Consideration of Locally Available Feedstocks for Codigestion and Renewable Energy Production on a Pennsylvania Farm

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DECEMBER 8, 2018
ABE 884: BIOMASS ENERGY SYSTEMS

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Summary

The project team has analyzed the potential for development of a medium scale anaerobic digester at the Dickinson College Farm near Boiling Springs, PA. The goal of the project is to generate renewable electricity and heat through anaerobic digestion of biomass - first to meet the energy needs of the farm, second (possibly) to export energy for financial gain and renewable energy credits. There are a variety of feedstocks available within close proximity to the farm digester site, each with its own energy and nutrient content, physical characteristics, and cost to deliver to the digester site. For the project to be successful, it needs to be economically viable while providing measurable environmental benefits. Selection of feedstocks will impact the capital and operating cost of the system as well as net energy and other benefits realized. Design of the digester and auxiliary components will also affect project financials and productivity.

The physical analysis has focused on conventional full-mix (CSTR) versus plug flow digesters because these are the most common in the northeast, are well documented, and can be built with local skills and readily available materials. The physical project description includes lists, function, and layout of components, component sizing based on feedstock scenario, and an operations plan.

The financial analysis is focused on the estimated capital cost of project construction, operating costs, and return from electricity and heat cogeneration as varies with different feedstock scenarios and digester designs. While most successful projects in the US have been on larger farms due to economies of scale (especially for power generation equipment), new products such as the commercially available Bioelectric mini digester system may make smaller scale facilities cost effective. This option will be weighed against a lower cost farmer-built digester, taking advantage of locally available construction resources. The impact of grants and other government cost-sharing options on financial outlook will also be discussed.

Introduction

The Dickinson College Farm is a working farm and educational program situated near the town of Boiling Springs in Cumberland County, Pennsylvania. The farm raises certified organic produce on 15 acres of tillable land and grazes sheep, beef cattle, and laying hens on 60 acres of pasture. Vegetable and meat products are sold to the College cafeteria, a consumer co-op, and at a farmers market in the nearby town of Carlisle. Educational activities on the property include field trips, lab exercises, student internships, and apprenticeships for young farmers.

From the inception of the farm in 2007, using renewable energy to meet power and fuel needs has been a guiding principle. The farm installed its first 5.25 kW solar electric array in 2007 and has since completed several smaller projects adding up to a total installed solar capacity of 8.0 kW. Solar electric production of approximately 9500 kWh per year accounts for roughly 1/5 of the farm's current electric power consumption and a solar thermal unit provides hot water for two residences. Farm personnel also produce biodiesel on site from used cooking oil for powering vehicles and tractors.

Seeking renewable energy for operations at the farm fits within the guiding principles of the college as a whole. Sustainability is a cornerstone of education and operations at Dickinson and has been identified as one of the college's unique identifying principles. Notable features include several LEED-certified buildings, the Center for a Sustainable Living residential unit, building integrated solar electric panels installed throughout the main campus and high-efficiency boilers installed in a central energy plant. Sustainability is also woven into the curriculum through the Center for Sustainability Education (CSE), a consortium of faculty, staff, and students that coordinate consideration of environmental issues in courses from all disciplines, run seminars for students seeking greener lifestyles, operate the campus's student-run bicycle shop and more. In 2007 then-president William Durden was an early signer of the American College and University Presidents' Climate Commitment, an agreement between higher education leaders to make substantial cuts to their campus' carbon footprints in an effort to mitigate climate change.

Dickinson set an ambitious goal of achieving carbon neutrality by 2020 through a combination of conservation and efficiency measures, the addition of green energy systems to campus, and purchase of renewable energy credits (RECs) and carbon offsets. A 3MW solar array installed on college property through a power purchasing agreement with Tesla Corp will come online in 2019 (X). After the solar array is commissioned, the campus will still purchase an additional 13,600,000 kWh per year of grid-supplied electricity. A green power premium of $.0009 per kWh is paid on this portion of the campus power bill to purchase RECs from wind farms in the Midwest (1).

Composting of food waste has been an integral part of sustainability in campus operations since 2008. All pre and post-consumer food scraps generated by the college's in-house dining services department are fed into an industrial Hobart pulper – extractor machine, where the food is ground (< 1" particle size) and free water are removed by centrifugal action. Processed food waste is collected in 10-gallon trashcans (about 23 kg each) and deposited on a loading dock. Students and staff working at the college farm haul the material to the farm daily as part of their work shift. At the farm, food waste is mixed with municipal leaves and wood chips for composting into a soil amendment for the organic produce operation. Raw food waste collection averages 115Mg per year for the past two fiscal years or about 378 kg per day during ten months of dining hall operations (2).

Anaerobic digestion is the controlled microbial decomposition of organic matter in the absence of oxygen, resulting in methane-rich biogas and nutrient-rich liquid effluent. The Dickinson College Farm developed its first demonstration-scale biogas system in 2010 and has continued since then to build homemade low-tech digesters for gas production, waste treatment, and education. Currently, the farm operates a 1000 gallon plug flow (sausage-shaped) digester made from EPDM rubber membrane, fed with livestock manure and ground food waste from the College cafeteria (fig 1). Gas

Fig. 1

produced in this system is used mostly for cooking stove fuel in farm residences, but has also been used for steam sterilization of potting soil and powering small stationary engines. The project serves a valuable educational role for the College – several students have earned independent study credit doing research or physical construction in the biogas plant. Public advocacy for small-scale biogas occurs through on-site farmer workshops and conference presentations.

In 2016 a student/faculty team of environmental engineers from Bucknell University collaborated with Dickinson students to conduct a thorough study of food waste digestion in the College Farm's 1000 gallon pilot unit (under the engineers' direction the digester was fed strictly food waste after seeding with cow manure and sludge from a previous digester). DiStefano and Schust (2016) found that the digestion process resulted in a high degree of solids destruction, producing biogas with a methane content of 65% at a rate of 0.15 m^3 per kg of food waste feedstock (3). After three seasons of operation, the pilot digester has functioned on nearly 100% food waste feedstock, maintaining gas quality at combustible levels of methane and pH in the neutral range.

The pilot digester is manually fed about 50 kg of food waste three times per week resulting in an average of approx.1.8 m^3/d of biogas (1.2 m^3/d methane). Food waste is diluted with water to approximately 10% solids (100-150 gallons slurry per feeding) in a mixing tank then gravity fed into the plug flow unit. Each feeding results in a nearly equivalent volume of liquid effluent flowing into a reception pit, where a sewage grinder pump is used to eject it to a mobile tank for land application or pumping to compost windrows. The digester is installed in an insulated trench within a dedicated greenhouse to gain and maintain solar thermal energy. An experimental solar heating system proved to be ineffective so the system is operational from April to October only. Pipes are drained and efforts are made to prevent freezing damage through the winter.

The 2016 Bucknell study left the farm with the question, "if the pilot digester can produce 1-3 m3 per day from a small fraction of the total food waste stream, what would happen if we digested the whole lot?" This question is the motivating force behind this design project. DiStefano and Schust (2016) estimated digestion of all of the campus food waste would result in approximately 7400 m^3 of methane per year (3). As this is considered, new questions arise. First, how would the farm utilize the biogas produced? At present, using up just the gas produced daily by the pilot digester can be a challenge. Gas storage (in EPDM bladders and floating drums) is limited to about two or three days of production, so the biogas must be used as it is generated or flared off. The current demand for gas as cooking fuel for six resident farmers and the commercial kitchen is about an even match for the pilot scale digester. Alternative uses such as steam sterilization of potting soil and a stationary engine log splitter require manual operation. The ideal scenario for utilizing the energy from a larger daily volume of biogas is likely conversion to electricity via a grid-connected generator coupled to an internal combustion engine. If the estimates of the 2016 study are extrapolated to present levels of food waste collection, the farm could likely eliminate its 37,000 kWh per year of purchased electricity (4). In a grid-tied configuration, any excess power generated would be sold back to the utility (Metropolitan Edison).

To capture the maximum energy value from the biogas, heat should be recovered from the engine through a combined heat and power (CHP) configuration. CHP equipped engines to capture thermal energy from both the exhaust and engine coolant. Thermal energy generated can be used on the farm to heat the anaerobic digester, provide winter greenhouse heating for produce operations, and water and space heating for buildings.

Statement of Problem: Economy of Scale

The pilot-scale digester at the Dickinson College Farm is largely manually operated – scaling up this design to process the full daily campus food waste stream will require some degree of mechanization to be practical. Additionally, the pilot scale digester made from a tube of 45 mil reinforced EPDM roofing membrane is vulnerable to failure. Examination of fig 1 shows two 1000 gallon digesters side by side. The digester on the right failed within six months of its commission date due to rodents chewing holes through the membrane. (Despite concerted efforts at trapping & baiting, rodents drawn to the warm, food-rich digester environment remain a challenge). A more durable, semi-automated system design will be required for expanded operations. While the ability to produce electricity from biogas with a stand-alone generator was demonstrated at the farm in 2018, consistently generating grid-quality power that seamlessly syncs up with the utility supply requires complex equipment for both power production and interconnection.

For an anaerobic digester project to be economically sustainable, the present value of free cash flows will need to exceed the capital costs. Alternatively, a farm must place an economic value on other digester services such as odor control or improved manure management ability. The high capital cost of mechanized farm digester systems equipped with grid-connected CHP units is a barrier to more widespread use of this technology. Chief among barriers to small-scale feedstock-to-power digesters is the relative dearth of small CHP systems adapted to run on biogas and the high upfront cost of interconnection equipment and engineering regardless of scale. Likewise, the cost of site preparation, materials, mechanical components, engineering and permitting for a durable, mechanized digester are also high, commonly running several hundred thousand dollars. In dairy case studies produced by the Cornell University manure management program (5), capital costs listed range often exceed $1,000,000, with a cited average about $1500 per cow (6). Summary data compiled by the University of Maryland biogas research program lists an installed cost range of $1200 to $2200 per cow depending on system design. The Dickinson College food waste stream of approx. 378 kg per day is roughly equivalent to 5 or 6 cows based on potential methane production (7). While small-scale biogas systems for cooking gas are common in China, India and other countries, and homestead biogas for cooking fuel units such as the Solar CITIES IBC digester (8) are gaining ground in the US, farm digesters for power production are mostly on larger operations due to the economy of scale. Extension and industry recommendations typically cite 500 cows as the minimum break-even project size (9).

This project seeks to reexamine the question of economy of scale considering newly available components and products. Our team has sought out options for both a commercially available package system as well as a potentially lower cost, owner built system. To analyze the potential economic viability of a project, we have developed a user-modifiable spreadsheet for productivity and financial calculations based on variations in digester feedstock volumes. We have also examined the impact of different feedstock scenarios on microbiological aspects of productivity.

In order to meet the minimum volume of feedstock to make the project economically viable, we have sought out additional materials from the farming community surrounding the Dickinson College Farm. Co-digestion of livestock manure with food waste and other feedstocks can result in synergistic increases in gas production and digester stability (10). Quantity, quality, and logistical issues for several local residual feedstocks were investigated. While a comprehensive survey of available local feedstocks was not possible for this project, the spreadsheet makes consideration of any mix of materials simple enough once the data are available. The potential benefits and challenges of a shared (community) digester versus a unit dedicated to Dickinson Farm waste only are briefly considered.

In summary, the question investigated is whether we can arrive at a digester model and feedstock scenario that pays for itself through energy products, effluent co-products, or other environmental benefits of value to the farming community.

Evaluation of alternatives

Our project has focused on local “wastes” such as animal manures, food waste, and dairy plant effluent, both for their low (or negative) delivered cost and the positive environmental benefits of biological waste treatment through the digester. Searchinger and colleagues (11) cite the use of waste products for feedstocks as less likely to cause increased greenhouse gas emissions through land use changes than systems that include the production of dedicated bioenergy crops. The low cost of waste product feedstock delivered to the farm gate helps keep operating cost of the project low, which is helpful since the margin between positive and negative cashflow on this project is very tight. Taking advantage of waste products that do not disrupt the food economy of the local area also fits well with the Dickinson College approach to sustainability.

The Dickinson College Farm is situated within a mixed-use residential and agricultural area with a strong local farming economy. While the farm itself has no agronomic crop equipment, commodity crops such as corn, soy, and rapeseed that could be used for bioenergy are found in abundance in the local area. Oil pressed from soy and rapeseed could be converted to biodiesel fuel for a compression ignition engine (12), but biodiesel production on the farm is not simple (13) and use of this pathway for power generation is not common. Further, these dual-purpose food and energy crops were not considered as their production requires resource inputs and they have economic value as food and livestock feed. Agricultural byproducts such as corn stover are also locally available, but their value as feed and bedding in the dairy industry leads to local prices ranging from $115 to $225 per ton plus delivery (14).

