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***Estimating the Economic Value of the Greenhouse Gas
Reductions Associated with Dairy Manure Anaerobic Digestion
Systems Located in New York State Treating Dairy Manure***

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ABSTRACT. *There are a number of benefits that anaerobic digestion (AD) of dairy manure conveys to the farm and to society as a whole. Historically, the major benefits have included odor control and the potential to generate income from the energy produced and from tipping fees received for imported organic waste co-digested – these and multiple other significant benefits are provided in Appendix A. Despite the many benefits AD offers, it has not been widely adopted by US dairy farms to date since the cost to own and operate an anaerobic digestion system (ADS) generally exceeded the revenues and direct avoided costs. From the perspective of the value of renewable energy produced, the price paid by the utility for the electricity generated has not fully valued the greenhouse gas (GHG) reductions that an ADS is able to deliver. The valuation of all benefits associated with AD is important to determine, in order to promote public policies that expand opportunities to implement renewable energy in New York State.*

GHG emission reductions (i.e., the mass of carbon dioxide equivalents [MT CO₂ eq.] associated with AD (in this analysis, an ADS followed by solid-liquid separation with liquid effluent stored long-term) in NYS, were quantified in this paper using the most current quantification protocols available. The reductions quantified include: 1) the replacement of fossil fuel-based electrical energy by using AD produced biogas to fuel an on-site engine-generator set, and 2) the GHG emissions (methane and nitrous oxide) from long-term manure storages required by a farm's Concentrated Animal Feeding Operation (CAFO) permit (for water quality purposes).

The difference between the baseline condition (4.58 MT CO₂ eq/cow-year) and the conditions post-implementation of an ADS, yields the farm's net GHG emissions associated with the implementation of an ADS (2.94 MT CO₂ eq/cow-year). The US Environmental Protection Agency (EPA)'s "social cost of carbon" (SC- CO₂) can be used to quantify the economic value of the reduced GHG emissions associated with AD. Using the net GHG reduction value and a three-year average SC- CO₂ of \$47.82/MT CO₂ eq. (average value used by the NYS Public Service Commission in a zero emission credit from US EPA at 3% discount value and adjusted for inflation over 2017 to 2019) (EPA, 2016), the GHG reduction component of the environmental economic value of farm-based AD (Eghg), expressed on an electrical energy generated basis is \$0.072/kWh. This value is in addition to the value of the electrons generated. If organic substrates are diverted from a landfill and used as co-digestion substrates, the Eghg would be increased; landfill diversion of organic waste is being discussed in NYS and has already been implemented in some neighboring states.

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INTRODUCTION

There is a worldwide concern in controlling the anthropogenic emissions of greenhouse gas (GHG) emissions. GHGs pertinent to this paper, include carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) and are expressed as CO₂ equivalents (CO₂ eq.). On a 100-year basis, CH₄ is 34 times as potent as CO₂, while N₂O is 298 times as potent as CO₂ (IPCC, 2013); CO₂ eq. is referred to as the global warming potential (GWP) of these gases.

The carbon from feed used on a dairy farm originally comes from CO₂ removed from the atmosphere during photosynthesis and so has a neutral impact on climate change. However, carbon that is converted to CH₄ along with N₂O is a significant concern since their GWPs are much higher. Dairy farm-based GHG emissions originate from several sources, including the use of fossil fuel-based sources to provide energy for the farm buildings and machinery, imported fertilizer used to grow crops, manure-based CH₄ and N₂O emissions and enteric-based CH₄ emissions. However, emissions in the form of enteric CH₄ and the GHGs resulting from manure management are much more significant due to the GWP of these gases versus CO₂. While every farm is different, estimates from Thoma et al. (2013) show that of the 34.9 Tg of CO₂ eq. from the US dairy supply chain, 19% comes from feed production and 53% comes from milk production. Of the milk production CO₂ eq., 49% is from enteric emissions while 44% is from manure management, predominately from CH₄ emissions from manure storages.

New York State, the third largest dairy state in the nation (NASS, 2015), has established ambitious overall renewable energy goals including incorporating 50% renewable energy in the electricity used in the State by 2030 (Energy to Lead, 2015) and reducing GHG emissions 40% by 2040 based on 1990 year baseline values (Executive Order, 2009). The New York State Public Service Commission (PSC) is charged with the responsibility of developing a system that encourages utilities to help meet these goals. This includes *Reforming the Energy Vision*, a new clean energy standard that is being developed to value electric products from distributed energy sources. A part of this initiative is to develop an economic value for the environmental attributes of these distributed energy sources (E).

