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Profits from Pollutants: Economic Feasibility of Integrated Anaerobic Digester Systems

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Abstract

We examine the economic feasibility of dairy waste management systems composed of two technology groups: an anaerobic digestion (AD) system that includes either animal waste input or combination animal/off-farm organic waste codigestion input and either compressed natural gas (CNG) or combined heat and power (CHP) output; and a filtration system that includes fiber separation, nutrient separation, and/or water recovery. The two technology groups interconnect through their use of methane and nutrients which we model structurally to examine economies of scope. As of 2015, anaerobic digesters operate on nearly 250 farms in the US, and there has been sustained interest from both environmental regulators and livestock associations to expand the use of AD technology. We conclude that AD setups without codigestion are only economically feasible under a limited set of conditions, but the most profitable scenarios which use codigestion have the potential to contribute to nutrient over-application. Trends for CNG and CHP match closely. Net present value (NPV) is greatest for AD with CNG scenarios. With environmental credits, estimated NPV is $2 million to $42 million for dairies with 1,600 wet cow equivalents (WCE) and 15,000 WCE, respectively. For these firm sizes, codigestion contributes an additional $5 million and $49 million, respectively, in estimated NPV, and fiber separation an additional $2.4 million and $22.8 million, respectively. Nutrient separation and water recovery both lead to decreases in scenario NPV with codigestion, but with the right policies, dairy owners may be willing to adopt AD with nutrient separation.

Keywords: Anaerobic digestion, codigestion, dairy waste management, economic feasibility, nutrient management technology.

JEL classification: Q16 R&D, Agricultural Technology; Q42 Alternative Energy Sources.

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Introduction

This paper evaluates the economic feasibility of adopting emerging waste management technologies in the US dairy industry, including anaerobic digestion (AD), codigestion of off-farm organic waste, production of compressed natural gas (CNG) or combined heat and power (CHP), fiber separation, nutrient separation, and water recovery. Environmental regulators and livestock producers maintain concerns about nutrient management on livestock operations and its effects, and integrated AD systems have the potential to mitigate multiple environmental concerns while providing a positive return to investment.

The UN Food and Agricultural Organization (Gerber *et al.* 2013) reports that milk production accounts for 2.9 percent of worldwide anthropogenic greenhouse gas (GHG) emissions. GHG emissions include methane (CH_4) and nitrous oxide (N_2O). They cite the following as potentially highly effective mitigating technologies: AD for both CH_4 and N_2O, fiber separation for CH_4, and consideration of soil nutrient balance before manure application and timing of manure application for N_2O. Smith *et al.* (2007) find similar results. They estimate that CH_4 from all livestock contributes 4.6 – 5.5 percent of world GHG emissions while nutrient application in crop production contributes 5.4 – 6.5 percent of world GHG emissions.

The Environmental Protection Agency's (EPA) (2014a) inventory of US GHG emissions found that agriculture contributed 8.1 percent of total carbon dioxide (CO_2) equivalent emissions during the past decade. Soil management, enteric fermentation by ruminant cattle, and manure management contributed 4.7 percent, 2.2 percent and 1.1 percent of total US emissions, respectively. Enteric fermentation and manure management are the first and fourth largest contributors to CH_4 emissions and contribute 24.9 percent and 9.3 percent of total US CH_4

emissions, respectively. Methane emissions increased 68 percent from 1990 to 2012 due to increasing use of liquid systems of dairy and swine manure storage and management. Focusing on policy instruments for cost-effectively reducing GHG emissions from agricultural livestock operations, Njuki and Bravo-Ureta (2015) recommend funding assistance programs for ADs.

In addition to GHG emissions, animals contribute to air and water pollution. Odor is a particularly noticeable effect of concentrated livestock production that impacts both producers and neighbors (Wright *et al.* 2004). Water pollution occurs most frequently through the over-application of nutrients. The EPA (2014b) reports that nutrients are the second and third largest causes of impairment of bodies of water and waterways, respectively, and agriculture is the third and first largest source of impairment of bodies of water and waterways, respectively.

Harms attributed to current nutrient management practices on US dairies include P and N eutrophication in US waterways (Kiely 1997; Van Breeman and Van Dijk 1988), the loss of 70 percent of manure N through ammonia volatilization (Council for Agricultural Science and Technology 2002), the creation of harmful particulate matter through ammonia reactions (Erisman and Schaap 2004), and blue baby syndrome and reproductive harm in humans from nitrate accumulation in the water supply (Washington State Department of Health 2005).

Ribaudo *et al.* (2003) found that US dairy farms on average produced 22 percent more N and 34 percent more P in manure than could be applied to the dairies' available cropland at agronomic rates. Without enforced regulation, Innes (2000) concludes that, when manure transport cost is high, producers will apply nutrients to near fields even if they exceed agronomic requirements.[1] Sanford, Posner and Hadley (2009) find a viable transport distance of only 3.2 to 7.6 km for dairy manure slurry as a fertilizer product for corn. In addition to over-application of

[1] The agronomic rate of N is the amount applied to maximize plant growth and minimize excess N percolating beyond the root zone into the groundwater (Natural Resources Conservation Service 2011, p.503-68).

nutrients, failure to incorporate manure into the soil can lead to further N pollutants (Rotz 2004). Regulators are increasingly enforcing environmental regulations on dairy producers to reduce over-application of nutrients (Schmit and Knoblauch 1995; Zhang and Parsons 2001; Huang, Magleby and Christensen 2005).

AD technology allows livestock producers to significantly reduce GHG emissions, odor, and pathogens while producing renewable energy and has been widely adopted in some countries (Lebuhn, Munk, and Effenberger 2014). However, due to high capital costs, limited revenue, and limited economic incentives to reduce GHG emissions, AD technology has yet to become a mainstream technology in US confined animal agriculture. As of 2015, ADs had been built on only 247 farms in the US (AgSTAR 2015), and most of those have been funded in part by subsidies (Cowley 2013).

One possible way to make AD adoption more appealing is to integrate additional technologies with the AD that would lead to water pollution mitigation while maintaining economic viability through economies of scope or new revenue streams. We examine the economic feasibility of a dairy waste management system composed of two technology groups that are interrelated: a filtration system that may include fiber separation, nutrient separation, and/or water recovery; and an AD system that includes on the input side either an animal waste or combination animal/off-farm organic waste AD and that includes on the output side either a CHP system or a CNG system, each of which may generate environmental credits. A graphical representation of the components is presented in Figure 1.

The two technology groups interconnect through their capture of nutrients and methane. This paper contributes to the literature by assessing the economic feasibility of technology combinations using nutrient and methane generation and utilization functions developed by AD engineers to structurally model complementary effects. Nutrient management technologies have the potential to reduce manure disposal costs for dairies, but they become even more important when codigestion of off-farm organics is considered. Off-farm organics can greatly increase the methane output of a digester as well as generate large tipping fees, but they increase nutrient over-application concerns. If most or all nutrients can be partitioned in solid form and sold off-farm, the concern is alleviated.

The results suggest that environmental credits are the biggest potential contributor to net present value (NPV) of the technology investment and that codigestion is the second largest contributor. When environmental credits are considered, NPV of CNG exceeds that of CHP. Fiber separation also contributes to larger NPVs. Nutrient separation and water recovery technologies both lead to NPV decreases. However, results indicate that scenarios with nutrient separation combined with ADs that codigest off-farm organic waste produce greater NPV than scenarios without nutrient separation and without codigestion. Thus, policy makers may be able to encourage adoption of nutrient separation technology through targeted grants that only provide funding for an AD with codigestion if firms also adopt nutrient separation.

