2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

An ASABE Meeting Presentation
DOI: https://doi.org/10.13031/aim.202100888
Paper Number: 2100888

Cost assessment of centralizing a swine manure and corn stover co-digestion system for biogas production

Gabrielle Myers[1], Daniel Andersen[2], D. Raj Raman[3]
[1]3332 Elings, 605 Bissell Rd., Ames, IA 50011-1098
[2]3348 Elings, 605 Bissell Rd., Ames, IA 50011-1098
[3]3356 Elings, 605 Bissell Rd., Ames, IA 50011-1098

Written for presentation at the
2021 Annual International Meeting
ASABE Virtual and On Demand
July 12–16, 2021

ABSTRACT. Iowa's livestock produces over 50 million tons of wet-basis manure each year. Biogas production from the manure can provide additional income to farmers, reduce greenhouse gas emissions, control odors, and provide a renewable energy source. Despite these benefits, biogas production is rarely deployed at swine farms. In this work, we explore the system economics to understand better the reasons for low deployment, as well as the benefits that might be realized via several additional steps, including: (1) cleaning and injection into the natural gas grid, (2) amending manure with biomass, and (3) digester centralization. Specifically, we present a static, spreadsheet-based techno-economic model that allows examining these scenarios and combinations thereof. We also present our results and the uncertainties therein. This work shows that under the model assumptions, distributed, farm-scale digesters are not competitive with natural gas prices in Iowa, while some centralized production scenarios can be competitive, providing that fertilizer value and RIN credits are sufficiently high.

Keywords. Anaerobic digestion, manure, swine, bioenergy, renewable fuels

Introduction

Anaerobic digestion (AD) is a process by which microbes break down organic materials in an oxygen-free environment. Anaerobic digestion feedstocks include industrial and municipal wastewater, manure, crop residues, and food wastes (Ward et al., 2008). The biogas produced from AD processes is composed mainly of the greenhouse gases methane and carbon dioxide. The AD process prevents these gases from entering the atmosphere and displaces fossil fuels when methane is utilized as an energy source (Ward et al., 2008). In addition to providing a form of renewable energy that is independent of short-term weather fluctuations (i.e., wind, sunlight), AD of animal manure offers other benefits, including reductions of odor, pathogen populations, and methane emissions (Chiumenti et al., 2009; Ward et al., 2008). Digester effluent (i.e., digestate) can be applied to cropland to improve soil health and serve as an effective fertilizer (EPA, 2017).

In 2020, manure-based anaerobic digesters in the US were estimated to have reduced greenhouse gas emissions by 5 million Mg CO2eq and generated the energy equivalent of 15.26 million GJ (AgSTAR, 2021a). There are currently 273 operational manure-based anaerobic digesters in the US, with 81% utilizing dairy manure and only 16% utilizing swine manure. (AgSTAR, 2021a). According to AgSTAR (2018), swine manure-based digestion systems can be profitable at greater than 2,000 head scales. Iowa has more swine farms that fit this category than any other US state, with over 2,000 eligible farms. These farms represent a combined 23 GJ/yr energy production potential.

Multiple investigators have attempted to understand the costs of farm-based energy from swine AD, with a wide range of results. Bhatt and Tao (2020) modeled costs for swine manure digestion ranging from flows of 1 – 227 Mg wet manure per day, finding estimated energy costs of \$20 – \$130 per GJ, much higher than the cost of natural gas in the United States. A much earlier study by Beddoes et al. (2007) reported swine manure AD followed by electricity generation to provide electricity at \$20 – \$30 per GJ. When considering only the biogas production portion of these systems, the cost of energy production ranged from \$3 - \$6 per GJ. Beddoes et al. (2007) reported the lowest value from a covered anaerobic lagoon and represented a single report. Faulhaber et al. (2012) explored the impact of digester size on AD energy costs and defined a dimensionless methane cost ratio (MCR) by dividing the biogas energy cost (\$/GJ) by the retail price of natural gas (\$/GJ). They showed that under baseline assumptions, even large (1000 head) systems had MCR > 1, but that carbon credits and low-interest loans could make these systems more economically competitive.

