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ECONOMIC FEASIBILITY OF ANAEROBIC DIGESTER SYSTEMS WITH NUTRIENT RECOVERY TECHNOLOGIES

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ECONOMIC FEASIBILITY OF ANAEROBIC DIGESTER SYSTEMS WITH NUTRIENT RECOVERY TECHNOLOGIES

By

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Abstract

Anaerobic digesters are used worldwide to produce bioenergy and sustainably treat organic waste from municipal, industrial, and agricultural operations. This publication analyzes the economic feasibility of three nutrient recovery technologies that work in tandem with anaerobic digester systems. The Anaerobic Digestion Systems Series provides research based information to improve decision-making for incorporating, augmenting, and maintaining anaerobic digestion systems for manures and food by-products.

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Economic Feasibility of Anaerobic Digester Systems with Nutrient Recovery Technologies

Preface

This Washington State University (WSU) Extension publication is an abbreviated review of information contained in the Renewable Natural Gas and Nutrient Recovery Feasibility for DeRuyter Dairy (Coppedge et al. 2012). It is part of the Anaerobic Digestion Systems Series, which aims to provide information that improves decision-making for anaerobic digestion systems. Readers interested in further details are encouraged to read the full WSU report. Furthermore, individuals interested in a specific digester installation should seek expert guidance from an Anaerobic Digestion System technology provider. The US EPA-AgSTAR project database contains a list of technology providers across the country.

This publication introduces key concerns regarding nutrient management. It discusses and compares the profitability of three nutrient recovery technologies that work in tandem with anaerobic digester systems. While one of the nutrient technologies was developed in collaboration with WSU, this publication does not intend to promote the WSU-patented technology. Rather, the emphases are on the technology's process of removing nutrients from dairy waste and an examination of its contribution to the profitability of an anaerobic digestion project compared to current alternatives.

Nutrient Management

Nutrient management is one of the most important concerns identified by dairy owners that can potentially have negative economic impacts (Bishop and Shumway 2009). Every year, a dairy cow generates 164 kg total nitrogen, 80 kg total ammonia nitrogen, and 28 kg total phosphorus (ASAE 2005). The microbial breakdown of manure can emit ammonia and other compounds that cause concerns in air quality and respiratory health (Archibeque et al. 2007; Erisman and Schaap 2004; McCubbin et al. 2002), as well as methane, which is a potent greenhouse gas (Shih et al. 2006). Meanwhile, long-term manure application on agricultural lands may result in excess nitrogen and phosphorus accumulation, which has contributed to problems with nitrate leaching, eutrophication, ammonia toxicity, and nitrate-induced blue baby syndrome (EPA 1996).

As a result of these concerns, a number of efforts to develop and commercialize nutrient recovery technologies appropriate for dairies and other livestock operations are underway. This publication focuses on the economic feasibility of nutrient recovery technologies that work in tandem with anaerobic digester systems. These technologies essentially recover phosphorus and nitrogen from used water streams, such as dairy waste, and transform the recovered nutrients into fertilizer. The rationale for nutrient recovery and a description of specific nutrient recovery technologies are covered more fully by Yorgey et al. (2013).

Anaerobic Digestion and Nutrient Recovery Technologies

Anaerobic digestion (AD) creates an anaerobic environment (without oxygen) in which naturally occurring microorganisms convert complex organic materials in manure and other wet organic wastes, such as food processing wastes, to biogas. Biogas can be used in a combined heat and power (CHP) model to generate renewable energy, or it can be further refined to renewable natural gas (RNG) which can be used as a transportation fuel. In addition to biogas, AD creates many co-benefits, including reductions in greenhouse gas emissions, decreased odors, waste stabilization, and lower pathogen counts (EPA 2004; EPA 2005; EPA 2008; Martin and Roos 2007).

Coppedge et al. (2012) examined an anaerobic digester in the Yakima Valley that processes feedstock from 5,000 dairy cows, generating 165,000 gallons of concentrated manure per day. Little to no off-farm materials are fed into the digester. The study looks at different configurations of AD projects. The current baseline is an AD-CHP system and has been operational since 2008. This system produces biogas that fuels a modified diesel engine and generator, which then produces electricity and recovered heat. The electrical power is sold to the grid. The initial capital cost for an AD-CHP system is approximately $4.4 million.

The second AD project is an investment scenario where biogas produced by the anaerobic digester is upgraded to RNG. The AD-RNG system is assumed to start producing renewable fuel two years after development of the infrastructure. The AD-RNG system is evaluated here under the scenario wherein the current AD-CHP is converted to this particular system (i.e., in 2012). The estimated total capital cost is $10.1 million, comprised of the initial investment for the AD-CHP ($4.4 million) plus a $5.7 million investment to convert the existing system and construct the infrastructure needed to produce renewable fuel. The RNG infrastructure includes a gas cleaning unit, digester modification for accepting non-manure inputs such as food processing substrates, transportation of gas off site via pipeline to an injection point, and a fueling station.

More details about the CHP and RNG systems of the AD project are beyond the scope of this publication, but they are discussed fully in the DeRuyter Feasibility Study (Coppedge et al. 2012).