Blume (2007) provides detailed, approachable plans for small-scale production of ethanol from various agricultural feedstocks. Whey byproduct from dairy product processing can yield 30 gallons of ethanol per 1000 gallons feedstock (15), thus the abundant waste stream from the Land O’ Lakes Carlisle plant two miles from the farm could be a viable resource for ethanol production. However, like biodiesel, small-scale ethanol production would require extensive labor input from a skilled operator, would have safety concerns, and production of large amounts of alcohol is likely not a great fit for a program with resident college students.

One residual waste biomass feedstock to energy pathway that is worthy of further investigation is the use of wood chips as fuel for a combustion boiler or gasifier CHP unit. The farm already serves as a dumping site for wood chips resulting from residential tree trimming and utility contractors clearing around power lines. The chips are currently used as carbon bulking agent for composting of the campus food waste resource, but could feasibly be diverted to heat and power generation if project economics proved feasible. The chips are delivered for free; a survey of current users of the dump site could determine their willingness to pay a tipping fee. Roughly 1000 cubic yards per year are dumped at present (based on approximate dimensions of the dump site) – more could be obtained with a limited outreach effort. Using a theoretical energy value of 593 kWh / yd^3 of wood chips (16), the energy content of the current woodchip supply is roughly 593,000 kWh per year less conversion efficiency losses. Utilization of this waste resource for energy may require the construction of a weather protected storage shed with concrete slab and purchase of handling equipment and the biomass conversion appliance. Hurst Boiler (17) markets small to medium scale wood chip combustion and gasification CHP systems, while All Power Labs (18) "Power Pallet" units convert woody biomass to grid-tied electricity and biochar through gasification. If we estimate the cost of a concrete floor storage/equipment shed at $40,000 and a 25kW Power Pallet CHP system at $30,000, a woodchip to energy & biochar project is worthy of serious consideration.

Our focus for this project report has been on anaerobic digestion of farm residues for electricity, heat and fertilizer production. Within that context, numerous alternative versions of feedstock combinations, digester designs, and power conversion equipment have been considered – discussion of these is woven throughout the remaining pages. Our investigation of small to medium scale biogas systems has been limited to plug flow and full-mix (CSTR) reactor designs. Numerous alternative reactor designs are described by Rittmann and McCarty (19) and Lansing (20), but such systems are not yet well proven in farm applications, so we chose to focus our efforts on the two most commonly used configurations. A novel fixed film digester visited by co-author Steiman at a dairy farm near Shippensburg PA failed within a few years of commissioning due to operational complexity.

System Design

Feedstocks available

The active agricultural landscape surrounding the Dickinson College Farm coupled with proximity to the town of Carlisle PA (pop. 19,250) result in many options for residual waste feedstocks for energy production through digestion (fig 2). The baseline materials available on the farm are food waste from the college cafeteria and manure from 20 beef mature cattle equivalents. In order to reach a workable economy of scale for digester and CHP equipment, importing of additional feedstock materials has been considered. Each available feedstock is described briefly below.

Fig 2: Potential sources of digester feedstock near the Dickinson College Farm

Food waste

Dickinson College food waste production and collection was described in the composting section of the introduction. At present, approximately 378 kg/day of partially dewatered food waste is mixed with leaves and woodchips for composting, with a small fraction diverted to the pilot scale digester. Dickinson food waste production is fairly steady over 10 months of the year, with breaks for winter holidays and a summer cleanout period at the cafeteria. The material is a non-homogenous mixture of all types of food served, including produce, cooked grains, meats, condiments, and desserts. A trace amount of non-biodegradable plastics (mustard packets, rubber bands, disposable gloves, etc.) is mixed in with the food scraps, but it is almost entirely free of metal cutlery or other hard contaminants. Analysis of samples of the Dickinson College food waste performed by co-author Iram resulted in values of 20.87% total solids, 16.37% volatile solids. No collection cost is charged to the project financial analysis since this activity is already ongoing for composting.

Food waste: Collection at Dickinson College Dining Services (L); unloading for compost at the farm (R).

Additional food waste may be available from local grocery stores and commercial food processing enterprises. Co-author Steiman spoke with managers at two large grocery stores in Carlisle but both already had food waste hauling arrangements in place. Further investigation of local options may yield substantial additional resources. The Carlisle School District will soon begin bringing their cafeteria waste to the Dickinson College campus for transportation to the farm – exact quantity to be determined. Brett Reinford, business manager of the digester and food waste collection at Reinford Farms dairy near Mifflintown PA suggested $20 per ton as a competitive tipping fee for this substrate. Their farm digester targets 50% food waste, 50% dairy manure for elevated gas production and income from the tipping fees (21).   In the "Scenarios" tab of our spreadsheet calculator, Dickinson College food waste is a fixed component in any mixture, while additional space linked to the calculations is provided for supplementary food waste and tipping fee inputs.

The choice of food waste collection method will affect labor cost and logistical complication. In a previous two-year trial with Weis Market in Carlisle PA, the Dickinson farm collected food waste for a tipping fee in 50 gallons wheeled plastic cans with flip top lids. These were stored in the produce cooler of the grocery store between biweekly pickups to minimize putrification. To collect the waste, farm staff would enter the store, find a manager, and then wheel the bins out to a pickup truck equipped with a lift gate. This arrangement worked OK but did cost more in labor time than the arrangement at the college cafeteria, where smaller bins are stored on the loading dock for quick pick up. A novel approach being employed at some grocery stores is the Emerson Grind2Energy system (22). Components of this system include a dedicated sink with industrial garbage disposal installed in the backroom of the store, where staff manually feed spoiled food for grinding. The system automatically adds the appropriate amount of water to produce a pumpable slurry. The slurry is stored in an insulated tank outside the store, equipped for remote monitoring of tank level by the entity servicing the tank. Food waste slurry is collected regularly via a pumper truck for delivery to the digester site. If capital costs are not overwhelming to the project balance sheet, the Grind2Energy system is attractive for its convenience, reduced labor costs, and the added benefit of receiving a pre-ground food waste substrate.

Cattle manure

Manure from beef and dairy cattle is an excellent substrate for anaerobic digestion. While not as energy-rich as food waste or other concentrated feedstocks (cattle have already made use of some of the energy contained in what was eaten), fresh cattle manure is rich in microbial seed, including the methanogenic organisms critical to success for a methane digester. Using cattle manure as feedstock constantly introduces microbial biomass to the digester and can help to avoid problems of washout of the slow-growing methanogens. Some of the cellulose fibers in cattle manure are slow to digest, providing a sustained substrate for balanced microbial growth and gas production throughout the hydraulic residence time of a volume of slurry through the digester. Slow digesting cattle manure has been found to balance against the volatility of faster-digesting substrates such as food waste, simple sugars, or fats oils and grease (FOG), while also providing some alkalinity for buffering against digester souring. Fresh cattle manure exits the animal at body temperature and is slow to freeze in winter at moderate temperatures (23).

The farm maintains a herd of beef cattle equivalent to about 20-1000 lb. animals, between mature cows, calves, and young stock. During warm months the herd is mostly on pasture, but during winter, wet periods, and times of extreme heat the cattle are in a roofed concrete heavy use area. This allows collection of their manure with a loader tractor – presently it is composted but it could be easily diverted to the digester project. Using a figure of 37 kg manure per animal per day (about 10 gallons), with 75% of excreted material collected over four months, we estimate 68 Mg of manure is available for digestion. The increased collection is possible if the farm makes better use of the covered concrete pad during hotter days in summer. Because manure collection for the digester will require additional labor and machinery time compared to its present use, we've charged a transport cost of $25 per load or $750 per year for this feedstock.

Triple L Farm is a family-run dairy farm operated by Lorin Hoover and his siblings. In addition to 180 milking cows maintained on the Hoover's property 6.5 miles from the proposed digester site, Triple L rents about half of the farmland and a homestead owned by Dickinson College, directly adjacent to the educational farm. 100 dairy heifers (young cows) and dry cows (between milk production cycles) are kept by Triple L on the land rented from Dickinson. Because dry cows and heifers are fed less than mature lactating dairy cattle, they produce less manure. Using a value of 37 kg per animal per day, with 50% collection over the entire year, we estimate that the Hoover's 100 dairy cattle will produce about 680 Mg of collectible manure per year. More could be collected with some infrastructure improvements to cattle feeding and loafing areas. Co-author Iram analyzed manure samples from Triple L farm and found mean values of 14.26% total solids, 10.42% volatile solids. The proximity of the Triple L Farm cattle housing to the proposed digester site makes this manure source very attractive to the project. Installation of a manure reception pit, mixing / transfer pump, and buried 6" pipeline and other components were estimated at a capital cost of $36,575 for the financial analysis spreadsheet (see Manure Transfer Cost tab). For more information on Hoover's dairy and relationship with Dickinson College Farm, see Appendix 2.

Working with Triple L farm to digest their manure would present many potential benefits. In addition, adding needed volume to approach the digestion capacity of smaller commercial digesters discussed below and the balancing effect of the manure on food waste, adding in the dairy manure would make the project eligible for cost-share grants from the Natural Resource Conservation Service (NRCS). These grants include funding for the digester itself on a per animal basis as well as grants for the manure collection improvements at the cattle housing area. NRCS can also provide engineering support for project design and will help ensure manure nutrients are managed according to best practices. NRCS funds would not apply to manure from animals residing on land not owned by the entity applying for funding, thus this benefit is unique to the dairy animals housed on land rented from Dickinson (24).

There are several additional dairy farms in relatively close proximity to the proposed digester site (fig 2). While the two farms we approached for the design project did not agree to commit to supplying the proposed digester, it does seem likely that further recruitment efforts could yield additional feedstock for digestion. The Hoover's home dairy produces roughly 4500 gallons of manure per day. Lorin Hoover estimated that using contracted services, it would cost $100 per 5000-gallon load to haul manure between his dairy and the digester site, while the purchase of a used manure tanker would cost $40,000 plus the tractor to pull it. We included manure from 100 cows on a hypothetical farm 2 miles away with a hauling cost of $50 per load in feedstock scenario C. As mentioned above, capital costs for additional digester and power production capacity would not be eligible for NRCS cost-share grants.

Duck manure

Lester Martin and family operate a duck production confined animal feeding operation (CAFO) about two road miles from the College Farm. Batches of 40,000 ducks are raised in a flush-cleaned barn, resulting in roughly 1,000,000 gallons per year of manure slurry at approximately 4 – 6 % solids. Odor complaints are a problem in the mixed agricultural/residential neighborhood (in warm conditions duck manure lagoons become anaerobic and produce substantial foul odors). When approached, Mr. Martin was open to the idea of sending his manure to the digester project, mostly due to the possibility of odor mitigation. We were not able to obtain a physical sample of this feedstock due to biosecurity access limitations and wet weather disrupting the normal manure hauling schedule. Presently the farm spreads about half of their manure on cropland, the rest is provided as fertilizer to a neighboring crop farmer at the low price of $1 per 1000 gallons. For a scenario incorporating the duck manure, we used an estimated cost of $50 per 5000-gallon load to haul the duck manure between farms. One benefit of this low solids feedstock would be that no additional water would need to be added to a codigestion slurry to dilute the overall mixture to a target range of 10-12% solids whereas all other scenarios considered would require hundreds of gallons of dilution water per day. On the other hand, an engineer familiar with successful project design (25) suggested that it would be more cost effective to partially dewater the duck manure feedstock before hauling. A small manure solids separation unit capable of processing the Martin duck farm daily flow into a stackable product with roughly 30% solids was quoted at $15,000 (26).