Historically, the failure rate of farm-based digesters is relatively high. In 1998, this rate was approximately 50% (Lusk, 1998). The low economic return on these systems may be one driving factor. According to more recent AgStar data, this rate has decreased to approximately 23% (AgStar, 2021b). Aside from design and equipment failures, farm-based digesters have failed due to a lack of technical expertise on the farm. Due to their large scale, centralized digesters handling the manure of multiple farms may allow a dedicated operations staff to manage day-to-day maintenance tasks, reducing the management burden on farmers and potentially reducing digester abandonment (Bothi and Aldrich, 2005).

The majority of anaerobic digester projects since 2000 have been combined heat and power systems (CHP), but in recent years projects focused on producing renewable natural gas (RNG) for use in vehicles have become popular (AgSTAR, 2021a). These RNG projects are more costly due to the need for equipment to upgrade the biogas for pipeline injection. Still, they allow for the methane to qualify for Renewable Identification Numbers (RINs), creating an additional revenue source for the biogas producer. Our model allows the user to vary RIN values, permitting exploration of overall economics under different RIN-value scenarios.

Co-digesting manure with crop residues can increase the biochemical methane potential (BMP) of a digester and its energy production efficiency (González et al., 2020). However, these crop residues increase the solids loading of the digester and the volume of digestate produced, increasing the land needed for its application. Corn stover, a widely available crop residue in Iowa, is considered in our model, along with a land-use balance for its harvest and application of digestate.

In this work, we conduct a modeling effort for AD at individual large-scale swine farms typical of Iowa and a single large digester receiving manure and stover from five large swine farms. In all scenarios, corn stover is co-digested with the swine manure to increase the energy production of the digester. Additionally, we consider the impact of government policies such as zero-interest loans and RIN availability on the system's economic viability.

Methods

Scenario description

The cost of producing biogas was calculated for six different scenarios (represented as S1 through S6), reflecting typical Midwest agriculture in 2020. In each scenario, costs are calculated based on farm sizes of 4800 pigs. S1 consists of a single digester, receiving deep-pit effluent to which no additional water is added, but corn stover is added until 12% solids are reached. The biogas is cleaned and injected into the natural gas grid on site. In the second scenario, the assumptions are identical to S1. However, a volume of water equivalent to manure volume is added to the digester to permit more corn stover and higher biogas production. The same assumption for water is also applied to the rest of the scenarios. S3 calculates costs for five decentralized digesters that share the cost of a centralized cleaning and injection site. In this scenario, biogas must be transported, but each farm uses its manure. In S4, we consider a centralized anaerobic digester. Five farms haul their manure to the central digester, where the biogas is produced, cleaned, and injected. S5 is identical to S4 but uses a D5 RIN price instead of D3. S6 is also identical to S4, but no interest is applied to the capital costs to examine the impact of incentivizing policy.

Digester Input

In each scenario, it is assumed that all of the manure produced is used in biogas production. The base manure production assumption is 4.5 L/day/head (Smith et al., 2017). The digesters are assumed to operate 24 hours per day for 340 days each year. The methane production potential for swine slurry is 350 mL/g volatile solids (VS) (Moody et al., 2011). We assume a total solids (TS) content of 8%, a VS content of 6%, and a density identical to water (1000 kg/m3). In each case, the manure is assumed to cost \$5/Mg (Aui and Wright). This cost is applied to all scenarios because we assume that a separate entity from the farm runs the digesters. Manure transportation is assumed to cost \$0.00057/L/km (0.0035/gal/mile; Andersen, 2016), and the distance to the central digester is 4 km (2.5 miles) for each farm. Manure transportation costs are only considered in S4. The manure transportation cost is considered in addition to the manure cost.

The methane potential of corn stover is 180.3 mL/g VS. The TS, and VS content of wet corn stover are 90.3% and 84.1%, respectively (Moody et al., 2011). The cost of corn stover is assumed to be \$20/Mg (Aui and Wright), including biomass transportation to the digesters. The digesters are assumed to achieve 75% of the biological methane potential.