In subsequent sections of this paper we explain each technological component of the integrated AD system and briefly examine the history and potential for environmental markets to affect firms' revenue, explain the method of analysis, describe the data used in the analysis, and present the results of the analysis. We conclude in the final section.

Integrated AD Systems

With the growing legislative emphasis on mitigating both GHG emissions and water pollution, we examine the economic viability of several environmentally-positive technological components that could be built into an integrated AD system.

Anaerobic Digestion

An anaerobic digester is an enclosed vessel that allows anaerobic bacteria to break down volatile solids in organic waste and convert them to biogas. For an overview of the history, engineering, chemistry and economics of AD, see Wilkinson (2011).

The use of AD technology varies throughout the world. Lebuhn, Munk, and Effenberger (2014) report that more than 7 million household-size anaerobic digersters are used for inexpensive cooking fuel in China and more than 1 million in India. Germany has over 7,700 larger scale, farm level digesters. Use of AD technology in the US has lagged well behind Germany, but adoption rates have increased in recent years. Of the 202 anaerobic digersters on dairies in the US, 166 have been built since 2005 (AgSTAR 2015). Combined, these farm projects reduce methane emissions by 3.48 million metric tons of CO_2 equivalent (tCO_2e) per year (AgSTAR 2015). AgSTAR (2011) estimates that there are another 2,645 US dairy farms that are likely candidates for AD adoption with a potential to reduce methane emissions by nearly 1.8 million tons per year or 41 million ton CO_2 equivalent per year. In addition to carbon emissions, AD technology mitigates the economic impact of foul odor that typically accompanies concentrated animal feed operations (CAFOs) (AgSTAR 2011).[2]

The biggest factors affecting the adoption of AD technology are environmental penalties and incentives, high initial capital costs, and sale price of AD coproducts. Recent economic research indicates that anaerobic digesters may be economically viable in the US, but only with some combination of codigestion, fiber separation, capital cost subsidies, and/or environmental credits (Bishop and Shumway 2009; ECOregon 2010; Key and Sneeringer 2011, Camarillo *et al.* 2012; Klavon *et al.* 2013; Manning and Hadrich 2015). AD also tends to favor larger operations

[2] Glover (1996) refers to a lawsuit brought against a CAFO in which it was determined that the CAFO was a source of unbearable odor and required payment to the plaintiffs of $500/day for each "smelly" day and $100/day for all other days. Palmquist, Roka and Vukina (1997) estimate that rural residences near swine operations lost 9 percent of their value.

(Leuer, Hyde and Richard 2008). Due to their potential to generate jobs in rural areas and reduce environmental harm, many of the ADs built in the US have been funded in part by government grants through programs like the Rural Energy for America Program, the Conservation Innovation Grants program, and the Environmental Quality Improvement Program. Grants have a large impact on the economic feasibility of AD projects, and most projects undertaken in the US have used grants to defray part of the initial capital expense (Cowley 2013).

Codigestion

Food waste from restaurants or food processing plants is the most common organic waste codigested with on-farm animal waste. Food waste generally contains much higher amounts of volatile solids than animal waste and leads to disproportionately larger amounts of methane generated (Lisboa and Lansing 2013). Higher methane output directly impacts the amount of electricity or natural gas generated by the AD.

In order to divert recyclable materials, some states (e.g., Connecticut, Vermont, Massachusetts, California, and Rhode Island) and cities (e.g., New York City and Seattle) have placed bans or mandates on disposing commercial food waste in landfills (Henricks 2014; US Composting Council, 2014; Executive Office of Energy and Environmental Affairs of the Commonwealth of Massachusetts 2015). Bans and mandates would greatly increase the demand for food waste disposal through ADs. Typically, the organic waste producer pays a tipping fee to whomever accepts the waste. These fees can generate a large portion of income for the AD owner, especially in cases where a source of organic waste is nearby so transportation costs are low. Methane capture from organic wastes qualify for many of the same environmental credits as methane capture from animal wastes, although at a lesser rate.

Compressed Natural Gas

Compressed natural gas production requires scrubbing the biogas of water and other contaminants before compressing it for delivery or use. Storage of compressed gasses is costly, so most AD owners who produce CNG establish a connection to a national CNG pipeline where all of their production is immediately accepted and metered. Connection fees to a natural gas pipeline can be quite costly. Pipeline connection fees are primarily determined by the distance to existing pipeline infrastructure and thus can vary widely from site to site (Murray, Galik and Vegh 2014). When comparing the investment value of CNG to CHP, not only are the prices of natural gas and electricity important, but the value of environmental credits that derive from each product are as well.

Combined Heat and Power

By far the most common use of methane from AD in the US, CHP is composed of a combustion engine and electric generator (typically called a genset) and a heat exchanger to capture excess heat from the engine. Unless the dairy needs all the electricity provided by the CHP, interconnection fees are required to sell electricity on the municipal grid. Interconnection fees vary widely depending on local conditions. As with CNG, the value of environmental credits are important renewable energy production is important to the economic viability of AD.

Environmental Markets

A number of governments have introduced policies to reduce carbon emissions. Policies include carbon taxes in Norway, Sweden, Denmark, and Finland introduced in the 1990's, the European Union Emission Trading Scheme enacted in 2005, the tradable carbon performance standard enacted in Alberta Canada in 2007, the revenue-neutral carbon tax in British Columbia Canada and the emissions trading scheme in New Zealand enacted in 2008, the Regional Greenhouse Gas Initiative's (RGGI) downstream cap-and-trade (emissions trading) program for electric power generators in the northeast United States initiated in 2009 (Aldy and Stavins 2012), and the most recognized environmental market currently operating in the US – the California mandatory GHG emissions reporting and cap-and-trade program which began in 2013 and allows trading in both carbon allowances and carbon offsets. Carbon offset prices in the California market averaged $12.75 per metric ton CO_2 equivalent in 2014 and the first half of 2015 (California Carbon Dashboard 2015).

Influenced by the success of the British Columbia carbon tax, the group Carbon Washington (2015) has introduced a 2016 voter initiative on the Washington State ballot to impose a revenue-neutral $25 per metric ton of CO_2 tax on fossil fuels in the state. If approved, carbon tax receipts will be offset by reductions in state sales and business tax rates. The enacted policies have been credited with inducing substantial reduction in GHG emissions (e.g., Elgie and McClay 2013; RGGI 2014). It is likely that environmental markets will become more prominent as concern about climate change increases.

Environmental incentives have contributed substantially to the adoption of AD technology in Europe. Germany introduced a feed-in tariff in 1991 which induced utilities to purchase renewable energy at a subsidized price. The tariff is widely credited as being the primary cause behind Germany's widespread adoption of ADs (Wilkinson 2011) from 140 in 1992 to 7,720 at the end of 2013 (Lebuhn, Munk, and Effenberger 2014). However, there is some evidence that the incentive structures implemented by the German government to encourage AD adoption have led to market distortions.[3]

[3] In 2013 the German Agency for Renewable Resources (FNR) reported that nearly 10 percent of German agricultural land was used to grow crops destined for biogas generation (Lebuhn, Munk, and Effenberger 2014). Osterburg and Röder (2013) found that conversion of grassland to biogas fuel crops has occurred in environmentally sensitive areas, and Britz and Delzeit (2013) concluded that German government incentives for biogas production are capable of impacting global agricultural markets, prices, quantities and land use.