Dairy processing wastes

Land O' Lakes Carlilse dairy plant is the largest butter production facility on the US east coast, located just 2 miles from the farm on the same road. Fluid milk from farms around the region (including Triple L farm) is trucked into the plant daily for conversion into butter and powdered milk products. All equipment in the processing lines must be flushed and sanitized daily, resulting in high flows of wash water laden with organic material. The plant was fined and generated negative press in the past decade due to fish kills caused by the release of wastewater with high biological oxygen demand (BOD) to a nearby creek. In 2015 the plant installed a $15 million wastewater treatment plant with aerobic activated sludge processing and successfully resolved pollution discharge problems. Dissolved air flotation (DAF) is used to remove fats oils and grease (FOG) from the wastewater prior to biological processing. In DAF systems, the water is pressurized in the presence of air to the point of saturation, then released from the pressure vessel into a large tank. Under ambient pressure, microbubbles of air emerge from the water and carry small fat particles to the tank surface where they have skimmed away for disposal. The Land O Lakes plant generates one 6000 gallon tanker load of DAF floatation waste per day. Staff environmental engineer Chris Roelke is charged with finding permissible sites for disposal of this waste stream – current options include anaerobic digesters and land application on farms. Mr. Roelke was not permitted to give us a detailed analysis of the DAF float material without a nondisclosure agreement, but he did explain that it has high BOD from residual milk sugars and fats, about 2% solids, and neutral pH. Metal coagulants such as aluminum chloride, aluminum sulfate or iron products are used as coagulants to aid in flocculation of fat particles for easier removal – these metal products end up in the DAF waste stream. An additional aspect of DAF float that would be attractive is temperature – the material emerges from the plant at 70-80 degrees F in winter, higher temperatures in summer. If used as digester feedstock this would result in substantial energy savings that would otherwise be expended to preheat incoming feedstocks, especially in winter. It was implied in our meeting that Land O Lakes pays for the material to be hauled to the digester sites and also pays a tipping fee (27). If we use $0.06 per gallon as a hypothetical tipping fee (AA), this would result in tipping fees of $360 per a load of DAF float delivered.

Lacking samples to analyze or other data from Land O Lakes, we reached out to a digester operator who has processed some of this waste stream. Brett Reinford of Reinford Farms dairy replied that while the DAF float does produce substantial gas increases when added to his digester, he has concerns about the long-term effect of metals from the coagulants having a negative impact on his soil (21). Given the lack of detailed information on feedstock characterization and potential conflicts of the metal coagulants with Dickinson College Farm's status as a certified organic produce operation, we did not explore this feedstock option further at this time. However, provided additional data can be obtained, the proximity, tipping fee, energy production potential, and high temperature do make this feedstock worthy of further investigation if the coagulant concerns can be overcome.

Community digester considerations

Centralized digesters shared by more than one farm are referred to as community digesters in the literature. When compared to a digester owned and dedicated to a single farm, community digesters present both advantages and potential challenges. Bothi and Aldrich (28) note centralized digester management, centralized compliance with regulations, and economy of scale for purchases of capital equipment such as the CHP unit and manure solids separators as likely advantages of a community digester approach. On the other hand, larger digesters may face more stringent environmental regulations due to size, and biosecurity concerns may arise when transporting manure and digester byproducts between farms. Transportation costs between farms are also a factor and will vary on a case-by-case basis depending on the distance between farms, topography, and location of obstacles. Aldrich and colleagues (29) considered options for shared digesters between four dairy farms in New York State and found that single-farm digesters and digesters shared by two nearby farms were more economically feasible than one centralized digester for all four farms. A community digester built on behalf of the Cayuga County Soil and Water Conservation District (NY) hauls manure from 1500 cows on two farms located 12 and 7 miles from the project site. The digester project owner purchased trucks dedicated to the task of daily manure hauling (30). This project received substantial public funding for capital costs so likely does not reflect the economic conditions faced by private farm digesters. Another important consideration is the amount of coordination required to enact a successful project shared between multiple farms. The NRCS will require extensive documentation to ensure nutrient flow between farms is being managed according to conservation plans (24). Out of concern for transportation costs and the energy required for relationship building, accounting for nutrients and settling of potential disagreements, we find feedstock scenarios limited to cooperation between the Dickinson College Farm and Triple L Farm to be the most approachable. If the digester project is built with spare capacity, it is feasible that additional substrates could be brought in overtime on a case-by-case basis.

Feedstock Scenarios

The following scenarios were considered using the financial and production spreadsheets developed for this project:

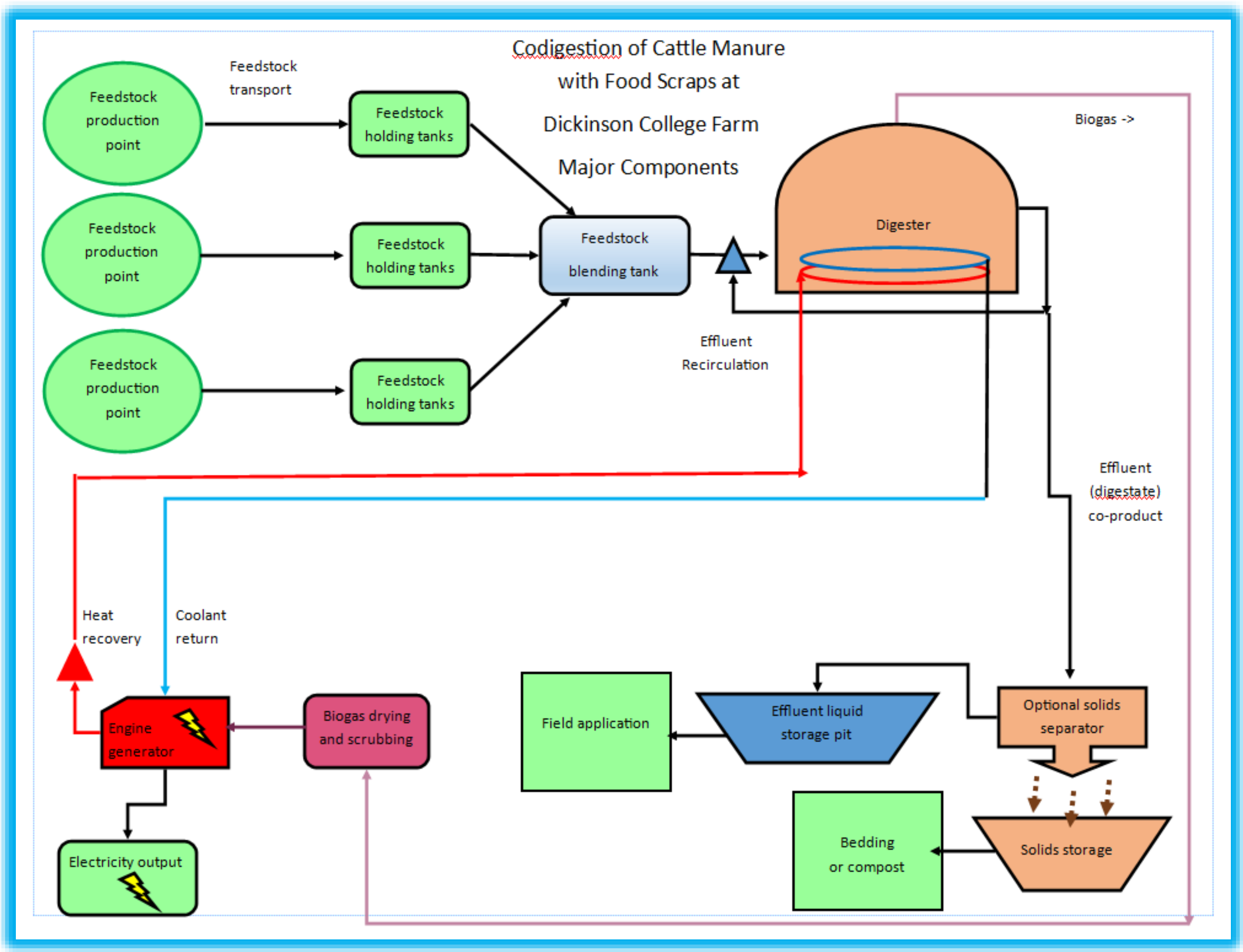
Scenario	A	B	C	D	E	F
Dickinson College Food Waste, 378 kg/d, 21% solids, 10.5 months/yr						
Triple L Farm 100 dry cows and heifers, 50% collected, 1865 kg/d, 14% solids						
Dickinson College Farm beef cattle (20), 75% collected, 566 kg/d, 14% solids, 4 months/yr						
Nearby dairy cows (100), 100% collected, 6709 kg/d, 14% solids						
Martin Duck Farm manure, 9963 kg/d, 6% solids						
Small grocery store, 10.3 kg/d, 21% solids						
Design flow (gal/d)	926	2570	3555	939	1145	415
Est. methane production (m^3/yr)	20294	25385	81514	20408	21246	4240
Est. transportation cost ($/yr)		10000	6734	237	748	748
Est. capital cost (PF)	191150	254156	442630	191447	196139	151485
Est. capital cost (CSTR)	314908	329702	453570	315025	316880	NA

Table 1. Description of feedstock scenarios for digestion and the resulting impact on design flow, methane production, transportation cost, and capital cost estimates for owner-built plug flow (PF) and purchased full mix digester packages.

Physical system design

The overall system will be composed of the following components: feedstock collection points, transport, holding tanks, and blending/preheat tank; anaerobic digester; biogas collection, dewatering, and H2S scrubbing; effluent recirculation, optional solids separation, and storage; CHP genset; heat transfer & utilization; electrical interconnection with utility power. The schematic arrangement of these components is pictured below in fig. 3. The results of the economic analysis may eliminate some components due to capital cost.

Fig 3



Digester design options: Plug flow vs. Continuously Stirred Tank Reactor

While numerous anaerobic digester designs have been successfully implemented, plug flow and full mix (also known as continuously stirred tank reactor – CSTR) systems are the most common designs used on farms. Each system has is potential benefits and drawbacks.

CSTR

In a completely stirred tank reactor, the entire contents are continuously mixed by an immersed propeller or an external circulation pump. Cylindrical tanks are typically made from insulated concrete or steel structures, with the gas collection at the top. By design, these systems have the benefit of constant agitation, keeping solid material in suspension and microbial biomass in contact with a digestible feedstock. One limitation of CSTR reactors is that due to full mixing, a portion of recently introduced feedstock will exit with effluent before it has fully converted to products (31). This can be compensated for by increasing the hydraulic retention time(32), but this requires an increase in tank volume with added expense.

A new CSTR package emerging on the US market is the Bioelectric Mini Digester, marketed in North America by Martin Energy Group. The Bioelectric company, based in Belgium, has completed about 150 digester projects in Europe on smaller dairy farms. The main tank kits are modular (with a variety of sizes to fit various farm scales), made from insulated stainless steel panels that bolt together, they are lined with a custom fit plastic liner. Following the pouring of a concrete pad at the digester site, the CSTR reactor tank can be constructed from the kit in a matter of days. An integrated power & control system is installed in a factory-fabricated shipping container delivered to the farm. The power unit includes a grid-connected CHP engine, with recovered heat used to maintain digester temperature. All dynamic components are coordinated via sensors and controls in the shipping container. The smallest available systems are sized for 50-100 cows, with an 11KW CHP unit. These smaller packages are priced around $250,000 for the concrete pad, digester, CHP and control system combined (33). The engines used for CHP are modular (in 11 and 22KW sizes) allowing multiple units to be combined for flexibility and efficiency.

Plug Flow

These digesters typically consist of a long, narrow concrete channel set in the ground, covered with a flexible or hard-topped gas collector. The flexible digester shown in figure 1 is another example of a plug flow design. A common length to width ratio is 5:1. With proper hydraulic design, digestible substrates flow through the reactor via gravity, with minimal energy input.   In an idealized plug flow reactor, a control volume of slurry moves from the influent to the effluent end without short-circuiting or mixing of the contents. This reduction in mixing results in a theoretically higher efficiency of conversion of substrates to products (34), and the lack of a constantly running pump or mixer will result in reduced power consumption compared to CSTR reactors. Lansing and colleagues (35) found that low-cost plug flow digesters were more efficient than expected at the conversion of manure to methane despite a lack of internal mixing.

Another potential benefit of the plug flow design is their comparatively simple construction. The Cornell University manure management team provides detailed plans for the construction of the concrete channel, cover mechanism, and gas piping for a plug flow reactor that are approachable to qualified contractors. Given the history of pilot-scale digester construction at the Dickinson College Farm, the simplistic yet durable design of concrete based plug flow reactors has its appeal. During the feedstock investigation phase of the project, co-author Steiman visited the Ebersol duck CAFO in Shippensburg, PA, where the clever farm owner built his plug flow digester from a converted manure trench (see Appendix 4). The farm has access to low cost, locally available resources, including a nearby cement quarry, friendly excavation contractors, and access to free EPDM gas cover membrane for R&D purposes from an industrial roofing plant in Carlisle. With this in mind, we added detailed construction estimates to the project financial analysis spreadsheet for an owner-built plug flow digester with EPDM cover.

In an “ideal” plug flow digester there is no mixing, but this may present complications such as settling of solids and scum formation. Some farm plug flow systems incorporate vertical slurry mixing via biogas recirculation through tubes near the tank bottom (5, Appendix 4). Heat recovered from the digester’s CHP unit is also circulated through pipes immersed in the slurry to keep the system in the mesophilic temperature range.