In each scenario, the mass of corn stover added to the digesters was calculated to meet a 12% solids content after the addition of manure and water. This amounted to stover mass flows in the range of 5 - 9% of the total mass of digester input. In S2 through S6, water and manure each accounted for 45% of digester input mass.

We compared the land required for this biomass demand to the land usage for manure application. Assuming a harvest rate of 3 tons/ac, the biomass demand's land requirement ranges from 50 ha/yr (125 ac/yr) in S1 to 1,000 ha/yr (2,500 ac/yr) in S4. We assumed the manure's nitrogen content to be 6 kg/m^3 (0.05 lb/gal) (Smith et al., 2017) and the manure application rate to be 168 kg/ha (150 lb/ac; Maximum Return to Nitrogen, 2021). This results in a land application requirement of 650 acres in scenarios one through three and 3200 acres in scenarios four through six. Therefore, the land needed for biomass harvest is 77% of the manure application land requirement at its maximum demand. Table 1 shows the details of this calculation.

Table 1. Biomass Use / Land Application Balance.

	Unit	S1	S2	S3	S4	S5	S6
Biomass Demand	Mg/yr	375	1500	1500	7500	7500	7500
Biomass Harvest Rate	Mg/ha	7.4	7.4	7.4	7.4	7.4	7.4
Biomass Land Requirement	ha/yr	50.6	202	202	1010	1010	1010
Annual Manure Production	m3/yr	7,340	7,340	7,340	36,700	36,700	36,700
Nitrogen Content of Manure	Mg/m^3	0.006	0.006	0.006	0.006	0.006	0.006
Nitrogen Production	Mg/yr	44.00	44.0	44.0	220.0	220.0	220.0
Land Application Requirement	ha/yr	261.7	261.7	261.7	1308.5	1308.5	1308.5
Land Portion Needed for Harvest		19%	77%	77%	77%	77%	77%

Biogas Production

After the digester inputs were calculated, the manure and corn stover's methane production was calculated and added to total methane production. This value was converted to biogas by assuming the biogas is 60% methane by volume (Aui and Wright). The annual biogas production ranged from approximately 230,000 m^3 in S1 to 2.4M m^3 in S4 and beyond. The annual energy production in each scenario was calculated by assuming the energy density of methane is 37.6 MJ/kg (1010 BTU/m^3; EIA, 2019) and applying a methane cleaning efficiency of 97% (Bekkering et al., 2010).

Digestate Production

Solid and liquid digestate production was calculated as the remaining mass after biogas had been produced. By assuming the biogas produced is 60% methane, 6% water vapor, and 34% carbon dioxide by volume, the total mass of biogas was calculated. The mass of solid digestate was calculated by subtracting the mass of methane and carbon dioxide from the input solids. The mass of liquid digestate was calculated by subtracting the mass of biogas and solid digestate from the total digester input.

We assume the liquid will be recycled and used as the water input to the digester and the solid digestate has value as a fertilizer. Credit applied for liquid digestate is \$2.64/Mg (Aui and Wright). In scenario one, the credit for solid digestate is \$35.25/Mg for solid (Aui and Wright). In scenarios two through six, we apply a \$20/Mg credit for solid digestate, similar to the value of beef manure (Value of Manure Nutrients, 2007) because additional corn stover is added, reducing the total nutrient value.

Capital costs

The digesters' capital costs were scaled similar to Aui and Wright, using a base digester cost from NREL, 2011. The based digester cost was approximately 27 million USD for an input flow of 9,434 tons/day. This cost was scaled for our flows ranging from 23 to 238 tons per day with a scaling factor (SF) of 0.6. Aui and Wright also include an "other" cost for equipment associated with the digester of \$58,000. This cost was scaled in an identical fashion to the digester cost. The scaled costs were then converted from 2011 USD to 2019 USD.

The capital cost of biogas cleaning equipment, manure and biomass storage, and injection is calculated following the methods of Bekkering et al., 2010. We assume the digesters or cleaning facilities are located 500 meters from the natural gas grid when computing injection capital costs. These costs were converted from 2010 Euros to 2010 USD, then to 2019 USD. In S3, the cost of a biogas compressor pipeline from the decentralized digesters to the central cleaning facility is calculated based on Hengeveld et al., 2014, and converted to 2019 USD. We assume the digesters are all 2.5 miles away from the central cleaning and injection point in this scenario.