The effect of developing carbon markets on US AD adoption could be large (Gloy 2011). In addition to the potential for generating income through established environmental markets, some AD owners in the US receive income through governmentally-sponsored renewable energy credits (REC), renewable identification number credits (RIN), low carbon fuel standard credits (LCFS), and tax credits.

For renewable electricity generation in the US, AD owners can receive carbon credits, RECs, and tax credits. Utility companies offer RECs under state government mandate to generate a certain proportion of renewable energy. In some states where mandates are strict, RECs can be highly priced (Informa Economics 2013). Also, some state governments offer tax credits to producers of renewable electricity.

For renewable natural gas generation in the US, RINs and LCFSs are available to AD owners. RINs are available nationally as a credit managed by the EPA. For AD owners whose biogas is used as transportation fuel in California, LCFS can be used in combination with RINs. The first half of 2013 saw an average LCFS price of $45/credit (or $4.01/MMBTU) Argus Media 2014).

Fiber Separation

Fiber separation mechanisms are commonly used with ADs. Fiber separation can be implemented on farms without ADs (Van Horn *et al.* 1994), but the fiber is commonly composted before it is used as bedding.[4] A 1997 survey (Meyer, Garnett and Guthrie) of 1840 California dairies indicated that 14 percent used mechanical solid separators and 39 percent used settling ponds to separate fiber from liquid waste.

[4] Digested fiber has far fewer pathogens than undigested fiber. However, there is some evidence that pathogen content of the bedding material may not be as important in the prevention of infections like mastitis as simply keeping animal stalls free of fresh manure and urine (Schwarz, Bonhotal and Staehr 2010).

Using separated fiber as bedding material contributes significant cost savings to dairies, but there is potential for even more gain if markets continue to develop for using digested fiber as peat moss replacement. A line of AD fiber product has recently been introduced as peat moss replacement in stores like Wal-Mart (The Prasino Group and Innovation Center for US Dairy 2014).

Nutrient Separation

It is important to note that while previous literature (Bishop and Shumway 2009) indicates that accepting off-farm organic waste in a codigestion scenario greatly increases the economic value of the AD system, there is also evidence that acceptance of certain forms of off-farm organic waste could increase nitrogen and phosphorous content to the farm (Atandi & Rahman 2012) and exacerbate nutrient over-application concerns. Thus, if nutrients could be transformed into transportable fertilizer products, dairies would be able to move nutrients off-farm and mitigate nutrient over-application.

Coppedge *et al.* (2012) assess three nutrient separation technologies and conclude that (a) P solids separation is cost effective to reduce excess P application but fails to affect N levels, (b) struvite crystallization incurs high operating costs for nutrient removal and is economically non-viable, and (c) combined P solids separation and ammonium sulfate removal is high cost but also effective in removing both P and N. Thus, we consider P separation and ammonium sulfate removal in the nutrient separation component.

Water Recovery

Membrane-based water recovery systems can remove an even larger amount of P and N from the wastewater along with potassium and other dissolved salts.[5] Water recovery requires effluent to be pretreated using P solids separation. Pretreating with ammonium sulfate removal would be redundant to the capabilities of the water recovery system (Chiumenti *et al.* 2013). Output from a water recovery system would provide the remaining nutrients in a concentrate and clean water in a permeate. Depending on the method and extent of filtration, water could be used to flush stalls or even be used as drinking water for livestock.

Water recovery systems are capital intensive and incur large operating costs because of chemical use. However, the potential benefits in terms of nutrient management are large. They include prevention of nutrient over-application, nutrient run-off, and salt buildup in soils. They can also offset water costs and provide revenue from organically certifiable nutrient sales.

Method of Analysis

This paper estimates the NPV for a variety of waste management technology combinations for different sized dairies. We examine dairies with 1,600, 4,500, and 15,000 head to provide insight into scale economies. Our data provides capital and operating costs for dairies close to these three sizes and allows us to account for scale economies in all technologies except for water recovery. In 2012, there were 1,231 dairies in the US with herd sizes of 1,000 to 2,499 and 576 dairies with herd sizes of 2,500 or more (National Agricultural Statistics Service 2012).

We use a four percent real discount rate calculated using Moody's Baa corporate bond yield over all maturities (Federal Reserve Economics Data 2014) less the rate of inflation given

[5] Current research focuses on trapping small, suspended, and dissolved particles behind a semi-permeable membrane as the fluid is pushed through, most commonly via a pressure gradient (Ma *et al.* 2013). The three most common membrane systems being researched are microfiltration, ultrafiltration, and reverse osmosis (ibid.)

by the CPI (Shiller) over the period 1919-2011. Net present values, internal rate of return (IRR), and modified internal rate of return (MIRR) are estimated using a capital lifetime of 20 years. For the calculation of MIRR we use a 7 percent capital reinvestment discount rate (Coppedge *et al.* 2012). Calculations are straightforward in many scenarios, but methane and nutrient functions have impacts on cost and revenue values when certain technology components are used concurrently. All calculations are carried out in the Anaerobic Digester System Enterprise Budget Calculator that we developed in tandem with this research paper.[6]

Methane and Nutrient Functions

The model uses functions developed by AD engineers to model methane and nutrient generation and utilization among the technology components. The methane function accounts for the conversion of volatile solids into usable methane and depends on the combination of animal waste and off-farm organic waste fed into the digester. Usable methane is then converted into biogas and then into either CNG or electricity. Methane production is a function of volatile solids (VS) and methane conversion ability of those solids, shown in the following equation using typical VS content for dairy scrape manure[7] (ASAE 2005), specific methane activity (SMA) conversion of fresh dairy manure (Ma *et al*. 2013), and co-digestion substrate VS and SMA (Camarillo *et al*. 2013):

$$(1) \qquad M = Q_A\mathrm{m}^3 \cdot \ 41.3\frac{\mathrm{kgVS}}{\mathrm{m}^3} \cdot 0.23\frac{\mathrm{m}^3\mathrm{CH}_4}{\mathrm{kg\,VS}} + \ Q_O\mathrm{m}^3 \cdot \ 163.4\frac{\mathrm{kgVS}}{\mathrm{m}^3} \cdot 0.37\frac{\mathrm{m}^3\mathrm{CH}_4}{\mathrm{kg\,VS}}.$$

[6] The Anaerobic Digester System Enterprise Budget Calculator can be downloaded from http://csanr.wsu.edu/anaerobic-digestion-systems/enterprise-budget-calculator/.

[7] Scrape manure is heavily diluted before use in the digester. We use 63 percent dilution of raw manure to simulate the VS concentration of scrape manure influent.

where M is total methane output, Q_A is volume of animal waste input to the digester, Q_O is the volume of off-farm organic waste input to the digester. If the firm is codigesting, we expect food waste, with a density of one m^3 per metric ton (Scott and Ma 2004), to make up 16 percent of total influent volume, which is regarded as an upper limit (Braun, Brachtl, and Grasmug 2003).[8]

We account for the flow of nutrients through the dairy when considering alternative scenarios by summing nutrient stream inputs and subtracting nutrient stream outputs to calculate the amount applied to fields as fertilizer:

$$(2) \qquad \sum_Y Q_{X,Y} - \sum_Z I_Z Q_{X,Z} = Q_{X,FA} \; \forall \, X \in \{N, P, S, E\}, Y \in \{C, O, W\}, Z \in \{AD, FS, PS, AS, WR\},$$

where X is the vector of nutrient stream components in which N denotes nitrogen, P phosphorus, E liquid effluent, and S suspended solids; Y is the vector of input sources, in which C refers to waste from cows, O off-farm organic waste, and W parlor water to dilute effluent; Z is the vector of technologies that remove nutrients from the stream, in which AD denotes anaerobic digester, FS fiber separation, PS phosphorous solids separation, AS ammonium sulfate removal, and WR water recovery; $Q_{X,Y}$ is the quantity (in tons) of nutrient component X contributed by source Y, $Q_{X,Z}$ the quantity (in tons) of nutrient component X removed by technology Z, and $Q_{X,FA}$ is the quantity (in tons) of nutrient component applied to fields as fertilizer; I_Z denotes indicator functions which are one if the technology is present and zero otherwise. The engineering parameters used to calculate quantities $Q_{X,Y}$ and $Q_{X,Z}$ are from Ma and Frear (2015) and Camarillo *et al.* (2013).

