Life Cycle Cost Analysis of the Operations of Anaerobic Digesters in Iowa.

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EXECUTIVE SUMMARY

Anaerobic digestion (AD) is an attractive and beneficial process for the conversion of agricultural, industrial and commercial waste into clean and useful renewable natural gas. Anaerobic digestion is a promising approach to achieving the economic and environmental goals outlined in the Iowa Energy Plan. This project aims to provide a life cycle cost assessment (LCCA) for Iowa anaerobic digesters and to identify opportunities for their profitable operation. Recent technological and policy developments have created opportunities to develop anaerobic digestion by providing an array of options to producers, farmers, and businesses.

This study evaluates the different costs that affect the conversion of manure into biogas for heat, power, and renewable natural gas markets. It describes the capital and operating costs involved in the industrial operations of anaerobic digesters; it evaluates the role of federal and state incentive programs in reducing commercialization risks. Finally, this project creates a business plan for stakeholders to evaluate the different opportunities and feedstocks available for the development of anaerobic digesters in Iowa.

Current results indicate that an anaerobic digester attached to a 2400 head of cattle operation, that is co-digested with glycerin and cornhusk has 950 kW of generation capacity. At a capital cost of $3.12 million, it could achieve an internal rate of return of 4.56% at electricity prices of 6.40 ¢/kWh. By replacing cornhusk with rye and wheat, the internal rate of return is still in the upper range of 4%. The main contributors to the cost include capital, labor, and operating capacity. Solid digestate credit is an important source of revenue based on its C:N content. The role of tipping fees largely depends on the energy content provided by the feed. In particular, glycerin has been shown to enhance the biogas potential of animal manure. Future work will include investigating the aspects related to upgrading biogas, its environmental impacts, and exploring other major policies or incentives that influence an AD system.

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INTRODUCTION

Manure is often categorized as a form of waste, but many disregard its economic value and potential to be a source of income. To many farming operations, manure is valuable as fertilizer that provides nutrients to crops and soils in the form of organic matter. However, manure production requires proper management to avoid undesired environmental and social impacts. Manure can result in methane emissions, which are a potent greenhouse gas with 28-36 times more global warming potential than carbon dioxide (US EPA). With anaerobic digestion, manure can be managed in a practical, yet economical and environmentally sustainable manner (Gebrezgabher et. at., 2010).

Anaerobic digestion is a biochemical process with a series of biological process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis - that uses microorganisms to break down organic matter in the absence of oxygen. AD produces biogas, which mainly consists of methane (approximately 50-70%), carbon dioxide (approximately 30-50%), hydrogen sulfide and other traces of gases such as nitrogen (Wellinger et al., 2013). Besides that, AD also produces by-products, which are highly rich in nutrients, and have potential economic values. Biogas is the main product of AD, and it is used in multiple different forms such as heat, power and can be upgraded into renewable natural gas, creating an even bigger market for renewable energy. With the availability of manure on farms, farmers can generate renewable energy and revenue, while dealing with the reduction of methane emissions and odor in a sustainable and cost-effective manner (Van Horn et al., 1994).

An AD system is a long-existing technology. There is a growing interest in using AD on organic waste such as manures, crop residues and industrial residues in the United States. However, it has been reported that the failure rate of a U.S. farm-based AD system is more than 50%. This failure rate was not only due to the system’s complicated design, but mostly, because of the limited economic sustainability (Beddoes et al., 2007). Despite that, there have been technological advancements, due in part to subsidies from the U.S. Department of Agriculture (USDA) and U.S. Department of Energy (DOE), and newly created incentive programs created to improve and encourage AD. Many studies have shown that it is possible for a farm-based AD system to be economically feasible. For instance, studies have shown that a farm-scale biogas plant of 280kWh of electricity has a positive net present value (NPV) of €27.74 ($34.16) million (Akbulut, 2012). Other studies have also reported that an AD system is economically viable for large farms, which are those with more than 500 cows in the farm (Klavon et al., 2013). Besides that, the use of digestate for agricultural applications is also the key to their economic feasibility. Furthermore, this can be environmentally sustainable, as the cost of fertilizers will be reduced (Pantaleo et al., 2013).

This study aims to investigate the profitability and sustainability of a 2400 cattle-based AD system. A few factors affecting the economic feasibility of a plant are the capital cost and the ability to generate adequate revenue from the digester. Although many studies report the economic feasibility of a farm-based AD system, most of the information regarding the initial investment, operating costs, biogas yields, and electricity prices is unavailable to the public. Therefore, the limited access to this financial information can heavily influence the demand to invest in these systems.

METHODOLOGY

This study conducts a life cycle cost assessment economic (LCCA) of a 950-kW anaerobic digestion process. The process converts a mixture of cow manure, an agricultural crop (corn husk, rye, or wheat), and glycerin into biogas. The biogas is then combusted to generate electricity and heat. This summary describes the process design, the economics of this conversion process, and the risks involved in this project.

I. PROCESS DESIGN

Figure 1 describes a simplified block diagram of the overall process. This process block diagram is based on a case study of electricity and heat generation from a farm-scale biogas plant. This process consists of four technical areas - mixing of the feedstocks, anaerobic digestion, by-products separation and steam and power generation. The solids lines in the figure depict the flow of feedstocks to the product. The dashed lines represent the heat produced in the system, while the dotted lines are the paths where heat is recycled back into the system. A mix of raw manure, glycerin and agricultural feedstocks are prepared and mixed into a slurry form before entering the digester, where anaerobic digestion happens. AD produces biogas and digestates. The biogas will be sent to a combined heat and power (CHP) unit, where it will generate electricity and heat. Electricity is sold to the grids, while heat is recycled in the process. Similarly, the digestate undergoes a separation and dewatering process and is distributed to the farm as fertilizer or livestock bedding.