All of the capital costs are summed, and an annual capital cost is computed assuming a 20-year life at 7% interest. In S6, no interest is applied to capital cost.

Operating costs

Operating costs for labor, maintenance, biogas cleaning, energy, and solids handling were calculated. Labor costs are based on Aui and Wright. For a daily biogas production of 8,432 m^3, the annual labor cost is \$131,853. This cost was converted to 2019 USD and scaled linearly with the daily biogas production in each scenario. The annual maintenance cost is assumed to be 1% of the annual capital cost. According to Bekkering et al., 2010, the yearly cost of operation and maintenance of biogas cleaning equipment is 385 euros times the hourly biogas production. The digester's energy use was assumed to be 1.235 MJ/m^3 biogas (Hengeveld et al., 2014). The average cost of industrial electricity in Iowa is \$0.0689/kWh (EIA, 2020a). The solids handling cost, per Aui and Wright, is \$5.00/Mg of digestate.

Renewable Fuel Identification Numbers

A source of income for biogas producers included in our model is Renewable Fuel Identification Numbers (RINs). RINs are bought and sold within fuel markets to meet compliance with the Renewable Fuel Standard. Biogas producers that utilize manure qualify for D3 RINs, defined as Cellulosic Fuels. We used the average price of D3 RINs from 2017 – 2020 of \$1.92 per gallon of ethanol equivalent (GEE) (EPA, 2020b). This value was converted to a price per GJ using a gallon of ethanol's energy content (0.08 GJ or 77,000 BTU), then applied this credit to each scenario's annual energy production.

Biogas producers that utilize food waste, fats, oils qualify for D5 RINs or Advanced Fuel RINs. In S5, we included a calculation of cost when using a D5 RIN, which averaged at \$0.58/GEE for 2017-2020 (EPA, 2020b).

Final Cost Calculation

The final cost was calculated by summing capital and operating costs and subtracting the RIN and digestate credit values. A sensitivity analysis was completed by varying each of the 34 model inputs individually by 1%. The change in final cost was observed, and the sensitivity coefficients (percent change in output/percent change in input) were calculated for each input.

Natural Gas Comparison

The ten-year average citygate price of natural gas in Iowa was used to compare to biogas cost. According to EIA (2020c), this price is \$5.21/1000 ft^3. Using the average Iowa natural gas energy content of 39.8 MJ/m^3 (1067 BTU/ft^3; EIA, 2020b), this translates to a cost of \$4.63/ GJ. Figure 1 shows the average city gate natural prices in Iowa since 1984 in both \$/MMBTU and \$/GJ.

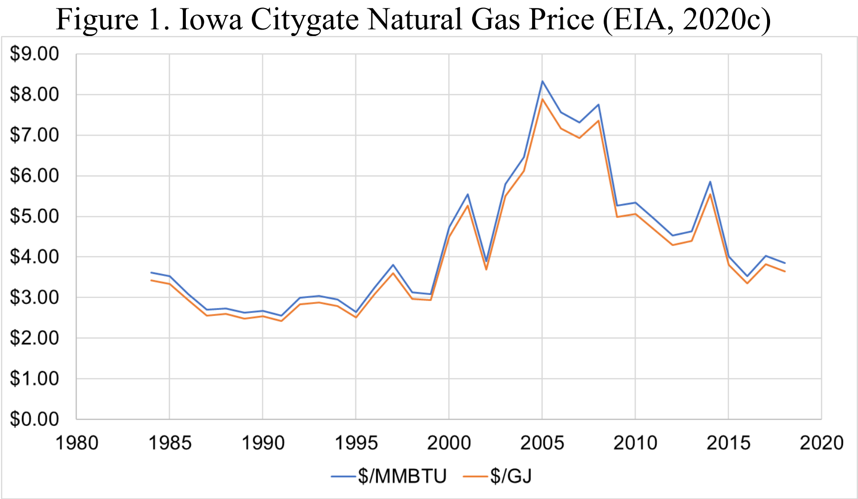


Figure 1. Iowa Citygate Natural Gas Price. The average citygate price for Iowa from 1884-2018 is shown. The most recent ten-year average was used in the model.