Standalone anaerobic digesters cannot address farm nutrient loading concerns because the digestion process does not remove or reduce nutrients (i.e., nitrogen and phosphorus are not gasified or reduced in liquid concentration during digestion). Thus, the total amount of nutrients is maintained, but it is partially converted from organic to inorganic forms. Nutrient management concerns can even be exacerbated if AD owners choose to co-digest manure with high-nutrient food processing residuals. This strategy, commonly used to improve AD economic performance, leads to the import of additional nutrients to the farm, which can potentially leach into the groundwater and cause pollution runoff (Camarillo et al. 2011).

An important consideration in evaluating the economic feasibility of nutrient recovery technology is that excess nutrients and nutrient loading concerns can be a fundamental barrier to technology adoption. In some cases, introduction of nutrient recovery technology may be essential to the feasibility of dairy manure management, even if the technology does not fully cover its own cost.

This publication evaluates three nutrient recovery technologies that can work in tandem with an AD system:

- AD-CHP: built into this AD is a screening/settling nutrient recovery system which partitions and exports fiber and phosphorus-containing manure fines from the effluent in the form of high-value products;
- AD-RNG-Struvite: a struvite crystallization process that produces a dry, slow-release phosphorus fertilizer; and
- AD-RNG-AIRTRAP: the WSU-patented nutrient recovery technology (AIRTRAP system), which combines ammonia stripping and phosphorus solids settling to produce two bio-fertilizers – a pathogen-free ammonium sulfate fertilizer and a phosphorus fertilizer.

Diagrams of the aforementioned systems are shown in Figures 1 and 2.

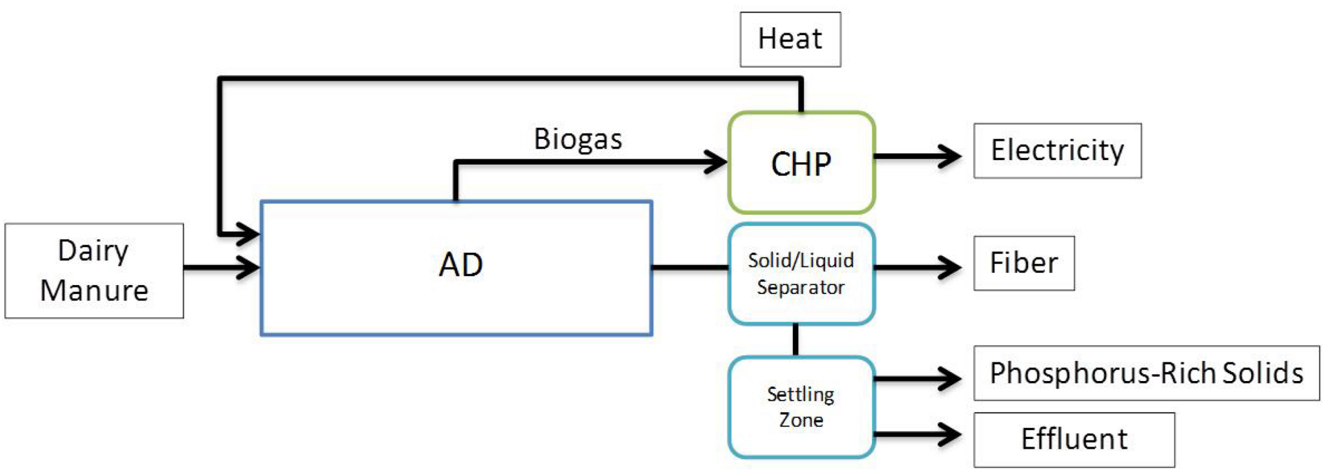

Figure 1. AD-CHP system with phosphorus screening/settling process.

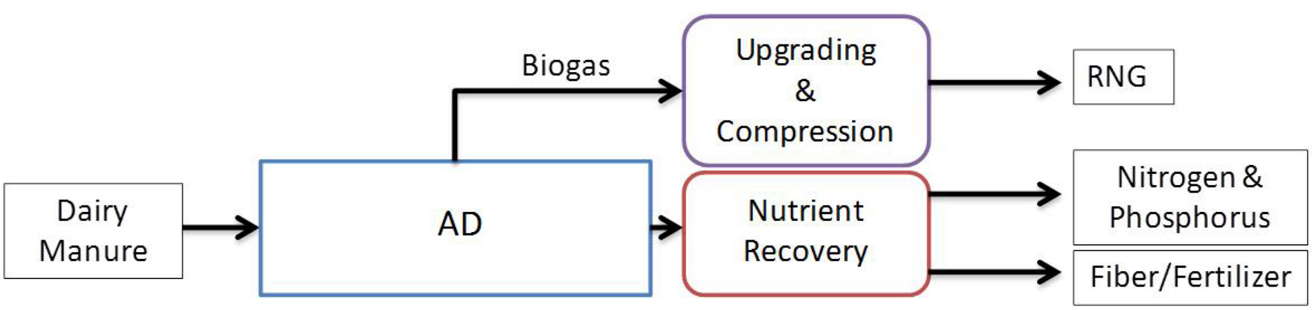

Figure 2. AD-RNG infrastructure. “Nutrient Recovery” refers to either the struvite crystallization process or AIRTRAP.

Phosphorus-containing fine solids

The screening/settling nutrient recovery is built into the AD-CHP; hence, there is no additional capital cost for the nutrient recovery technology. The technology removes approximately 50% of total phosphorus from the effluent stream and screens/settles fine solids, which are then sold as a value-added fertilizer.