An attempt to fully quantify the environmental benefits of AD (E) might be expressed as follows:

$$E_{total} = \sum E_{ghg} + E_{air\ quality} + E_{water\ quality} + E_{soil\ quality} + E \dots$$

As the State's renewable energy goals are realized, there needs to be a way for the process to include special provisions for those renewable energy sources that have extra societal benefits, including economic and environmental, and that support the rural character of upstate NY. The dairy industry is New York's leading agricultural sector, accounting for more than one-half of the state's total agricultural receipts. The increased milk supply has been very important in helping to meet the tremendous growth in the production of yogurt in NYS. However, the margin between the cost of producing milk and the price received for milk sales, is shrinking. Investing in farm facilities like ADSs will need to be analyzed carefully to ensure a return on investment that merits their implementation. An economic value for the environmental attributes of electricity produced from an ADS would help to represent this benefit quantitatively.

Dairy farms are also under increasing pressure to improve conditions environmentally. The New York State Department of Environmental Conservation (NYSDEC) revisions for the CAFO state permit, regulating the water quality impact of farms with more than 300 cows, will require manure storages to be built to limit spreading on at-risk fields during the winter and early spring seasons. These are farm sizes where manure-based ADSs have been built in the past and where many more could be implemented, given a reasonable rate of return. Manure storages are an important best management practice (BMP) to reduce the potential for water pollution by allowing farms to avoid manure spreading during inappropriate times. Unfortunately, if the manure system does not have a way to capture the GHGs produced, they are released into the atmosphere. Manure-based ADSs installed on farms would be a win-win-win to capture and reduce GHGs and to produce renewable energy from the captured CH₄, furthermore helping to meet the NYS renewable energy and GHG reduction goals. ADSs installed on farms would stimulate the rural economy and also provide the farm and rural community with all of the additional benefits listed in Appendix A.

This paper presents an analysis of the GHG reduction potential for a NYS dairy manure management system that includes AD, post-digestion solid-liquid separation (SLS) and long-term manure storage of SLS liquid effluent. This system is representative of almost all of the 27 ADSs currently operating on-farm in NYS today.

METHODS

The mass of GHG emission reductions (i.e., the mass of carbon dioxide equivalents [MT CO₂ eq.]) associated with AD (in this analysis, AD followed by SLS with liquid effluent stored long-term) located in New York State (NYS), was quantified

and is discussed in this paper. The following protocols were used: IPCC (2006), AgSTAR (2011), and EPA (Federal Register, 2009) combined with reasonable input values that are representative of a farm’s baseline condition (long-term manure storage with no pre-treatment by ADS). The reductions quantified include: 1) the replacement of fossil fuel-based electrical energy by using AD produced biogas to operate an on-site engine-generator set, and 2) the GHG emissions from CAFO required (for water quality purposes) long-term manure storages. The difference between the baseline condition and the conditions post-implementation of an ADS yields the farm’s net GHG emission reductions due to the implementation of an ADS. To quantify the economic value of the GHG emission reductions, the EPA social cost of carbon (SC-CO₂) was used (EPA, 2016).

PROCEDURE

The baseline condition is represented in Figure 1. Typical liquid/slurry long-term manure storages have manure that consists of urine plus feces, soiled bedding and milking center washwater, added continuously as is produced on-farm. A natural crust may form as lighter organic material floats to the surface. A few storages have a SLS prior to storage, while very few have a manure storage cover. Without a cover, they are exposed to rainfall from both annual precipitation and from extreme storms. To determine the baseline emission condition, storage with no SLS and without a natural crust was considered.

