Partnering Commercial Greenhouses with Dairy Manure Based Anaerobic Digestion Systems – Quantifying Energy Synergies[A]

Timothy J. Shelford[1], Curt A. Gooch[2], and Peter E. Wright[3]

Biological and Environmental Engineering

Cornell University, Ithaca, NY

[1]Research Associate, [2]Senior Extension Associate, [3]Agricultural Engineer

August 7, 2016

Executive Summary

One way to improve the economics of dairy manure-based anaerobic digestion systems (ADS), controlled environment agriculture systems, and overall sustainability for both dairy and greenhouse enterprises is to share surplus electricity and heat produced by the farm-based digesters with greenhouses. A three-year project we recently completed had an overall goal of *quantifying* the synergies of surplus heat and electricity produced by manure-based anaerobic digesters and the electrical and heat demands of commercial greenhouses. As a part of the project, on-site data was collected over its duration from three commercial dairy farms with operating anaerobic digesters (two in NY and one in ME) and from two smaller commercial greenhouses (NY and Ontario, Canada). Collected data, along with other available data and engineering principles, were used to develop and validate computer models with a purpose of predicting surplus heat and electricity from ADS and the associated demands of commercial greenhouses. The computer models were then developed into a user-friendly software package that we refer to as "Cornell Digester Greenhouse Simulation Software" (CDGSS).

For this paper, CDGSS was used to determine the maximum size of commercial greenhouses that could use the waste heat and surplus electricity from dairy farms of varying size (500 to 3,000 lactating cow equivalents) with varying types and quantities of co-digestion material (imported off-farm generated organic wastes, which can significantly increase biogas production).

[A]USDA Hatch and Smith Lever Grant: Coupling Dairy Manure Anaerobic Digesters with Commercial Greenhouses – An assessment of Technical and Economic Feasibility. Project No. NYC-147400.

For the range of the analysis performed, results showed that the annual economic value of the available (surplus) electricity and thermal heat ranged from $11,600 to $235,000/yr. The results do not indicate whether the annual economic values are sufficient to implement an anaerobic digester/greenhouse (AD/GH) synergy project; a complete economic and market analyses needs to be conducted as part of the investigating an AD/GH synergy project.

Overall, the CDGSS can be used to determine the electrical and heat energy synergies for any specific ADS and greenhouse configuration. The purpose of the results presented herein are to demonstrate the sizes of greenhouses that can be supported by ADSs and to show overall that viable economic synergies do exist between manure-based anaerobic digester enterprises and commercial greenhouse enterprises. The model can be used to quantify these synergies.

Goals

The goals of this paper are to:

- Provide brief information about dairy manure-based anaerobic digestion, commercial greenhouses, and specifically the synergistic relationships that exists between the two.
- Discuss briefly some of the benefits, considerations and implications of AD/GH synergy projects.
- Provide an array of results using representative farm data input in the project-developed CDGSS.

Introduction

This section of the paper will provide basic background on anaerobic digestion, commercial greenhouses and introduce the synergistic opportunity.

Dairy Anaerobic Digestion Systems

Many dairy farmers have examined the use of manure-based anaerobic digestion systems (ADS) to help manage their manure. The advantages to the dairy farm include energy production, odor and greenhouse gas emissions reductions, improved nutrient management potential, and pathogen and weed seed reductions, leaving the effluent in a better form to be recycled as a fertilizer and soil amendment. Anaerobic digestion (AD) is a microbial process where operative microbes consume organic material and create a combustible biogas that can be used in a combined heat and power (CHP) system to produce electricity and heat. Generally, the electrical energy generated by a biogas fueled CHP exceeds the farm's demands. However the economics of farm-based ADSs needs to be improved. Often, farms are only paid the wholesale price (currently 3 to 5 cents/kWh in New York State) for electricity sold to the grid. In addition, up to 60% of the energy from an ADS (in the form of excess heat) goes unused (project measured data). Making use of ADS's surplus heat (currently wasted to the ambient environment) and making better use of the electrical energy produced is a real opportunity.