Struvite

Crystallization in the form of struvite (magnesium ammonium phosphate hexahydrate, or $MgNH_4PO_4 \cdot 6H_2O$) is an emerging commercially viable phosphorus removal and recovery process (Battistoni et al. 2006; Burns et al. 2001; Westerman et al. 2009). Struvite formation requires that three soluble ions in the wastewater solution (Mg^{2+}, NH^{4+}, and PO_4^{3-}) react to form precipitates with low solubility (pKsp of 12.6). A gas-agitated fluidized-bed reactor is used as a crystallization reactor. The resulting struvite product can be marketed as a slow release fertilizer. Adding a struvite crystallization process to an AD-RNG system is estimated to cost an extra $485,550.

Combined ammonia stripping and phosphorus settling

The process uses high temperature (55°C) and limited, non-biological aeration to elevate pH and strip ammonia, producing an ammonium sulfate solution as a salable bio-fertilizer (Jiang et al. 2011; Jiang et al. 2014). Aeration also removes supersaturated CO_2 to facilitate downstream settling/dewatering of phosphorus-containing solids, thereby producing a second salable product: phosphorus-rich fine solids. Additionally, a residual nutrient-reduced AD effluent is produced. This separation of nutrients allows for three different waste streams, each with its own fertilizer ratio, for optimal use on dairy soils or as a bio-fertilizer. The addition of AIRTRAP to an AD-RNG system is approximately $2.1 million.

Economic Analyses of Different Nutrient Recovery Technologies Working in Tandem with AD Systems

Capital costs and operating costs

The estimated capital cost, operating cost, and revenue of the AD systems with different nutrient recovery technologies are presented in Table 1. The average annual capital cost of the AD-RNG-AIRTRAP is higher than the AD-RNG-Struvite and the AD-CHP by 16% and 179%, respectively.

The operating costs of the baseline AD-CHP system with phosphorus screening/settling include the labor, maintenance, and repair costs for the digester and generator. For the AD-RNG system, the operating costs include the expense of repairing and maintaining the digester and gas cleaning unit, pipeline and fuel station, as well as the costs of labor and the fuel station's ground lease. The additional operating costs when incorporating a nutrient recovery technology into the AD-RNG system include electricity and chemical costs for the struvite crystallization process; and labor, maintenance, electricity, and chemical costs for the AIRTRAP system.

The average annual operating costs of the AD-RNG-Struvite are highest among the three alternatives, which is about $1.18 million per year compared to $0.28 million per year for the AD-CHP and $0.98 million per year for the AD-RNG-AIRTRAP. The high operating costs for the AD-RNG-Struvite are attributed to the chemical inputs needed for the crystallizer, which account for about 52.4% of the total operating costs. The remaining operating costs are for the production of renewable natural gas and delivery of gas to the fueling station (47.2%), and electricity used to produce struvites (0.4%).

Table 1. Average annual capital and operating costs of different AD and nutrient recovery systems.

Systems	Total capital cost	Average annual capital cost[1]	Average annual operating cost[2]	Average annual revenue[3]
AD-CHP (baseline)	$4,400,000	$176,000	$283,270	$1,015,505
AD-RNG-Struvite	$10,600,044	$424,002	$1,183,463	$2,756,793
AD-RNG-AIRTRAP	$12,259,094	$490,364	$983,302	$3,054,191

Source: Coppedge et al. (2012)

[1]Average annual capital cost = total capital cost divided by 25 years.

[2]Operating costs of the baseline AD-CHP system include the labor and maintenance and repair of the digester and generator. For the AD-RNG systems, operating costs include the: repair and maintenance of the digester and gas cleaning unit, pipeline and fuel station, labor, and the fuel station's ground lease. The additional operating costs of the AD-RNG systems include electricity and chemical costs for the struvite crystallization process and labor, maintenance, electricity, and chemical costs for the AIRTRAP system.

[3]Revenue sources include electricity sales, fiber and nutrient sales, and carbon credits for the AD-CHP; electricity sales, fiber and nutrient sales, carbon credits, renewable natural gas, and RINs for the two AD-RNG systems.

Potential revenue sources

The average annual revenue for each AD system is shown in Table 1. The estimated average annual revenue of the AD-RNG-AIRTRAP is higher than that of the AD-CHP by 201% and the AD-RNG-Struvite by 11%. An AD system has four general sources of revenue:

1. sale of energy;
2. energy credits and incentives;
3. sale of fiber and nutrients; and
4. environmental payments, such as carbon credits from avoided methane emissions and Renewable Fuel Standard (RFS) credits or Renewable Identification Numbers (RINs).

Energy sales and incentives

In the case of the AD-CHP, excess electricity produced is sold to the grid. Electric utilities are required to purchase the output of qualified small power production facilities (i.e., production capacity of 80 megawatts), as mandated by the federal Public Utility Regulatory Policies Act of 1978, through a Power Purchase Agreement (PPA). A PPA with Pacific Power pays a rate based on the tariff schedule implemented by the Washington Utilities and Transportation Commission. A rate of $0.654/kWh is used in the study. Other incentives for electricity production include additional electricity revenue from selling Renewable Energy Certificates, and a maximum of $5,000/year paid by the Washington State Renewable Energy Incentive to a participating utility through 2020.