Results and Discussion

Annual Production and Costs

The annual production of biogas, methane, and energy are summarized in Table 2. Because S1 does not utilize corn stover, it is the lowest production scenario. S2 and S3 have equal productions, and S4 through S6 have five times the production volume.

Table 2. Annual Production

	S1	S2	S3	S4-6
Biogas (m^3)	264,000	477,000	477,000	2,390,000
Methane (m^3)	158,000	278,000	278,000	1,390,000
Energy (GJ)	5,330	10,500	10,500	52,300

Table 3 shows the costs per GJ of energy produced for each cost category considered in the model. S1, the decentralized scenario, is the most expensive. This scenario does not have an economy of scale advantage or utilize biomass to increase methane production potential. By allowing for corn stover use, S2 is about $7/GJ less costly than scenario one. In addition to the increased BMP from adding corn stover, the increased input mass and production required an increased size of digester and cleaning equipment, which allowed for the economy of scale advantage in this scenario. S3 was more costly than S2. This result shows that the centralized cleaning facility alone (i.e., without centralized digestion) does not have any economic benefit over a decentralized scenario for the swine farms at the scales examined in this study. S4 is the least costly scenario with a non-zero interest rate. The economy of scale associated with totally centralized production was more significant than the disadvantage of transporting manure. This result is consistent with the findings of Hengeveld et al., 2014. Using a D5 RIN price makes S5 the most expensive of any other scenario. With no interest cost considered, S6 has a $5/GJ advantage over scenario four.

Table 3. Cost Breakdown

Costs (USD/GJ)	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**
Manure	$6.35	$3.51	$3.51	$3.51	$3.51	$3.51
Corn Stover	$1.30	$2.87	$2.87	$2.87	$2.87	$2.87
Manure Transport	$0.00	$0.00	$0.00	$1.69	$1.62	$1.62
Capital	$25.60	$20.29	$23.38	$9.89	$9.89	$5.24
Operating Costs	$7.55	$7.63	$7.66	$7.53	$7.53	$7.48
Cost (Pre-Credit)	**$40.80**	**$34.30**	**$37.43**	**$25.49**	**$25.42**	**$20.73**
Digestate Credit	-$7.03	-$6.34	-$6.34	-$6.34	-$6.34	-$6.34
RIN	-$23.63	-$23.63	-$23.63	-$23.63	-$7.14	-$23.63
Cost (Including Credits)	**$10.13**	**$4.33**	**$7.46**	**-$4.48**	**$11.94**	**-$9.25**

Capital

The annual capital costs of each component are summarized in Table 4. The digester makes up the highest portion of capital costs in S4 through S6 at 67% and the lowest in scenario one at 52%. The cleaning costs in scenario three are lower than the other scenarios because the cleaning equipment cost is shared between five digesters. However, the biogas grid costs bring S3's total annual capital costs to about $30,000 more than S2. The capital costs of S4 and S5 are much higher than in any other scenario. With no interest cost considered, the capital cost in S6 is $240,000 less than in scenarios four and five.