Co-digestion of additional organic materials by an ADS provides several advantageous opportunities. Co-digested organic material typically consists of material that is a byproduct of food preparation such as cheese whey, or fats oils and greases (FOG) that are often disposed of in landfills. By diverting these materials to ADSs, the biogas output can be increased, and often a "tipping fee" or fee for disposing of the material can be collected. However with no incentive to maximize biogas production (for increased electricity sales) along with some other challenges, co-digestion is not as widespread as it could be in the US.

Commercial Greenhouse Systems

Greenhouses can provide high value crops with the possibility of year-round production. They are viewed by many as the way to meet the demand for fresh, local food and to provide economic development in rural areas. Society is looking for ways to assure a continuous, reasonably-priced, local supply of wholesome high quality vegetables that have enhanced food safety. To maintain year-round production, greenhouses require considerable heat in the colder months and electricity for supplemental lighting during months of reduced photoperiod. In the Northeast and other similar climates, heat and electricity represent a major expense for greenhouse production (on the order of $10 to $20 per square foot of greenhouse space annually, when supplemental lighting is installed and used). Meeting consumer expectations of sustainability and environmental issues such as limiting carbon footprints and the use of renewable energy can be an important marketing message for locally grown foods.

Optimized greenhouses provide consistent year-round production that is attractive both from a local production perspective as well as from the ability to provide long-term production contracts to wholesalers. Local diversified and distributed production is more resilient to climate change and makes more efficient use of water and nutrients.

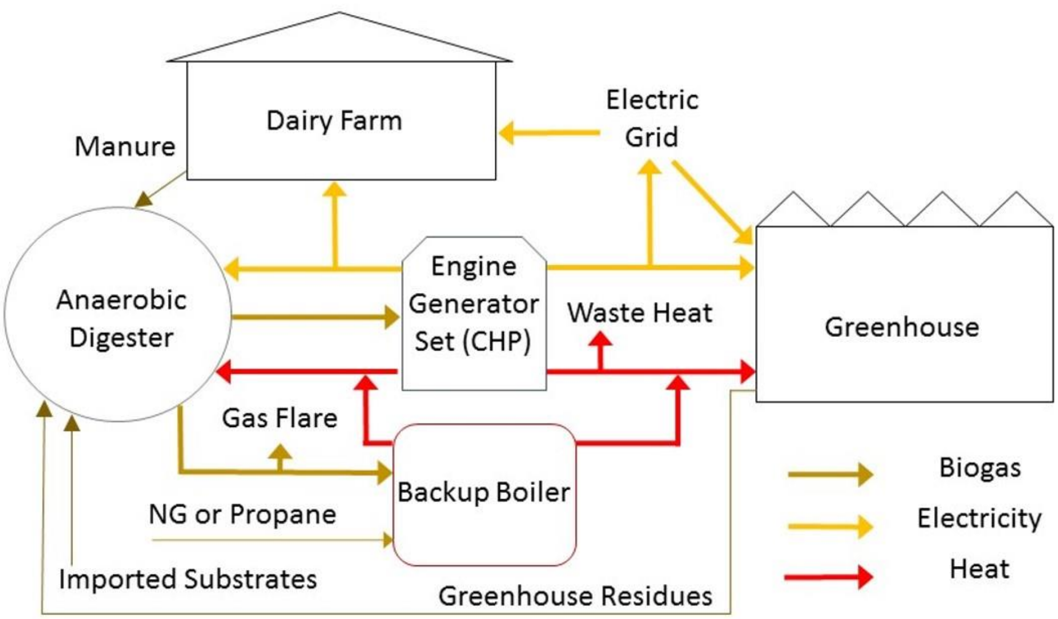

Figure 1. Typical manure-based anaerobic digester and commercial greenhouse synergistic relationship.

Dairy Anaerobic Digester and Commercial Greenhouse Synergies

Greenhouses in the Northeast and other similar climates are excellent candidates to partner with ADSs to utilize their surplus heat and electrical energy. Greenhouses can make use of the excess heat from an ADS to provide the necessary growing conditions for year-round production. Such a system is shown in Figure 1.