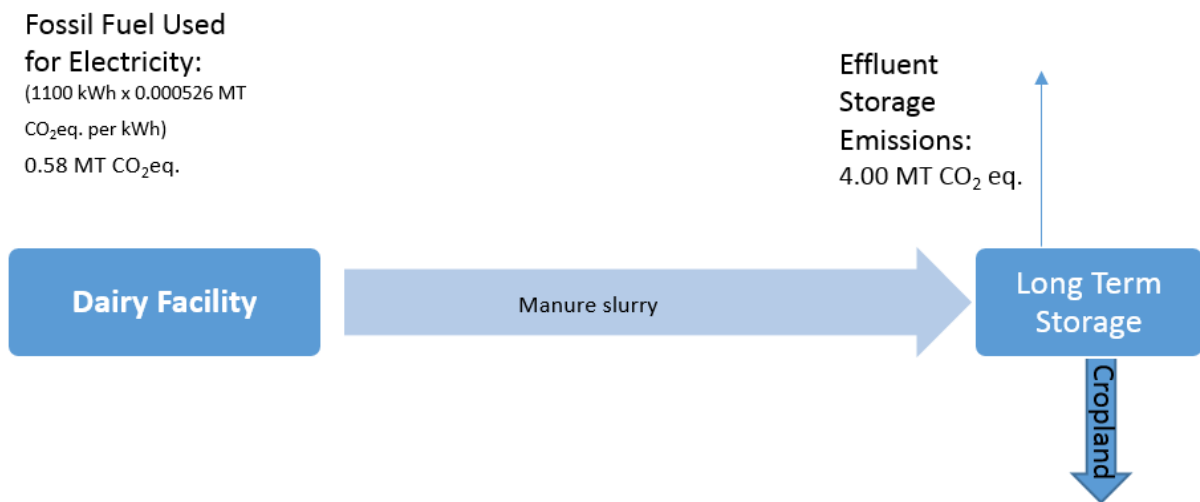


Figure 1. Electrical energy and manure storage baseline emissions from a NYS dairy farm with a long-term manure storage and no renewable energy system (Per cow per year)

Establishing Farm Electrical Energy Baseline Emissions

Electricity is used for a number of vital systems in a modern dairy farm. These systems include the milking system, milk cooling, feed and manure handling, lighting and ventilation. The actual amount of energy used per cow per year varies. A baseline value of 1,100 kWh is used to represent a typical NYS dairy farm’s energy usage (Shelford, 2012). The electricity to power these systems is obtained off-site (i.e., from the electricity grid) in the baseline condition, creating GHG emissions that represent a mixture of fuel sources used to generate the electricity. In NYS, that mixture yields 0.000526 MT CO₂ eq. per kWh (PSC, 2016). Presently there is no mechanism to receive an E value for any electricity consumed behind the meter. Without the capability of capturing this E value it is very likely all the renewable electricity produced would be exported from the farm and the farm would continue to consume fossil fuel generated electricity.

Establishing Long-Term Manure Storage Baseline Emissions

Part I - Estimating typical CH₄ emissions from a long-term manure storage

An independent panel of experts agreed (USDA, 2014) that GHG emission reductions are best estimated using the Intergovernmental Panel on Climate Change (IPCC) Tier 2 method. For long-term manure storages, the daily methane emissions can be calculated by using Equation 1.

Equation 1. $ECH_4 = VS \times B_o \times 0.67 \times (MCF/100)$

where:

ECH_4 = Mass of CH₄ emissions (kg CH₄/cow-day)

VS = Mass of volatile solids in manure going to storage (kg/cow-day)

B_o = Maximum volume of CH₄ producing capacity for manure (m³ CH₄/kg VS)
 = 0.24 m³ CH₄/kg VS (for dairy cow manure)

0.67 = Conversion factor for m³ CH₄ to kg CH₄

MCF = CH₄ conversion factor for the manure management system

Yearly CH₄ emissions (kg CH₄/cow-yr.) can be estimated by summing the daily emissions (or by multiplying an average representative daily emission for the year by 365 days). The MCF is largely dependent on the temperature and the type of manure management system. The MCF will change throughout the year as the manure storage temperature changes. The MCF was determined using a summer average ambient temperature representative of Upstate New York, of 18°C (64°F) and a winter average ambient temperature of < 10°C (< 50°F). A farm can reduce the impact of the MCF used in the equation by limiting the amount of material stored, and by reducing the time material is in storage during the warmer months. Different manure systems also have a different MCF based on the oxygen levels, interception of CH₄ gases, and moisture content.

The two variables in Equation 1 that can be controlled by farm management are the VS (volatile solids) loading per cow and the methane conversion factor (MCF). The VS loading rate can be reduced by any pre-manure storage treatment process that reduces the storage organic loading rate; fine tuning the diet to reduce VS in the manure and SLS are examples of two methods used to control the VS.

