; Wang et al., 2011; Bishop and Shumway, 2009; Kruger et al., 2008; Stokes et al., 2008; Lazarus and Rudstrom, 2007). Most literature on the economic feasibility of anaerobic digestion systems has utilized site-specific case studies. In contrast to these site-specific case studies, we are the first to use a nation-wide survey of anaerobic digester operators to estimate production and cost functions. The survey was sent to 83% of all dairy and swine operations with an anaerobic digester and thus responses capture the variation across the entire industry that is absent from previous research.

The USDA included anaerobic digesters as one of 10 building blocks in a plan to reduce net carbon dioxide emissions by over 120 million metric tons by 2025. To evaluate the likely success of such proposals, a better and broader understanding of anaerobic digester economic feasibility is needed. Currently there is not enough empirical evidence to know the specifics of what works best for successful implementation of anaerobic digesters. For example, what sizes of CAFOs (in terms of number of animals or animal units) are typically the most profitable?

The products and co-products from anaerobic digestion vary depending on the inputs, economics of the system, and the desires of the owner/operator. However, *all* anaerobic digestion systems produce methane. Therefore, the objective of this study is to estimate a production function, a fixed cost function, and a variable cost function for the population of dairy and swine anaerobic digesters constructed in the United States up to 2014. Using the estimated functions, the secondary objective is to determine the expected net present value of installing an anaerobic digester under alternative digester sizes, alternative inputs and outputs, and digester types. These results can help producers to make decisions about constructing an anaerobic digester, and can also help evaluate the effectiveness of policies like construction grants.

* Corresponding author at: Omaha Branch – Federal Reserve Bank of Kansas City, 2201 Farnam Street, Omaha, NE 68102, United States of America.
E-mail address: Cortney.Cowley@kc.frb.org (C. Cowley).

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2. The Economic Problem

The expected net present value maximizing decision maker's problem for an anaerobic digester on a dairy or swine operation of fixed size is

$$\max_{n} E(NPV_i) = \sum_{t=1}^{T} \left[\frac{\sum_{i=0}^{n} (p_i y_i) - AVC_i y_i}{(1+r)^t} \right]_t - AFC_i y_i \quad (1)$$

s. t. $E(NPV_i) \geq 0$

$y_{it} = f(\boldsymbol{x_{it}}; \boldsymbol{\beta}, \boldsymbol{\gamma})$

$AFC_{it} = f(\boldsymbol{x_{it}}; \boldsymbol{r}, \boldsymbol{\psi})$

$AVC_{it} = f(\boldsymbol{x_{it}}; \boldsymbol{\omega}, \boldsymbol{\varphi})$

where n is a choice variable for the outputs that the producer wishes to produce, where, $i = 0$ is no production, $i = 1$ is recovered methane, $i = 2, \ldots n$ are any additional value-added co-products, $E(NPV_i)$ is the expected present value of the anaerobic digester investment, r_t is the discount rate for the t^{th} year, where $t = 1, \ldots, T$ and $T = 25$ years, and $r = 6\%$ and 10%, p_{it} is the price of each co-product in \$/unit, y_{it} is a methane production function for anaerobic digestion systems, which estimates methane production in MJ/year and is also used to estimate the production of additional co-products, AFC_i represents the average fixed cost function for producing methane and other digester co-products in \$/MJ/year, AVC_{it} is the average variable cost function for methane production in an anaerobic digester in \$/MJ/year, and $\boldsymbol{x_{it}}$ is a vector of digester design parameters, inputs, and farm characteristics.

3. Background: Methane Production Fundamentals

The economic feasibility of any production process depends not only on prices but also on the science, technology, and physical possibilities of the system (Heady and Dillon, 1961; Dicks and Doll, 1983). Therefore, it is important to understand the fundamentals of how methane is created through anaerobic digestion.

During anaerobic digestion, organic matter is broken down via four chemical and biochemical reactions: hydrolysis, fermentation (or acidogenesis), acetogenesis, and methanogenesis (Tchobanoglous et al., 2014). Several factors affect these chemical and biochemical reactions.[1] The temperature of the system affects the rate of bacterial growth and waste degradation and thus the quantity of gas produced (Burke, 2001). Maintaining a stable temperature in the anaerobic digester can be even more important than selecting an operating temperature (Tchobanoglous et al., 2014). The range of standard operating temperatures for plug flow and complete mix digesters is very small (95–104 °F) (NRCS, 2009).