To more specifically show the opportunity for a synergistic relationship between manure-based digesters and commercial greenhouses, the measured waste heat produced from one project monitored dairy farm with 3,200 cows feeding (no co-digestion) an ADS was plotted vs the measured heat demand from an 8,000 ft^2 commercial greenhouse (both located near Ithaca, NY) – see Figure 2. Even during the winter months when less surplus heat is available (more heat required to operate the ADS), the recovered surplus heat is more than adequate to support the greenhouse demand.

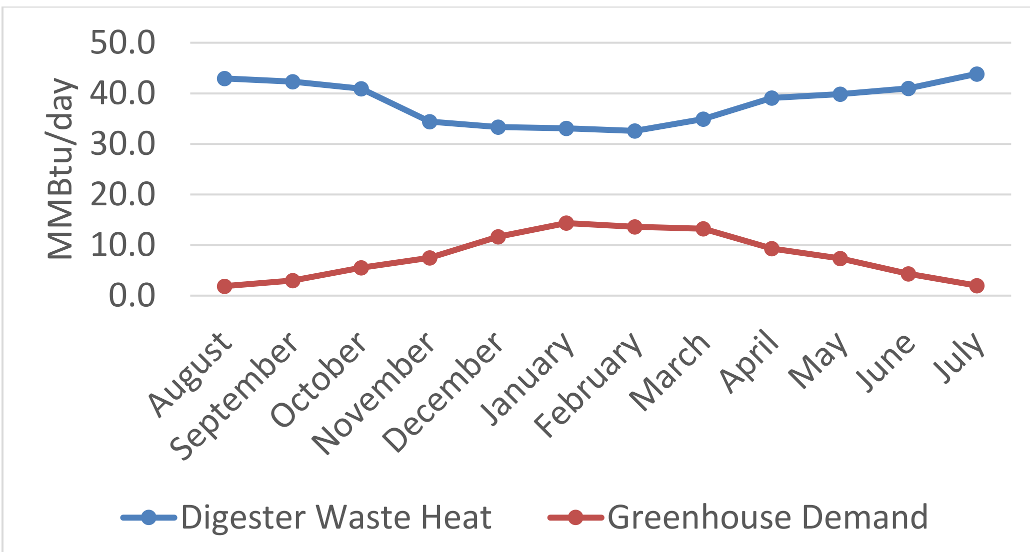

Figure 2. Average measured daily waste heat produced from a 3,200-cow dairy ADS and average daily heat demand of an 8,000 ft^2, commercial greenhouse both located near Ithaca, NY.

Excess electricity from biogas fueled CHP systems can be used to power greenhouse supplemental lighting systems to provide light levels necessary to keep production constant throughout the year. The production of electricity from a project-monitored 3,200-cow dairy ADS system, as well as the quantity of electricity used by the dairy farm and an 8,000 ft^2 commercial greenhouse is shown in Figure 3. The figure shows that there is a large surplus of electricity available that can more than meet the demand of the greenhouse. (Note: Table 1 shows a 3,000 cow ADS could support a 21,000 ft^2 greenhouse.) Peak usage of the dairy farm is during the summer months when electrically-driven fans are used for cow cooling, which is the opposite of the greenhouse when the demand is greatest in the winter months for supplemental crop lighting.

The synergy of AD/GH systems will enhance the viability of both the dairy and greenhouse industries in NY State and the Northeast U.S. Larger greenhouses benefit more from savings in electricity. If it isn't possible to locate a greenhouse adjacent (or close enough) to a digester, it may be possible to take advantage of "remote net-metering" to supply the electrical needs of a greenhouse located in a more suitable location (perhaps in an area supplied by natural gas). Though the greenhouse and digester would not realize the benefits of using waste heat, the financial benefits of digester supplied electricity are still substantial.