Gas management

In either reactor design, biogas rising to the top of the digester slurry will be collected and transferred to the power unit via gas piping. Due to the warm temperatures of mesophilic digestion, the aqueous environment of the slurry and the chemical reactions taking place, biogas is nearly saturated with water. Water vapor in the gas can be condensed for removal by burying the gas pipe below grade (36) or actively using a powered gas chiller (37). Hydrogen sulfide is toxic to humans and has the potential to corrode metal and foul engine components. This contaminant is commonly scrubbed out by passing it through a layer of iron particles, where redox reactions convert the sulfur to iron sulfate. The Bioelectric system uses an injection of a dilute amount of ambient air into the biogas headspace – microbes living on a suspended net in the gas space use the oxygen in the injected air to convert the sulfur to sulfate particles that drop by gravity into the slurry below (37, 38).

CHP unit

Commercially available small-scale CHP engines adapted to run on biogas are hard to come by. Engines in the 5 to 10kW size are often referred to in the industry as micro CHP systems. Yanmar America (39) and Marathon Energy (40) market micro CHP systems using internal combustion engines designed to run on natural gas or propane at a cost of about $10,000 per kW installed. In order to run digester gas through one of these units, gas would need to be upgraded by scrubbing out carbon dioxide to increase the concentration of methane to near pipeline quality. Energy produces a free piston Stirling engine that runs on raw biogas – these also cost about $10,000 per kW installed (41). We used this factor in calculating the cost of CHP in the financials spreadsheet.

Effluent management

For the volume of feedstock slurry that is fed into the digester, nearly the same volume will exit as effluent (a fraction of the feedstock solids and water leave as biogas). While carbon, hydrogen, oxygen and some sulfur leave the system as biogas (CH_4, CO_2, H_2S), the majority of the crop nutrients contained in the original feedstock will be contained in the effluent. These nutrients (N, P, K, etc.) present a valuable resource but need to be managed to prevent environmental contamination through runoff. Working with Triple L Farm, the proposed digester project will combine nutrient streams from two farms together into one liquid flow. The project will work with NRCS engineers to design an effluent lagoon of proper size and construction to prevent unintended nutrient release. Triple L Farm operators will collect digested effluent for land application on dairy feed crops using conventional liquid manure equipment. The Dickinson College Farm will apply effluent to existing compost piles or will land-apply the material as a liquid via spray irrigation. A detailed accounting of effluent volumes utilized will be necessary to comply with nutrient management plans established on each farm.

Separation of the post-digestion solids for recovery as livestock bedding is common in larger dairy farm digesters. This would be attractive to both farms in the proposed project: Triple L Farm uses at least $5000 worth of bedding per year for their cattle (23) and more would be used if the manure management system is upgraded to aid in the collection for digester feed. Likewise, bedding beef cattle on the Dickinson side costs about $1500 per year. However, new commercial manure separation equipment appropriate for bedding production costs roughly $85,000 (42), though it is possible that used equipment could be procured and adapted with some effort.

Process highlights

Microbiology

The microbiology of anaerobic digestion is as much complex as the underlying reactions and directions that can be taken by the microbial consortia based on their culture conditions. Three most important factors to consider in the design of an anaerobic bioreactor are:

1. Metabolic capacities of the microbes
2. Functional redundancy in the individual microbial communities and
3. Interactions between different species

Based on the above-mentioned factors, it can be fairly assumed that the characterization of the microbial consortia in the digester is required. Based on these factors, the microbial communities can be divided into different categories based on their functional capabilities or taxonomic groups (43). The three major taxonomic groups in the biodigester are bacterial (mainly dominated by *Firmicutes* and *Bacteriodetes*), archaeal (*Methanosarcina* and *Methanoculleus*) and fungal (*Agaricomycotina* and *Mucoromycotina*) (44). While all these microbial communities can be characterized according to their sRNA fingerprints, their characterization in the biodigester according to their functionality is extremely necessary. For this purpose, in this report, the microbial communities are presented according to the types of reactions carried out by such species.

Types of reactions in the anaerobic biodigester

In this biodigester design, biological digestion of three types of organic substrates: cow manure, food waste, and duck manure. For the anaerobic digestion of such complex substrates, the number of reactions to produce methane as an end-product can be as many as the involving microbial communities. However, all such reactions can be carried out into three major categories:

- Hydrolysis and acidogenesis
- Acetogenesis and syntrophy
- Methanogenesis

Hydrolysis and acidogenesis are carried out by the bacterial hydrolytic and acidogenic communities in such a way that the complex organic macromolecules such as lipids, carbohydrates, and proteins are converted into soluble monomers like long-chain fatty acids, sugars, and amino acids. The fungal species also work at this stage to break the complex cellulosic strands into simpler sugars. The extracellular enzymes are secreted which break down the complex polymers. The monomers resulted in this stage can further be oxidized by Embden–Meyerhof–Parnas (EMP) or Enter–Doudoroff (ED) pathways.

Acetogenesis is mostly done through Wood–Ljungdahl (W–L) pathway or acetyl-CoA pathway. The pathway consists of two main steps. First is done to conserve energy while the other is done to fix carbon. The two branches of the pathway can be categorized into methyl and carbonyl branches which are composed of a series of different reactions. In the end, two carbon dioxide molecules are reduced in this pathway to produce one acetate molecule.

Methanogenesis is the last step in the anaerobic food chain to produce biogas. In this step, methanogens (mainly archaebacteria) converts the products of acidogenesis and acetogenesis into methane.

Table 2. Microbial Diversity according to reaction types in the anaerobic biodigester

Reaction Type	Microbial Communities	Examples	Common substrates	Common products	References
Degradation of macromolecules	Fungal Strains	Agaricomycotina, Pezizomycotina Mucoromycotina, Pucciniomycotina and Saccharomycotina	Long chain carbohydrates, cellulosic fibrils, hemicellulose	Long chain alkanes	(Kazda et al., 2014)
Hydrolysis and acidogenesis	Bacteria	Actinobacteria, bacteroidetes, α-proteobacteria, firmicutes, β-proteobacteria, and γ-proteobacteria	Polyaromatic rings, long-chain aliphatic hydrocarbons, and organic acids, lipids, proteins	Single ringed aromatic compounds, shorter chain aliphatic hydrocarbon, long chain fatty acids, amino acids	(Schnürer, 2016)
Acetogenesis and syntrophic reactions	Syntrophic bacteria	δ-proteobacteria, and ε-proteobacteria	Water-soluble compounds, Organic acids, fatty acids, Sulphates, Nitrates, and Alkanes	Acetate, Short chain aliphatic compounds, benzene, H_2+CO_2, and Single carbon compounds	(Adiga et al., 2012)
Methanogenesis	Methanogens	Methanobacteriales, Methanomicrobiales, Methanopyrales, Methanococcales, Methanocellales, Methanosarcinales	H_2+CO_2, Acetate, and methyl groups	CH_4 and CO_2	(Benstead et al., 1990)

The concentration of the substrates is a critical factor at this stage as the low concentration of hydrogen and acetate can shift the reaction to produce hydrogen, acetate and carbon dioxide instead of methane. Therefore, the analysis of the intermediate microbial reactions is very crucial for the maintenance of the bioreactor. Methanogens can be divided into two main groups based on the substrate utilized by these microorganisms. The first type of methanogens is called hydrogenotrophs which utilize hydrogen or formate and reduce carbon dioxide into methane, The second group is called Methylotrophic methanogens which utilize methyl groups along with carbon monoxide, hydrogen, carbon dioxide, acetate, and other compounds as the energy source and reduce the methyl groups into methane. The microbial diversity of all these reaction types is given in Table 2.

Reaction Kinetics

As it has been mentioned before, the microbiology of the anaerobic digestion of organic matter is quite complex. There are multiple intermediate reactions and products that are being produced and degraded before the production of desired products which is methane. Therefore, it is important to do the mass-balance analysis of the carbon, hydrogen, oxygen, nitrogen and other compounds at each stage. In addition to the elements, an electron balance is also necessary to maintain. In this regard, the basic strategy is to analyze the electron equivalents which are conserved in the form of CH_4. For the sake of simplicity, the reaction kinetics of acetogenic and methanogenic pathways will be discussed here as the initial hydrolysis and breaking down of complex substrates cannot be determined using simplified reaction processes.

Mass and Energy Balance

Mass Balance

Typical electron donors in most of the acetogenic reactions are CO, H2, Formate, Methyl chloride, pyruvate, etc. On the other hand, the electron acceptors in such reactions are CO2, Fumarate, Nitrate, Thiosulfate, and Acetaldehyde along with many others (45). The typical acetogenesis reactions are given below:

$$CH_3CH_2COO^- + 3H_2O \leftrightharpoons CH_3COO^- + H^+ + HCO_3^- + 3H_2$$

$$C_6H_{12}O_6 + 2H_2O \leftrightharpoons 2CH_3COOH + 2CO_2 + 4H_2$$

$$CH_3CH_2OH + 2H_2O \leftrightharpoons CH_3COO^- + 3H_2 + H^+$$

After acetogenesis, the acetate produced is converted into methane through the following reaction:

$$CH_3COO^- + H_2O \leftrightharpoons CH_4 + HCO_3^-$$

This reaction can be divided into two steps:

$$1.\ 1/8\ CH_3COO^- + 3/8\ H_2O \leftrightharpoons 1/8\ CO_2 + 1/8\ HCO_3^- + H^+ + e^-$$

$$2.\ 1/8\ CO_2 + H^+ + e^- \leftrightharpoons 1/8\ CH_4 + 1/4\ H_2O$$

Combining the two reactions will give:

$$1/8\ CH_3COO^- + 1/8\ H_2O \leftrightharpoons 1/8\ CH_4 + 1/8\ HCO_3^-$$

Dividing the equation by 8 will give the overall equation for this stage.

For an organic compound with an empirical formula of $C_nH_aO_bN_c$, we can develop the same reaction kinetics as follows:

$$C_nH_aO_bN_c + (2n+c-b-(9df_s/20)-(df_e/4))H_2O \rightarrow$$

$$df_e/8\ CH_4 + (n-c-(df_s/5)-(df_e/8))CO_2 + df_s/20\ C_5H_7O_2N + (c-(df_s/20))\ NH_4^+\ (c-(df_s/20))\ HCO_3^-$$

Here:

$$d=4n+a-2b-3c$$

Also here f_s is the fraction of the substrate converted into cells and f_e is the fraction converted into energy.

Theoretically $f_s + f_e = 1$.

According to Rittman and McCarty (45), the typical empirical formulas for carbohydrates, proteins, and lipids are $C_6H_{10}O_5$, $C_{16}H_{24}O_5N_4$, and $C_{16}H_{32}O_2$ respectively. The composition of the chosen feedstocks in this study is given in table 3, and the mixing of different scenarios is given in Table 4.

Table 3 Nutrient value of the feedstocks

	Food waste	Cow manure
Carbohydrates (%)	59.0	71.4
Proteins (%)	33.0	26.6
Lipids (%)	8.0	2.0

Table4. Summary of scenarios considered in this study

Scenarios	Flow rate	Cow Manure	Food waste

	(gal/day)	(%)	(%)
A	926	85	15
B	2570	100	0
C	3555	96	4
D	939	84	16
E	1145	88	12
F	415	62	38

Based on the empirical formulas, the electron-donor equations can be written for carbohydrates, proteins, and lipids.

For carbohydrates:

$$1/4CO_2+H^++e^- \rightarrow 1/24C_6H_{10}O_5+7/24H_2O$$

For Proteins:

$$2/11CO_2+2/33NH_4^++2/33HCO_3^-+H^++e^- \rightarrow 1/66C_{16}H_{24}O_5N_4+31/66H_2O$$

For lipids:

$$4/23CO_2+H^++e^- \rightarrow 1/92C_{16}H_{32}O_2+15/46H_2O$$

Combining the equation according to scenario E from Table 3:

$$0.076CO_2+0.0055NH_4^++0.0055HCO_3^-+H^++e^- \rightarrow 0.011C_{7.3}H_{61.54}O_{4.9}N_{0.49}+0.114H_2O$$

The stochiometric equation then becomes if we assume 100% efficiency (fs=0.0467, fe=0.9533)

$$C_{7.3}H_{61.54}O_{4.9}N_{0.49} + 4.65CO2 \rightarrow 10.64CH_4+13H_2O+0.21C_5H_7O_2N+ 0.29HCO_3^-+0.29NH_4^+$$

Energy Balance

For energy balance, we have to consider the anaerobic digestion with respect to energy inputs and outputs. Figure 1 represents a typical energy flow in the anaerobic biodigester.