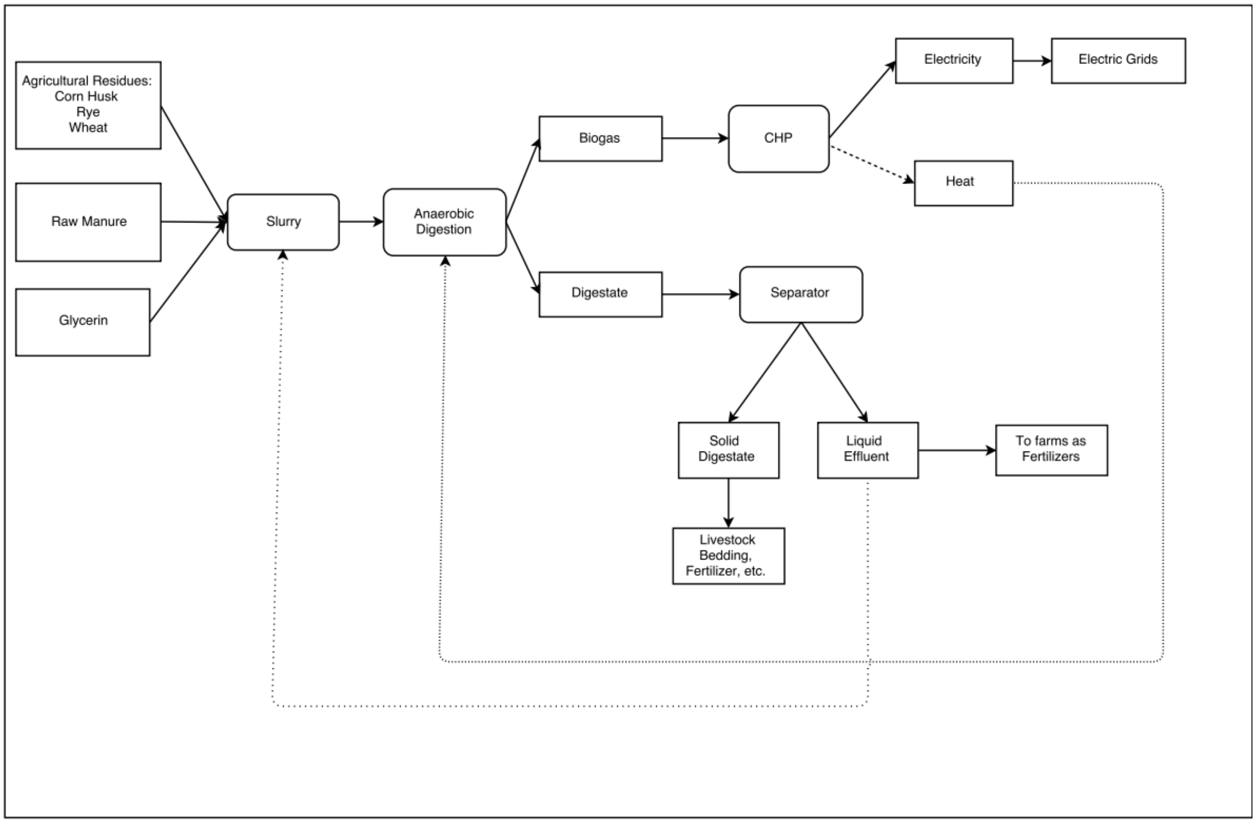


Figure 1: Process Block Diagram of an Anaerobic Digestion System (Akbulut, 2012)

The ultimate and proximate analysis of each feedstock used in the process is presented in Table 1. This study assumes that raw manure has a moisture content of 88% and is expected to be at 9% total solids (TS) before digestion. Hence, the system initially mixes raw manure with water, forming manure slurry. The digestion is categorized as a wet digestion when feedstocks have less than 20% TS. Generally, AD is not economically feasible when the total solids content of the feedstock is less than 5%. This is because the feedstock would most likely have low energy contents (Baldwin et. al, 2009).

According to the ECN's Phyllis2 database for biomass and waste, the higher heating value (HHV) and carbon content of manure are 20000MJ/ton and 0.39% respectively. The volatile solids content for manure is obtained from the Manure Characteristics chapter from the Manure Management Series by Lorimor et al. According to the Biogas Handbook, methane yield of cattle manure is estimated to be 200 m^3/ton. It is also estimated that 50-75% of the biogas is methane. In this study, a ratio of 5:3 of biogas to methane yield is assumed. With this assumption, the biogas yield of cattle slurry is estimated to be approximately 333 m^3/ton (Wellinger et al., 2013).

Table 1: Proximate and Ultimate Analysis of Selected Feedstocks

Element / Feedstock	**Moisture Content (%)**	**Volatile Solids (kg/kg)**	**Higher Heating Value (MJ/tons)**	**Biogas Potentials (m^3/ton)**	**Methane Potentials (m^3/ton)**	**Carbon Content (%)**
Manure	88	0.85	20000	333	200	0.39
Corn Husk	60	0.94	18880	585	348	0.44
Glycerin	-	1.00	16000	306	183.6	0.88
Rye	60	0.96	17020	387.5	232.5	0.49
Wheat	60	0.98	17678	405	243	0.43

This process also studies the co-digestion of manure with agricultural biomass such as cornhusk, wheat and rye, and glycerin, an organic waste. Co-digestion is beneficial in this process in terms of increasing biogas yields. Although manure is one of the most available resources in many farms, it is often co-digested with agricultural and industrial waste, such as: crop residues, food, and beverage, starch, sugar, pharmaceuticals, and biochemicals. Industrial waste is often encouraged, mainly because they are known to be homogenous, rich in lipids, proteins, and sugars, and also easily digestible; in other words, they are known as "methane boosters" (Wellinger et al., 2013). Most organic waste has higher methane yield than manure. For instance, they are often in the range of 30-500 methane per cubic meter of feedstock (Angelidaki, 2002). Glycerin has a methane potential of approximately 184m^3/ton. Hence, by incorporating industrial waste like glycerin with cattle manure, biogas yield will certainly increase. Furthermore, co-digestion of manure with industrial waste can increase process stability by preventing inhibitors such as ammonia. This can also help economically, as biogas plants can get supplementary income known as “gate or tipping fees” (Wellinger et al., 2013). In this study, glycerin has a HHV of 16000MJ/ton. This data was obtained through a study of glycerol combustion and emissions by Myles et. al (2011). The volatile solids and carbon content of glycerin was estimated to be 0.99 kg/kg and 0.88% respectively. These values were obtained via similar studies as well (Astals, 2011; Aguilar, 2017). In an optimization of co-digestion study by Aguilar et al., the reported biogas yield for glycerin is between 217-308 m^3/ton. The ratio of biogas and methane yield is also computed to be 5:3.

This study also includes the co-digestion of manure with agricultural biomass. The biomass investigated in this study are cornhusk, wheat, and rye. The properties of cornhusk are as such: the HHV of corn husk is 18880MJ/ton and was also obtained from the same database - ECN Phyllis2. According to Li et al.’s (2011) study on biogas production from co-digestion of corn and chicken manure, the volatile solids and carbon content of corn is estimated to be 0.94 kg/kg and 0.44% respectively. In this study, the moisture content of cornhusk is assumed to be at 60%. The biogas and methane potential of cornhusk are 585 and 348 m^3/ton respectively. This was obtained through a study of corn stover for biogas production (Lizasoain et al., 2017).

The other feedstocks investigated in this study are wheat and rye. It is also reported in an AD study that the volatile solids and carbon content of wheat are 0.98 and 0.43 respectively (Cui et al., 2011). The volatile solids for rye is 0.96 kg/kg and was also obtained from a co-digestion study (Li et al., 2015). The higher heating value and carbon content of rye were also obtained from the ECN Phyllis2 database. The biogas potentials for wheat and rye was obtained through the CROPGEN database provided by the National Non-Food Crops Centre (NNFCC). The same method used to estimate the methane yield from biogas potential in glycerin is employed with wheat and rye. The moisture content of both wheat and rye are assumed to be the same as the moisture content of corn husk. This is to ensure consistency in the analysis.