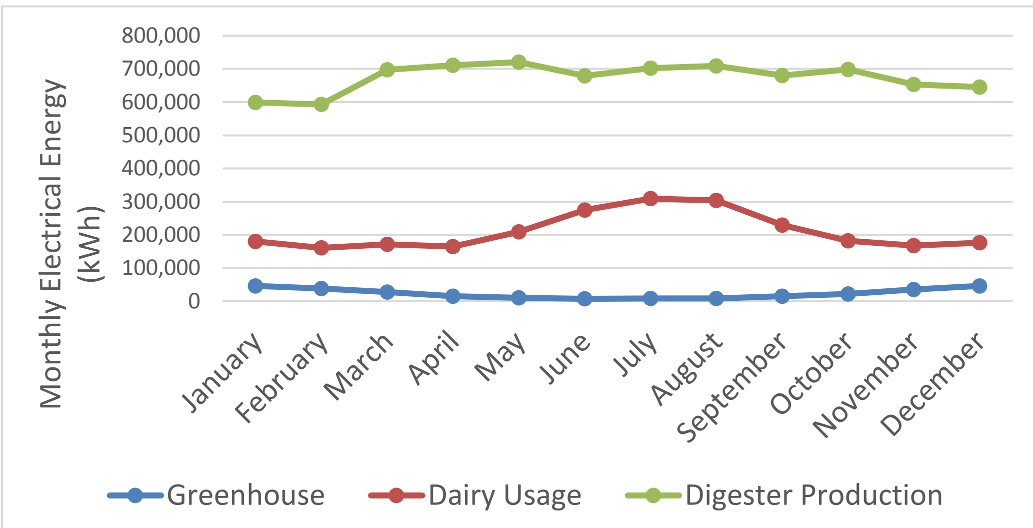

Figure 3. Average measured monthly electricity production from a 3,200-cow ADS, estimated monthly electricity demand of the 3,200-cow dairy, and measured electricity demand of an 8,000 ft^2 commercial greenhouse, located near Ithaca, NY.

Before undertaking an AD/GH synergy project, a thorough financial and market analysis should be conducted to determine the size of greenhouse operation necessary to be economically viable.

Model Development – Approach Used

In the first part of the project, three dairy farm ADSs (two NY and one ME) and two greenhouses (one NY and one Ontario, CA) were monitored. The second part of the project was to develop a software package (Cornell Digester Greenhouse Simulation Software (CDGSS)) that can be used to explore and quantify synergistic relationships between ADSs and commercial greenhouse operations. CDGSS quantifies both the magnitude and timing of the energy availability from the ADS compared to greenhouse requirements based on user inputs. Constructing a new greenhouse in a location next to an ADS that has less expensive power may prove more economical since heat and electricity typically represent one third of production cost.

The CDGSS software package is a combination of two pieces of software. The Cornell Digester Simulation Module (CDSM) was developed by combining existing anaerobic digestion models and project collected data. Similarly the greenhouse portion combined existing greenhouse models (Shelford, 2010) and project data. Matlab® was then used to program the models and develop the graphical user interface. A description of the programs is outlined in Appendix A, and a listing of the software inputs is outlined in Appendix B.

Model Application - Results

The results of predicting energy outputs from variously sized and biomass supplied ADSs, the size of commercial greenhouses that could be supported by such systems, and an estimate of typical economic benefits available to the operators of a greenhouse and ADS based on the value of the energy (heat and electricity) is shown in Table 1. The table values were developed using the CDGSS; inputs/assumptions used are provided in Appendix C. For this particular application of the model, the greenhouses were sized such that the available heat from the ADS could supply 95% of the heat necessary for year-round production of head lettuce in an average year based on the project being located near Ithaca, NY. Not relying on the ADS to support 100% of the heat required for the greenhouse is an appropriate basis for analysis since an ADS supported greenhouse would need a source of back up (supplemental) heat capable of maintaining greenhouse temperature when the ADS system is off line (whether for scheduled maintenance or failure) and the backup system would also be used to meet the demand when the ADS heat is insufficient. In addition, the climate dataset used to develop the results, represents an average year, and thus additional heat would be necessary in colder than average years.

The economic benefit column represents the market value of electricity and heat to the greenhouse that could be shared between the AD/GH enterprises. This synergistic relationship could provide an economic advantage for both the dairy farm enterprise and the greenhouse enterprise that cannot be realized without a partnership.

The potential electrical benefit to the greenhouse increases proportionally as the size of the greenhouse increases because supplemental lighting (which is the bulk of electricity usage) is relatively constant on a square foot basis. The heat benefit decreases as greenhouse size increases due to the fact that larger greenhouses lose less heat on a unit area basis.