Typically in NYS, manure is stored both in the summer and winter in a liquid/slurry system with no natural crust. Using average typical winter and summer manure storage temperatures, average MCF values can be used in Equation 1 to estimate average methane emissions for these 6-month storage periods. The MCF values are shown in Table 1.

Table 1. Typical Long-Term Manure Storage Methane Conversion Factors for Storage Periods in NYS^a

Storage Period	Winter	Summer
Average Manure Storage Temperature (°C)	<10	18
MCF	17	35

^aThese numbers are based on liquid/slurry storage without a natural crust cover. (Source: IPCC, 2006)

Using these MCF values shown in Table 1 and a per-cow VS excretion rate of 7.7 kg/cow-day (representative of high producing NY dairy cows [ASABE, 2006]), manure storages were estimated to produce 38 kg CH₄/cow (for the winter storage period) and 79 kg CH₄/cow (for the summer storage period) or an average of 4 metric tons (MT) of CO₂ eq. per cow per year since 1 kg of CH₄ = 34 kg CO₂ eq.

Part II - Estimating typical N₂O emissions from a long-term manure storage

There could be N₂O emissions from a raw manure storage facility. The CO₂ equivalent from N₂O emissions can be estimated by using Equation 2 (IPCC, 2006).

Equation 2. $CO_{2eq} = 298 CO_2/N_2O \text{ GWP} \times EF_3 \times N \times 44 N_2O/28 N_2O-N$

where:

CO₂ eq = Equivalent global warming potential expressed as carbon dioxide

298 CO₂/N₂O = GWP factor for N₂O

EF₃ = Emission Factor for N₂O-N emissions from manure management

N = Mass of N excreted per cow per day = 0.45 kg/cow-day (ASAE, 2005)

The EF₃ value for a manure storage without a natural crust is 0 (IPCC, 2006). Using an EF₃ value of 0.005 (USEPA, 2009) for long-term storage of slurry manure with a crust and multiplying it by 0.45 kg of N/cow-day and by 365 days per year yields an additional 0.38 MT of CO₂ eq. per cow per year from N₂O emissions from a long-term manure storage facility with a crust. However most dairies now limit their bedding use so no crust typically exists. There for an EF₃ value of 0 is used and no N₂O emissions are included in the baseline condition.

Summary of electrical energy and long-term storage GHG emissions

The CO₂ eq. per cow per year from CH₄ emissions from a manure storage facility without a crust provides a baseline

emission of 4.00 MT of CO₂ eq. per cow per year from the manure storage systems that the NYS CAFO permit requires. The total baseline emission is the combination of the manure storage baseline emissions and the electrical energy baseline emissions; that sum is 4.58 MT CO₂ eq. The baseline of 4.00 MT CO₂ eq. is used assuming all the electricity produced will be sold to the grid to obtain the E value. These emissions can be mitigated by implementing a renewable energy system including an ADS with SLS of the digestate before storage.

Establishing GHG Emissions and Emission Reductions for an ADS

If a manure-based ADS was installed on a farm, it could reduce the GHG emissions from manure management as well as replace fossil fuels used for energy production and farm machinery, for both the farm and other users. By capturing the CH₄ produced, and combusting it for energy or simply flaring the excess, CH₄ releases are converted back to the neutral CO₂ originally consumed by the animals in the form of feed products. An ADS could help to meet NYS renewable energy and GHG reduction goals, however, farms with an ADS would need to manage the system to minimize leaks. With no incentives to control leaks, the CH₄ produced potentially could add to overall farm GHG emissions.

Part I - Estimating typical CH₄ emissions and emission reductions

There are a number of factors that need to be taken into consideration when estimating the GHG reductions that an ADS will provide. Leaks in the ADS can be very detrimental as more methane is produced in an ADS than is emitted naturally from a manure storage facility in the baseline condition. In addition, there are uncombusted CH₄ losses from flares and even some from the engine as well. Although every farm system is different, typical values can be determined from the literature, on-farm measurements, and experience.

ADSs designed and built to supply only the quantity of electricity consumed on-farm and to reduce odors may not be as effective as systems designed specifically to reduce GHG emissions. The **conservative** values in Table 2 could be used to describe these types of systems. ADSs built specifically to reduce GHG emissions in addition to maximizing the renewable energy produced would achieve significantly better GHG reductions. The **optimum** numbers are achievable, while the **obtainable** values are based on ADSs that consider GHG emissions and are built to optimize CH₄ production.