The digester is also operating at mesophilic temperatures, at approximately 35℃. Although the rate of a chemical reaction is supposed to increase with temperature, digesters operating at mesophilic temperatures are more stable and easier to handle in comparison to digesters operating at thermophilic temperatures ($55 - 60$°C) (Baldwin et al., 2009). The thermal and electrical efficiencies assumed in this project are 45% and 42% respectively, which are the typical efficiencies for a gas turbine as quoted from the Biogas handbook by Wellinger et al. (2013). Also, according to the Biogas handbook, the typical organic loading rate (OLR) for a continuously stirred tank reactors (CSTR) is between 2 and 3 kg VDM/m^3-day. It is also reported that a biogas plant with a complete-mix anaerobic digester has a hydraulic retention time (HRT) of 10-25 days (Chen and Neibling, 2014). However, feedstock substrates consisting of fats and oils and known for having higher methane yields would normally require a longer HRT and larger digester volume as well (Wellinger, 2013).

II. ECONOMICS

The techno-economic analysis methodology proposed by Peters and Timmerhaus (2004), was used to determine the economic feasibility of this study. The major costs involved in this study are the capital cost, operating cost, and maintenance and labor cost.

The capital cost of this study was based on Process Design for Biochemical Conversion of Lignocellulosic Biomass to Ethanol by NREL (Humbird et al., 2011). In that study, the Harris Group also managed to obtain vendor quotes on the equipment and were able to provide estimates for them used in the study. Based on the specifications detailed in the report, the AD processes in both studies are very similar. Hence, it is assumed that similar equipment is used in both studies. The equipment cost provided in the report by NREL was computed based on a baseline flow of 9434 tons/day. Employing the 'Economy of Scale Law' in capital cost described by Jenkins' et al. (1997), the installed capital cost is computed for all the equipment based on a scaled flow of 144 tons/day. The scaled flow is obtained from the mass and energy balances. Subsequently, the scaling exponent for all the equipment except for the gas turbine used in the combined heat and power (CHP) unit is 0.6. This value, given by Peters and Timmerhaus, was predicted based on the sixth-tenth factor rule, whereby cost data can be estimated for new equipment of similar capacity. The gas turbine has a scaling exponent of 0.72. Based on the study by Daugaard et al. (2015), it is reported that bio-refineries have exhibited scaling factors between 0.63 to 0.72 for thermochemical processes. Hence, a 0.72 scaling exponent was assumed in this study for the power generator. A storage cost was also included for the storage of liquid effluent. This cost was estimated based on the total number of cows on the farm and the average liquid effluent produced per cow as suggested by the Natural Resources Conservation Service (Edmonds et al., 2003).

Table 2: Operating Cost Assumptions for the Economic Analysis

Data	Price ($/metric ton)	Consumption per year (metric ton)
Manure	$5	22,995
Corn Husk/Rye/Wheat	$20	2,875
Glycerin	$0	1,150
Solids Handling	$5	2,411
Liquid Effluent Credit	-$2.64	16,380
Solid Digestate Credit	-$35.25	2,411
Renewable Tax Credit	-$0.015/kWh	12.53 GWh
Labor & Maintenance	2% of FCI	-
Power Cost	$0.064	6.07 GWh

Table 2 summarizes the assumptions used to calculate the operating cost of an anaerobic digester operation. According to the DOE's U.S. Billion-Ton study, the delivered costs of agricultural residues range between $10 to $30 per dry ton (Perlack et al., 2005). Since they are collected and distributed locally, the cost of corn husk was assumed to be $20 per ton. This study also assumes the cost of manure to be bought at $5 per ton. Glycerin was assumed to be available at no additional cost based on a negligible tipping fee. The solid digestate and liquid effluent were assumed to generate by-product credits at prices of $(35.25) and $(2.64) per ton. Both solid digestate and liquid effluent have credits as they are assumed to be recycled and used on the farm as fertilizers. However, solid digestates incur an additional handling cost of $5 per ton. Additionally, the Iowa Utilities Board also grants a renewable tax credit of $(0.015) per kWh of energy generated from biogas. The cost of electricity assumed in this study is 6.40 ¢/kWh, which is lower than the average rate of electricity of 12.60 ¢/kWh in the state of Iowa in 2017 (Energy Information Administration, 2018). This is mainly because biogas facilities sell their electricity to local power companies at a contracted rate, often times lower than the average cost of electricity.

The other half of the operating cost is comprised of labor and maintenance cost, depreciation and taxes. Labor cost includes the salary for a plant manager and two-yard employees. Both salaries are assumed to be $71,900 and $60,000 per year respectively. These salaries were assumed from the 2011 Bureau of Labor Statistics' database. The overhead and maintenance which includes lab technicians contribute $6595 per year, and insurance costs $62,500 per year.

Once the Equipment Cost is obtained, the Fixed Capital Investment (FCI) and Total Project Investment (TPI) can be determined using Peters and Timmerhaus factors. The insurance was computed based on Peters and Timmerhaus' assumptions, where it is 2% of the Fixed Capital Investment, while the overhead and maintenance cost are 5% of the Labor Cost. The results were then used as inputs into the discounted cash flow rate of return (DCROR) analysis spreadsheet to compute the IRR. Table 4 details the main assumptions in the economic analysis.

Table 3: Major Economic Analysis Assumptions

Plant life (years)	30
Operating hours per year	6570
Equity	40%
General Plant Depreciation	200 Double Declining Balance (DDB)
Steam Plant Depreciation	150 DDB
Depreciation Period (years)	
General Plant	7
Steam Plant	20
Construction Period (years)	2.5
Fraction spent in year – 3 (%)	8.00
Fraction spent in year – 2 (%)	60.00
Fraction spent in year – 1 (%)	32.00
Start-up Time (years)	0.5
Revenue (% of normal)	50%

Variable Cost (% of normal)	75%
Fixed Cost (% of normal)	100%
Income Tax	39%

The DCROR analysis was conducted based on the major assumptions tabulated in the table above. The DCROR varies the IRR to achieve a 0 Net Present Value (NPV) over a 30-year period at electricity of 6.40 ¢/kWh. Finally, the Earnings Before Interest, Taxes, Depreciation, and Amortization (EBIDTA) for the project is also calculated.

III. RISK ANALYSIS

Sensitivity analysis was conducted in this study to investigate the significant impacts of each operating parameter towards the IRR. The sensitivity analysis was computed about the baseline values and has a range of ± 20%. The assumptions used in the analysis is tabulated in the Table below.

Table 4: Operating Parameters and Assumptions for Sensitivity and Uncertainty Analysis

Operating Parameters	**Distribution Shape**	**Unfavorable**	**Base Case**	**Favorable**
Power Efficiency (%)	Triangular Distribution	33.4	42	50.4
Operating Capacity (%)	Triangular Distribution	68	85	102
Capital Cost ($MM)	Triangular Distribution	3.75	3.12	2.50
Waste per Cattle (tons/day)	Triangular Distribution	0.028	0.035	0.042
Manure Price ($/ton)	Triangular Distribution	6	5	4
Solid Digestate Price ($/ton)	Triangular Distribution	-28.20	-35.25	-42.30
Biomass Price ($/ton)	Triangular Distribution	24	20	16
Liquid Effluent Price ($/ton)	Triangular Distribution	-2.11	-2.64	-3.17

The IRR and NPV were selected as sensitivity variables in this study because of the uncertainty associated with the estimate. For the uncertainty analysis, the NPV is measured. This is because the uncertainty in the NPV can also be caused by the variability in operating parameters. Using the Monte Carlo analysis, the operating parameters from the sensitivity analysis are incorporated directly into the financial spreadsheet. A triangular distribution was assigned to the NPV and all its variables. Data sets with 10,000 random samples are obtained from the probability distributions. The uncertainty analysis results were reported as distributions of NPV.