Table 1. Simulation results from Dairy Anaerobic Digesters supplied by various farm sizes and feed stocks, the size of a commercial lettuce producing greenhouse, and the value of the heat and electricity supplied.

Farm Size (LCE[1])	Co Digestion[2]	Greenhouse Size (ft^2)	Value of Heat[3] ($/year)	Value of Electricity[4] ($/year)	Benefit[5] ($/year)
500	none	580	$9,975	$1,650	$11,625
	10% whey	720	$11,548	$2,100	$13,648
	25% whey	1,325	$17,035	$3,900	$20,935
	5% FOG	1,125	$15,107	$3,300	$18,407
	10% FOG	1,500	$18,874	$4,350	$23,224
1,000	none	3,250	$23,170	$9,600	$32,770
	10% whey	4,000	$26,500	$11,700	$38,200
	25% whey	6,750	$31,865	$19,800	$51,665
	5% FOG	6,000	$29,479	$17,550	$47,029
	10% FOG	7,500	$34,316	$21,900	$56,216
1,500	none	7,875	$35,344	$22,950	$58,294
	10% whey	9,375	$39,613	$27,450	$67,063
	25% whey	15,500	$49,345	$45,300	$94,645
	5% FOG	13,000	$43,712	$37,950	$81,662
	10% FOG	16,500	$51,725	$48,300	$100,025
2,000	none	14,500	$46,967	$42,450	$89,417
	10% whey	16,500	$51,725	$48,300	$100,025
	25% whey	20,000	$60,224	$58,350	$118,574
	5% FOG	19,000	$57,424	$55,500	$112,924
	10% FOG	21,000	$62,879	$61,350	$124,229
3,000	none	21,000	$62,879	$61,350	$124,229
	10% whey	28,125	$69,628	$82,200	$151,828
	25% whey	43,750	$84,545	$127,800	$212,345
	5% FOG	33,750	$73,909	$98,700	$172,609
	10% FOG	50,000	$89,050	$146,100	$235,150

[1]LCE = Lactating Cow Equivalent (17 lbs. of Volatile Solids per cow per day)

[2]Percentage based on Volatile Solids (VS)

[3]Based on an electricity price of $0.10 per kWh

[4]Based on a heat price of $10/mmBtu

[5]Benefit = Economic value that can be negotiated to benefit both the digester and greenhouse enterprises in a mutually beneficial way.

Discussion

It is clear from Table 1 that relatively modestly sized dairy ADS projects produce enough surplus energy to support commercial greenhouses. The table does not indicate whether such greenhouses are large enough to be economically viable operations, and a detailed economic and market analysis would need to be conducted before project initiation to ensure the economic sustainability of an AD/GH synergy project. The project associated greenhouse located in Ithaca NY, is 8,000 ft^2, and its heating needs could be met by a dairy farm with 1,500 Lactating Cow Equivalents (LCE) which is approximately 1,000 mature cows and their associated replacements (heifers).

Adding co-digestion organic wastes to ADS increases the energy output and the ability to support a larger greenhouse system. As the table shows, fats, oils, and grease (FOG) have significantly more energy available than typical whey from dairy processors. The larger the farm and the more co-digestion material added to the ADS increases the potential greenhouse area that can be supported. The energy saved by co-locating can be a significant proportion of the net profits to the greenhouse and may help the dairy farm achieve sufficient added value to justify increased management of the ADS to achieve optimal energy output. Currently there is little incentive for many ADS enterprises to maximize biogas production, beyond what is required to meet on-farm demand where only wholesale electric price are paid.

Successful business enterprise partnerships provide an opportunity for an increased number of on-farm digesters to be constructed and operated, thus reducing greenhouse gas (GHG) emissions while providing long-term, lower cost, non-fossil-fuel based renewable energy for local greenhouse growers. Anaerobic digesters alone reduce farm carbon emissions by approximately 2.5 to 3 metric tons per year per cow (Pronto and Gooch, 2010) and even more when coupled with an engine-generator set producing renewable electricity by way of displacing fossil fuel based emissions.