Table 4. Annual capital costs by component

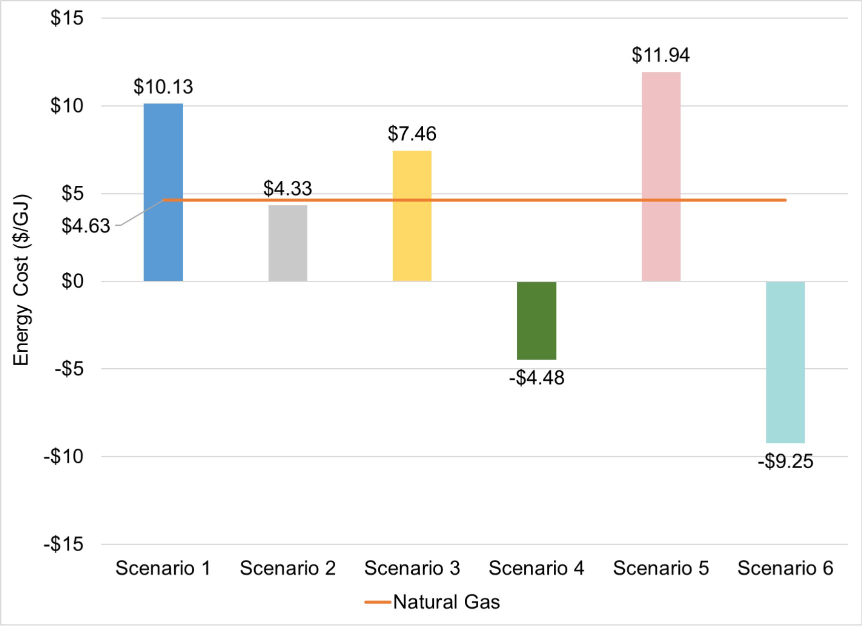
Component	S1	S2	S3	S4	S5	S6
Digester	$77,500	$121,000	$121,000	$317,000	$317,000	$168,000
Cleaning	$57,300	$75,000	$31,200	$156,000	$156,000	$82,700

Injection	$9,400	$9,400	$9,400	$9,400	$9,400	$4,980
Biogas Grid	$0.00	$0.00	$76,200	$0.00	$0.00	$0.00
Storage	$3,740	$6,760	$6,760	$33,800	$33,800	$17,900
Total	**$148,000**	**$212,000**	**$244,404**	**$517,000**	**$517,000**	**$274,000**

Natural Gas Comparison

Figure 2 shows the scenario costs compared to the average price of natural gas in Iowa. S2, S4, and S6 are less expensive than the cost of natural gas, with S6 (no interest) being the most competitive option.

Figure 2. Energy production costs compared to Iowa natural gas price



Sensitivity Analysis

The sensitivity analysis results for the ten most sensitive inputs are shown in Figure 3. The three most highly sensitive inputs are the RIN price, the annual operating days, and the biogas methane cleaning efficiency.

Figure 3. Sensitivity Analysis Results

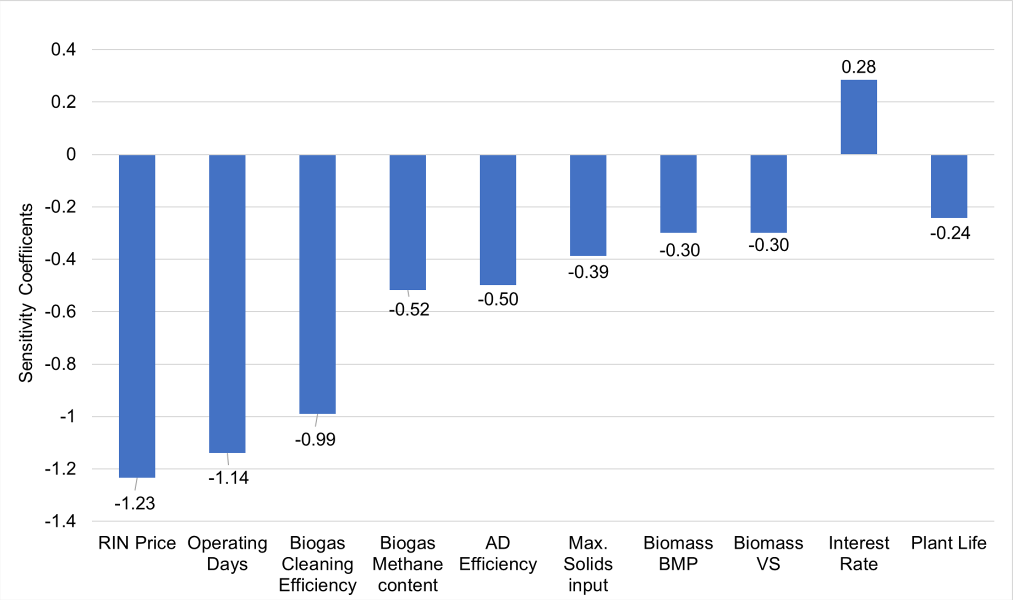


Figure 3. Sensitivity analysis results. The sensitivity coefficients for the ten most sensitive assumptions in S4 are shown.