RESULTS

I. MASS AND ENERGY BALANCE

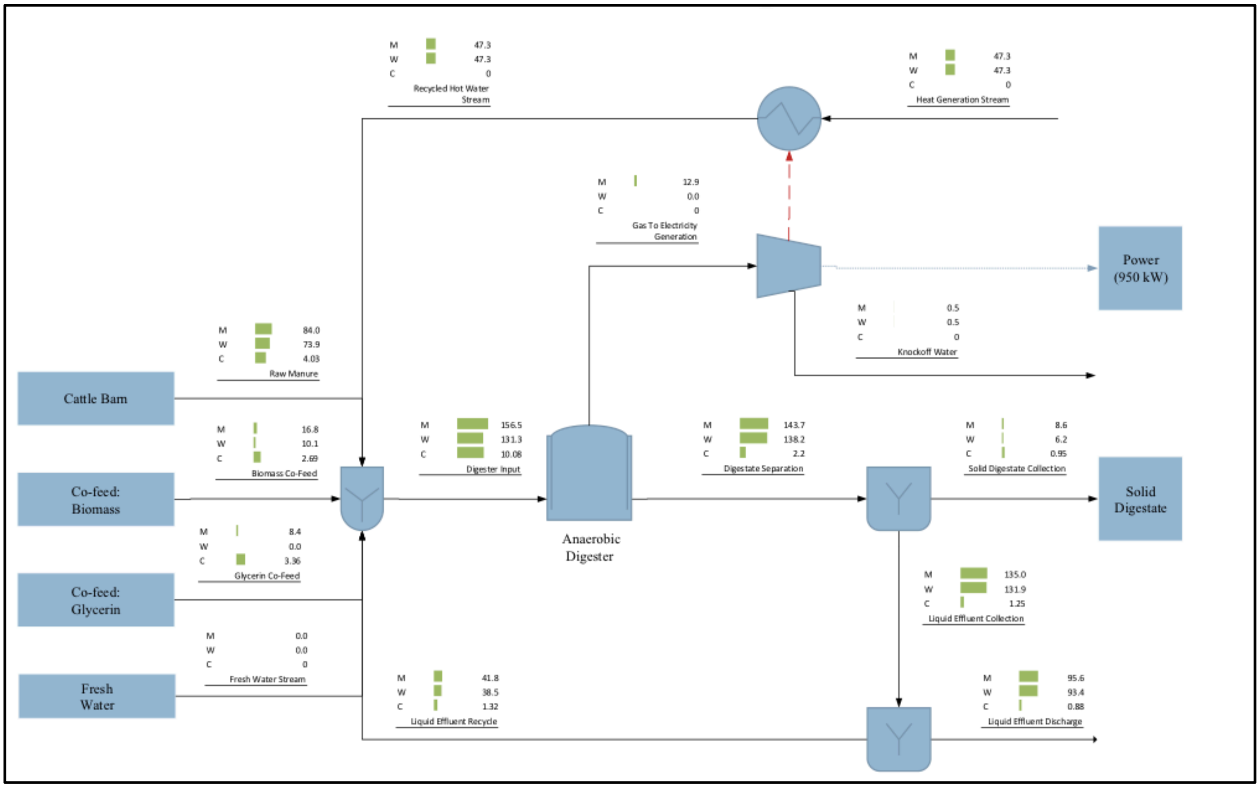


Figure 2: Process Flow Diagram of an Anaerobic Digestion System

Figure 2 describes the process flow diagram of the system. The figure shows the mass, volume and carbon flows in the system. The inputs of the digester include wet cattle manure (84 tons per day), glycerin and cornhusk. In this study, different feedstocks such as rye and wheat are studied as replacement of cornhusk in the process. Through the mass and energy balance conducted, the digester requires a combination of 7 and 3 wt. % of agricultural crop and glycerin respectively to produce approximately 950 kWh of electricity. Since this is a wet digestion process, water is added into the mixture of manure and co-feeds producing a slurry. This yields 134 tons of digester input per day. After AD, the digester generates 8,342 cubic meters of biogas containing 3.56 tons of methane per day. A gas combined heat and power unit generates up to 950 kW of electricity from the biogas and 34 tons of heat in the form of steam. The heat generated is recycled to heat the digester, which lowers the operating cost, as steam does not need to be purchased. AD also creates by-products called digestates, both in liquid and solid form. The process produces solid digestate (5.4 tons per day) and liquid effluent (114 tons per day) containing carbon and nitrogen among various soil nutrients, which can be employed on-site to reduce fertilizer costs. The solid digestate is dewatered and can be used as fertilizers and livestock beddings. Approximately 43% of the liquid effluent are also recycled and used to create slurry mixtures of manure and its feedstocks. This amount of electricity generated by the system translates to approximately 0.40 kW/cow.

The system also has a continuous demand in electricity and heat to operate mixers and blowers on the plant and maintain the temperature of digester at mesophilic temperatures respectively. Based on Li et.al.'s (2018) study on solid state anaerobic digestion, the parasitic load can be computed using the factor of 0.0082 kWh/kg of input on a dry basis. This yields a parasitic load of approximately 137 kW. For the heating load, it is assumed that heat is only required to maintain digester at mesophilic temperatures. Hence, heat is added into the system via feedstock and recycled hot water. From this assumption, it is computed that the heat load required by the system is approximately 152 kW. After taking into account both parasitic and heat load, the system generates a total of 12.53 GWh per year of energy. The energy, carbon, and mass flows are also illustrated as Sankey diagrams in the Appendix.

II. ECONOMICS

The total project investment that includes the capital cost, indirect cost, and working capital is estimated to be $3.12 MM. Capital costs for a 2400-cattle based anaerobic digester operation in Iowa is tabulated in the table below.

Table 5: Capital Costs of an Anaerobic Digestion Operation

Equipment	Total
Digester	$2,126,500
Other	$4,500
Storage	$90,000
CHP	$903,100
Grand Total	$3,124,200

The majority of the cost is attributed to the digester and CHP unit, which are estimated at $2.13 million and $0.90 million respectively. The total cost translates to an expense of $1302/cow or $0.40/kWh, which are comparable to values reported by the Environmental Protection Agency (EPA) of $258-2820/cow and $0.46-3.15/kWh.