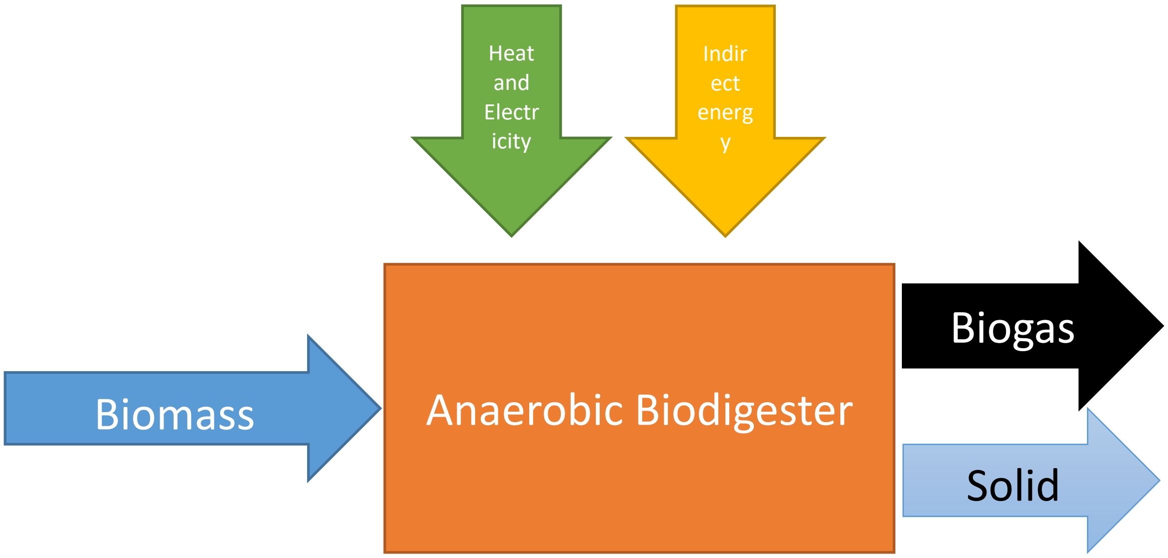


Figure4. Energy Flow in and out of the system

There are two types of energy inputs that will go into the systems: direct energy (heat and electricity) and indirect (machinery, construction, etc).

$$E_{ti} = E_{di} + E_{indi}$$

Here

E_{ti} is the total energy input (MJ/t).

E_{di} is the direct energy inputs (MJ/t).

And E_{indi} is the indirect energy inputs (MJ/t).

The output energy can be categorized into biogas production and loss of heat to the environment.

$$E_{to} = E_{biogas} + E_{heat\text{-}loss}$$

For most of the times, energy output is the function of temperature so different operating temperatures will produce different output energies. For anaerobic biodigester designs, the total output energy can vary from 3822 MJ·t-1 at 57 ºC to 6089 MJ·t-1at 52 ºC (46).

Financial Analysis

Pro forma financial statements have been prepared to determine the profits and associated cash flows over the life of the project. A discounted cash flow model has been used as the basis for the financial analysis, which allows for the calculation of net present value. Specifically, we have used the free cash flow to equity discounted cash flow model (which is after debt servicing and repayment) rather than free cash flow to the firm.

It is important to recognize that the discounted cash flow model is based on numerous assumptions that are merely best estimates of unknowable future prices and volumes. Therefore, we have also presented a sensitivity analysis for some of the key financial assumptions.

Base Case Assumptions

System Design

For this analysis we have focused on Scenario E. Though we investigated a plug-flow digestor coupled with a CHP system purchased through an independent retailer, we have assumed a packaged system, with the anaerobic digestor and CHP systems purchased together. Martin Energy Group is an example of a distributor of such integrated systems and we have used capital costs they have provided. Though the capital costs are higher for the packaged system, we prefer this approach for greater certainty of operating performance.

Capital Structure

We have assumed the federal (Natural Resources Conservation Service' Rural Energy for America) and state (Alternative Clean Energy) programs are utilized and cover 28% and 22% of the capital costs respectively (both below the maximum grant levels of 30%). We have assumed the residual of the project cost is financed through a 50/50 mix of equity from the College and debt. Due to the guarantee associated with the REAP program, we assume a low cost of debt of 4.5% fixed throughout the life of the project.

Discount rate

We have assumed a discount rate of 6.0%, which is an estimate of the College's real cost of equity. We have used the cost of equity rather than the weighted average cost of capital because the model is discounting free cash flow to equity (not free cash flow to the firm). Additionally, we are using a real (inflation-adjusted) discount rate because cash flows over the life of the project have not been increased by inflation. The cost of equity includes a premium over the 20-year risk-free rate to reflect additional risk of the project and the opportunity cost of the College investing capital in the project.

Revenue

We have assumed two tiers of electricity prices. For electricity used internally, we have used the opportunity cost which is buying from the grid at $0.14 /kWh. A wholesale rate of $0.10 is assumed for electricity generated and available for export to the grid. This is above the wholesale rate of electricity and is dependent on being able to achieve agreements with neighboring properties. Similarly, for the heating output of the CHP, we have calculated the gas use that is offset and have assumed a price of $11.40 per thousand cubic feet, which is equal to the retail price according to the EIA.

Revenues are based on total CHP efficiency of 85% (42% electricity and 43% heat recovery). Tipping fees have been included for food waste and are estimated at $22 per tonne. No revenue or benefit from stock bedding or fertilizer has been included in the financial model.

Tax, Incentives and Other Benefits

We have assumed that the tax rate of the College is 0%. MACRS depreciation is available, though this has no benefit with tax exemption. For simplicity and due to the small scale of the project, we have not considered tax equity partnerships.

We have assumed the project is eligible for tier 1 Alternative Energy Credits (AEC's) as part of a Pennsylvania state program. The weighted average value of an AEC in 2017 was $12.16 (with one credit corresponding to one MWh). AEP tier 1 prices ranged from $1.75 to $79.24 in 2017. Since the output of the digester will not be sold as renewable gas, we have ignored any value associated with RINs.

The project will reduce greenhouse gas emissions through multiple channels, most notably through the reduction of methane emitted to the atmosphere every year. Since Pennsylvania does not currently have a carbon tax or trading scheme, we have not included this in the financial model. However, we note that if Pennsylvania were to adopt a carbon trading scheme, there could be considerable value to these emission reductions.

Operating and Maintenance Costs

Operating and maintenance costs are equal to $0.02 per kWh and half an hour of labor per day.

Economic Life

The project's life is assumed to be 20 years. Other than annual maintenance, no allowance is made for replacing any major components during the project.

Pro Forma Financial Statements

Profit and loss and cash flow statements for the establishment year and the first five years of operation are shown below, based on Scenario E and the base case financial assumptions.

Table 5 Profit and Loss Statements

Profit and Loss Statement						
	2019	**2020**	**2021**	**2022**	**2023**	**2024**
Revenue						
Electricity Offset		4,158	4,158	4,158	4,158	4,158
Electricity Sold		5,905	5,905	5,905	5,905	5,905
Gas Offset		2,814	2,814	2,814	2,814	2,814
RECs		1,079	1,079	1,079	1,079	1,079
RINs		-	-	-	-	-
Tipping Fees		2,395	2,395	2,395	2,395	2,395
Total Revenue		16,351	16,351	16,351	16,351	16,351
Expenses						
Transport Cost		748	748	748	748	748
Op and Maintenance Expenses - AD		1,775	1,775	1,775	1,775	1,775
Op and Maintenance Expenses - CHP		4,777	4,777	4,777	4,777	4,777
Total Expenses		7,300	7,300	7,300	7,300	7,300
Earnings before Interest, Tax and Depreciation		9,051	9,051	9,051	9,051	9,051
Depreciation Rate (5 Year MACRS)		20%	32%	19%	12%	12%
Depreciation Expense		15,844	25,350	15,210	9,126	9,126
Earnings Before Interest and Tax		- 6,793	- 16,299	- 6,159	- 75	- 75
Interest Expense		3,565	3,387	3,208	3,030	2,852
Profit Before Tax		- 10,358	- 19,686	- 9,367	- 3,105	- 2,927
Tax (0%)		-	-	-	-	-
Net Profit		- 10,358	- 19,686	- 9,367	- 3,105	- 2,927

Table 6. Cash Flow Statements

Cashflow Statement						
	2019	**2020**	**2021**	**2022**	**2023**	**2024**
Operating Cashflows						
Net Profit		- 10,358	- 19,686	- 9,367	- 3,105	- 2,927
Add back non-cash items						
Depreciation		15,844	25,350	15,210	9,126	9,126
Changes in Working Capital		-	-	-	-	-
Operating Cashflow		5,486	5,665	5,843	6,021	6,199
Financing Cashflows						
Equity Financing	79,220					
Debt Financing	79,220	- 3,961	- 3,961	- 3,961	- 3,961	- 3,961
Financing Cashflow	158,440					
Investing Cashflows						
Capital Expenditure	- 158,440					
Net Change in Cash	-	5,486	5,665	5,843	6,021	6,199

Base Case Results

The project is expected to cost ~$317,000 in total, comprising ~$250,000 for the integrated digestor and CHP system, ~$37,000 for the manure collection and transfer from LLL farm, ~$10,000 for effluent holding ponds, and ~$20,000 for the electrical system upgrade for interconnection.

This is covered by an estimated ~$125,000 from the grant programs, ~$79,000 in low-cost guaranteed debt and a ~$79,000 equity contribution from the College.

On the previously mentioned assumptions, we estimate revenue in the first year to be ~$16,300, and earnings before interest, tax and depreciation to be ~$9,000. Net profit is expected to be negative in the first year, due to the front-loading of the depreciation expense while operating cash flow is expected to be ~$5,500.

The project is expected to deliver positive free cash flows (after debt repayment) to the College as the equity investor that increase over time as the debt is repaid. These free cashflows to equity have a present value of ~$33,000.

On the initial outlay of ~$79,000, the result is a negative net present value of ~$46,000 and is equivalent to an internal rate of return of -1.6% (below the cost of capital). This implies that the project is not viable on financial merits alone.

However, there are many non-financial benefits that have not been included in the financial model, such as the publicity the project could bring to the College, and the opportunities for student education in agricultural energy systems. We reiterate that the financial model does not include carbon pricing due to the lack of any legislation in Pennsylvania. The project could be a viable option for reducing significant methane emissions over 20 years should the College wish to act ahead of legislation.

Table 7 Net Present Value

Net Present Value						
	2019	**2020**	**2021**	**2022**	**2023**	**2024**
Capital Expenditures (Equity)	- 79,220					
Operating Cash Flow	-	5,486	5,665	5,843	6,021	6,199
Debt Repayment		- 3,961	- 3,961	- 3,961	- 3,961	- 3,961
Free Cashflow to Equity	- 79,220	1,525	1,704	1,882	2,060	2,238
Discount Rate - Real Cost of Equity	6.00%					
Present Value of Cashflows	**33,043**	1,439	1,516	1,580	1,632	1,673
Net Present Value	**- 46,177**					
Internal Rate of Return	**-2%**					

Note Only the first five years of operation shown.

Sensitivity Analysis

As previously mentioned, the base case net present value analysis is highly dependent on the assumptions listed. We have therefore provided the following sensitivity analysis to demonstrate how the economics of the project change with five of the most important assumptions.

Methane Production	+5%	Base Case	-5%
NPV	-$ 44,346	-$ 46,177	-$ 49,742
IRR	-1.3%	-1.6%	-2.4%

Project economics are relatively insensitive to methane production as these mainly impact exported electricity and gas savings (which are lower items than internally used electricity and tipping fees). Additionally, this is asymmetric as increases in production are limited by the capacity of the CHP unit and add little to project economics as higher value internally used electricity needs are mostly already met.

Electricity and gas prices	+20%	Base Case	-20%
NPV	-$ 16,638	-$ 46,177	-$ 75,715

IRR	3.5%	-1.6%	-9.4%

The above demonstrates that the project economics are highly sensitive to changes in energy prices.

Discount Rate	+1%	Base Case	-1%
NPV	-$ 49,245	-$ 46,177	-$ 42,656
IRR	-1.6%	-1.6%	-1.6%

As is usual for a long-life project, the net present value is sensitive to assumptions around changes in the discount rate (the inflation-adjusted cost of equity). However, the internal rate of return is unaffected.

Capital Expenditure	+20%	Base Case	-20%
NPV	-$ 76,175	-$ 46,177	-$ 16,178
IRR	-5.6%	-1.6%	3.0%

Capital expenditure has a significant impact on the project viability. This is relevant from multiple perspectives. Firstly, the project cost is only estimated and could be higher or lower. Secondly, there is the possibility that the full grants are not available. Thirdly, the net cost to the College may be reduced if donors are found.

