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Cost and Returns Analysis of Manure Management Systems Evaluated in 2005 under the North Carolina Attorney General Agreements with Smithfield Foods, Premium Standard Farms, and Front Line Farmers

TECHNOLOGY REPORT: RE-CYCLE GASIFIER

Prepared as Part of the Full Economic Assessment of Alternative Swine Waste Management Systems Under the Agreement Between the North Carolina Attorney General and Smithfield Foods

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1. Summary

This report differs significantly from some of the other technology reports in this series. The differences arise from the facts that the evaluation was conducted in pilot scale rather than farm prototype scale and that no invoiced construction costs were available. The technology providers and principal investigators provided their best estimates of expected construction costs of various sizes of the gasifier evaluated. Actual performance data on propane fuel use, ash production, nutrient content of ash, and other variables were applied in this cost and returns model. Annualized costs of farm scale systems were generated based on the information provided to the Task 1 team. In cooperation with the technology providers and the principal investigators, a substantial effort was made to also model a future version of the gasifier which would be a continuous feed system rather than the batch system that was actually evaluated. Results of these modeling efforts are described in this report.

The gasifier evaluated is a batch unit that processed 18 to 30 pounds of dry matter (DM) per hour. The gasifier was evaluated using two types of manure solids that were 52% moisture and 21% moisture, respectively. The 52% moisture solids were representative of the solids collected from the RE-Cycle belt system evaluated in 2004. The drier (21% moisture) solids required 56% less propane and attained 53% greater throughput (lbs. DM / hour) and were intended to demonstrate the benefits of prior drying of belt-separated solids. The five sizes of representative feeder-to-finish farms modeled here are assumed to produce from 1,370 to 18,935 pounds of dry matter per day. Therefore, all of the gasifiers modeled here would have larger capacity than the unit that was evaluated. Annualized costs over a 10-year expected economic life were predicted for each of five sizes of representative feeder-to-finish farms. The estimates for the batch system gasifier are as follows. Confidence in these estimates is medium-low to low.

> Batch gasifier predicted costs when fed manure solids with 50% moisture:
> \$273 to \$313 per 1,000 pounds SSLW = \$183 to \$209 per ton of dry matter loaded = \$1,498 to \$1,715 per ton of ash produced. When avoided costs of land applying manure solids are subtracted, these estimates become:
> \$264 to \$278 per 1,000 lbs. SSLW = \$177 to \$186 per ton of dry matter loaded = \$1,448 to \$1,523 per ton of ash produced.

> Batch gasifier predicted costs when fed manure solids with 21% moisture:
> \$131 to \$184 per 1,000 pounds SSLW = \$87 to \$123 per ton of dry matter loaded = \$717 to \$1,006 per ton of ash produced. When avoided costs of land applying manure solids are subtracted, these estimates become:
> \$122 to \$149 per 1,000 lbs. SSLW = \$81 to \$99 per ton of dry matter loaded = \$666 to \$815 per ton of ash produced.

Future planned development of the BGP gasifier includes a continuous feed system that would further reduce the propane use and further increase the throughput of the system. Cost estimates are provided here but they are highly speculative since no performance data or cost data are available for such a system.

> Proposed continuous feed gasifier predicted costs when fed manure solids with 50% moisture: $50 to $121 per 1,000 pounds SSLW = $33 to $81 per ton of dry matter loaded = $275 to $663 per ton of ash produced. When avoided costs of land applying manure solids are subtracted, these estimates become:
> $41 to $86 per 1,000 lbs. SSLW = $27 to $58 per ton of dry matter loaded = $224 to $472 per ton of ash produced.

> Proposed continuous feed gasifier predicted costs when fed manure solids with 21% moisture: $43 to $127 per 1,000 pounds SSLW = $29 to $85 per ton of dry matter loaded = $237 to $698 per ton of ash produced. When avoided costs of land applying manure solids are subtracted, these estimates become:
> $34 to $92 per 1,000 lbs. SSLW = $23 to $62 per ton of dry matter loaded = $187 to $507 per ton of ash produced.

No by-products of gasification were used or marketed during the evaluation. However, an implied price of $345 per ton of ash as a feed ingredient was calculated based on a price of dicalcium phosphate and a dietary phosphorus based substitution ratio provided by the principal investigator. Heat and synthesis gas as an ingredient to liquid fuel or other chemical manufacture are other potential by-products of the gasification process.

2. Technology Description

The gasification technology described in this report is part of a total treatment technology known as the RE-Cycle system. As the first part of the RE-Cycle system, belt-based housing is used to separate liquid and solid portions of the waste stream. More on the economics of belt systems can be found in a previous report (Belt Systems). The gasification technology described in this report is the second part of the RE-Cycle system and is used to treat belt-separated solids.