The most sensitive input to scenario 4 was RIN price, with a sensitivity coefficient of 1.23. As shown in Figure 4, the price of D3 RINs has varied greatly since 2013. Given the high sensitivity of the model results to the RIN price, the volatility in this price would profoundly affect the profitability of the system. The average price of D5 RINs is over 3x lower than D3 RINs, so agricultural digesters continuing to utilize D3 RINs will be extremely important. In 2020, the volume standard for D3 RINs was 0.59 billion GEE (47 million GJ) (EPA, 2020a). This volume would accommodate approximately 900 systems in S4 configuration. The standard for D5 RINs is much higher at 5.09 billion GEE (400 million GJ). This volume could accommodate 8000 S4 systems, but as shown in the sensitivity analysis and the results of S5, the lower price of D5 RINs would decrease profitability and the system's competitiveness.

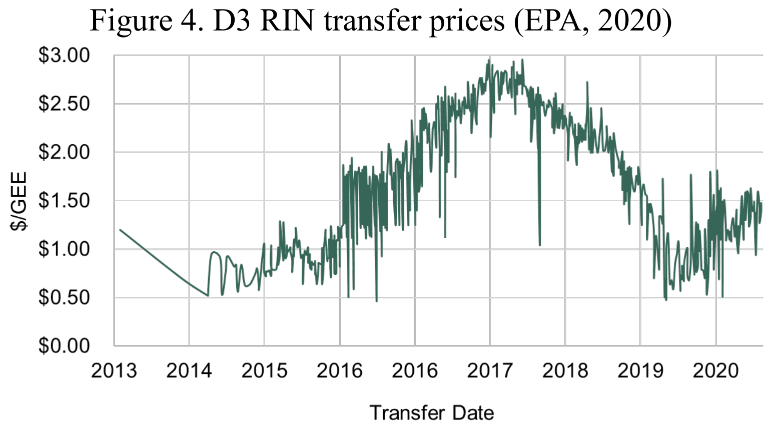


Figure 4. D3 RIN Transfer Prices. The transfer prices for transactions from 2013 to 2020 are shown.

The next most sensitive input was the assumption of annual operating days. A 1% change in the 340-day assumption caused a 1.14% change in the final cost. This result shows a prolonged shutdown would have a significant negative effect on the system's profitability, but any improvements in increased days of operation could have a significant positive effect. Another highly sensitive input was the biogas cleaning efficiency. Improving efficiency would decrease costs as more methane would be available for energy production.

Less sensitive inputs include the process assumptions for methane content of biogas, the digester efficiency, the maximum solids input, and the BMP and VS content of the biomass. While these inputs can be altered slightly with digester type or feedstock changes, they are not as volatile or easily changed as the other sensitive inputs. Interest rate and plant life, inputs that affect the capital costs were also in the ten most sensitive inputs. As shown in scenario 6, government programs offering zero-interest loans on capital would be useful for the system's profitability.

Conclusion

The model created shows that centralizing biogas production systems utilizing swine manure and corn stover is more cost-effective than a decentralized system. However, without centralization, costs competitive with the price of natural gas can be reached when corn stover input is increased through water addition to the digester. In each case, sufficiently high RIN prices are needed to reach cost parity with natural gas. Given the uncertainty of RIN price, other incentives such as zero-interest loans may aid in the adoption of centralized systems.

References

AgSTAR. (2021a, April). *AgSTAR Data and Trends*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/agstar/agstar-data-and-trends

AgSTAR. (2021b, April). *Livestock Anaerobic Digester Database*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/agstar/livestock-anaerobic-digester-database

Andersen, D. (2016, May). *What does manure application cost?* (I. S. Outreach, Producer) Retrieved from The Manure Scoop: http://themanurescoop.blogspot.com/2016/05/what-does-manure-application-cost.html

Aui, A., & Wright, M. (n.d.). *Life Cycle Cost Analysis of the Operation of Anaerobic Digesters in Iowa.* Iowa State University, Department of Mechanical Engineering. Iowa Economic Development Authority.