Economic Life	+5 Years	Base Case	-5 Years
NPV	-$ 40,905	-$ 46,177	-$ 54,147
IRR	0.4%	-1.6%	-6.4%

The economic life of the project is unknown and only estimated at 20 years. Changes in this factor also have an asymmetric impact on the project economics as cash flows in years 21-25 are ‘devalued’ more in discounting back to a present value (which is the reverse of compounding).

Discussion

Financial

The financial statements are based on expected methane production of ~21,000 m3 per year, which is equivalent to ~211,000 kWh before conversion. With a capacity of 11kW and a capacity factor of 95%, the CHP system could theoretically generate 91,000 kWh per year. However, this is constrained by the available gas which limits electricity production to ~89,000 kWh. Given energy demands from the two accounts total 33,000 kWh per year, and there will be occasions when power demand exceeds capacity, it is assumed that ~30,000 kWh is consumed internally and ~59,000 kWh is 'exported' to the grid or sold to neighbors. This produces the two largest revenue items for the project.

Other revenue items included are the gas offset, renewable energy credits, and tipping fees. It is assumed that 80% of the heat energy recovered is able to be utilized, which reduces the amount of gas needed to be purchased externally. Though this heat represents a significant volume in terms of energy, the low price of gas means this is a less significant item in the financial statements compared to the electricity. Though not all items are strictly new revenue to the owner, these have been treated as revenue from the project perspective due to the benefit of purchasing less gas, less RECs elsewhere and avoiding paying tipping fees.

A small allowance is made for transport costs, but the main expenses are related to operating and maintenance of the anaerobic digester and combined heat and power. Depreciation is included in the profit and loss statement (and is front-loaded according to the MACRs 5 year schedule) but is added back in the cash flow statement as it is a non-cash expense. The other major expense is interest, which declines over time due to straight line repayment of the debt.

Digester design

While the owner built plug flow design is attractive from a do-it-yourself perspective, and the capital cost savings versus a purchased package are significant, there are many limitations as well. In order to qualify for federal cost-share funds, NRCS will require the farm to work with an experienced engineering firm with a successful track record on digester projects (24). In addition, the sophistication of the integrated sensor and control modules in the factory built Bioelectric power system will be impossible to match with local resources and the technical skill of farm personnel. In this case, it appears that the experience, technical abilities, and design skill of a professional firm like Martin Energy Group will be well worth the added cost. In addition, the Bioelectric units can be constructed and commissioned in a matter of weeks, while an owner-built system would undoubtedly take much longer. Appendix 3 details the trials and tribulations of the Ebersol duck farm digester – a very ambitious project that has been offline due to the failure of improvised components. Finally, the land impact of the Bioelectric digester is limited to a modest sized concrete pad – if either project should fail, the long-term impact on the landscape would be much greater for the deep concrete trench of a plug flow design.

Conclusions

Much work remains before we are ready to convert the findings of this document into a functional digester project. Feedstocks will need to be more thoroughly vetted and analyzed, relationships will need to be cemented, designs selected, and funds secured. The process of applying for and (hopefully) winning federal and state grants can take months or years alone. This document also does not consider state environmental permits, interconnection agreements with the utility or the details of nutrient management planning between farms. Once a reasonable plan is in place, capital funds from Dickinson College will need to be lobbied for amidst many other institutional priorities.

Nonetheless, the financial & production estimation spreadsheet of this project should be a useful tool for consideration of future feedstock scenarios. If Dickinson College (or any other entity using considering such a project) decides to go forward with a full-scale digester for energy production, the spreadsheet will be an excellent starting place for examining the feasibility of various feedstock scenarios. By editing feedstock quantities and relevant parameters, any combination of available materials can be assessed for flow rate, digester and CHP unit sizing, methane production, and system construction cost. The detailed financial calculations allow a thorough analysis of the long-term return on investment of the project. The sensitivity analysis and nuances of this spreadsheet have shown how small changes in some factors can produce major shifts in the financial outlook of the proposed project.

This project has also demonstrated the complexity involved in launching even a small scale community digester project. Many hours were spent tracking down and analyzing potential feedstocks, finding and pricing components and construction materials, and considering various designs. What seems like a relatively simple process on the surface – producing electricity from waste via anaerobic fermentation of residual biomass – becomes quite complex when considering the financial, physical, and microbiological aspects of the project. However, we are optimistic that Dickinson College will find value in the opportunity to reduce methane emissions while producing clean power from residual waste.

References:

1. Ken Shultes, Cody Rosenbarker (Dickinson College Center for Sustainability Education), Personal Communication 12/3/18

2. Dickinson Dashboard – Compilation of sustainability statistics of Dickinson College: Retrieved from: http://marcomm.dickinson.edu/dashboard/waste_minmization.html See also calculation 1, appendix A

3. DiStefano & Schust (2016). "Evaluation of anaerobic digestion of food residue at Dickinson College", Bucknell University summer engineering study (unpublished).

4. See calculation 2, appendix A.

5. Cornell Manure Management Program: Case studies of farm digesters in NY State. Retrieved from: http://northeast.manuremanagement.cornell.edu/Pages/Popular_Pages/Case_Studies.html

6. Curt Gooch, P.E., Cornell Manure Management Progam, personal communication, October 2018.

7. See calculation 4, appendix A.

8. Solar CITIES small scale biogas digester from IBC tote design and description: Retrieved from: http://www.solarcities.eu/education/388

9. EPA Agstar program figures, ideal farm size for AD projects: Retrieved from: https://www.epa.gov/agstar/anaerobic-digestion-right-your-farm

10. Scott, N. & Ma, J. (2004). "A Guideline for Codigestion of Food Wastes in Farm-based Anaerobic Digesters". Retrieved from Cornell Manure Management Program: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Fact_Sheets/Codigestion_factsheet.pdf

11. Searchinger, T., Heimlich, R, Houghton, R.A., … Yu, T. (2008). Use of U.S.Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science, (319)*5867. pp. 1238-1240.

12. SARE Biodiesel from Canola on farm: Retreived from: https://www.sare.org/Learning-Center/Bulletins/Clean-Energy-Farming/Text-Version/Profile-Roger-Rainville

13. Penn State Extension. 2008. "Biodiesel Safety and Best Management Practices for Small-Scale Noncommercial Use and Production". Retrieved from: http://pubs.cas.psu.edu/freepubs/pdfs/agrs103.pdf

14. Central PA Hay and Feed Prices, Retrieved from: https://www.ams.usda.gov/mnreports/qa_gr111.txt (12/5/18)

15. Blume, D. (2007). *Alcohol Can Be A Gas. Fueling a Revolution for the 21st Century.* Santa Cruz, Ca: International Institute for Ecological Agriculture. p 178.

16. See calculations 3, Appendix A

17. Hurst Biomass Boilers and CHP appliances: Retrieved from: https://www.hurstboiler.com/biomass_boiler_systems

18. All Power Labs Power Pallet product. Retrieved from: http://www.allpowerlabs.com/products/product-overview and spec sheet: http://www.allpowerlabs.com/wp-content/uploads/2018/03/APL-PP30-information-English.pdf

19. Rittmann, B. E., McCarty, P. L. (2012). *Environmental biotechnology: principles and applications*. Tata McGraw-Hill Education.

20. Lansing, S. & Felton, G. (2013). Anaerobic Digesters: Designs. University of Maryland Extension Fact Sheet.

21. Grind2Energy foodwaste collection system. Retrieved from: https://www.emerson.com/en-us/commercial-residential/grind2energy

23. Lorin Hoover, personal communication. See Appendix 2.

24. Diana Dillinger, personal communication 12/6/18. NRCS Supervisory District Conservationist Cumberland/Franklin County. 717-249-1037 |Diana.dellinger@pa.usda.gov

25. Eric Fast, Martin Energy Group. Personal communication 11/30/18.

26. Jim Dewitt, FAN Separators dealer. Personal communication 12/4/18.

27. Chris Roelke, Land O' Lakes Carlisle environmental engineer. Personal communication 11/29/18.

28. Bothi, K.L. & Aldrich, B. (2005). "Centralized Anaerobic Digestion Options for Groups of Dairy Farms". Cornell Manure Management Fact Sheets. Retrieved from: http://www.manuremanagement.cornell.edu/Pages/Popular_Pages/Fact_Sheets.html

29. Aldrich, B., Minott, S., & Scott, N. (2005). "Single, Paired, and Aggregated Anaerobic Digester Options for Four Dairy Farms in Perry, New York". Cornell Manure Management Fact Sheets. Retrieved from: http://www.manuremanagement.cornell.edu/Pages/General_Docs/Fact_Sheets/Perry_Feas_Study_factsheet.pdf

30. Shelford, T., Pronto, J., & Gooch, C. (2012). "Anaerobic Digestion at Cayuga County Soil and Water Conservation District's Community Digester". Cornell Manure Management Case Studies. Retrieved from: http://northeast.manuremanagement.cornell.edu/Pages/General_Docs/Case_Studies/Cayuga_case_study_revision_3.pdf

31. Rittmann, B. E., McCarty, P. L. (2012). *Environmental biotechnology: principles and applications*. Tata McGraw-Hill Education. p 273.

32. Viessman, W. & Hammer, M. J. (2009). *Water Supply and Pollution Control*. Upper Saddle River, NJ. Prentice Hall. p. 556.

33. See Appendix 3.

34. Rittmann, B. E., McCarty, P. L. (2012). *Environmental biotechnology: principles and applications*. Tata McGraw-Hill Education. p 275.

35. Lansing, S., Viquez, J., Martinez, H., Botero, R, & Martin, J. (2008). "Quantifying electricity generation and waste transformations in a low-cost, plug-flow anaerobic digestion system." *Ecological Engineering (34).*

36. Oliver, J. & Gooch, C. (2016). "Anaerobic Digestion at Noblehurst Farms, Inc. (Updated)." Cornell Manure Management Program Case Studies. Retrieved from: http://northeast.manuremanagement.cornell.edu/Pages/Popular_Pages/Case_Studies.html

37. Lee Lutz, Martin Energy Group, personal communication 12/5/18

38. Oliver, J. & Gooch, C. (2016). "Hydrogen Sulfide Removal From Biogas." Cornell Manure Mangement Program Fact Sheets. Retrieved from: http://northeast.manuremanagement.cornell.edu/Pages/Popular_Pages/Fact_Sheets.html

39. Yanmar America (n.d.). Yanmar Combined Heat and Power Products. Retrieved from: http://www.yanmar-es.com/products/mchp/

40. Marathon Engine Systems (n.d.). Ecopower Cogeneration. Retrieved from https://www.marathonengine.com/cogeneration.html

41. Qnergy (n.d.). Qnergy Remote Power Products. Retrieved from https://www.qnergy.com/remote-power/

42. Jim Dewitt, FAN Separators, personal communication, 12/4/18

43. Koch, C., Müller, S., Harms, H., Harnisch, F. (2014). Microbiomes in bioenergy production: from analysis to management. *Current Opinion in Biotechnology*, *27*, 65–72.

44. Schnürer, A. (2016). Biogas production: microbiology and technology. In *Anaerobes in Biotechnology* (pp. 195–234). Springer.

45. Rittmann, B. E., McCarty, P. L. (2012). *Environmental biotechnology: principles and applications*. Tata McGraw-Hill Education.

46. U.S. Energy Information Administration (2018). Pennsylvania Natural Gas Prices. Retrieved from: https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_SPA_a.htm

47. Pennsylvania Public Utility Commission (2018). Pennsylvania Alternative Energy Credit Program. Retrieved from: http://www.pennaeps.com/reports/

48. Adiga, S., Ramya, R., Shankar, B. B., Patil, J. H., Geetha, C. R. (2012). Kinetics of anaerobic digestion of water hyacinth, poultry litter, cow manure and primary sludge: A comparative study. *International Proceedings of Chemical, Biological and Environmental Engineering (IPCBEE)*, *42*(2012), 73–78.

49. Benstead, J., Archer, D. B., Lloyd, D. (1990). Role of hydrogen in the growth of mutualistic methanogenic cocultures. In *Microbiology and Biochemistry of Strict Anaerobes Involved in Interspecies Hydrogen Transfer* (pp. 161–171). Springer.

50. Kazda, M., Langer, S., Bengelsdorf, F. R. (2014). Fungi open new possibilities for anaerobic fermentation of organic residues. *Energy, Sustainability and Society*, *4*(1), 6.

51. Navickas, K., Venslauskas, K., Petrauskas, A., Zuperka, V., Nekrosius, A. (2013). Energy balances of biogas production from industrial wastes and energy plants. *Energy*, *4*, 6.

52. Koelsch, R.K, Fabian, E.E., Guest, R.W, & Campbell, J.K. (n.d.). "Anaerobic Digesters for Dairy Farms". Cornell Agricultural and Biological Engineering Extension Bulletin 458. (Design document for spreadsheet plug flow calculations).