The gasifier used by the RE-Cycle technology is produced by Brookes Gasification Process (BGP). It is a fixed-bed, indirectly-heated, batch-fed gasifier that is suitable for processing a wide range of feedstock materials, including swine manure solids. The BGP gasifier consists of two chambers—a lower 'burner' (or secondary) chamber and an upper 'gasification' (or primary) chamber. Hot gases from the burner chamber heat the refractory bricks that line each of the two chambers. Meanwhile, the feedstock (e.g. , separated swine solids) sits undisturbed on the hearth of the primary chamber where it is indirectly heated to 600-1000º C (1100-1800º F) by heat transfer (Koger, et al.).

The feedstock is broken down into low molecular weight gases and volatile hydrocarbons, which are subsequently drawn into the secondary chamber through a small opening. Energy from these out-gases provides fuel that can sustain the entire gasification process. During gasification start-up, the secondary chamber must be heated using propane or product gas from another gasifier unit (Koger, et al.).

The BGP gasifier used in this study has dimensions of 6 feet in length, 5 feet in width, and 5 feet in height. The gasifier is comprised of a mild steel outer shell, then a layer of high-grade ceramic insulation, and, finally, an inner layer of refractory firebrick. The hearth of the primary chamber consists of a high-temperature ceramic tile floor. The dimensions of the primary chamber are: 42 inches in depth, 47 inches in width, and 22 inches in length. The primary chamber has a door constructed with a mild steel shell which is packed with ceramic insulation. Evenly spaced along the width of the chamber door are three air doors (or ports), each measuring 2.5 inches in diameter. The air doors have plates that can be adjusted to allow varying rates of air to enter the primary chamber.

Two different burners were tested with the pilot-scale gasifier. The first burner installed was the Midco Incinomite J83-D3 with a firing rate of 100,000-800,000 MBH (million BTU's / hour). Testing revealed this burner to be too large, so it was replaced with a Midco Economite EC200 burner with a firing rate of 70,000-200,000 MBH. A low-pressure secondary air blower was located inches away from the burner and used to provide auxiliary air. This blower had a 50-watt motor and was always on during the gasification process. The flue stack in the pilot-scale gasifier measured

14 inches in diameter with a height of 12 feet (as measured from the top of the gasifier). At the base of the stack was a barometric damper that could be used to control the amount of draft in the gasifier.

Variables that could be controlled or adjusted during the gasification process included: 1.) burner output; 2.) burner airflow; 3.) secondary air output; 4.) air doors; 5.) amount of draft; 6.) amount of feedstock loaded; and 7.) dry matter content of the feedstock. These parameters were adjusted during testing to maximize the efficiency of the gasification process (Koger, et al).

3. Gasifier Operating and Performance Data (Tables GAS.1-GAS.2)

During performance verification trials, the gasifier temperature was set at a series of temperatures ranging from between 700°C and 950°C. The optimal temperature to maximize gasifier efficiency was found to be 800°C. Table GAS.1 shows the processing efficiency of the gasifier, as measured at a set temperature of 800°C. In addition to the set temperature of the gasifier, the dry matter content of the feedstock can also impact gasifier efficiency. Table GAS.1 lists processing efficiency for two trials in which different dry matter (DM) content feedstocks were loaded into the gasifier. The first DM content loaded into the gasifier was 48% (52% moisture content), while the second DM content tested was 79% (21% moisture content). A DM content of 48% is consistent with the separated swine solids that were being collected using the RE-Cycle belt system (Belt Systems Final Report). To achieve a DM content of 79%, some additional drying of the separated solids would be necessary. Table GAS.1 shows the benefits to gasifier efficiency by loading a dryer (higher DM content) feedstock into the gasifier. Specifically, gasifier trials demonstrated that throughput (DM processing rate) will increase by 53% and propane usage will decrease by 56% when increasing the DM content from 48% to 79%.

As currently designed, the BGP gasifier consumes its own product gases. Product gases are combusted to sustain the reaction in the gasifier rather than being recovered for energy use. As designed and operated in the performance verification trials, the only available energy output from the BGP gasifier is heat exiting from the flue stack. This heat could possibly be consumed for on-farm uses such as steam generation, hot water, heating animal barns, etc. In the technology verification process, this energy was not used. However, in future generations of the gasifier technology, the technology providers hope to capture and utilize the energy output from the flue stack heat.