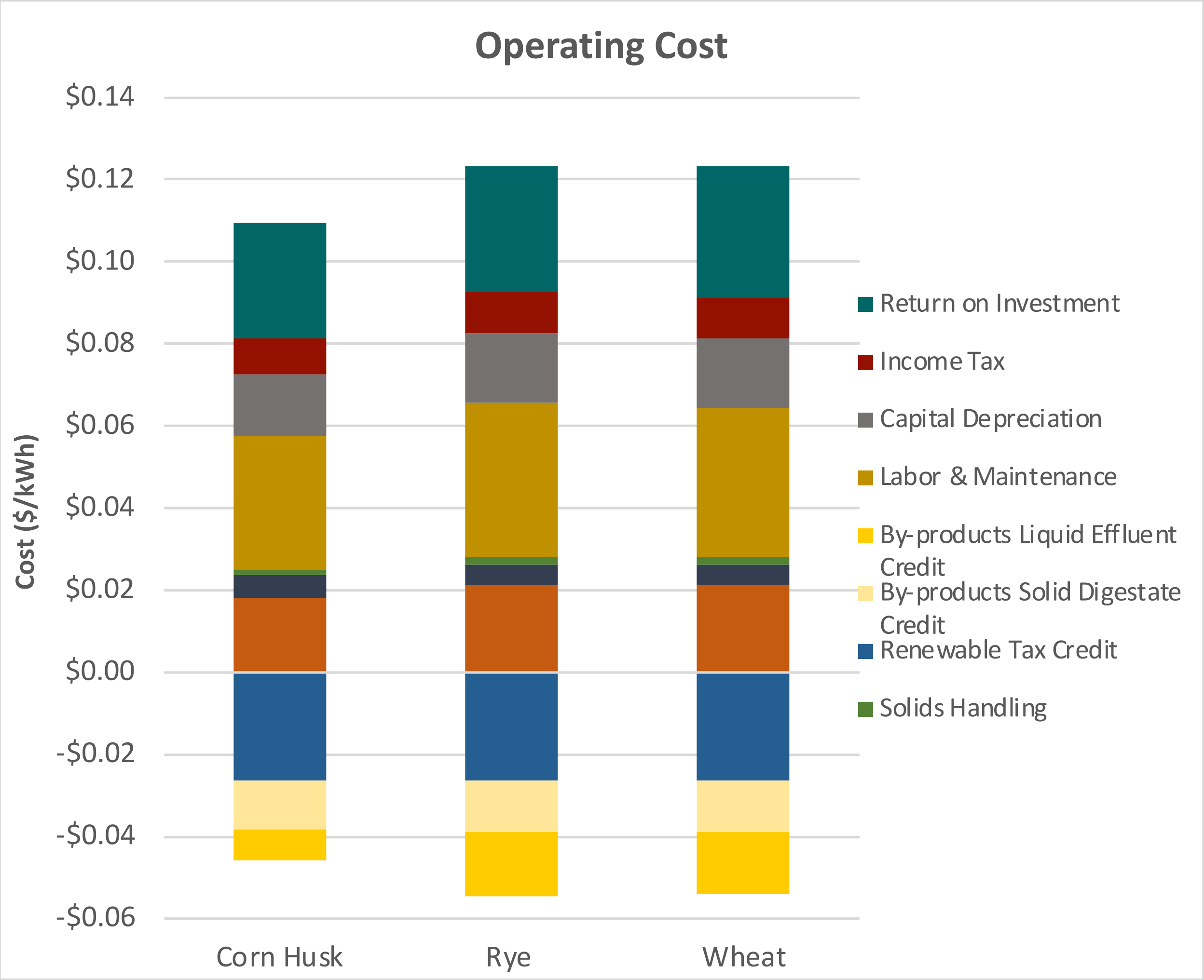


Figure 3: Annual Costs of Operating the Anaerobic Digester

Figure 3 summarizes the annual operating costs of the anaerobic digester for corn husk, rye, and wheat. The total variable operating costs are the cost of raw materials and by-products credits and handlings. The by-products credits are primarily from the sale or reuse of fertilizers. There is no cost from electricity, as the process generates enough electricity to power the process itself and allows for sale of excess electricity. The Renewable Tax Credit is claimed on the net power and thermal energy generated, which is after the deduction of parasitic and heat load. This allows the project to claim a total of $187,900 per year which is a significant amount in lowering the total operating costs. From the figure, it can be observed that despite the large cost for labor and maintenance, the project also has a substantial amount of credits to be claimed from having by-products and generating renewable energy.

Table 6: Internal Rate of Return of Co-digestion of manure with varying feedstocks

Biomass	Corn Husk	Rye	Wheat
IRR (%)	4.56	4.38	4.49

Table 6 tabulates the IRR of the project based on the co-digestion of manure and its respective biomass. From the DCFROR analysis, the project achieves an IRR for all varying biomass in the upper range of 4%. The DCFROR analysis was computed based on a project lifetime of 30 years, and capital depreciation and income taxes of 7-years and 39% respectively. Through this analysis, co-digestion of manure and cornhusk has the highest IRR, while the digestion of manure and rye has the lowest IRR. Table 7 tabulates the EBIDTA data. The EBIDTA of the project is $498,530. Based on the electricity price of $0.064 per kWh, the EBITDA is estimated at $0.07 per kWh.

Table 7: Earnings Before Interest, Taxes, Depreciation, and Amortization

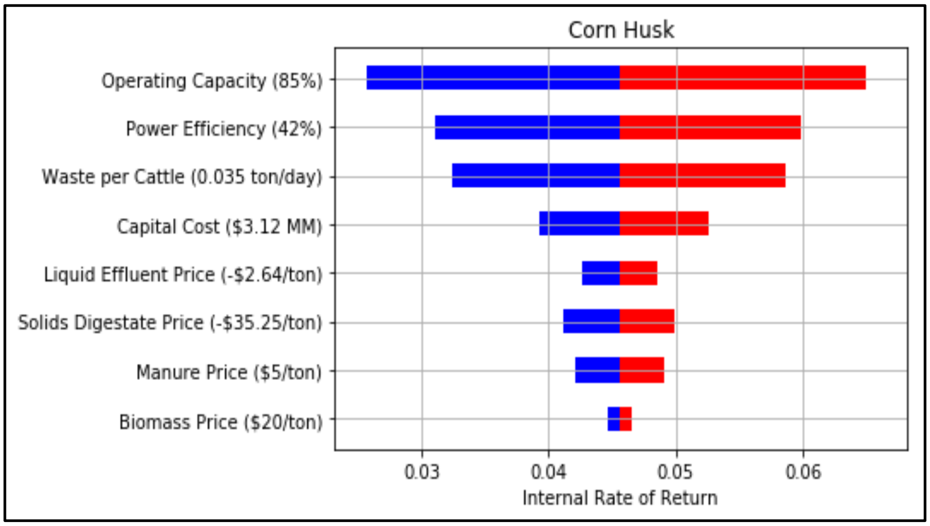
Data	**Cost ($/year)**	**Cost ($/kWh)**
Earnings	$585,284	$0.08
Operating Costs	$86,757	$0.01
EBITDA	$498,527	$0.07
Depreciation	$104,139	$0.01
Interest	$251,710	$0.04
Taxes	$142,679	$0.02

A combination of capital and operating costs incentives could make biogas electricity from this system cost competitive, and they will be explored in future work.