Appendix A: Calculations

Dickinson College food waste feedstock per day, FY 17-18

The waste tab of the Dickinson sustainability dashboard shows 126-127 tons of food waste collected from Dining Services per year. (http://marcomm.dickinson.edu/dashboard/waste_minmization.html) These data are based on tallies of food waste bins filled at the Hobart pulping machine, multiplied by a factor of 50 lbs/bin.

126.5 tons X (2000lb/ton) X (1kg/2.2lb) = 115,000 kg food waste per year.

115,000 kg /year /[(10months of collection /12months) x (365 days/year)] = 378 kg/day (831lb/d)

Estimate of power production from full food waste load, based on DiStefano & Schust (2016).

Table 2. of the 2016 study (page 13) estimated that 25,571 kWh would be generated from 77,318 kg of food waste. Current levels of food waste collection are approximately 115,000 kg per year.

(25,571 kwh / 77,318 kg FW) x 115,000 kg FW = 38033 kWh per year

Farm power bills from 2018 (appendix X) show annual purchased electricity of 37238 for the two main services. Note that estimates of power production do not account for parasitic electrical loads consumed by an expanded mechanized digester system.

Estimate of energy content of wood chips, based on value of BTU per pound of urban waste wood chips

https://www.biomasscenter.org/images/stories/Woodchip_Heating_Fuel_Specs_electronic.pdf

4785 Btu/ lb green chips x 2.2 lb/kg x 250 kg chips / m3 x 1 m3 / 1.3 yd3 = 2.02 MMBtu / yd3

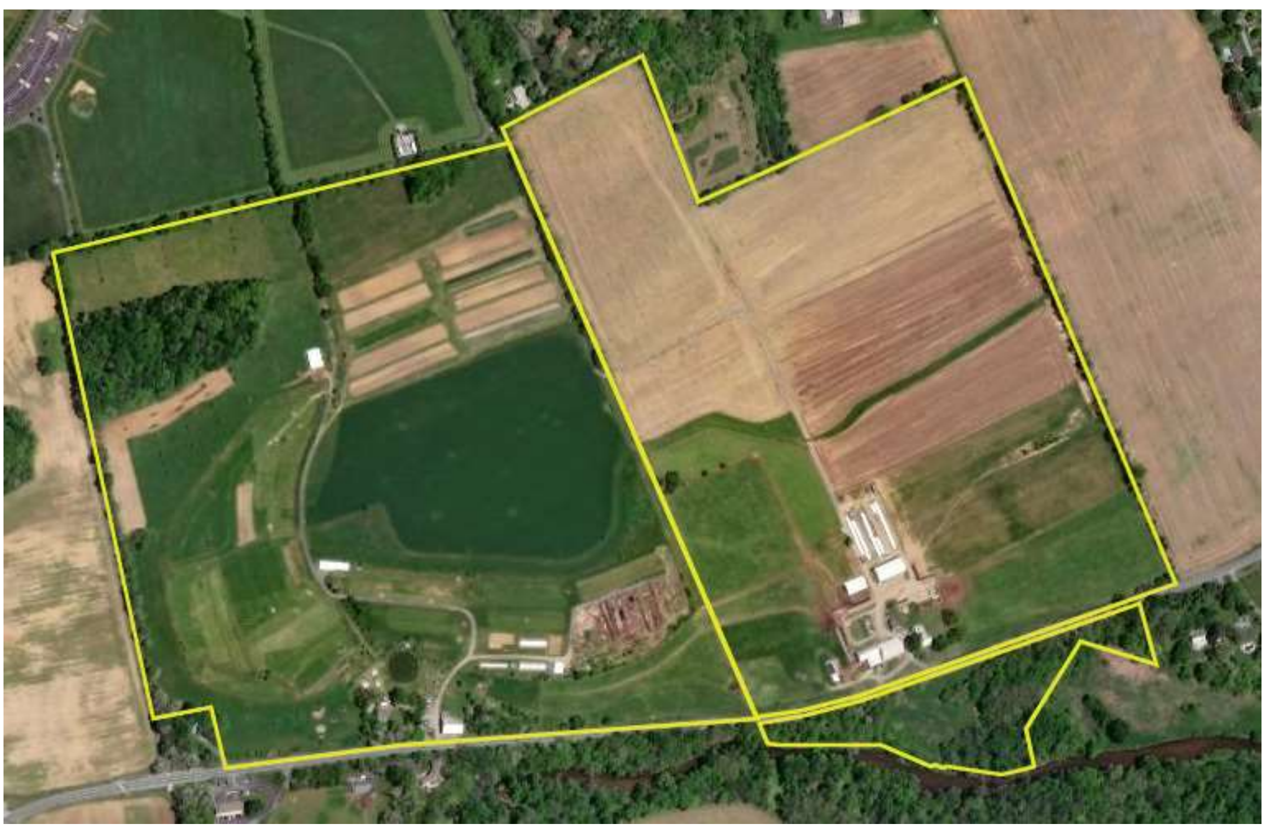
2.02 MMBtu / yd3 / 3412 Btu/ kWh = 593 kWh / yd3 of chips.

APPENDIX B: Notes on interview with Loren Hoover, Co-owner of Triple L Farm near Carlisle PA.

Conducted by Matt Steiman, 11/28/18

Background: The Dickinson College Farm comprises 187 acres, split into two rectangular properties of roughly equal size. Each property contains its own farmstead with house, barn and outbuildings. The Hoover family has been renting most of the acreage and one farmstead for over 30 years. At present, the educational/ production farm operated by Dickinson College has grown to occupy the western half of the land. Loren Hoover's sister (Linea Hoover Charles) and her family live in the farmhouse on the eastern half of the land and look after about 100 dairy heifers (young females) and dry cows (females between lactations) located on the property.

The Triple L Farm business is made up of several hundred acres of land spread throughout the Carlisle / Boiling Springs area of Cumberland County PA. The Hoover family owns the main farm where the milking dairy cows are based, and rents most of the other land. The extended Hoover family and several paid employees operate the dairy and agronomic crop production to support the farm. Dickinson College Farm and Triple L Farm maintain a friendly neighbor relationship. While commercial activity has been limited to occasional hay trading, we do occasionally share farming tools and help each other in livestock emergencies. I approached Loren Hoover about investigating the feasibility of a mixed feedstock digester that would utilize his cow manure, and he has been willing to discuss the project to see if it could benefit both farms.



Dickinson College Property at 553 Park Drive. Educational farm is on left, Hoover family rents the farmstead and land on the right. Park Drive runs to the south of the farms, with the Yellow Breeches Creek seen below in a riparian area.

Data: Park Drive Farm (Boiling Springs PA).

Distance to proposed digester site: <1000 linear feet of pipeline.

Cattle on site at Park Drive (adjoining Dickinson College Farm): about 50 full size adult cows (14-1500 lbs each) and 50 heifers (700-800 lbs each).

Approximate manure production about 10 gallons per day per animal (about 82 pounds).

% of time cattle spend on concrete manure collection pad: 30-40% currently, but could be increased if funds available for adding concrete infrastructure.

> Currently the farm has more animals than building space will cover
>
> Cattle are allowed access to pasture often so that they spread their own manure.
>
> If a value proposition were identified for the manure, Mr. Hoover could collect more.
>
> He is open to investing in manure management infrastructure if a long term beneficial relationship is realistic

Bedding used: hay, straw, corn fodder, about 2100 kg per week.

Loren estimates an annual bedding cost of $5000

The farm has worked with composted digester solids as bedding in the past – they paid between $55 to $68.75 per 1000 kg to a farm near Shippensburg PA.

> He rated the digester solids as excellent cow bedding in a free stall barn – better than sawdust if well managed. Digester solids as bedding can help keep the cows' somatic cell count low (a health indicator in lactating dairy cows). It must be kept dry or it will return to a manure like nature.

Loren would see the availability of reasonably priced clean digester solids as bedding material to be a major benefit to his farm

There are no odor complaints related to manure storage or use at the Park Drive farm.

The main cattle housing at the Park Drive farm could be easily converted to a free stall barn with a modest investment. A free stall barn would be better for the cattle health and also facilitate easier manure collection. Loren would be open to making this investment or a portion in support of the digester initiative.

A benefit to Triple L of the digester project would be reduced daily hauling and spreading of raw cow manure. Reducing regular spreading would improve local water quality by reducing runoff and allowing better management of spread timing (avoiding spreading on frozen ground, wet ground etc.).

Triple L farm would use as much liquid digestate as we would let go. He understands that the Dickinson College Farm would also like some for nutrients & irrigation.

The Hoovers have a tractor powered manure suction pump on wheels that draws manure slurry from a pond / lagoon. About 100 horsepower is required and the pump arm is 25 feet long. Loren would be willing to use his pump or a dedicated electric pump to load digester effluent for nutrient application. He is willing to come to the Dickinson side of the property (the digester site) to collect the effluent from a storage lagoon. There are about 120 acres on or near the Park Drive farm where the Hoovers could spread digestate.

There are no regular antibiotics used at Park Drive. Copper sulfate is used very sparingly for foot disease management. More common is a "hoof zinc" product that is more beneficial to the soil. Excessive copper can hurt the soil and might also inhibit microbes in the digester system. Rumensin is not used at Park Drive.

Loren says cow manure does not freeze until temperatures fall below about 20 degrees F. Proper timing of manure management can be helpful in deep winter, so that manure is collected before it can freeze.

During sub zero weather, the farm stacks manure in a pile and then spreads it when appropriate. This is only required about 14 days per year on average.

Data: Triple L Farmstead, Adams Rd, Carlisle PA.

Distance by road to Dickinson College Farm: 6.5 miles

Cattle on site at Triple L Home farm: 180 mature milking cows

Estimated manure production per animal day, about 20 gallons (160 pounds per cow per day)

There are no odor complaints related to manure storage and use at the home farm. The Hoovers try to keep good relations with residential neighbors by giving out butter and holiday cards each year

Home farm is set up to be a flush dairy, with sloped floors and free stall barns leading to a manure trench and storage pond

Currently the farm uses fine sawdust as bedding, at a cost of $1100 per 100 cubic yards.

Cows in freestall barn with sawdust bedding.

Hauling manure from Triple L to Dickinson College Farm (6.5 miles) would be expensive, especially if we don't own the equipment. A used manure tanker would cost about $40,000 and would need to be powered by a tractor. It takes about 1 hour on a tractor to complete the 6.5 mile round trip between farms.

There is a local hauling firm (Jones) that will haul 5200- 6300 gallon loads of manure slurry for about $100 per load. There are equipment rental services that would also cost about $100 per 5200-6300 gallon load to transport this distance.

Sometimes Triple L farm uses equipment shared by cooperating neighbors at a rate of $15 per load for occasional use, but this is unlikely to apply to the regular hauls that would be required to bring manure from the dairy to Park Drive.

Rumensin is sometimes used at the home farm, but currently it is not.

The home farm has a 1.5 million gallon manure pit (storage and processing lagoon). They paid about $75,000 to construct the pit, but the cost would have been much higher (maybe $120,000) if not for a family member who did a lot of the earthwork.

MANADA company installs manure pits with leak detectors commercially in this area.

1.5 million gal lined manure storage pit at Triple L home farm. Note manure pump on boom connected to tractor at left. This style of pump is appropriate for pumping from ponds with a sloped bank, but not from concrete walled tanks.

Appendix C:

Meeting with Lee Lutz, Martin Energy Group & Visit to Kurtz Valley Holstein Farm, Mifflintown PA

By Matt Steiman, 12/5/18

After seeing the grid tied biogas combined heat and power (CHP) unit at the Nathan Ebersol duck farm in Shippensburg PA, I looked up Martin Energy Group, the contracting firm that engineered and installed the CHP system for that project. A quick browse of their website led me to the newly offered "mini-digester" product – a plug and play full-mix anaerobic digester system with integrated CHP designed for smaller farms. Following a phone discussion with regional sales manager Lee Lutz, I was invited to visit the first installation of the mini digester system in Pennsylvania at the Kurtz Valley Holsteins dairy farm (Mifflintown). What follows is a transcript of the notes from that visit. All data provided in this report were communicated verbally by Mr. Lutz on 12/5/18. All photos are by Matt Steiman except the complete mini digester (from https://martinenergygroup.com/minidigester/).

Martin Energy Group (MEG) has offices in Ephrata, PA and Oakland, CA and a factory in Missouri. Their original business was building CHP engine systems but has expanded into digester system construction as well. About 90% of the CHP engines in US commercial digesters are MEG products – this is their specialty. After purchasing a nationwide digester company (RCM Digesters), MEG added digester construction to their service offerings. The owner of the company comes from a farming background and had an interest in digesters appropriate for smaller scale farms. The company did an exhaustive search of available technologies, ruled out some that have proven to be ineffective, and finally settled on the Biolectric Mini Digester system.