In the case of the AD-RNG system, the projected annual production of compressed natural gas is 1,190,503 gasoline gallon equivalents (GGE) that are sold at the fuel station for a retail price of $2.00/GGE. The average annual revenue from energy sales and incentives to produce energy is $0.55 million per year for the AD-CHP system and $1.95 million per year for the AD-RNG system. As shown in Figure 3, energy sales account for the largest percentage of the annual average gross revenue: about 50% in the AD-CHP (electricity), 70% in the AD-RNG-Struvite, and 63% in the AD-RNG-AIRTRAP (electricity and renewable natural gas for both AD-RNG systems).

Fiber and nutrient sales

After digestion, manure fiber and phosphorus solids that remain in the digester effluent are screened, settled, and harvested and can be sold to a fertilizer manufacturer. In the baseline AD-CHP, the anaerobic digester produces an average of 42,000 cubic yards of fiber per year, at a market value of $7/ton. Two hundred and fifty tons of phosphorus solids are produced annually by the digester during the first 6 years, 750 tons in the seventh year, and 1,000 tons/year thereafter at a value of $75/ton. Sale of these products as soil amendments yields an average of $0.36 million per year.

Coppedge et al. (2012) assume that once the struvite system becomes operational, it takes three years to achieve full production. A struvite crystallizer is projected to generate 1.65 tons of struvite per day once full operation is achieved. Hence, during the first and second years of operation, 200 tons and 400 tons of struvites will be produced, respectively, and about 602 tons per year thereafter. Struvite is projected to sell at $150/ton, and revenue is projected at $0.37 million per year on average.

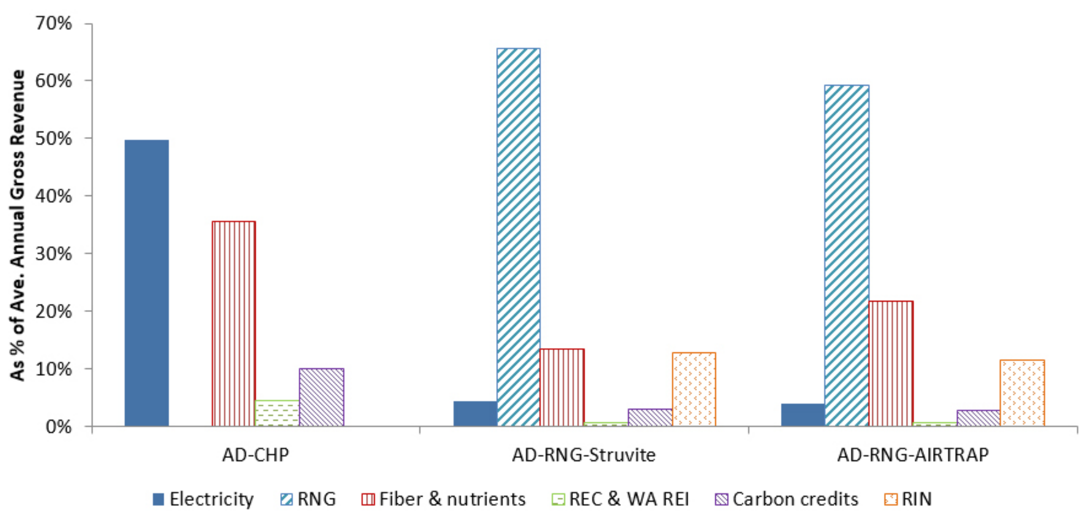

Figure 3. Revenue from digester products and environmental incentives. Source: Coppedge et al. (2012). (REC – renewable energy certificate; WA REI – Washington State Renewable Energy Incentive)

From the AIRTRAP, multiple revenue streams are anticipated, particularly: a 20% increase in fiber production due to screens with tighter mesh openings; increased phosphorus-containing solids production due to the aeration process (500 extra tons/year), plus a potential 10% increase in market value due to a higher concentration of phosphorus and other nutrients ($82.5/ton); and sale of an ammonium sulfate solution as a fertilizer ($212/ton). The average annual revenue from fiber and nutrient sales is projected at $0.67 million.

Potential income from fiber and nutrients are therefore important. They comprise about 36% of the total revenue in the baseline AD-CHP system, and 13% including struvite or 22% including ammonium sulfate within an AD-RNG system (Figure 3).

Environmental payments

There is an opportunity to sell carbon credits for the methane emissions avoided due to digester use. As shown in Figure 3, projected revenue from carbon credits represents about 10% of the gross revenues for the AD-CHP and about 3% for both AD-RNG-Struvite and AD-RNG-AIRTRAP.

Most AD projects certify and sell voluntary credits under the Climate Action Reserve Livestock Protocol. Carbon credits under this protocol were first issued to the DeRuyter AD in 2010 (Climate Action Reserve, n.d.). Another venue for carbon credits is the California carbon market, implemented in 2013 and regulated by the California Air Resource Board. The DeRuyter study assumes that the AD project would sell credits to the Climate Action Reserve Livestock Protocol until 2013 at $8.50 per credit, and then transfer to the California program in 2014 and sell credits at $10 per credit. The price of carbon credits is higher in regulated markets than in voluntary markets. The study also assumes that the AD project would generate credits for ten years (i.e., 2014–2023), with the option of being renewed if the project met the eligibility criteria of the newest protocol available at that time.