[8] Food processing and industrial greases that supplement animal wastes can greatly increase methane generation (Braun, Brachtl, and Grasmug 2003). However, at too high levels, food waste can lead to conditions that kill off anaerobic bacteria populations (Neves, Oliveira, and Alves 2008; Demirel and Scherer 2008).

Data

Due to the emergent nature of some of the technologies, survey data of established operations is unavailable or very limited. AD, off-farm organic waste intake, CNG, CHP, environmental REC and tax credits, fiber separation, nutrient separation, and water recovery data were gathered from previous research and from industry partners. They pertain to Washington State. Environmental carbon credits and RINs apply at the national level, while LCFS credits pertain to California and nearby states. All monetary values were adjusted to 2013 values using the Chemical Engineering Price of Construction Indices (CEPCI) for capital infrastructure and CPI for operating costs and output prices. We examine 1,600, 4,500 and 15,000 wet cow equivalent (WCE) sized AD systems. When data does not conform directly to those sizes, we use linear approximations between the two nearest data points.

Anaerobic Digester and Codigestion

We calculate the volume of digester influent using 0.13 m^3 animal waste per WCE per day (Frear 2015), and anticipate that 90 percent of the waste enters the digester. Equation (1) estimates an 86 percent increase in biogas produced from codigestion.

Juergens and Powell (2014) report capital costs for three digester sizes subdivided into freight, excavation, vessel, insulation, roof, piping, equipment, permitting & engineering, and system start-up. Total cost is $1.878 million for a 1,600 WCE dairy, $1.984 million for a 2,500 WCE dairy, and $9.648 million for a 15,000 WCE dairy. We estimate the cost for each subcomponent for a 4,500 WCE dairy by fitting linear segments between observed points. When codigestion is present, capital costs increase by the same percentage as the percentage of total volume comprised by off-farm organic waste. We consider a scrape dairy. A flush dairy would require a pre-digestion collection pit for thickening the effluent. When the firm accepts off-farm organics, a pre-digestion pit for mixing is required. The cost of a pre-digestion pit for a medium sized digester is reported by Juergens and Powell (2014).

Annual operating costs consist of operation and maintenance which is reported to be $10 per m^3 effluent for all sizes (Frear 2015). If the dairy accepts off-farm organics, they generate tipping fee revenue of $25.00 per ton (Frear 2015), and we convert the volume of off-farm organic waste used in equation (2) to tons assuming a density of 1.102 ton per m^3 (Frear 2015).

Compressed Natural Gas

A dairy with a digester will always have either CNG or CHP; otherwise the dairy would be getting no value for the methane generated. Coppedge *et al.* (2012) report capital costs for CNG generation for a 5,000 WCE dairy in Washington State, which we convert to an average capital cost per m^3 scrubbed natural gas produced per year. They report the average cost of gas cleaning equipment is $0.34 per m^3 CH_4 expected annual flow, construction and installation is $0.10 per m^3 CH_4 expected annual flow, and spare parts is $0.02 per m^3 CH_4 expected annual flow.

We use their reported cost of $1 million for the natural gas pipeline injection point for all herd sizes because it is a fixed fee. Transportation to the pipeline injection point occurs via tube trailer, for which Coppedge *et al.* report a capital cost per m^3 CH_4 expected annual flow of $0.01 for construction and installation, $0.15 for tube trailers, and $0.07 for on-site compression. They report a cost of $10,000 for a tractor to pull the trailers. Also included in total capital costs are several add-ons specified as a percent of construction cost – 5 percent design allowance, 7.9 percent sales tax, 10 percent contingency, 4 percent project management.

Annual operating costs (Coppedge *et al.* 2012) include water at a price of $0.01 per gallon used at a rate of 0.42 gallons per thousand m^3 CH_4 and pipeline injection at a price of $0.41 per million BTU (MMBTU). Tube trailer cost is $1 per mile at 26 miles per day, and trailer repair and maintenance is an additional 50 percent. Equipment maintenance and repair cost per year is 0.51 percent of equipment capital cost. Lubrication oil costs $500 per million m^3 CH_4 and remote monitoring costs $3,795 per million m^3 CH_4. Labor costs $36,423 per full-time equivalent (FTE) at a rate of 0.23 FTE of labor per million m^3 CH_4, and electricity costs $0.06 per kWh at a rate of 0.35 kWh per m^3 CH_4.

Coppedge *et al.* (2012) report that when only animal waste is digested, 52 percent of the volume of biogas remains after scrubbing it to pipeline standard purity, while if the AD codigests off-farm organics 58 percent of the volume of biogas remains after scrubbing. This biogas is sold at the reported low wholesale price of $3.87 per MMBTU.

Combined Heat and Power

Juergens and Powell (2014) report capital costs for a 1,500 kWh and for a 4,500 kWh capacity generator from which we linearly approximate an average cost per kWh of capacity for sizes between the two data points. We maintain the same cost per kWh of capacity as the nearest data point for sizes that are below or above those points.

Juergens and Powell (2014) report annual operating cost for CHP for 1,600, 4,500, and 15,000 WCE with 20 percent of energy generated by codigestion to be $135,000, $375,000, and $1,100,000 respectively. We use 80 percent of reported annual operating costs for CHP scenarios without codigestion.

On average each cubic meter of digester CH_4 produces 3.51 kWh of electricity. To handle variations in output, the generator is sized such that maximum electricity output is 80 percent of total capacity. Revenues are based on the generator transforming methane output into electricity 92 percent of the year and experiencing an 8 percent loss due to parasitic load. Electricity price is $0.07 per kWh, the median wholesale price from Cowley's (2013) survey of AD owners.

Environmental Credits

Compressed natural gas is eligible for nationally traded RIN credits and also for LCFS credits for fuel sold for transportation use in California. These environmental credits incur no capital costs, but RINs have transaction costs of 10 percent of revenues (Coppedge *et al.* 2012). RIN credits are established under the EPA's Renewable Fuel Standard based on the fuel source material and the amount of greenhouse gas emissions reductions the fuel generates. In his estimation of the value of RIN credits for a 5,000 WCE AD with codigestion, Weisberg (2012) reported that 100 percent of gas generated from animal waste is eligible for RINs and 80 percent of gas generated from organic waste is eligible. Each m^3 CH_4 of eligible gas generates 0.48 RIN (Coppedge *et al.* 2012). In July 2014 the EPA began classifying biogas from AD as "cellulosic biofuel" as opposed to its previous classification of "advanced biofuel" (Weisberg 2014), which led to a large price increase to $1.09 per RIN (Weisberg 2015) compared to the May 2012 to June 2013 average price of $0.56 per RIN (Weisberg 2013). We use the current advanced biofuel price of $0.47 per RIN for RINs generated by organic waste.