III. RISK ANALYSIS

The figures below depict the results of the sensitivity analysis of the IRR from its operating parameters for a favorable case and unfavorable case. Favorable assumptions are higher operating capacity, waste per cattle and power efficiency and lower biomass price, digestate credits and capital cost. These operating parameters can highly impact the performance and economics of the process.

a



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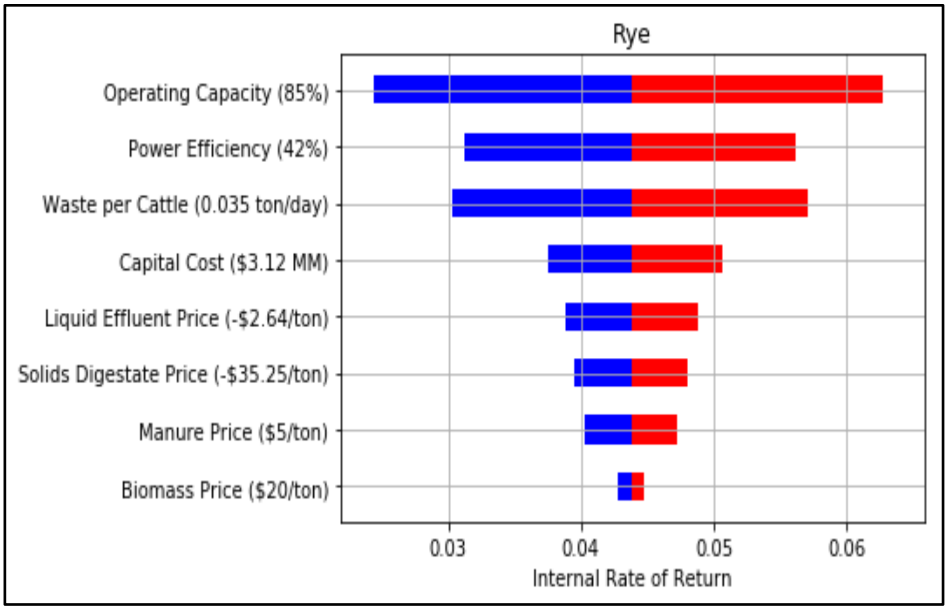

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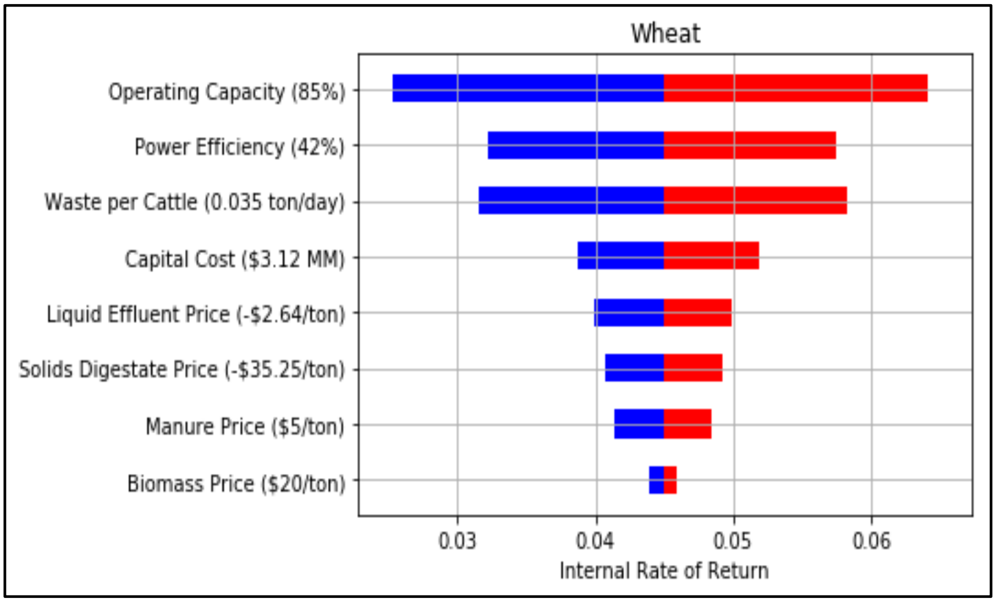

Figure 4: Impacts of Operating Parameters on Sensitivity Analysis for the Agricultural Feedstocks: a) Corn husk, b) Rye and c) Wheat

Through this analysis, it can be observed that for all the various biomass, the three most impactful parameters are the operating capacity, waste per cattle and power efficiency. Although, in the scenario with rye and wheat, the effects of waste per cattle is more significant than the effects of power efficiency. Additionally, the liquid effluent credit is also more significant in rye and wheat, in compared to corn husk. Otherwise, for all three parameters, biomass price is the least significant among all other parameters. An uncertainty analysis was also performed on the process with varying agricultural feedstock for the NPV for each case. Figure 4 shows the fitted probability density functions (PDF) of the NPV for the three different feedstocks.