It is projected that the AD-CHP system generates 21,063 credits per year that amount to an average annual net revenue of $0.10 million. Net revenue is calculated as carbon offset gross revenue minus transaction costs for monitoring and verification of credits. On the other hand, the AD-RNG systems are projected to generate 17,495 credits per year, yielding an average net revenue of $0.09 million per year. Carbon credits are lower in the AD-RNG systems due to the addition of substrates (i.e., non-manure inputs) that are used to increase biogas production to around 500 cubic feet per minute. Coppedge et al. (2012) assume that some escaped methane emissions from the digester itself under the AD-RNG systems results in lower net avoided methane emissions and thus lower overall carbon credits compared to the AD-CHP system.

Furthermore, in the AD-RNG systems, renewable natural gas can qualify for RINs if the gas is used as transportation fuel. It is assumed that the retail price of compressed natural gas is received and combined with the applicable RIN rate that is paid through the RFS program. A full explanation of the RFS program will not be presented in this publication, but interested readers can refer to EPA (2013) for details about the regulations and standards. Also, Coppedge et al. (2012) have a detailed discussion about transportation fuel projects and potential of these projects to earn RINs. The average annual revenue from RINs is projected at about $0.35 million, and contributes 13% to the gross revenues of the AD-RNG-Struvite, and 12% to that of the AD-RNG-AIRTRAP.

Economic feasibility of different AD systems with nutrient recovery technologies

The economic feasibility of an AD system with a nutrient recovery technology is evaluated by using two investment decision criteria: the net present value (NPV) and the benefit-cost ratio (BCR). NPV is the sum of the discounted cash flows minus the initial investment. Cash flow is the difference in the cash inflow (or benefits) and cash outflow (or costs) from the first year to the last year of the project, and it is discounted back to its present value. The BCR is the ratio of the present value of estimated benefits and the present value of estimated costs (Robison and Barry 1996). The present value is the value of future cash flows that is discounted to reflect the current value. A Weighted Average Cost of Capital (WACC) of 6.5% (Asselin-Balencon and Jolliet 2014) is used as the discount rate in the NPV and BCR calculations. The WACC is a financial metric that takes into account the two main sources of financing an investment: equity and debt. Hence, using the WACC as the discount rate represents both the opportunity cost of equity capital and the cost of debt to finance the investment. The term of the analysis is 25 years (i.e., from 2008 to 2032).

Appendix Tables A1 to A3 show the cash flows using 2012 prices for the different systems and are accessible on the Center for Sustaining Agriculture and Natural Resources website.

Table 2 shows the NPV and BCR for the three systems given different sources of revenues. In general, the decision rule is to accept a project when NPV is greater than zero. The NPV can also be used to compare the viability of different project alternatives. The greater the NPV, the better the investment. If the AD system only sells the energy produced (i.e., electricity, renewable natural gas, or both), none of the three systems will be feasible to implement. Positive NPV is calculated for all systems only when revenues are generated from the sale of both energy and fiber and nutrients, at the very least. This result supports the importance of developing these value-added products in order to maintain or augment profits. The AD-RNG-AIRTRAP consistently has the highest NPV relative to other alternatives given different revenue streams.

Under BCR, the ratio should be greater than 1.0 for a project to be acceptable. While NPV is an absolute measure of project viability, BCR is a relative measure of project viability and thus provides an indication of how much the project's benefits outweigh its costs. BCR also indicates the return per dollar of expenditure. For example, the AD-CHP that receives revenues from sales of energy, fiber and nutrients, energy incentives, and carbon credits has a BCR of 1.60, implying that the project has a return of $1.60 for every dollar spent as compared to $1.14 in the AD-RNG-Struvite and $1.28 in the AD-RNG-AIRTRAP.

The results of the NPV and BCR show different outcomes when we only consider benefits from four sources: energy, fiber and nutrients, energy incentives, and carbon credits. Based on the BCR, a producer more concerned with getting more "bang for the buck" would prefer the AD-CHP over the two other alternatives. On the other hand, based on the NPV, a producer more concerned with overall net benefits would prefer the AD-RNG-AIRTRAP compared to the other systems.

Sensitivity Analyses

The results of the economic analysis show that any of the three nutrient recovery technologies, operated in tandem with an AD system, can be economically feasible given the included revenue streams. We further examine the sensitivity of these outcomes when values of certain parameters are changed, particularly the following factors:

- carbon credits and RINs;
- the price of energy (electricity or renewable fuel);
- the price of fiber and phosphorus fertilizer;
- the price of ammonium sulfate in the AIRTRAP system; and
- the discount rate.

Carbon credits and RINs

Even without the environmental payments (i.e., carbon credits, RINs), the AD-RNG-AIRTRAP remains the most financially viable among the options being evaluated based on the NPV (Table 2). This result is mainly due to (1) the greater quantities of fiber produced and (2) more concentrated phosphorus-containing fine solids produced and projected at a higher value relative to those produced in the alternative AD systems. Also, ammonium sulfate solution is another value-added product not generated by the other nutrient recovery technologies. However, the system's BCR is slightly lower than that of the AD-CHP.

When the revenue streams include carbon credits and RINs, the NPV of the AD-RNG-Struvite only becomes higher than that of the AD-CHP when RINs are included as an additional revenue source.