We use the same transaction costs for LCFS credits as for RINS – 10 percent of revenue. Off-farm organic wastes fed into an AD generate different amounts of LCFS credits depending on their alternative disposal destination and their greenhouse gas potential (California Air Resource Board 2014). We assume an 80 percent eligibility, acknowledging that any project would need to establish its own qualifications based on the characteristics of the organic wastes it codigests. Each MMBTU of eligible CH_4 generates 0.0892 LCFS credits (Weisberg 2013) at a price of $72 per metric tCO_2e (California Air Resources Board 2015a) or $6.44 per MMBTU (Weisberg 2013). In September 2015, the California Air Resources Board (2015b) announced their intention to include manure methane destruction in their calculation of carbon intensity for LCFS credits which would increase prices by an additional $0.14 per MMBTU for CNG from dairy ADs. We use a price of $6.58 per MMBTU.

Electricity generated from CHP is eligible for carbon credits, tax credits, and REC credits, each of which has no capital cost. Weisberg (2012) reports that an average dairy with a digester would generate about 3 carbon credits per WCE and about 0.5 carbon credits per metric ton of off-farm organic waste. Operating costs include an annual verification fee of $10,500 and a credit issuance fee of $0.23 per credit (Weisberg 2013). Weisberg (2015) reports prices of $9 per carbon credit from energy derived from animal waste and sold on the California market and $4 per credit for renewable energy derived from off-farm organic waste and sold on alternative markets.

Depending on state and local governments, ADs that produce electricity may be eligible for tax credits. We use the rate for New York State of $0.025 per kWh (New York State Energy Research and Development Authority 2015) which is close to the $0.02 per kWh Bishop and Shumway (2009) report for Washington State. Electricity generated may also be eligible for REC credits from the regional power company. Transaction costs are 1 percent of revenues. We use a price of $0.01 per kWh (Coppedge *et al.* 2012) for both animal and off-farm organic waste.

Fiber Separation

Fiber separation capital include a liquid solid separator and, if no AD is used, a composter. Terre-Source (2003) reports the cost of a liquid solid separator and a composter as one line item for a 6,000 WCE dairy from which we compute a combined average capital cost of $120 per WCE. Ma *et al.* (2013) reports the average cost for the liquid solid separator to be $40 per WCE from which we infer the average price of the composter after adjusting for inflation.

Terre-Source reports annual operating cost per ton of fiber as $5 for the liquid solid separator and $10 for the composter. If fiber separation is used without AD, Jensen *et al.* (2015) report that 50 percent of fiber is typically used as replacement bedding at an avoided price of $96 per ton and the remaining 50 percent can be sold for $44 per ton as composted fiber. If fiber separation is used with AD, 100 percent of fiber can be sold for $143 per ton as a peat moss replacement.

Nutrient Separation

In the nutrient separation component, we anticipate that firms will use both P solids separation and ammonium sulfate removal and that P solids are separated before ammonium sulfate is removed. Thus, tons of waste effluent from fiber separation equals tons of waste influent to P solids separation, and tons of waste effluent from P solids separation equals tons of waste influent to ammonium sulfate removal. P solids are removed via dissolved air filtration (DAF), the average capital cost of which reported by Yorgey *et al.* (2015) is $130-180 per cow or on average $3.32 per ton of waste influent. We estimate DAF building construction cost using building costs of $50 per square foot (Painter and Gray 2012) for a 15 by 15 foot building.

Yorgey *et al.* (2015) report annual operating costs to be $30-35 per WCE per year or on average $0.70 per ton of waste influent per year. Promus Energy (2014) reports a sale price of $90 per ton of P solids.

Promus Energy (2014) reports that ammonium sulfate removal capital costs are $5.91 per ton of waste influent capacity.[9] They do not report costs for a crystallizer, drier, and/or pelletizer, meaning that costs may be higher if certain product characteristics are required by the market.

Annual operating costs include labor, electricity, acid, and materials. Promus Energy (2014) reports 3 FTE labor used per million tons of waste influent per year and 8.58 kWh electricity used per ton waste influent. Reported acid used is 6 pounds per ton waste influent. Prices of labor and electricity are the same as those for P separation. Acid price per pound is reported to be $0.10, and price of materials per ton waste influent per year is $0.08.

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[9] In the budget calculator we break out capital costs into subcomponents (heat exchangers, aeration system, acid contact tower, acid storage, etc.) according to the proportions reported by Coppedge *et al.* (2012).

Ma and Frear (2015) estimate that the quantity of ammonium sulfate removed is 28 percent of N by weight. Promus Energy (2014) reports the sale price of ammonium sulfate to be $100 per ton of ammonium sulfate solution.

Water Recovery

Water recovery uses both ultrafiltration (UF) and reverse osmosis (RO) technologies. Firms are expected to omit ammonium sulfate removal when using water recovery due to redundancy between the two technologies. Thus, total influent to water recovery equals total effluent from P solids separation. Ma *et. al* (2013) estimate average capital costs to be $1,500 to $1,800 per WCE for combined fiber separation, P solids separation, and water recovery. We subtract the average capital cost for fiber and P solids separation from the average combined cost and obtain $34 average capital cost per ton of water recovery influent capacity. The capital cost for a water recovery building is expected to be the same as for a nutrient separation building.

Annual operating costs are comprised of electricity, chemicals, labor, and maintenance. Electricity requirements are reported by Chiumenti *et al.* (2013) to be 15.75 kWh per m^3 of influent. Price of electricity is the same as for other technologies. Halpern (2013) reports that 14 gallons of acid are required per m^3 influent at a price of $0.96 per gallon. Labor requirements and price are expected to be the same as for ammonium sulfate removal. Maintenance is charged at three percent of capital cost following Coppedge *et al.* (2012) for ammonium sulfate removal.

Influent is pushed through membrane filters, of which 68 percent becomes clean water priced at $0.01 per gallon (Coppedge *et al.* 2012). The remaining liquid is a concentrate and is worth approximately one quarter the price of ammonium sulfate in concentrate form, $25 per ton (Promus Energy 2014).

Hauling Costs

We consider the cost of manure transportation and application for AD, codigestion, fiber separation, nutrient separation, and water recovery. All technologies except codigestion reduce hauling costs, and codigestion increases it. Camberato and Nielsen (2015) report the agronomic application rate for N on corn to be 183 – 233 lbs N per acre and depends on soil type. We use an average rate of 200 lbs N per acre with manure effluent incorporated via injection within three days following best practices (Madison *et al.* 1995). The amount of waste effluent applied per acre depends on the concentration of N and varies by technology component in the system.

AD increases N concentration by reducing volatile solids in the effluent; codigestion of organics decreases N concentration by adding water; fiber separation, P solids separation, ammonium sulfate removal, and water recovery decrease N concentration by removing N. If the farm has no AD system technologies, dairies would require about one acre per WCE for 200 lbs N application. We conduct our analysis for a dairy that has half that amount of land in near fields and the other half in far fields or neighbors' fields. The dairy applies manure effluent at the agronomic rate to their near fields first, and, if any remains, it applies effluent at the agronomic rate to their far fields and neighbors fields, summing up to $Q_{E,FA}$ from equation (2).

Harrigan (2011) reports hauling distances for Michigan dairies with 175, 350, 700, and 1,400 WCE average 1, 1.5, 2, and 2.5 miles, respectively, and maximum hauling distances reach 2, 3, 3, and 4 miles, respectively. We predict hauling distances for 1,500, 4,500, and 15,000 WCE size dairies using linear regression of distance on log size to average 2.5, 3.3, and 4.2 miles, respectively, with maxima of 4.1, 5.1, and 6.3 miles, respectively. We use the average hauling distance for the dairy's near fields and maximum distance for the dairy's far fields and neighbors' fields.[10] For all fields, application via liquid injection is expected to cost $13.50 per 1,000 gallons (Plastina, Johanns, and Weets 2015).