Biolectric is based in Belgium. About 150 Biolectric mini digesters have been installed in Europe with an 85% success rate. Success of digester projects depends on the attention of the operator as much as the quality of the system – Mr. Lutz seemed to imply that system failures were mostly a result of poor management.

The mini digester package is a kit designed for quick installation (1-2 weeks or less). After a system is sized to meet feedstock loading volume and owner goals, a concrete pad is poured according to company specifications. The digester body is built from a stainless steel frame that is delivered in sections then bolted together and lagged to the concrete pad to make a sturdy cylindrical ring. The base case height is 8 feet, with an additional 4 foot ring height extension available. Options for tank diameter are 25, 35, 43, and 51 feet. An insulated version (the "Nordic" tank) and an uninsulated version are available. Insulation in the Nordic tank is about 3" rigid foam with a foil liner. After insulation is fixed in place in tank walls and floors, the seams are caulked with expanding foam. The concrete pad beneath the tank does not need to be insulated.

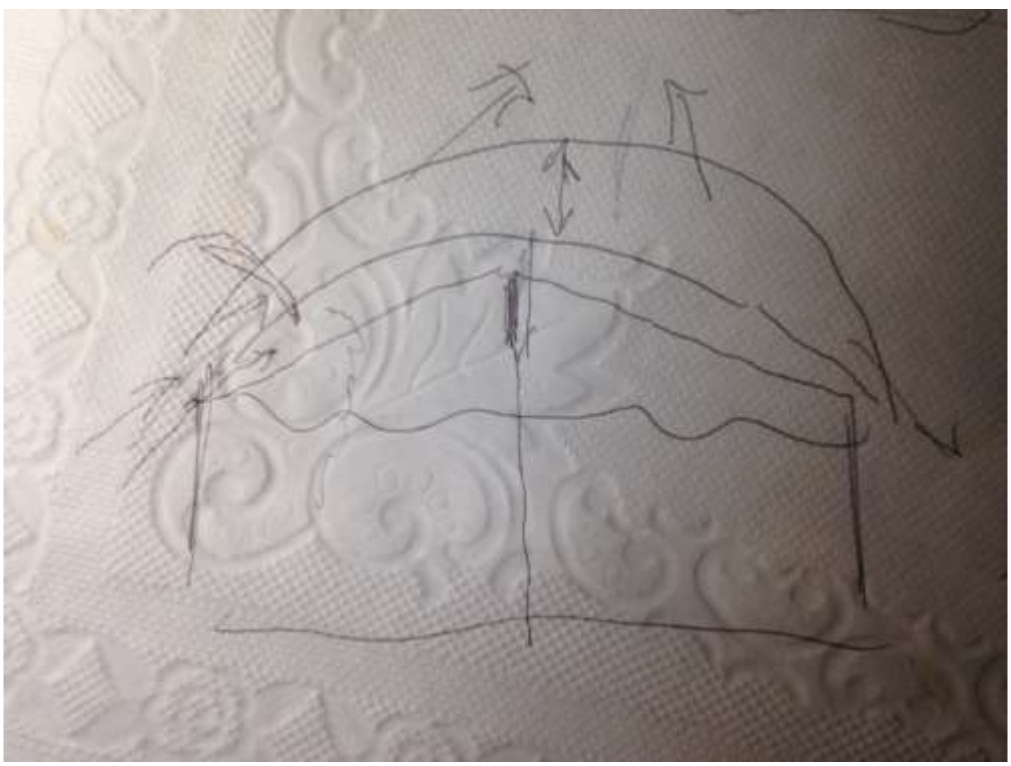
The insulated tank form being caulked. White cylinder in the background is vessel for "iron sponge" H_2S scrubbing system.

The tank forms are lined with a heavy duty plastic liner custom built to fit the specific tank size. The Kurtz Valley Holsteins project used a thicker liner than normal due to Natural Resource Conservation Service requirements (NRCS is co-funding the project through a grant). The thick liner was cumbersome to install in the cold weather of early December.

Second digester tank with plastic liner installed. Note heat distribution pipes mounted around the inner edge of the tank base. The pipe stub at the center will support a mast that forms the peak of the gas holder membrane. The stainless steel mast at the far edge is one of two – these support propeller mixers that can be raised and lowered via a cable / crank system outside the digester. Prop mixer is pictured at right.

Three layers will form the upper works of the digester system:

1. A plastic net supported by the center mast serves as habitat for sulfur oxidizing microbes in the biogas headspace. A gas analyzer in the control room constantly monitors the hydrogen sulfide content of the biogas. Small amounts of ambient external air will be injected into the gas headspace by a blower controlled with input from the H_2S sensor, providing oxygen for sulfur oxidation. This process serves to extend the purchased iron sponge material in the scrubber.
2. A gas impermeable flexible inner membrane serves as the top of the gas headspace.
3. A flexible external top membrane protects the inner membrane

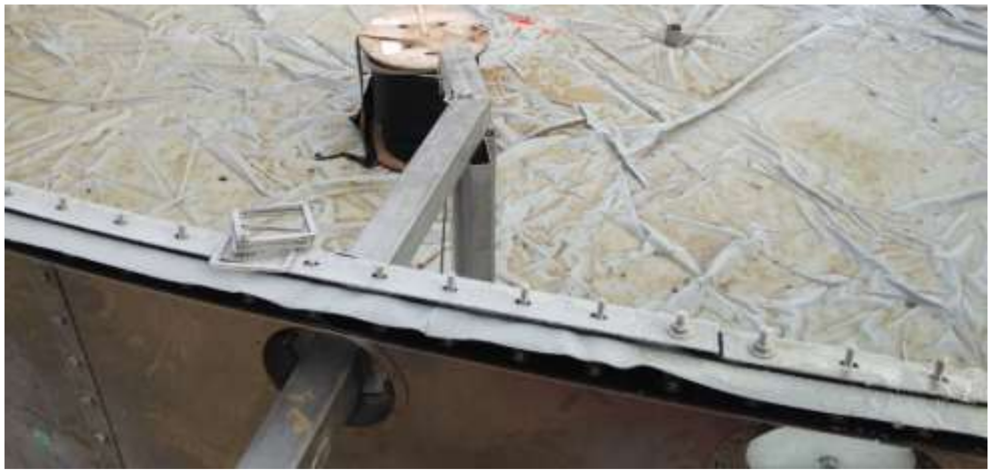


Placemat drawing showing upper layers of the digester and the central mast. Diagram by Lee Lutz.

External air is blown into the space between the top and inner membrane to generate pressure against the gas in the headspace. Air is constantly blown in from one side and wasted out the other. Sensors in the center of the dome translate the distance between the upper and lower membrane into a available gas volume data – this information controls the start and stop of the

CHP generator motor. The simplistic control of the mini digester CHP turns the engine either on or off. Power production is not “feathered” with gas production as in more complex control systems. If the system operator finds the engine is short-cycling on and off, the power production and gas consumption rate of the CHP unit may be decreased below full power to better match the gas production rate. Control is automatic but can be user modified through a wifi connected smartphone app that also serves as a monitoring portal.

The figure at right shows the upper tank edge – the gas membrane and cover will be attached to this rim via the exposed bolts – seal is achieved via metal hold down strips over a soft rubber layer on the rim.



Manure slurry will be pumped into the digester tank via piping passed through the top of the tank wall. Effluent will exit the tank via a larger pipe at the bottom. This pipe passes into the container building where a sensor reading system back pressure controls a diaphragm pump that evacuates the digester. This allows feeding the digester in small batches throughout the day – as influent is fed by the external pump, the diaphragm pump evacuates the tank according to maintain a set pressure.

Mr. Lutz recommended regular feeding for stable operation – a minimum of twice per day. This batch feeding process can be automated.

This external view of the tank under construction shows the stainless steel panels bolted together and lagged to the concrete slab. Black influent pipes are at top, white effluent pipe at bottom. Smaller diameter steel pipes (with orange safety tape) connect to the heat transfer rings inside the digester tank. Also seen at top are the cable crank for adjusting prop mixer height and a small plexiglass window into the gas head space. This digester has two windows on opposite sides for light infiltration to aid visibility. This digester shows the 8 foot base level (bottom two sections) with an additional 4 foot extension bolted on.

The plastic liner and foam insulation are not vulnerable to rodents due to the complete seal of the bolted lower tank edge to the concrete. If a liner fails it can be replaced. If the gas membrane or cover fail they can be repaired.

The power and control building contains the CHP unit and a variety of sensors and control modules. CHP systems are Martin Energy Group's specialty. Heat is recovered from both the engine exhaust and liquid coolant. The smallest mini digesters are connected to 11 kW or 22 kW generators coupled via belt drive to small Kubota spark ignition engines. The digester package can be ordered with a single 11kW engine with room to expand to a second 11kW engine as feedstock and budget permit. Mr. Lutz recommended leaving room for expansion in the project (within reason) rather than buying the smallest possible unit – if a second CHP unit is desired in the future it is most cost effective if the power/control container is set up to accommodate this from the beginning. Also if the digester tank is oversized with room for growth in feedstock quantity, the system will run at a longer hydraulic retention time at first, producing relatively more gas per unit of feedstock.

Lee Lutz with *150 kW CHP genset at Kurtz Valley Holsteins, built by Martin Energy Group. Note the flexible insulation around exhaust gas heat exchangers. Manure from the farm's 330 mature milk cows will be mixed with food waste to produce gas to power the engine.*

Kubota CHP belt drive system, either 11 or 22kW. Photos by Martin Energy Group

Inside the mini-digester power/control container. Two Kubota CHP units in noise dampening enclosures, with exhaust heat recovery shown. Photo by Martin Energy Group

A basic mini-digester system will consist of the following components:

- A reception pit for livestock manure. This pit can also possibly be used for blending manure and food waste or other substrates. Must include a pump for mixing in tank and ejecting feedstock to the digester (one pump, two functions).
- A slab poured in place to MEG specifications
- The digester as described above.
- The pre-fabricated container with controls and CHP engine. Also includes safety flare for periods of engine maintenance or overproduction.
- An effluent receiving pit.
- Utility upgrade for electrical interconnection.

Approximate cost for complete system with 11KW CHP: $250,000

The likely benefits of the mini digester package are:

- Quick installation due to pre-fab modular parts
- Well integrated controls and CHP with high degree of automation. Mr. Lutz says an early adopter in Ontario spends just minutes per day on system operations. Maintenance requirements are biweekly oil changes and spark plug changes.

Matt's take home impression: Martin Energy Group is highly skilled at CHP fabrication and control with years of experience. They also have several experienced people who understand the logistics, physical construction, permitting, funding, and biochemistry of complex AD systems. The beauty of the plug & play prefabricated kit cannot be overstated… the quality and ease of operation of this relatively affordable system are very attractive when compared to the manually operated owner built system at Dickinson Farm. A package project, once complete, would efficiently produce substantial green energy yet allow the farm to focus on farming.

Helpful rule-of-thumb design figures and other wisdom from Lee Lutz:

Converting thermal energy in gas into electric power:

12000 BTU/ kW   650 BTU/ ft3 biogas   2.75 kW/ ft3/min

Typically in CSTR tank, use 2 feet of freeboard depth at tank top for safety (1.5 feet min).

The manure from a mature milking cow will produce about 0.2 – 0.25 kW

Mature cows on milk feeding regimen will produce about 25 gallons of manure/day. Figure 3-5 gallons per cow of wash water. Heifers and dry cows are fed less and will produce about 10 gallons manure per day.

For dairy manure waste, hydraulic retention should be minimum 21 days. Food waste converts to biogas faster and may reach high conversion in just 15 days. Longer HRT will result in more gas/feedstock unit. If the digester is not fed at capacity, its just running at longer HRT.

MEG experience shows that a minimum of 25% of feed should be manure when codigested with food waste. Most of the heat energy recovered from the CHP unit will go to the digester in winter. Some may be available for winter greenhouse heating.

Solids for separation: figure 0.75 ft3 solids per cow per day at about 35% dry matter after separation. Food waste in the digester reduces quality of the resulting bedding. Also with good conversion to biogas (as is the case with food waste) there will be less solids for bedding.

Parasitic loads and capital cost of new off the shelf solids separation equipment are high. Maybe a used separator can be found but the wisdom of this is questionable.

In Pennsylvania the Commonwealth Financing Administration has been a helpful source for AD project funds – they may match up to 1/3 of interconnected system cost. I looked it up – they do fund RE projects up to 30%. https://dced.pa.gov/programs/alternative-clean-energy-program-ace/