Table 2. NPV and BCR of different AD and nutrient recovery systems given different revenue streams.

Revenue stream[1,2]	AD-CHP		AD-RNG-Struvite		AD-RNG-AIRTRAP	
	NPV	BCR	NPV	BCR	NPV	BCR
Energy	-$1.68 million	0.79	-$2.80 million	0.88	-$2.52 million	0.88
Energy and fiber and nutrients	$2.65 million	1.34	$1.59 million	1.07	$4.77 million	1.21
Energy, fiber and nutrients, and energy incentives	$3.33 million	1.42	$1.98 million	1.09	$5.16 million	1.23
Energy, fiber and nutrients, energy incentives, and carbon credits	$4.71 million	1.60	$3.15 million	1.14	$6.33 million	1.28
Energy, fiber and nutrients, energy incentives, and RINs	—	—	$5.39 million	1.24	$8.57 million	1.38
Energy, fiber and nutrients, energy incentives, carbon credits, and RINs	—	—	$6.55 million	1.29	$9.73 million	1.43

[1]Energy mainly refers to electricity produced by the AD-CHP system, and renewable natural gas produced by the AD-RNG systems.
[2]Energy incentives include the Washington Energy Initiative and Renewable Energy Certificates.

The sensitivity of the outcomes to changes in the RIN value, holding all else constant, is shown in Figure 4. When there are no RIN payments received, the AD-RNG-AIRTRAP appears as the most economically feasible option. Also, the AD-CHP is more economically feasible than the AD-RNG-Struvite. Furthermore, as the RIN value increases, the relative difference shrinks between the NPV of the two AD-RNG systems. For instance, at an RIN value of $0.03/RIN, $0.25/RIN, and $0.75/RIN, the NPV of the AD-RNG-AIRTRAP is higher than the NPV of the AD-RNG-Struvite by 91%, 49%, and 24%, respectively.

Price of energy

The average annual growth rate of electricity prices between 2004 and 2013 in Washington is about 2.26% (EIA 2015). All else constant, the NPV of the AD-CHP increases when the price of electricity increases. At 2% more than the baseline price of $0.0654/kWh, the NPV of the AD-CHP is about $4.79 million. When the price of electricity is 10% more than the baseline price, the NPV increases to $5.11 million. However, these NPVs are still lower than the NPV of the AD-RNG-Struvite or AD-RNG-AIRTRAP (Table 3).

At the baseline retail price of compressed natural gas (i.e., $2.00/GGE), the AD-RNG systems are more viable than the AD-CHP system. The scenarios illustrated in Table 3 are based on a lower retail price, while holding all else constant. When the retail price goes down by 10% relative to the baseline (i.e., $1.80/GGE), the NPV of the AD-RNG-Struvite becomes lower than the NPV of the AD-CHP, indicating that the latter is more economically feasible. Similarly, the NPV of the AD-RNG-AIRTRAP becomes lower than that of the AD-CHP when the retail price of compressed natural gas is 30% lower than the baseline (i.e., $1.40/GGE). While the retail price of compressed natural gas fluctuates, a decrease in price by more than 52% is not realistic. Based on the average retail price of compressed natural gas in the US between 2000 and 2014, the price has not gone lower than $0.96/GGE (EERE 2015).

Prices of fiber and phosphorus fertilizer

Fiber material, as an alternative to peat moss, and recovered phosphorus for soil amendments are important revenue sources for an AD project. We examine the change in the NPV of the AD system with different nutrient recovery technologies when the selling prices of these co-products are different from the baseline, while holding all else constant. Sensitivity analysis shows that the NPVs of the AD-RNG-AIRTRAP are nearly two times greater than the NPV of the baseline AD-CHP system with phosphorus screening/settling. However, as the price increases, the gap becomes smaller between the NPV of the baseline system and the NPV of either of the two AD systems with more advanced nutrient recovery technologies (Table 4).

Price of ammonium sulfate from AIRTRAP

As mentioned previously, ammonium sulfate solution is a bio-fertilizer produced by AIRTRAP and a revenue source in addition to sales of fiber material and phosphorus fertilizer. The retail price of an ammonium sulfate solution is assumed at $424/ton and the wholesale price is 50% off the retail price.