Results

We examine a wide range of integrated technology combinations and account for the interactive effects between technologies. Capital cost of each technological component is given in Table 1. The AD costs nearly $1.9 million for a 1,600 WCE dairy and $9.6 million for a 15,000 WCE dairy. At the 1,600 WCE and 15,000 WCE sizes respectively, fiber separation is the least expensive component at 3-6 percent the cost of AD, while nutrient separation costs 37-66 percent as much as the AD, and water recovery costs 121-219 percent as much as the AD. Compressed natural gas is more expensive than CHP – the former costs 53-91 percent as much as the AD while the latter costs 48-59 percent as much. Codigesting 16 percent of AD volume using off-farm organic waste increases costs by 14-19 percent for AD, nutrient separation, and water recovery. It does not add any capital cost for fiber separation, and it adds 26-82 percent to the capital cost for CNG and CHP. Off-farm organics generally have no fiber content, and thus fiber separation faces no additional material to process. Costs for both CNG and CHP are based on the amount of methane produced, and off-farm organic waste generates 86 percent more methane than animal waste which greatly expands the capacity requirements for these components.

Annual average revenue by component and herd size is reported in Table 2 along with the additional revenue from codigestion. Revenues increase almost linearly for each component across sizes. Without codigestion, water recovery provides the largest revenue and is followed by

[10] Based on 2010 ARMS data in which 70 percent of dairies that removed manure from the farm gave it to neighbors at no charge (Astill 2016), we treat manure applied to neighbors' fields as having zero marginal value and the same transportation and application costs as when applied to the dairy's far fields.

CNG environmental credits. Fiber separation, nutrient separation, CHP, and CHP environmental credits produce similar revenues. The National Agricultural Statistics Service (2012) reports that average annual milk sale revenue in 2012 for US dairies with 1,000 to 2,499 cows was $6.3 million and that for dairies with more than 2,500 cows was $18.1 million. Thus, revenues from integrated AD technologies could comprise a significant portion of the operation's revenues.

Avoided hauling and application costs comprise around 30 percent of water recovery revenue with small variations between sizes. Twelve percent of fiber separation revenue and four percent of nutrient separation revenue are from avoided hauling and application costs of manure with small variations between sizes. About three percent of AD revenue is made up of avoided cost, but codigestion leads to a hauling and application cost increase of five percent of AD revenue. The large additional revenue from codigestion in the AD row is comprised mainly of tipping fees. Environmental credits make a large contribution to both CNG and CHP—718 percent beyond CNG revenues and 72 percent beyond CHP revenue without codigestion.

Annual average operating costs by component and herd size are presented in Table 3 along with additional revenue from codigestion. Water recovery is by far the most costly technology to operate.

Annual average net revenues are presented in Table 4. The largest contributors to net revenue are CNG environmental credits, fiber separation, and CHP environmental credits. Except for water recovery, the other options generate positive net revenues. Water recovery generates large negative net revenues for all herd sizes. Net revenues for nutrient separation and water recovery are reduced at all sizes when codigestion is used because the off-farm organic waste is high in volatile solids and added water but relatively low in N and P. This causes large increases in volume of effluent processed but relatively small increases in product sold. Codigestion provides large gains in AD net revenues due to tipping fees. Codigestion also leads to large gains in net revenues for CNG, CNG environmental credits, CHP, and CHP environmental credits due to increased methane output.

Not every component is required for an operational waste management system, some must be used in combination, and others are mutually exclusive. For example, nutrient separation cannot be implemented without fiber separation, and water recovery cannot be implemented without P solids separation. A dairy can choose between CNG and CHP and each carries unique environmental credits. Due to the nutrient and methane production functions, costs and revenues are subject to the component combination. To examine these scope effects, we calculate NPV of various component combinations for the three herd sizes. Results are presented in Table 5.

All positive NPVs increase across herd size, and most negative NPVs get worse with larger size. Fiber separation generates positive NPVs, nutrient separation with fiber separation generates positive but slightly smaller NPVs, and water recovery in conjunction with the other two technologies generates negative NPVs. When used in combination with AD and CNG or CHP, the NPV of each of the combined technologies is greater than the sum of the NPVs from the subtechnologies, thus providing clear evidence of economies of scope in technology implementation.

For example, consider the difference in NPV for the combined technology of fiber separation, AD, CNG, and CNG environmental credits with the same technology without fiber separation (i.e., the AD, CNG, and CNG environmental credits combined technology). For a 1,600 WCE size dairy, the incremental NPV from adding fiber separation is $2.4 million, but the NPV from the stand-alone fiber separation technology is only $1 million. Thus, as a component of a larger system, the technology adds an additional $1.4 million to total NPV compared to its stand-alone NPV. This scope effect is present for all AD scenarios with fiber separation and for all AD scenarios with fiber separation and nutrient separation. It is not present for AD with fiber separation, nutrient separation, and water recovery. The gains and losses in NPV from adding fiber separation, nutrient separation, or water recovery to an AD system are the same whether methane is converted to CNG or CHP.

Three systems dominate in expected NPV. The AD system that codigests organic waste, converts methane into CNG, receives CNG environmental credits, and has a fiber separator achieves the highest NPV for all herd sizes. It is followed closely by the same system with the addition of nutrient separation and then by the same AD system without fiber or nutrient separation. In all options, receiving organics increases NPV, and converting methane into CNG results in higher NPV than conversion into CHP if environmental credits are received.

Separating nutrients reduced NPV slightly when combined only with fiber separation, reduced NPV by 2-3 percent when combined with AD and codigestion, but increased NPV up to 2 percent for AD without codigestion. However, note that the NPV for AD with codigestion and fiber and nutrient separation exceeds the NPV for AD with fiber separation but without codigestion by $4.8 to $46.8 million for CNG and $5.4 to $52.7 million for CHP at the 1,600 WCE and 15,000 WCE sizes, respectively. If government environmental agencies are concerned with the potential for nutrient over-application on a dairy from codigestion, requiring nutrient separation technology for ADs with codigestion mitigates those concerns while providing larger NPV than the most profitable scenario with no codigestion.

Unlike nutrient recovery, inducing adoption of water recovery technology on dairies would require extremely large subsidies. Water recovery reduces NPV much more and in 2/5 of scenarios results in negative NPV. Stand-alone ADs that convert methane into CNG or CHP but receive no environmental credits also have negative NPVs. Only one other scenario has negative NPV, and only for the smallest of the three herd sizes. The NPVs reveal the presence of multioutput economies of scale in all AD technology systems; those with positive NPVs not only generate higher NPVs on larger dairies but higher NPVs per WCE.

We report IRR for each technology system in Table 6. The trends for IRR are identical to NPV. Scenarios with largest NPV have IRRs that far exceed a capital reinvestment discount rate of seven percent. Of scenarios with positive NPV, only one has an IRR that is below seven percent. We also computed MIRR for each technology system using a capital reinvestment discount rate of 7 percent. MIRR accounts for reinvestment of returns and dampens rates compared to the IRR. Trends remain the same with the highest rate of return calculated to be 10 to 14 percent compared to 23 to 47 percent for IRR. MIRR results are available upon request.