The table and model should only be used as a guide to the size of digester project necessary to partner with for various sized greenhouses. Greenhouse economic viability is essential to ensuring that the AD/GH synergy will be able to continue operations.

Summary

The economics of owning and operating a manure-based ADS is currently very challenging in most US states, and taking advantage of the surplus energy produced represents a significant opportunity towards improving the sustainability of existing ADS projects, and encouraging new ones.

Commercial greenhouse production in the Northeast can provide year-round fresh local produce to meet the increasing demand for healthy food. However energy consumption both in terms of heat and electricity for year-round production represents approximately one-third of the production cost for greenhouse produce. Typically the heat for greenhouses is from non-renewable combustion of natural gas, and the electricity from the grid also represents a significant contribution to greenhouse gas emissions. Taking advantage of a renewable source of heat and electricity available at a lower cost than if purchased from the utility provides a means to improve both the environmental and economic sustainability of greenhouse production systems.

To foster the synergistic pairing of ADS and commercial greenhouses, we developed the Cornell Digester Greenhouse Simulation Software (CDGSS). Its purpose is to facilitate the quantification of the available energy from ADS (existing or proposed), and the required energy for operating commercial greenhouses (existing or proposed). With the CDGSS, the requirements for potential synergistic projects can be readily investigated, providing a means to quickly compare operational strategies on energy production and usage.

CDGSS provides a first step in determining the viability of potential projects, and should be coupled with a detailed economic and market analysis to ensure the long-term sustainability of proposed projects. With proper planning and detailed analysis, co-location of ADS and greenhouse production can lead to several positive outcomes including: 1) reduced greenhouse gas emissions, 2) additional revenue streams for the ADS business enterprise, 3) lower the cost renewable energy supply for a greenhouse business enterprise, and 4) contribution to sustainability of rural communities through income and employment opportunities.

For more information on using CDGSS for case by case analysis, please contact Tim Shelford, tjs47@cornell.edu (primary contact) or Curt Gooch, cag26@cornell.edu.

Acknowledgements

Funding to support the development of the models came from the USDA Hatch and Smith Lever funds and the Cornell PRO-DAIRY program.

References

Abdel-Ghany, A.M. and Kozai, T. 2005. Dynamic modeling of the environment in a naturally ventilated, fog-cooled greenhouse. Renewable Energy 31:1521-1539.

ASABE 2005, Manure Production and Characteristics, ASAE D384.2 MAR2005

ASABE 2003, Heating, Ventilating and Cooling Greenhouses, ASAE EP406.4 JAN03

ASABE 2004, Commercial Greenhouse Design and Layout, ASAE EP460 JUL1993 (R2004)

Axaopoulos, P., Panagakis, P., Tsavdaris, A., Georgakakis, D. 2001. Simulation and Experimental Performance of a Solar Heated Anaerobic Digester. Solar Energy Vol. 70, No. 2, pp. 155–164.

Batstone, D.J., Keller, J., Angelidaki, I., Kalyuzhnyi, S.V., Pavlostathis, S.G., Rozzi, A., Sanders,W.T.M., Siegrist, H., Vavilin, V.A., 2002. Anaerobic Digestion Model No. 1. IWA Task Group on Mathematical Modelling of Anaerobic Digestion Processes. IWA Scientific and Technical Report No. 13.

Bot, G.P.A. 1983. Greenhouse climate: from physical processes to a dynamic model. Ph.D. dissertation, Agricultural University, Wageningen, The Netherlands.

Chandra, P. and Albright, L.D. 1980. Analytical Determination of the Effect on Greenhouse Heating Requirements of Using Night Curtains. Transactions of the ASAE. 23(4): 994:1000.

Gebremedhin, K.G., B. Wu, C. Gooch, and S. Inglis. 2005. Heat transfer model for plug-flow anaerobic digesters. Trans. of ASAE, 48(2):777-785.

Gebremedhin, K.G. and S.F. Inglis. 2007. Validation of a biogas production model and determination of thermal energy from plug-flow anaerobic digesters. Transactions of ASABE 50(3): 975-979.