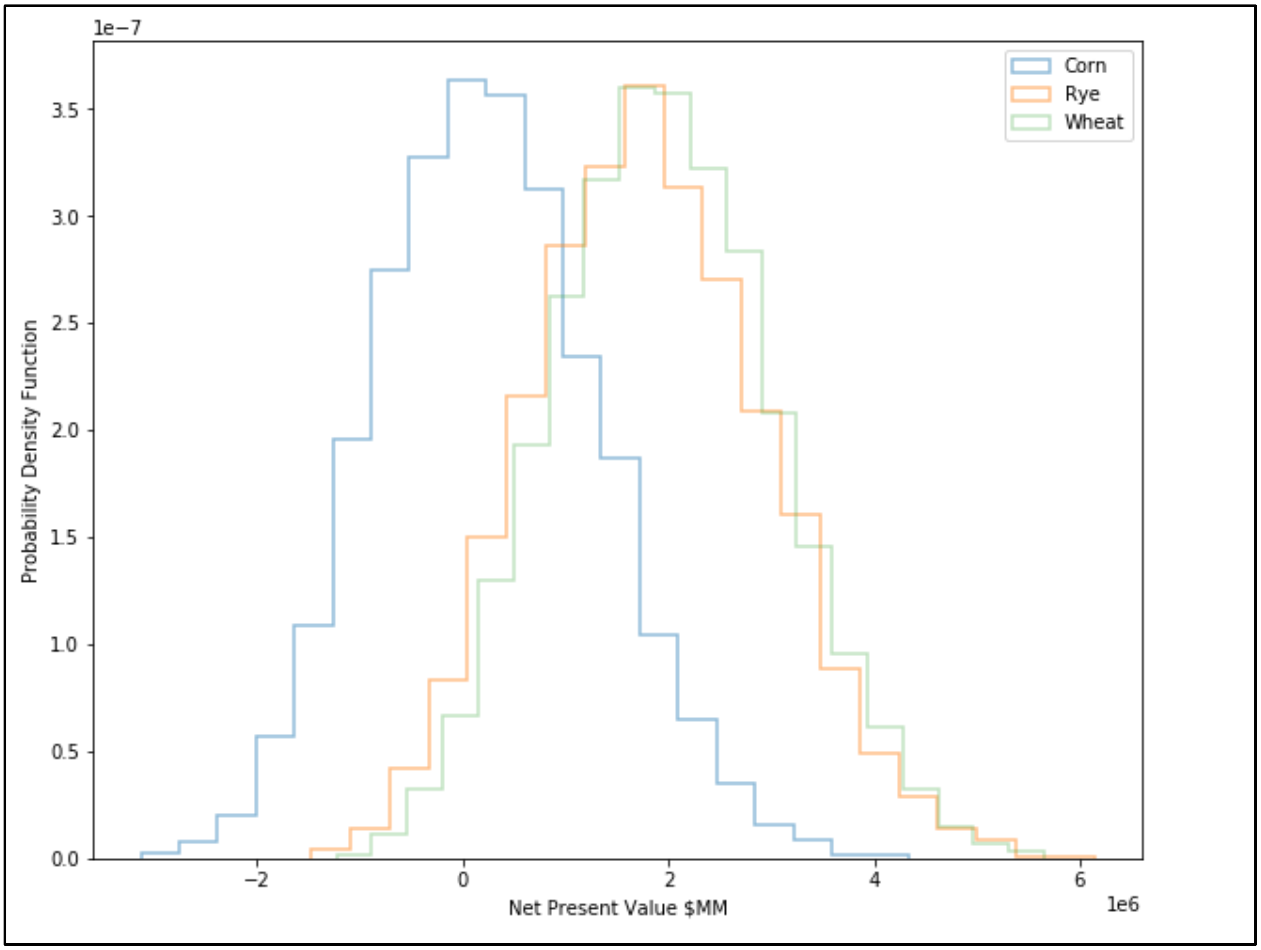

Figure 5: Probability Density Function of Net Present Value for Corn, Rye, and Wheat

From the analysis, it can be observed that co-digestion of manure and wheat or rye has the highest NPV average of approximately $2.5MM, in compared to the co-digestion with corn. Although, corn has the lowest NPV average, it has the highest probability in obtaining the highest internal rate of return in compared to the scenario with wheat and rye. Based on Figure 6, it can also be observed that for all three scenarios to obtain a NPV of $2MM, wheat and rye has a probability of 30-35%, while corn has a probability of 8-10%. In all three cases, there is a possibility that the project will yield a negative NPV. The scenario of co-digestion with corn has the largest probability of yielding a negative NPV of approximately 42%, while the probability of yielding a negative NPV with the co-digestion with wheat and rye is approximately 3.7%.

CONCLUSION

This project's primary objective was to evaluate the costs of generating biogas power from a cattle-based operation in Iowa, and subsequently, the system's economic feasibility. Through the economic analysis, the capital cost of this system was estimated at \$3.12 MM, where the cost of the digester unit is most significant. The operating costs are \$344,000 per year which comprises mostly from the cost of labor and maintenance which are \$232,000. Labor costs could be restructured since the operation is co-located with a farm operation. The by-products credits of solid digestate and liquid effluent respectively, \$(35.25) and \$(2.64) per metric tons lowers the fertilizer cost on the farm, as nutrient-rich digestate from the process can be recycled for this purpose. The ability to qualify for the Renewable Tax Credit by the Iowa Utilities Board also reduces the operating cost by over 40%. The plant is also operating at 85% which is 7,446 hours per year. Using the DCROR analysis based on a 30-year project lifetime and a minimum selling electricity price of 6.40 ¢/kWh, the IRR for a 2400-cattle based anaerobic digester operation in Iowa is within the upper range of 4% for all three different agriculture feedstocks. The feedstock that yields the highest IRR of 3.71% when digested with manure and glycerin is cornhusk. From this study, it also can be observed that the methane yield and IRR increase approximately 2 times as much when 3 wt. % of glycerin is added into the digester. This result is similar to those indicated in literature. This project also yields a positive EBITDA of \$498,530.

Risk analysis was conducted on this project to evaluate commercialization risks of the technology used in an AD operation. The IRR's sensitivity range is $\pm 20\%$.Through the sensitivity analysis, it can be seen from the tornado charts in Figure 4, that the three most significant parameters that will impact the IRR are the operating capacity, waste per cattle and power efficiency. For all three cases, biomass price is the least significant parameter. From the uncertainty analysis, it can be observed that AD with rye and wheat results in a greater NPV average in compared to the co-digestion with cornhusk. Additionally, wheat and rye has an average of just 4% probability of falling in the negative NPV region. Future work will identify the range of potential costs for the digester unit, as it affects the capital cost of the project the most.