Construction grants have been frequently used to induce construction of AD systems. We examine the percent construction grants that would be needed to produce the same NPV as the most profitable AD system if regulations required nutrient separation or water recovery to be part of the system. Grants covering only 5-7 percent of total capital costs would be sufficient if nutrient separation were required, but much larger grants (83-117 percent) would be needed to generate the same NPV if both nutrient separation and water recovery were required.

The specific results of this paper apply most directly to Washington State, but they are also relevant to other states. The broader policy implications for stimulating adoption of nutrient recovery to mitigate the effects of codigestion are applicable nationally. However, the exact percent of capital costs required to induce firms to adopt an AD system with nutrient recovery would depend on local circumstances. It is also important to recall that environmental credits have a short history and provide limited data which we use to establish a baseline. The rapid transformation of environmental markets makes forecasted future markets highly uncertain.

We examine the effects of altering the prices of environmental credits in a brief sensitivity analysis. If the AD project is unable to qualify for LCFS credits (in the case that

California is geographically remote), NPV decreases by $0.2 million for the no-codigestion cases and $0.4 million for codigestion cases for 1,600 WCE dairies and by $2.2 million for no-codigestion cases and $3.8 million for codigestion cases for 15,000 WCE dairies. Depending on the scenario, these decreases would range from 3 to 34 percent of NPV. Additionally, if RIN price decreases by 50 percent, NPV for CNG scenarios decreases by $3.1 million for no-codigestion cases and $4.1 million for codigestion cases for 1,600 WCE dairies and by $29.1 million for no-codigestion cases and $38.7 million for codigestion cases for 15,000 WCE dairies. Depending on the scenario, these decreases would range from 33 to 437 percent of NPV. If carbon, REC, and tax credit prices all decrease by 50 percent, NPV for CHP scenarios decreases by $1.1 million for the no-codigestion cases and $1.6 million for codigestion cases for 1,600 WCE dairies and by $10.1 million for no-codigestion and $15.3 million for codigestion cases for 15,000 WCE dairies. Depending on the scenario, these decreases would range from 20 to 619 percent of NPV.

Another point to consider is the body of literature that explores the real options approach to technology investment (Stokes, Rajagopalan, and Stefanou 2008; Anderson and Weersink 2014). Real options establish a value of waiting to invest which decreases as the uncertainty about future returns decreases. The rule that a firm invests in a project with positive NPV is likely to over-predict investment. Scenarios in which NPV is very slightly positive are unlikely to induce dairies to invest because the value of waiting may exceed the small current NPV. Thus, our findings suggest that widespread AD adoption in unlikely to occur without fiber separation, environmental credits, and codigestion, and adoption will occur more rapidly on large dairies. One result of previous real options research (Astill 2016) indicates that as more firms adopt and share information, the uncertainty surrounding future returns decreases which in turn decreases the value of waiting and can spur adoption of otherwise profitable technology.

Conclusions

US dairy trade groups (e.g., the Innovation Center for US Dairy) and US governmental organizations (like the EPA's program AgSTAR) have promoted the widespread adoption of AD as a partial solution to pollution concerns surrounding large dairy operations. Unfortunately, stand-alone ADs have not often proven to be economically viable in the US, and adoption has been slow. At present there are fewer than 250 digesters on confined animal operations in the US. This paper explores the economic viability of alternative technology combinations within an integrated AD system to mitigate multiple forms of pollution.

The most profitable AD scenarios include codigestion of off-farm organic wastes, due primarily to tipping fees for accepting waste but also to increased methane output. However, the additional organic waste contributes to nutrient over-application and necessitates increased land availability for nutrient disposal or alternative management of nutrients. Energy production from extracted methane also contributes substantially to AD system profitability. Compressed natural gas (CNG) is generally a more valuable use of the methane than combined heat and power (CHP) because of current differences in environmental credit values. Environmental credits have the potential to produce large increases in NPV. Fiber separation also increases NPV but not as much as codigestion or energy production (with corresponding environmental credits).

Integrated AD systems that include nutrient separation generally produce positive NPVs when combined with energy creation and fiber separation, but it modestly decreases overall NPV with codigestion. Water recovery technology is currently sufficiently expensive to plunge NPV into the negative range for nearly half of the scenarios that include it.

As previous literature documents, farmers have the incentive to over-apply nutrients to near fields due to transportation cost when there is no direct oversight. This is especially important in light of the large value that codigestion brings to an AD project and the additional nutrients that codigestion adds. Although nutrient separation leads to an overall decrease in the NPV of the project, policy makers can encourage adoption of this technology through targeted grants or minor regulations. The NPV of AD codigestion systems with nutrient and fiber separation far exceeds the NPV of AD systems without codigestion and nutrient separation. Thus, requiring nutrient separation technology for ADs that accept off-farm organic waste can mitigate nutrient over-application concerns while enabling an investment that is at least as viable.

As expected, we found evidence of economies of scale in AD systems, even over the range of very large dairies we considered. We also found substantial economies of scope when combining technologies into an integrated AD system. Our findings are important to the US dairy industry and environmental regulators. Our method of economic evaluation of integrated technologies using engineering functions to structurally model complementary effects may also prove useful for examining adoption of other potentially complementary technological processes.

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Figure 1. Effluent flows to AD system components

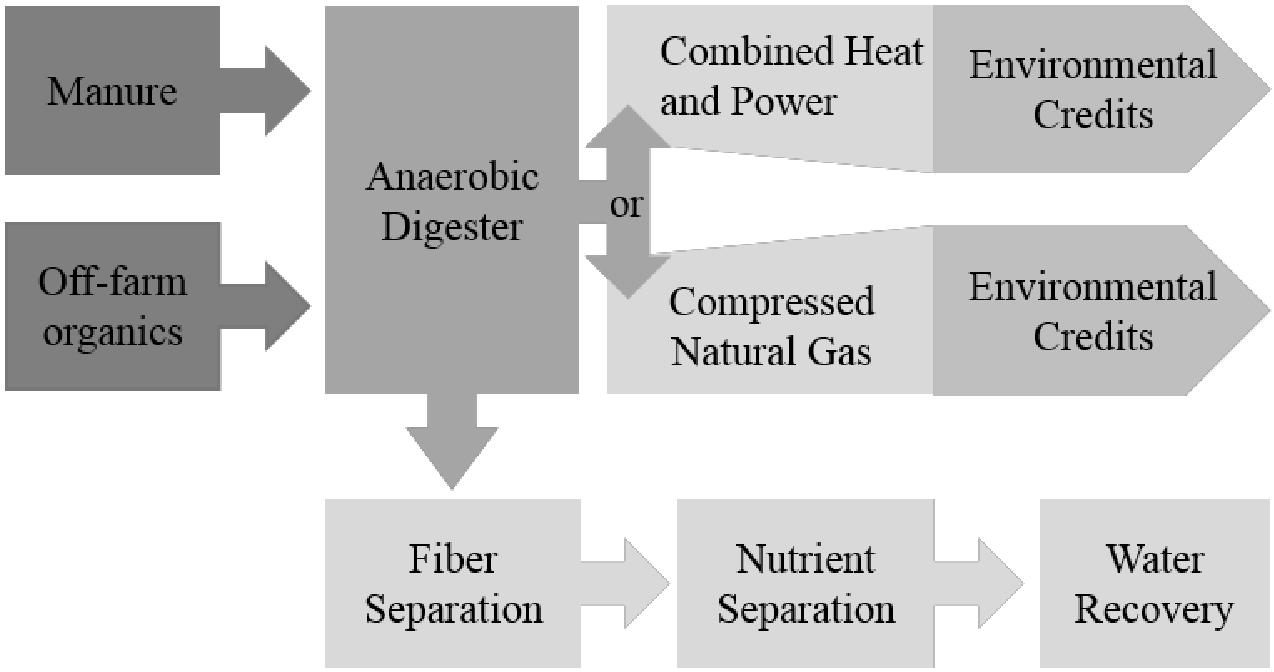

Table 1. Capital cost by technology component, herd size, and codigestion ($1,000s)