Gijzen, H., Heuvelink, E., Challa, H., Marcelis, L.F.M., Dayan, E., Cohen, S., and Fuchs, M. 1998. HORTISIM: A model for greenhouse crops and greenhouse climate. Acta Hort 456: 441-450.

Labatut, R., Angenent, L., Scott, N., 2011. Biochemical methane potential and biodegradability of complex organic substrates. Bioresource Technology 102 (2011) 2255–2264.

Lubken, M., Wicherna, M., Schlattmannb, M., Gronauerb, A., and Horna, H. 2007. Modeling the energy balance of an anaerobic digester fed with cattle manure and renewable energy crops. Water Research 41 (2007) 4085 – 4096.

Martin, Jr., J.H. and K.F. Roos. 2007. Comparison of the Performance of a Conventional and a Modified Plug-Flow Digester for Scraped Dairy Manure. Written for presentation at the International Symposium on Air Quality and Waste Management for Agriculture Conference, Broomfield, Colorado, September 16 – 19, 2007.

Nayyeri, M.A., Kianmehr, M.H. , Arabhosseini, A., Hassan-Beygi, S.R. 2009. Thermal properties of dairy cattle manure. Int. Agrophysics, 2009, 23, 359-366

Peterson, Richard. 2011. President, Northeast Agriculture Technology Corporation. Personal Communication

Pronto, J.P., and C.A. Gooch. 2010. Greenhouse Gas Emission Reductions for Seven On-Farm Dairy Manure-based Anaerobic Digestion Systems – Final Results. Written for presentation at the 2010 ASABE International Air Quality and Manure Management Symposium, Dallas, Texas, September 13 – 16, 2010. ASAE 2950 Niles Road, St. Joseph, MI 49085-9659.

Shelford, T.J. 2010. The Risk Of *Pythium Aphanidermatum* In Hydroponic Baby-Leaf Spinach Production. Ph.D. Dissertation, Cornell University, Ithaca, NY.

APPENDIX A

Cornell Digester Greenhouse Simulation Software Methodology

The Cornell Digester Greenhouse Simulation Software (CDGSS) is built upon a system of submodels brought together to mechanistically simulate the operations of dairy manure-based anaerobic digester systems and commercial greenhouses. The submodels are themselves either mechanistic or empirically based and were either modified/adapted from existing models, or developed from first principles or project collected data. Modelled subsystems include manure-based anaerobic digesters and commercial greenhouses; the methodology for each system is briefly outlined below.

Digester Simulation Module Methodology

- Climate: Based on the NREL Typical Meterological Year Data (TMY3) data that provides the necessary climate data for the simulation for sites throughout New York and the United States.
- Manure production: Based on farm herd demographics, following the standards published in ASABE (ASABE, 2005).
- Biogas yield. Including from any additional co-digested organic materials. (Labutat et al. 2011).
- Manure (influent) temperature: Relative to ambient temperatures (Project developed data).
- Heat used to warm influent to digester operating temperature. Estimating heat capacity of influent based on composition and moisture content. (Nayyeri et al., 2009).
- Heat lost from digester: Including solar gain, conduction and convection losses. Losses to the ground include modelling the soil thermal properties. (Axaopoulos et al., 2001; Batstone et al., 2002; Gebrehmedin et al., 2005 and 2007; Lubken et al., 2007; Martin and Roos, 2007).
- Biogas usage: How biogas is used on the farm, conversion efficiencies (to heat and electricity), heat recovery. (First principles and project developed data).
- Farm energy usage: Energy usage for general farm operation and for cow cooling and manure solids separation, (Peterson, 2011).

Greenhouse Simulation Module Methodology

- Climate: Based on the NREL Typical Meterological Year Data (TMY3) data that provides the necessary climate data for the simulation for sites throughout New York and the United States.
- Greenhouse construction and heat loss. Based on the standards published in ASABE 2003, ASABE 2005 modified and expanded, (Bot, 1983 Gijzen et. al 1998, Abdel-Ghany and Kozai, 2005
- Greenhouse electricity usage, based on simulated control algorithms for lighting and shade control, ventilation and other greenhouse equipment usage (Chandra and Albright, 1980).