Beddoes, J. C., Bracmort, K. S., Burns, R. T., & Lazarus, W. F. (2007). *An Analysis of Energy Production Costs from Anaerobic Digestion Systems on US Livestock Production Facilities.* Unitied States Department of Agriculture Natural Resources Conservation Service. Retrieved from https://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=22533.wba%20table%204?

Bekkering, J., Broekhuis, T. A., & van Gemert, W. J. (2010). Operational modeling of a sustainable gas supply chain.

Engineering in Life Sciences, 10(6), 585-594.

Bothi, K., & Aldrich, B. (2005). *Centralized Anaerobic Digestion Options for Groups of Dairy Farms.* Cornell University, Dept. of Biological and Environmental Engineering. Retrieved from http://northeast.manuremanagement.cornell.edu/Pages/General_Docs/Fact_Sheets/Centralized_Digesters_factsheet.pdf

Chiumenti, R., Chiumenti, A., da Borso, F., Limina, S., & Landa, A. (2009). Anaerobic digestion of swine manure in conventional and hybrid pilot scale plants: performance and gaseous emissions reduction. *American Society of Agricultural and Biological Engineers.* Reno, Nevada.

EIA. (2019, August 9). *EIA uses the heat content of fossil fuels to compare and aggregate energy sources*. Retrieved from US Energy Information Administration: https://www.eia.gov/todayinenergy/detail.php?id=40833#

EIA. (2020a). *Electric Power Monthly*. Retrieved from US Energy Information Administration: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

EIA. (2020b). *Heat Content of Natural Gas Consumed*. Retrieved from US Energy Information Administration: https://www.eia.gov/dnav/ng/ng_cons_heat_a_EPG0_VGTH_btucf_a.htm

EIA. (2020c). *Natural Gas Prices*. Retrieved from US Energy Information Administration: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SIA_a.htm

EPA. (2017, September). *Environmental Benefits of Anaerobic Digestion (AD)*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/anaerobic-digestion/environmental-benefits-anaerobic-digestion-ad

EPA. (2020a, November). *Final Renewable Fuel Standards for 2020, and the Biomass-Based Diesel Volume for 2021*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/renewable-fuel-standard-program/final-renewable-fuel-standards-2020-and-biomass-based-diesel-volume#additional-resources

EPA. (2020b, November). *RIN Trades and Price Information*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information#:~:text=Price%3A%20%240.05%20%26%20Max.,Price%3A%20%243.50

Faulhaber, C. R., Raman, D. R., & Burns, R. (2012). An Engineering-Economic Model for Analyzing Dairy Plug-Flow Anaerobic Digesters: Cost Structures and Policy Implications. *Transactions of the ASABE, 55*(1), 201-209. doi:10.13031/2013.41247

González, R., González, J., Rosas, J. G., Smith, R., & Gómez , X. (2020). Biochar and Energy Production: Valorizing Swine Manure through Coupling Co-Digestion and Pyrolysis. *Journal of Carbon Research, 6*(2). doi:10.3390/c6020043

Lusk, P. (1998). *Methane Recovery from Animal Manures The Current Opportunities Casebook.* Golden, Colorado: National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy99osti/25145.pdf

Moody, L., Burns, R., Bishop, G., Sell, S., & Spajic, R. (2011). Using biochemical methane potential assays to aid in co-substrate selection for co-digestion. *Applied Engineering in Agriculture, 27*(3), 433-439.

Smith, B. C., Andersen, D. S., Harmon, J. D., & Stinn, J. P. (2017). Case study of swine finishing manure nutrient characteristics for land application. *2017 ASABE Annual International Meeting.* American Society of Agricultural and Biological Engineers.

Ward, A. J., Hobbs, P. J., Holliman, P. J., & Jones, D. L. (2008). Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technology, 99*, 7928-7940.