Acronym	Component	Capital cost for herd size (WCE)			Codigestion addition for herd size (WCE)		
		1,600	4,500	15,000	1,600	4,500	15,000
FS	Fiber separation	$63	$176	$588	$0	$0	$0
NS	Nutrient separation	$691	$1,911	$6,333	$107	$301	$1,005
WR	Water recovery	$2,265	$6,336	$21,086	$322	$907	$3,023
AD	Anaerobic digester	$1,879	$3,210	$9,648	$355	$587	$1,646
CNG	Compressed natural gas	$1,718	$2,463	$5,160	$443	$1,246	$4,153
CHP	Combined heat & power	$1,103	$1,875	$4,670	$368	$1,034	$3,812

Table 2. Annual revenue by technology component, herd size, and codigestion ($1,000s)

Acronym	Component	Revenue for herd size (WCE)			Codigestion addition for herd size (WCE)		
		1,600	4,500	15,000	1,600	4,500	15,000
FS	Fiber separation	$212	$595	$1,985	$0	$0	$0
NS	Nutrient separation	$211	$595	$1,984	$11	$30	$100
WR	Water recovery	$808	$2,274	$7,587	$69	$194	$648
AD	Anaerobic digester	$6	$18	$59	$251	$706	$2,350
CNG	Compressed natural gas	$68	$191	$638	$73	$206	$688
CNGEC	CNG environmental credits	$488	$1,373	$4,578	$13	$38	$126
CHP	Combined heat & power	$191	$536	$1,788	$165	$463	$1,543
CHPEC	CHP environmental credits	$138	$387	$1,291	$103	$290	$966

Table 3. Annual operating cost by technology component, herd size, and codigestion ($1,000s)

Acronym	Component	Operating cost for herd size (WCE)			Codigestion addition for herd size (WCE)		
		1,600	4,500	15,000	1,600	4,500	15,000
FS	Fiber separation	$5	$14	$47	$0	$0	$0
NS	Nutrient separation	$158	$444	$1,480	$23	$64	$213
WR	Water recovery	$1,027	$2,886	$9,620	$172	$482	$1,608
AD	Anaerobic digester	$41	$116	$386	$8	$22	$74
CNG	Compressed natural gas	$61	$103	$256	$25	$71	$235
CNGEC	CNG environmental credits	$49	$137	$458	$15	$43	$143
CHP	Combined heat & power	$113	$313	$917	$18	$50	$147
CHPEC	CHP environmental credits	$6	$8	$13	$1	$3	$9

Table 4. Annual net revenue by technology component, herd size, and codigestion ($1,000s)

Acronym	Component	Net revenue for herd size (WCE)			Codigestion addition for herd size (WCE)		
		1,600	4,500	15,000	1,600	4,500	15,000
FS	Fiber separation	$207	$581	$1,938	$0	$0	$0
NS	Nutrient separation	$53	$151	$504	-$12	-$34	-$113
WR	Water recovery	-$219	-$612	-$2,034	-$103	-$289	-$960
AD	Anaerobic digester	$6	$18	$59	$251	$706	$2,350
CNG	Compressed natural gas	$7	$88	$382	$48	$136	$453
CNGEC	CNG environmental credits	$440	$1,236	$4,120	$138	$387	$1,291
CHP	Combined heat & power	$78	$224	$1,475	$147	$413	$1,493
CHPEC	CHP environmental credits	$132	$380	$1,278	$102	$287	$957

Table 5. Twenty year NPV by scenario and herd size (WCE, $ millions)

Scenario combination	1,600	4,500	15,000
FS	$1.0	$2.9	$9.8
FS, NS	$1.0	$2.9	$9.7
FS, NS, WR	-$3.6	-$9.9	-$32.8
AD, CNG	-$4.0	-$5.8	-$14.1
AD, CNG, CNGEC	$2.0	$11.0	$41.9
AD, CO, CNG, CNGEC	$7.0	$25.6	$90.8
FS, AD, CNG, CNGEC	$4.4	$17.8	$64.7
FS, AD, CO, CNG, CNGEC	$9.5	$32.4	$113.6
FS, NS, AD, CNG, CNGEC	$4.5	$18.0	$65.3
FS, NS, AD, CO, CNG, CNGEC	$9.2	$31.8	$111.6
FS, NS, WR, AD, CNG, CNGEC	$0.1	$5.9	$25.1
FS, NS, WR, AD, CO, CNG, CNGEC	$3.4	$15.4	$57.2
AD, CHP	-$2.4	-$3.4	-$6.9
AD, CHP, CHPEC	-$0.3	$2.6	$13.2
AD, CO, CHP, CHPEC	$5.4	$19.0	$67.9
FS, AD, CHP, CHPEC	$2.1	$9.4	$36.0
FS, AD, CO, CHP, CHPEC	$7.8	$25.8	$90.7
FS, NS, AD, CHP, CHPEC	$2.2	$9.6	$36.5
FS, NS, AD, CO, CHP, CHPEC	$7.6	$25.2	$88.7
FS, NS, WR, AD, CHP, CHPEC	-$2.2	-$2.5	-$3.6
FS, NS, WR, AD, CO, CHP, CHPEC	$1.7	$8.8	$34.4

Notes: AD: anaerobic digester; CNG: compressed natural gas; CNGEC: CNG environmental credits; CO: codigest organics; CHP: combined heat and power; CHPEC: CHP environmental credits; FS: fiber separation; NS: nutrient separation; and WR: water recovery.

Table 6. Twenty year IRR by scenario and herd size (WCE)

Scenario combination	1,600	4,500	15,000
FS	38%	38%	38%
FS, NS	14%	14%	14%
FS, NS, WR	<-100%	<-100%	<-100%
AD, CNG	<-100%	<-100%	-18%
AD, CNG, CNGEC	10%	21%	28%
AD, CO, CNG, CNGEC	18%	32%	40%
FS, AD, CNG, CNGEC	15%	30%	39%
FS, AD, CO, CNG, CNGEC	23%	39%	47%
FS, NS, AD, CNG, CNGEC	14%	24%	29%
FS, NS, AD, CO, CNG, CNGEC	20%	31%	36%
FS, NS, WR, AD, CNG, CNGEC	4%	9%	10%
FS, NS, WR, AD, CO, CNG, CNGEC	9%	13%	15%
AD, CHP	-10%	-6%	-2%
AD, CHP, CHPEC	3%	9%	13%
AD, CO, CHP, CHPEC	17%	28%	33%
FS, AD, CHP, CHPEC	11%	20%	25%
FS, AD, CO, CHP, CHPEC	22%	35%	40%
FS, NS, AD, CHP, CHPEC	10%	16%	20%
FS, NS, AD, CO, CHP, CHPEC	19%	28%	31%
FS, NS, WR, AD, CHP, CHPEC	-1%	2%	3%
FS, NS, WR, AD, CO, CHP, CHPEC	7%	10%	11%

Notes: AD: anaerobic digester; CNG: compressed natural gas; CNGEC: CNG environmental credits; CO: codigest organics; CHP: combined heat and power; CHPEC: CHP environmental credits; FS: fiber separation; NS: nutrient separation; and WR: water recovery.