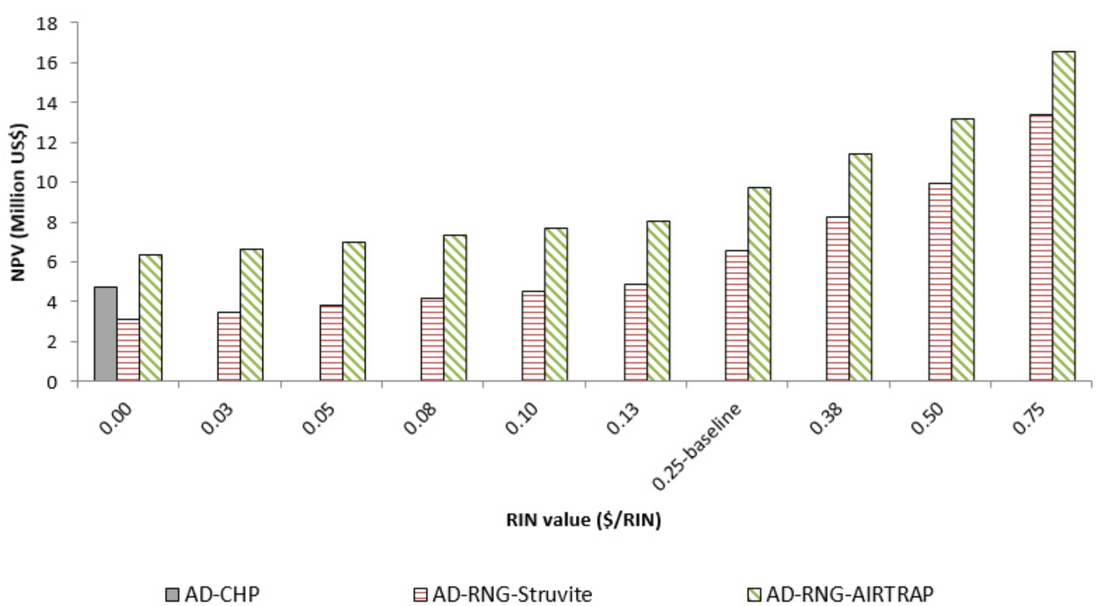

Figure 4. NPV, in million dollars, of the different AD and nutrient recovery systems given different RIN values.

Table 3. NPV, in million dollars, of AD with different nutrient recovery technologies given changes in energy price.

Paramater	AD-CHP	AD-RNG-Struvite	AD-RNG-AIRTRIP
A. Price of electricity (percentage increase with respect to the baseline price)			
0% (baseline)	$4.71		
2%	$4.79		
4%	$4.87		
6%	$4.95		
8%	$5.03		
10%	$5.11		
B. Price of renewable natural gas (percentage decrease with respect to the baseline price)			
0% (baseline)		$6.55	$9.73
-5%		$5.68	$8.86
-10%		$4.80	$7.98
-15%		$3.92	$7.10
-20%		$3.05	$6.23
-25%		$2.17	$5.35
-30%		$1.30	$4.48
-35%		$0.42	$3.60
-40%		-$0.45	$2.72
-45%		-$1.33	$1.85
-50%		-$2.21	$0.97

Notes:
NPV considers all revenue streams (energy sales and incentives, fiber and nutrients, carbon credits, and RINs).
Baseline price of electricity = $0.0654/kWh.
Baseline price of renewable gas = $2.00/GGE.

Table 4. NPV, in million dollars, of AD with different nutrient recovery technologies given changes in the prices of value-added products.

Paramater	AD-CHP	AD-RNG-Struvite	AD-RNG-AIRTRIP	$NPV_{AD\text{-}RNG\text{-}AIRTRAP}$ / $NPV_{AD\text{-}RNG\text{-}Struvite}$	$NPV_{AD\text{-}RNG\text{-}AIRTRAP}$ / $NPV_{AD\text{-}CHP}$	$NPV_{AD\text{-}RNG\text{-}Struvite}$ / $NPV_{AD\text{-}CHP}$
A. Prices of fiber and phosphorus fertilizer (percentage increase with respect to the baseline price)						
0% (baseline)	$4.71	$6.55	$9.73	1.49	2.07	1.39
5%	$4.92	$6.77	$9.99	1.48	2.03	1.38
10%	$5.14	$6.99	$10.24	1.46	1.99	1.36
15%	$5.36	$7.21	$10.50	1.46	1.96	1.35
20%	$5.57	$7.43	$10.76	1.45	1.93	1.33
25%	$5.79	$7.65	$11.01	1.44	1.90	1.32
B. Price of ammonium sulfate solution						
Wholesale price (baseline, 50% of retail price)			$9.73			
Retail price			$11.90			

Notes: NPV considers all revenue streams (energy sales and incentives, fiber and nutrients, carbon credits, and RINs).

If the retail price is received, the NPV of the AD-RNG-AIRTRAP is 22% higher than when the bio-fertilizer is sold at the wholesale price (Table 4).

Discount rate

The NPV is inversely proportional to the discount rate (Figure 5). A higher discount rate means that more value is placed on current money than future money. A project's internal rate of return (IRR) is the discount rate at which that project's NPV equals zero, which means the project's cash flows are equal to its costs (Brigham and Ehrhardt 2011). When accounting for all the revenue sources of the different AD systems (energy, fiber and nutrients, energy incentives, and environmental payments), the IRRs are estimated at 16.51% for the AD-CHP, 11.25% for the AD-RNG-Struvite, and 12.09% for the AD-RNG-AIRTRAP. These IRRs are all higher than the assumed opportunity cost of capital (i.e., 6.5%). The IRR shows that any one of the projects is worth investing in. However, when ranking mutually exclusive projects, it is better to compare each project's NPV. The NPV assumes that the cash flows will be invested at the project's current cost of capital, while the IRR assumes that the cash flows will be invested at the project's own IRR, which can be too high.

Figure 5 shows the NPV given different discount rates for the three mutually exclusive projects. The left-most area of the chart shows the range at which the AD-RNG-AIRTRAP is a better investment because it has higher NPV although its IRR is lower than the AD-CHP with phosphorus screening/settling. The middle area in the chart shows that the AD-CHP is a better investment since its NPV is higher than those of the alternative systems. Also, between 12.09% and 16.51%, AD-CHP is the only project with a positive NPV in that range of discount rates.