It was shown during the performance verification that belt-harvested swine solids contained 12.2% ash on a dry matter basis. For every 100 dry pounds (or 200 wet pounds at a DM content of 50%) of separated swine solids that are loaded into the gasifier, 12.2 pounds of ash were produced and recovered. Table GAS.2 lists the nutrient composition of the recovered ash produced from the gasification of separated swine solids. For comparison purposes, Table GAS.2 also lists the nutrient content of ash recovered from gasifying other feedstocks (e.g., chicken litter, turkey litter, swine mortalities). Table GAS.2 shows that the ash recovered from the gasification of separated swine solids is much higher in P and K than the ash recovered from the gasification of either chicken litter or turkey litter. For this reason, swine solids gasifier ash has a higher value as a fertilizer input than chicken/turkey litter gasifier ash. Table GAS.2 can also be used to assess the potential value of swine solids gasifier ash as an animal feed ingredient (as a substitute for dicalcium phosphate).

4. Predicted Standardized Costs of the Single-Batch Gasifier Technology (as demonstrated)

4.1. Gasifier Sizing Assumptions (Table GAS.3)

No cost invoices were collected or reported to the economics team for the gasifier technology. The economics team did work with the principal investigators and commercial collaborators to determine estimated gasifier costs for representatively-sized feeder-to-finish farms. The cost of an individual gasifier is a function of hearth size, which is a function of the feedstock loading rate. Gasifier sizes and costs were estimated for each of five standardized feeder-to-finish farms. These farms represent the standardized sizes within each category for SF/PSF finishing facilities in North Carolina, and range from 1,240 to 17,136 head. Using these representative sizes, an estimate for total solids produced and collected (via the belt system) can be determined. To calculate the amount of total solids produced at each representative farm, the numbers contained in Appendix A, Table A.25 of the Combined Appendices Report were used (Combined Appendices Report). Estimated total solids for each farm are reported in Table GAS.3. It is assumed that 100% of total solids are captured by the belt system. This upper-bound assumption was used by the economics team in the absence of any data of belt system collection efficiency. Based on data collected and reported for the RE-Cycle belt system, the dry matter (DM) content of the belt-separated solids is assumed to be 50% (Belt System Report).

The total solids amounts reported in the bottom line of Table GAS.3 were provided to the principal investigators who, in turn, provided them to the commercial collaborators. Based on these amounts, the commercial collaborators (Brookes Gasification Process) were able to estimate the appropriate gasifier sizes and corresponding gasifier costs for each of the five standardized finishing farms. These costs are reported in Table GAS.4. Sizing of the gasifier unit is a function of gasification rate. The gasification rate on the unit for which the performance verification was conducted ranged from 18 to 30 lbs. / hour (depending on the DM content of the feedstock). Because this unit had a single hearth, the per hearth gasification rate is also 18-30 lbs. / hour. By stacking additional hearths, one above the other, it would be possible to double (adding one more hearth) or triple (adding two more hearths) the total gasification rate. The second way to increase the gasification rate is by increasing the area of the hearth. By increasing hearth area, more feedstock can be loaded into the gasifier for every cycle (batch). Gasifiers of the sizes reported in Table GAS.4 have not been constructed or tested yet. The cost estimates in this table are based on the expertise and design equations of the gasification engineers, not on actual cost invoices or performance data. By increasing the gasification rates on the units, it is possible to handle the daily separated solids amounts produced at the representatively-sized finishing farms. It is assumed that propane efficiency rate (gallons of propane / DM lb. of feedstock loaded) stays constant as gasification rates increase.

4.2. Predicted Annualized Costs for a Single-Batch Gasifier Loaded with 50% DM Separated Swine Solids (Table GAS.4)

Table GAS.4 shows the annualized costs associated with installing and operating a single-batch gasifier on representatively-sized North Carolina finishing farms. The costs shown in this table assume that 50% DM swine solids are loaded into the gasifier. The total gasifier cost in the first row is based on estimates provided by the principal investigators and commercial collaborators. Most of the operating expense is the cost of propane necessary to fuel the single-batch gasifier. The bottom line of Table GAS.4 lists the total annualized costs of the single-batch gasifier. These annual costs range from $52,352 for the smallest size category to $631,872 for the largest size category of finishing farms. Propane costs account for 81% to 94% of total annualized costs across the various size categories.

4.3. Per-Unit and Breakeven Costs for a Single-Batch Gasifier Loaded with 50% DM Separated Swine Solids (Table GAS.5)

Table GAS.5 reports the total annualized costs for a single-batch gasifier loaded with 50% DM swine solids (as calculated in Table GAS.4) using several denominators. The first metric used is $ per 1,000 pounds steady state live weight (SSLW). These costs range from $273.14 to $312.73 per 1,000 pounds SSLW and decrease as farm size increases. Gasification of separated solids also implies an avoided land application cost. In the belt systems report, it was assumed that belt-separated solids were land applied. If, instead, the solids were loaded into the gasifier, then the cost of land applying the solids would be avoided. The second row of Table GAS.5 shows the avoided land application costs associated with the gasifier technology. Avoided costs are greater for larger farms, as larger farms produce more solids and incur more machine application hours and higher application costs (see Appendix C in the Combined Appendices Report for a more detailed description of land application of solids). After subtracting avoided land application costs, the range of predicted gasification costs in $ / 1,000 lbs. SSLW becomes $263.98 to $277.80 across farm size categories.