Loading rate refers to the solids concentration of material entering the digester per unit of time. NRCS (2009) standards recommend total solids concentrations between 11% and 14% for plug flow digesters and < 11% for complete mix digesters. The reactions that take place inside the digester (hydrolysis, fermentation, acetogenesis, and methanogenesis) are directly related to hydrolic retention time (HRT) and solids retention time (SRT) (Tchobanoglous et al., 2014).[2] Retention time must be set above the minimum time required for each reaction. The minimum retention time for plug flow digesters is 20 days, and the minimum retention time for complete mix digesters is 17 days (NRCS, 2009).

Other physical parameters that could influence methane production include quantity of manure, digester volume, type of digester, and the composition of inputs. Unlike those described in the previous paragraph, these parameters do not have published guidelines for optimal methane production, and little is known as to how they affect profitability of anaerobic digesters. The primary input for methane production in an anaerobic digester is manure. The quantity and composition of the manure excreted by livestock will determine the digester's design parameters (Tchobanoglous et al., 2014; USDA, 2008). Multiplying the amount of manure excreted per cow by the number of cows at the dairy and the required retention time for manure (in days) will approximate the volume of the digester.

While all anaerobic digesters perform the same, basic functions, digesters are typically split into three categories: passive systems, low rate systems, and high rate systems (Hamilton, 2013). For passive systems, methane recovery is added to existing manure management or treatment infrastructure. In low rate systems, manure is the primary source of methane-forming microorganisms. High rate systems differ in that methane-forming microorganisms are added to and contained in the digester to increase methane production efficiency (Hamilton, 2013). For agricultural applications, the most common anaerobic digesters are covered lagoons (passive systems), complete mix digesters, and plug flow digesters (both low rate systems).

For methane production, inputs other than manure could increase or decrease methane produced in an anaerobic digester. Food processing wastes that have similar characteristics as livestock manure, in terms of moisture, total solids, and volatile solids content and chemical/biological oxygen demand, can improve the methane output of an anaerobic digester (Scott and Ma, 2004). Food wastes have twice the methane yield per pound of volatile solids when compared to manure (Goldstein, 2012) and Astill and Shumway (2016) find that tipping fees from accepting such wastes could help digesters become economical. However, most anaerobic digesters on farms in the U.S. are only handling animal wastes.

When considering anaerobic digestion for manure management livestock producers are primarily concerned with how much the system costs and whether or not their farm is large enough (in terms of number of animals or animal units) to generate the revenues to overcome the large capital costs of the system. Fig. 1 shows results from a question asked of producers who do not currently operate anaerobic digesters. The producers were asked to rank the reasons they would *not* want anaerobic digesters on their farms. On average, the two most important reasons for producers not wanting anaerobic digesters were 1) that the costs of the digester exceeded the benefits and 2) that they believed their operations were too small to support anaerobic digesters.

While the economic feasibility of anaerobic digesters on dairy farms has been researched, little academic information is available on anaerobic digester economies of size, especially on swine farms. Leuer et al. (2008) tested three different dairy farm sizes and determined that methane digesters are only profitable for farms with 1000 or more cows. Gloy (2011) discussed how substantial economies of size with anaerobic digesters on dairy farms could contribute to the distributional impacts of policies that create markets for carbon dioxide offset trading. Although previous studies have estimated economies of size and observed positive relationships among livestock numbers and methane production, our study provides estimates of how varying digester design and input parameters affect digester scale economies.

4. Data

Data were collected with a 2013–2014 nationwide survey of dairy and swine producers. After obtaining informed consent from each participant, the survey started by asking a set of introductory questions,

[1] Hydrolysis is considered the most important, or rate-limiting, step in the anaerobic digestion process (Mata-Alvarez and Llabrés, 2000). During hydrolysis, dissolved, insoluble particles are broken down into fermentable sugars by enzymes (Poulsen, 1983). Fermentation is the process by which sugars are converted to alcohol by bacteria and possibly small populations of protozoa, fungi, and yeasts (Poulsen, 1983; Tchobanoglous et al., 2014). During acetogenesis, fermentation products are oxidized into substrates appropriate for methanogenesis, which is the bacterial conversion of oxidized organic compounds into methane and carbon dioxide (Tchobanoglous et al., 2014).

[2] Retention time is defined as the time that the liquids and solids are held in the digester (usually in days).