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APPENDIX

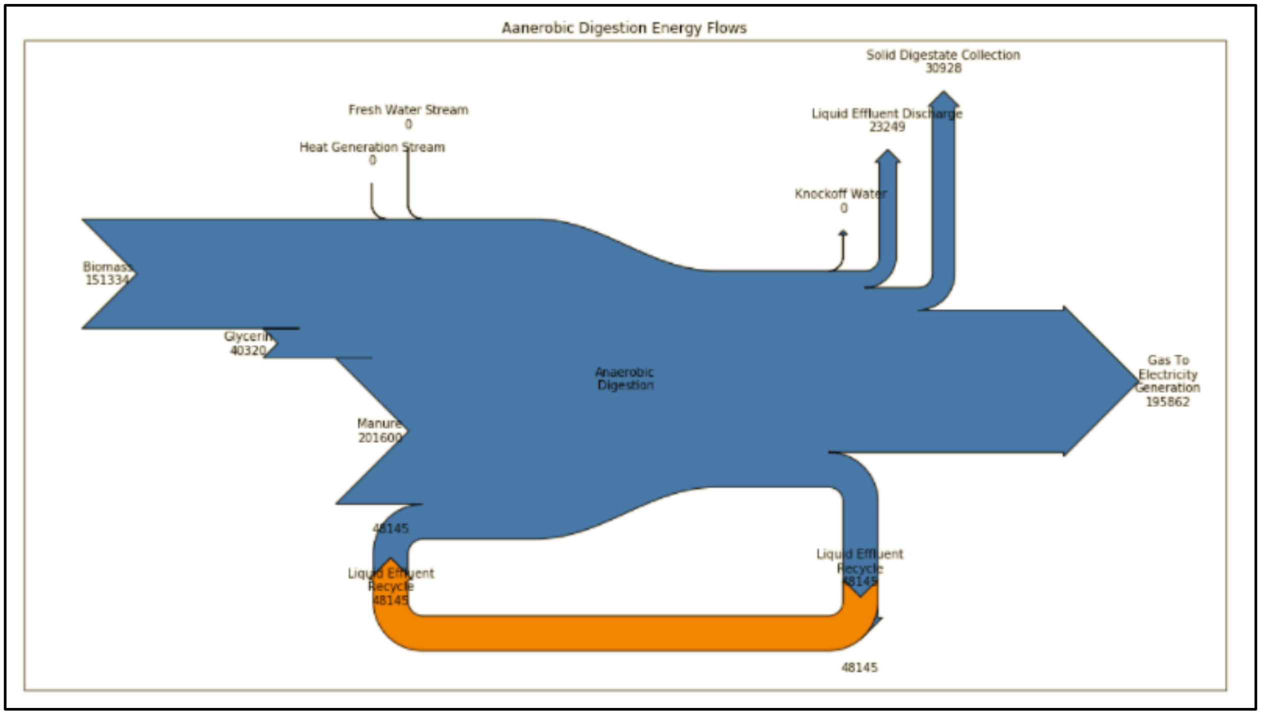

Figure 6: Energy flow of Anaerobic Digestion System

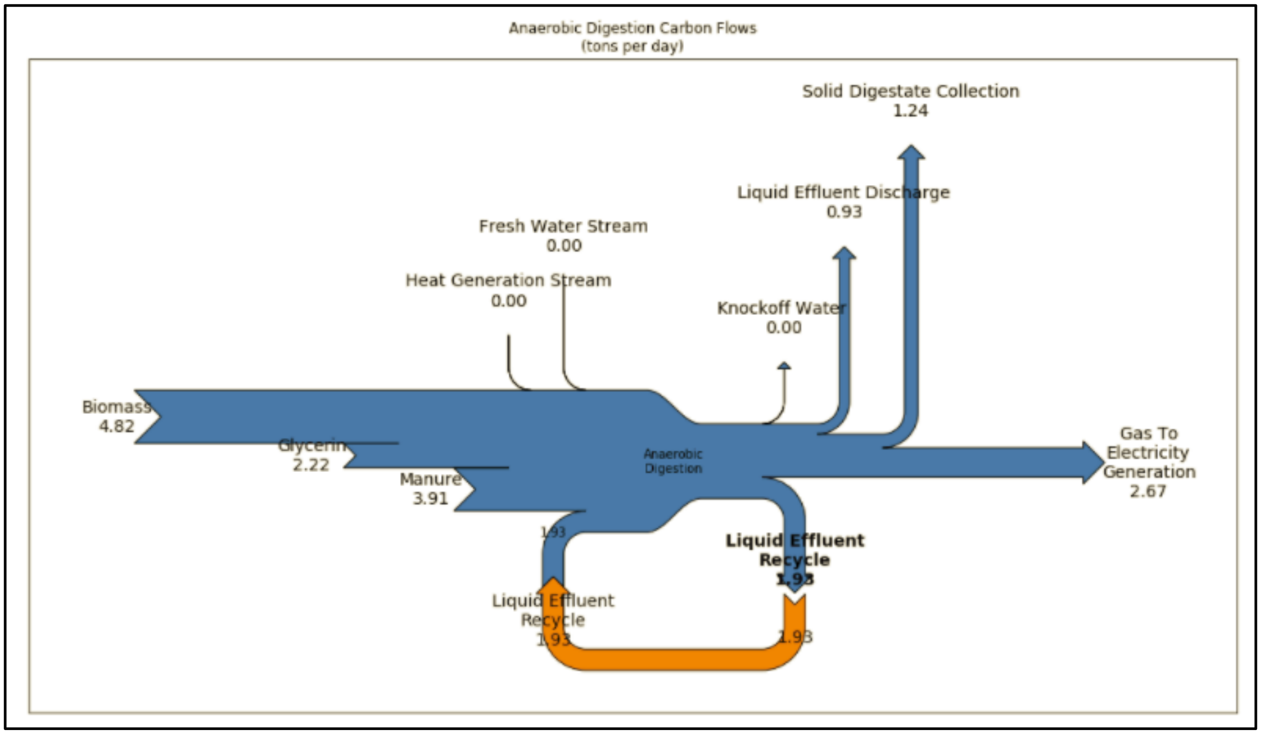

Figure 7: Carbon flow of Anaerobic Digestion System

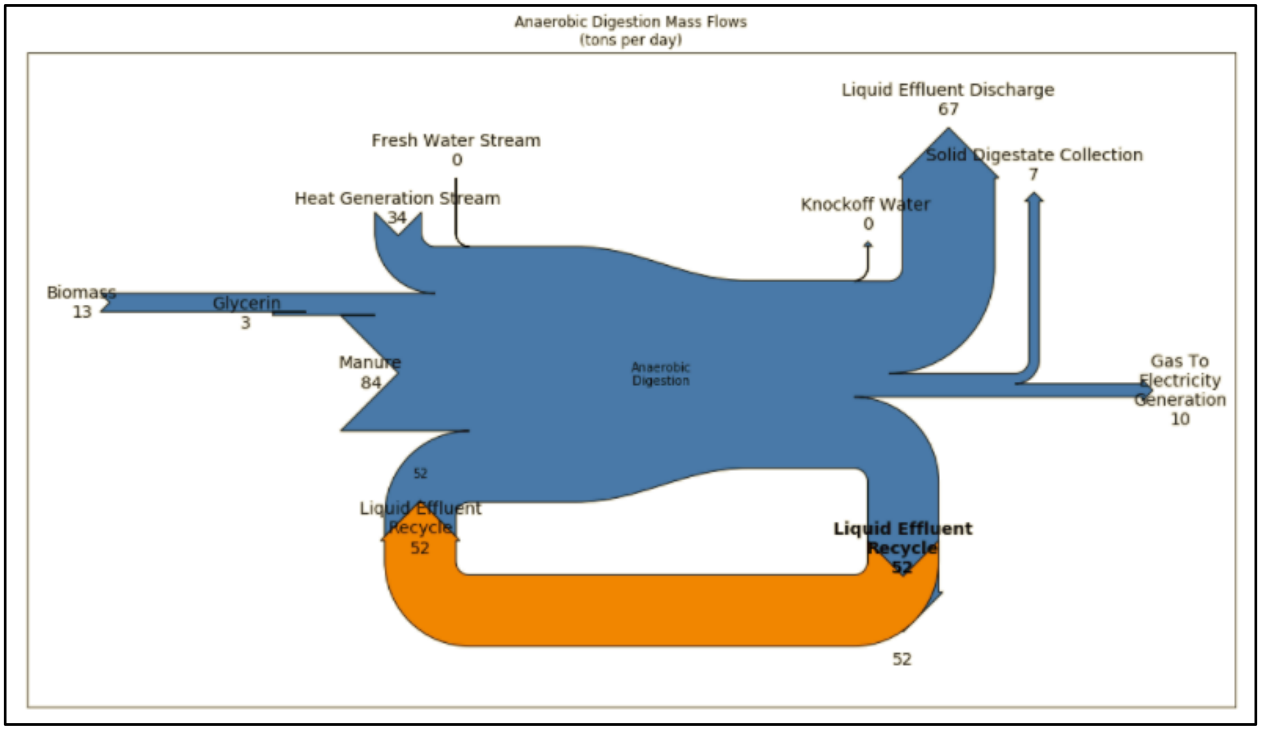

Figure 8: Mass flow of Anaerobic Digestion System