APPENDIX B

Model Inputs:

Cornell Digester Simulation Software Module

Climate:

Location in NY to automatically select TMY3 file, or upload TMY3 file from other location.

Digester System Characteristics:

- Digester Operation
  - Target operating temperature
  - Digester type (mixed, plug flow)
- Digester Influent
  - Volume: Number of Lactating cows, Dry cows, Replacements
    Co-digestion used, type
  - Composition: Moisture content, Volatile solids, Specific Methane Yield, Density
  - Temperature: Ambient, Ambient + offset, Minimum
- Digester Structure
  - Shape: Dimensions: depth below ground
  - Insulation: R values for digester walls, base, cover
  - Soil Properties: Soil type, Soil saturation
- Equipment
  - Generator: Rating, Efficiency, Time online, Actual Output, Heat Recovery
  - Boiler: Rating, Efficiency, Time online, Actual Output
  - Parasitic Heat Losses
  - Parasitic Heat Losses

Farm:

Farm Electricity Usage by month, whether cow cooling or solids separation used

Recovered Heat used on farm

Greenhouse Simulation Module

Climate:

- Location in NY to automatically select TMY3 file, or upload TMY3 file from other location.

Structure:

- Dimensions:
  - Length, Width, Gutter height, number of roof peaks, peak height, roof style, knee wall information,
- Materials:
  - Walls, knee walls, roof, shade curtain, roof transmissivity, greenhouse tightness,
- Equipment:
  - Continuous use: Pumps, number, size
    - Circulation fans, number, size
    - Control Computers, number size
    - Miscellaneous
  - Periodic Use equipment:
    - Supplemental lights, size, number, light output
    - Evaporative Cooling Pad Pumps
  - Heating Infrastructure:
    - Heating Type Number, Size, Efficiency, Fuel, Heat Circulation fans, number, size
    - Additional Heat sources used
  - Ventilation:
    - Fans, number, output, input

Environmental Control:

- Light and Shade Control:
  - Light Control: None, LASSI, Supplemental, Fixed Interval, Manually Specified
  - Shade Control: None, LASSI, Intensity, Fixed Interval, Manually Specified
- Heating Control: Constant, Day/Night, Manually Specified

APPENDIX C

Model input variables and considerations used in the development of Table 1 results

Anaerobic Digester Operation:

- Biogas yields from the digested materials (manure and co-digested products) were estimated from Labatut et al., 2014. These estimates are conservative on the yield of biogas, and it is possible that more biogas could be realized from the digestion process.
- A Capacity Factor of 0.9 was used, (defined as the amount of electricity actually generated divided by the total amount of electricity that could have been produced had the engines operated at full capacity, 100% of the time).
- An engine generator efficiency of 30% was used (30% of input fuel energy converted to electricity). Of the 70% of fuel energy not converted to electricity, it was assumed that 55% was recovered as usable heat (for heating the digester and greenhouse and system losses).
- Binghamton, NY climate data was used.

Greenhouse Operation:

- All greenhouses were modelled as modern, glass glazed greenhouses, equipped with shade/thermal curtains and supplemental lighting (high pressure sodium).
- All greenhouses were modelled with typical operational parameters for hydroponic lettuce production (75 F/66 F, day/night temperature, 17 Mols/m^2 Photosynthetically Active Radiation (PAR) (maximum and optimum level).
- 85% of the area of the greenhouses was modelled as available for production, and that lettuce production in the greenhouses was 80 heads per ft^2 per year.
- Binghamton, NY climate data was used.

Synergistic operation:

- 10% of the available surplus heat from the engine-generator set was lost in transmission to the greenhouse.
- The surplus heat for each scenario was adequate to supply 95% of the yearly heating demand of the greenhouses (during colder periods of the year additional heat would be required from an alternative source). Such a backup system should also be sized to handle more extreme weather events, which are not present in the Typical Meterological Year (TMY3) data used in the simulations.

Financial considerations:

- The economic value of heat was based on using Natural Gas supplied at $1.00 per Therm ($10/MMBtu), with a conversion efficiency of 85%.
- The value of electricity to the greenhouse was $0.10 per kWh (incorporating both supply and demand charges).
- Capital costs of greenhouse/synergy construction were not included.