Table 2. ADS variables that can be controlled by the system equipment, operation, and management

	Conservative	Optimum	Obtainable	Reference
Leaks from system (% CH ₄)	10	0	1	AgSTAR (2011) and on-farm measurements
Flare Efficiency (%)	90	99	95	AgSTAR (2011) and on-farm measurements
Engine capacity factor (decimal)	0.85	0.97	0.95	On-farm measurements
Engine efficiency (%)	38	42	38	On-farm measurements
ADS parasitic load (kWh/cow-yr)	0.30	0.07	0.18	On-farm measurements
Biodegradability post-digestion (%)	70	50	60	On-farm measurements
VS left after SLS (%)	60	20	50	On-farm measurements

The additional societal benefit of this technology can be calculated using EPA's SC-CO₂ of \$47.82 as the 2017-2019 average SC CO₂ value per metric ton of CO₂ eq. (at a 3% discount rate) for the methane and nitrous oxide emissions (EPA, 2016).

Part II - Estimating typical N₂O emissions and emission reductions for an ADS

An EF₃ value of 0 (IPCC, 2006) for an uncovered liquid manure storage represents the typical emission factor from an ADS with SLS since post-digestion there would be no free oxygen, and after solids removal, there would not be a crust forming on the long-term storage.

The resulting calculations from the **conservative**, **optimum** and **obtainable** ADS values are shown in Table 3. The fossil fuels avoided are based on the electrical energy (kWh) produced minus the ADS parasitic load. The uncombusted CH₄ from the engine is based on a rich burn engine. The CO₂ equivalents from the system leaks and the digestate storage are the major emissions in the conservative scenario, the uncombusted emissions from the flare and the digestate storage are minor emissions from the optimum scenario, while storage contributes the most to the continuing emissions from the obtainable scenario.

The values for E shown, on a \$/kWh basis, were calculated by dividing the SC-CO₂ benefit by the gross energy produced by the biogas-fueled engine-generator set based on the capacity factors shown in Table 2.

Table 3. GHG Emissions from electric production converted with a \$47.82 SC-CO₂ into a value of E for conservative, optimum and obtainable ADS with solid separation of the digestate before storage.

	Units	Conservative	Optimum	Obtainable	Reference
Fossil Fuels Avoided	MT CO ₂ eq/cow-yr	0.78	1.16	0.99	(PSC, 2016)
Engine uncommuted CH ₄	MT CO ₂ eq/cow-yr	2.5 x 10 ⁻³	3.2 x 10 ⁻³	3.1 x 10 ⁻³	(Protocal, 2011)
Flare uncommuted CH ₄	MT CO ₂ eq/cow-yr	0.19	0.00	0.03	(Protocal, 2011)
System Leaks CH ₄	MT CO ₂ eq/cow-yr	1.41	0.00	0.14	(Protocal, 2011)
Storage emissions CH ₄	MT CO ₂ eq/cow-yr	2.98	0.50	1.87	(IPCC, 2006) and professional judgement
ΣCO ₂ eq emitted - FF avoided	MT CO ₂ eq/cow-yr	3.81	(0.65)	1.06	Calculation
Baseline	MT CO ₂ eq/cow-yr	4.00	4.00	4.00	(IPCC, 2006)
Reduction in CO₂ eq	MT CO ₂ eq/cow-yr	0.19	4.64	2.94	Calculation
SC-CO ₂ Benefit	\$/cow-yr	\$9	\$222	\$141	(EPA, 2006)
Gross Electricity Produced	kWh/cow-yr	1,590	2,229	1,955	On-farm measurements and professional judgment
Value of E	\$/kWh	0.006	0.100	0.072	Calculation

Summary of long-term storage GHG emissions

The obtainable value of E of \$0.072/kWh, for an ADS with SLS of the digestate, could be used to better determine the value of renewable energy in meeting NYS's goals of reducing GHG emissions, increasing renewable energy, and supporting the dairy industry, and the upstate NY economy.

More specific values for each individual ADS could be determined as a more granulated value (i.e., a value based on a more detailed/thorough analysis) through the implementation of NYS's *Renewable Energy Vision*. By using a value of E that reflects the actual environmental benefit of an ADS, this would incentivize dairy farms with an ADS to improve their CH₄ production to produce more electrical energy. This would also increase the interest of more dairy farms in controlling GHG emissions and producing renewable energy by investing in ADS on their farms.