Discussion

The AD systems evaluated in this publication have different revenue sources. Energy sales comprise the biggest share of the gross revenue of the three systems. Environmental payments such as carbon credits and RINs are also key revenue streams. The AD-RNG systems only surpass the AD-CHP as a feasible option, in terms of both higher NPV and BCR, when there are revenues coming from RINs in addition to energy sales and incentives and fiber and nutrients.

Nutrient recovery technology can be an essential investment dairies make to balance nutrient management needs. Fiber and nutrients are undeniably important value-added products as

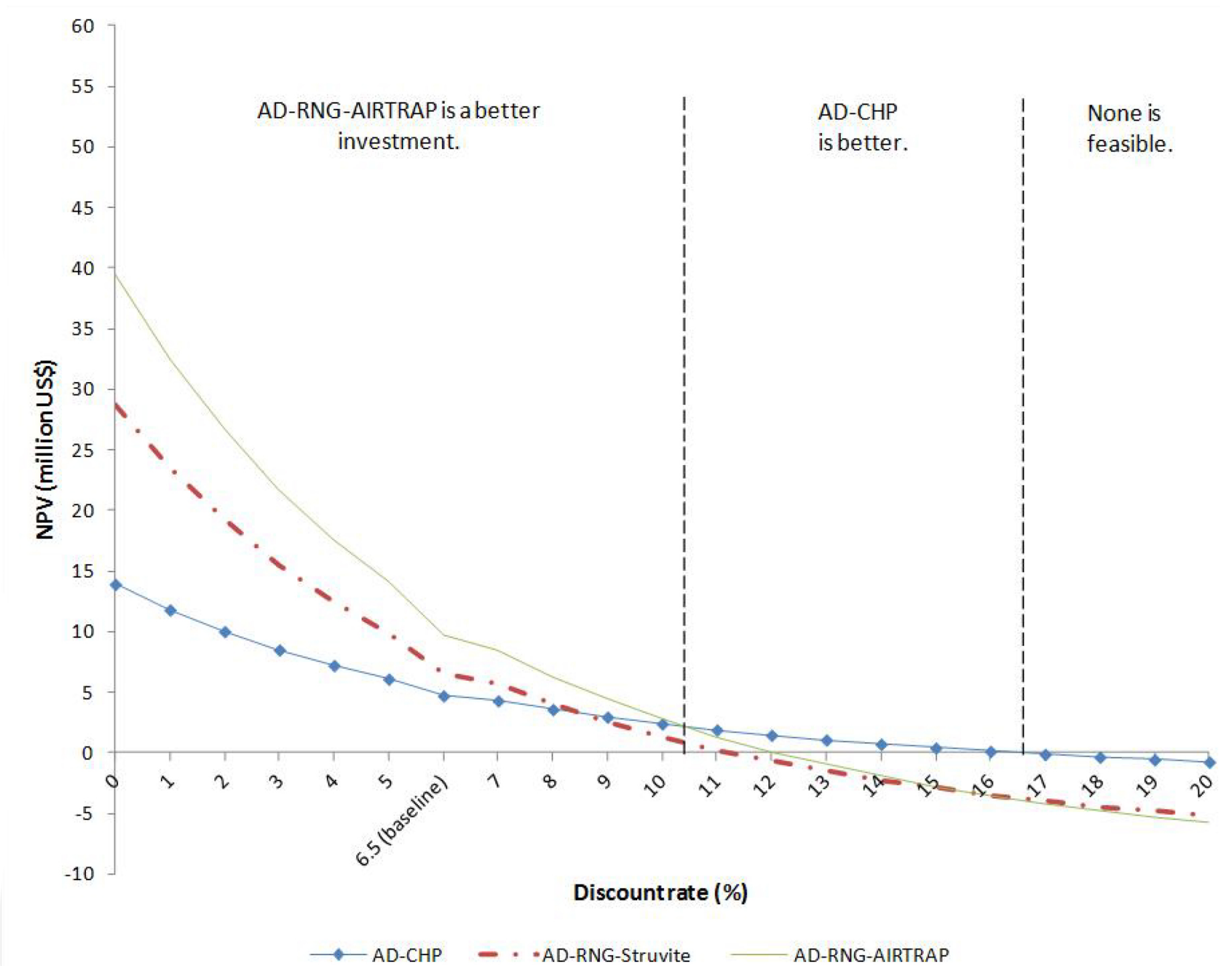

Figure 5. NPV, in million dollars, of the different AD and nutrient recovery systems given different discount rates.

they are the second main sources of revenue for the AD-CHP. Two new approaches to nutrient recovery are examined in this publication: (1) struvite crystallization, which is a primarily phosphorus recovery approach and (2) a combined ammonia-stripping and phosphorus-settling approach (i.e., AIRTRAP). Fiber and nutrients sold as soil amendments are the second main revenue source for the AD-RNG-AIRTRAP, and the third main source for the AD-RNG-Struvite. Hence, including nutrient recovery as part of an AD system facilitates processes and product streams that can be beneficial to project feasibility.

The outcomes of the economic analyses underscore the available options for integrating dedicated nutrient recovery technology in an AD system to help a dairy balance its nutrient management challenges. However, the need for such a technology must be carefully evaluated given its high capital and operating costs.

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