DISCUSSION

ADSs can provide additional renewable energy and GHG reductions by utilizing organic wastes that currently go to landfills or aerobic waste treatment facilities. Some landfills may be able to capture a portion of the CH₄ that the organic waste produces as renewable energy, but typically the leaks from a landfill gas recovery system are greater than those of farm-based ADS. NYS has some interest in diverting organic waste from landfills to reduce the fill rate, the potential GHG emissions, and O&M costs in landfills. The value of the diverted organic waste can be best recovered by society if the energy is recovered through manure-based AD since the nutrients would also be recovered by mixing the food waste with manure, digesting it and recycling the nutrients in the effluent to the land for growing crops.

Nutrients to grow crops that are currently utilized in the form of commercial fertilizer, could be offset by the nutrients contained in a post-digested liquid, which would also reduce the energy and accompanying fossil fuel emissions now emitted when manufacturing commercial nutrients.

Aerobic treatment of organic wastes requires additional energy that adds to the fossil fuel-based carbon dioxide emissions and typically does not recover nutrients. While anaerobic digestion creates renewable energy and preserves nutrients.

Typical ADSs produce a large portion of energy from CH₄ as waste heat from the engine(s). Operating a Combined Heat and Power (CHP) system in conjunction with an enterprise that would utilize the heat produced, would enable the system to harvest even more renewable energy.

ADSs could improve GHG mitigation efforts if the effluent storage was covered and if the gas collected was included in the biogas utilization system, eliminating any emissions from the effluent storage while producing even more renewable energy.

Farm Disadvantages

Managing a complex and expensive ADS requires dedication and a sophisticated management effort that clearly competes for time with other tasks on the farm. There is the potential to emit excess CH₄ if: 1) leaks are not properly controlled, 2) the engine generator, boiler and/or flare are not efficient or, 3) if the effluent storage continues to produce uncontained CH₄. These can all be compounded if off-site organics are imported to the farm. The existing NYS net metering program makes the current price paid for exported electricity, very low. This reduces the motivation to produce and capture the maximum amount of CH₄ from the ADS.

Planning and installing an on-farm ADS takes time to consider the benefits and costs so that a business decision can be reached. Capital costs of ADSs vary, but can range from \$4,000 to \$5,500 per kW of generation capacity. Operating costs have been estimated at \$0.02 to \$0.03 per kWh for the engine-generator set alone. Much of the capital investment is considered lost capital by lenders. The existing manure management system should be examined to determine any disadvantages from extra solids, contaminants, or dilution. If the successful operation of the ADS depends on tipping fees from imported organics, the reliability and quality of these sources needs to be determined. If electricity is to be sold, the utility should be consulted to determine how/if the distribution lines to the farm can handle what is expected to be generated.

CONCLUSIONS

ADSs can be used to reduce the manure management-generated GHG emissions from dairy farms. With careful management, 2.94 MT of CO₂ eq. per cow-year can be credited to the ADS. Using EPA's SC-CO₂ average price during 2017-2019 of \$47.82, this could amount to a GHG benefit of almost \$141/cow-year. At this time, the benefit to society is unrewarded and high costs for ADSs both to construct and to operate, discourage farms from installing them. Working towards New York State's renewable energy goals, as well as the reduction in GHG emission goals by compensating farms for the societal value of \$0.072 per kWh of electricity produced from a well-run ADS would better incentivize farms to both install and operate ADSs to the advantage of the State.

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Appendix A

Benefits of Anaerobic Digestion of Manure

There are many benefits of farm-based anaerobic digestion systems that benefit farmers and non-farmers alike, providing sustainability to the animal agriculture industry by: increasing renewable energy production, increasing the potential for off farm sales of by-products and recycling of nutrients, improving water and air quality, and positioning animal agriculture for the future. The potential benefits include:

- **Reduction of Greenhouse Gas Emissions** – Cornell applied research has shown that on average for every two cows' worth of manure digested annually, one US car's worth of GHG emissions are removed. There are additional GHG reductions when AD is combined with electric generation and heat production replacing fossil fuel derived energy. The potential for this can significantly increase when other waste organics are co-digested instead of sent to landfills. This is good for the environment and further shows consumers that farmers strive to be good environmental stewards.
- **Odor Reduction** – Manure is commonly stored long-term (6 months or more) to reduce the chance of pollution to water bodies. Long-term storage of raw (untreated) manure releases offensive odor emissions, especially when the storage is agitated prior to emptying and when applied to a farm's cropland. This creates conflicts with other economic development opportunities in rural areas. However, digested manure can be stored and recycled to the farm's land base with far less odorous emissions; less odor allows a farmer to be more flexible in dealing with how manure is stored and recycled to the land base. This flexibility allows the nutrients to be more efficiently recycled on a larger land base without impacting non-farm rural life.
- **Conservation of Crop Nutrients** – The anaerobic digestion process does not consume the manure or co-digested organic nutrients, nitrogen (N), phosphorus (P), or potassium (K), all of which are important for crop production. Recycling of these nutrients appropriately to a land base of growing crops, as opposed to fertilizer purchase, saves money and the energy needed to produce the fertilizers. The ratio of N, P, and K to meet crop nutrient demand is often different than digester effluent, however AD provides for the opportunity to further process manure to partition the nutrients and the moisture contents for more efficient application of fertilizer to both farm and non-farm land.
- **Improvement in Crop Utilization of Manure Nutrients** – Manure application at the times during the year when plant growth is minimal has the potential for nutrient loss. Effluent from digesters can be stored long-term without significant odor problems allowing farmers to apply nutrients to even sensitive crops in an agronomic, timely fashion, thus reducing the potential for surface water and/or groundwater contamination. Odor issues often prevent stored manure from being applied to fields near residences. Additionally, the specific forms of the crop nutrients N and P are more available for use by planted crops than raw manure, increasing potential nutrient recapture when managed properly. Precision feeding for production requires quality forage production. Precision fertilizer application to achieve high quality forage and higher production per acre will be needed as farms become more efficient in the future.
- **Improvement of Water Quality** – Application of AD treated manure can be readily made in the late spring and in the summer on hay fields in compliance with Comprehensive Nutrient Management Plan requirements and without causing neighbor relations issues. These growing crops are perfectly suited to utilize the additional nutrients, while water quality is protected as the risk of water run-off and leaching is low. There are a number of watersheds under TMDL regulations that include N and P load reductions. To reduce nutrient loading in sensitive watersheds portioning nutrients to specific products is needed. These products would then be available for easier transportation or to crop farms. AD is an important precursor to obtain nutrient partitioning from manure and co-digested organics. Climate change, wetter winters and more intense rainfall, will create even more concern in this area.
- **Generation of Renewable Fuel/Energy** – Biogas can be used to generate electricity and utilize heat as hot water and/or dry materials such as corn and cow bedding, or used in a number of other potential alternative uses that can be used on- or off-farm, including liquid fossil fuel replacement. This distributed renewable energy can be produced at a much steadier rate than both wind and solar. The additional utilization of the energy potential from waste organics significantly increases the energy available during AD.

- Revenue Potential – Besides reducing on-farm purchased energy costs for electricity and/or heat, the digester may facilitate other enterprises such as digested manure solids sale as compost or bedding, excess electricity sales, or co-digestion of food waste for a tipping fee. Both green energy and GHG credits are potential revenue sources. Utilizing the methane for resale or as a transportation fuel are also possibilities.
- Pathogen Reduction – Cornell research has shown a 99.9 percent reduction of indicator organisms (those that are commonly used to evaluate the success of a system's performance relative to killing pathogens). Food safety, hazard reduction procedures and traceback of pathogen contamination will make this factor much more important in the future for agriculture to remain sustainable in the US. Complete pathogen reduction by pasteurization of portions of the AD effluent is also possible.
- Pre-treatment – Anaerobic digestion produces a consistent effluent material (same temperature and pH) that is in a useful form for further treatment including solid, ammonia nitrogen, and phosphorus separation into discrete, usable forms for sale or on-farm use. Energy production from the AD would also provide low cost electric and heat for the additional treatment processes.
- Co-digestion – The performance of farm-based digesters is enhanced by adding off-farm substrates. Many of these substrates are costly to dispose of by other means and are not fully utilized for their energy and nutrient values. Society's goal to eliminate organics from landfills will create a need for organic treatment and recycling. Treating these organics with the stability of a manure stream and then recycling the nutrients to the land is a much better alternative than separate compost operations or incorporation into sewage treatment plants.