The second denominator used in Table GAS.5 is dry tons of separated solids processed. This metric represents the gasification costs associated with processing one dry ton of loaded swine solids. The total annual number of dry tons processed is also reported in Table GAS.5 for each of the five size categories. As reported in Table GAS.5, the cost per dry ton of loaded solids ranges from $182.72 to $209.22 across the five size categories. After subtracting the avoided costs of land application, the range of predicted costs per dry ton loaded falls to $176.59 to $185.85.

Table GAS.5 presents gasifier costs per ton of ash produced. Gasifier ash can be used as a fertilizer input or as a feed ingredient (replacing dicalcium phosphate as a phosphorus source) and therefore has a potential revenue stream associated with it. For this reason, the $ / ton of ash produced cost reported in Table GAS.5 can be interpreted a breakeven cost for the gasifier technology. As mentioned in Section 2, 12.2% of dry matter swine solids loaded into the gasifier were recovered as ash. The total amount of ash produced and recovered is reported in Table GAS.5 for each of the five representative finishing farms. The cost per ton of ash produced is calculated by dividing the total annualized technology costs reported in Table GAS.4 by the total tons of ash produced. This predicted cost ranges from $1,498 to $1,715 across the five farm size categories. After subtracting avoided land application costs, the breakeven costs of the gasifier technology range from $1,448 to $1,523 per ton of ash. The price of dicalcium phosphate was recently listed as $22.01 per cwt (112 lbs.) (Steevens and Olson, Howard and Shaver). This is the equivalent of $0.197 per pound or $393.04 per ton. Dicalcium phosphate contains 18% phosphorus, as compared to 13.07% in gasifier ash. Calculations provided by the principal investigator showed that 1.14 tons of gasifier ash will provide the phosphorus equivalency of 1 ton of dicalcium phosphate (Koger). Based on this feed substitution ratio and the per ton price of dicalcium phosphate, the implied price of gasifier ash can be estimated as $344.77 per ton (or $0.172 / pound, or $19.31 / cwt).

4.4. Predicted Annualized Costs for a Single-Batch Gasifier Loaded with 79% DM Separated Swine Solids (Table GAS.6)

Table GAS.6 shows the predicted annualized costs associated with installing and operating a single-batch gasifier on representatively-sized North Carolina finishing farms. The costs shown in this table assume that 79% dry matter (DM) swine solids are loaded into the gasifier. The total gasifier cost listed in the first row is based on estimates provided by the principal investigators and commercial collaborators. In this model, a storage tank is included for separated solids. By allowing for storage, the DM content of the belt-separated solids can be increased from 50% to 79%. Most of the operating expenses are comprised of propane costs necessary to fuel the single-batch gasifier. While still significant, propane costs are greatly reduced in this model because of the higher DM content of the solids. Propane usage drops from 0.057 to 0.025 gallons per DM pound of loaded solids (see Table GAS.1). The bottom line of Table GAS.6 lists the total annualized costs of the single-batch gasifier. These predicted annual costs range from $30,720 for the smallest size category to $302,291 for the largest size category of finishing farms. Propane costs account for 61% to 86% of total annualized costs across the various size categories.

4.5. Per-Unit and Breakeven Costs for a Single-Batch Gasifier Loaded with 79% DM Separated Swine Solids (Table GAS.7)

Table GAS.7 reports the total annualized costs for a single-batch gasifier loaded with 79% DM swine solids (as calculated in Table GAS.6) using several denominators. The first metric used is $ per 1,000 pounds steady state live weight (SSLW). These costs range from $130.67 to $183.51 per 1,000 pounds SSLW and decrease as farm size increases. Gasification of separated solids also implies an avoided land application cost. In the belt systems report, it was assumed that belt-separated solids were land applied. If, instead, the solids were loaded into the gasifier, then the cost of land applying the solids would be avoided. The second row of Table GAS.7 shows the avoided land application costs associated with the gasifier technology. Avoided costs are greater for larger farms, as larger farms produce more solids and incur more machine application hours and higher application costs (see Appendix C in the Combined Appendices Report for a more detailed description of land application of solids). After subtracting avoided land application costs, the range becomes $121.51 to $148.58 per 1,000 lbs. SSLW across farm size categories.

The second denominator used in Table GAS.7 is dry tons of separated solids processed. This metric represents the gasification costs associated with processing one dry ton of loaded swine solids. The total annual number of dry tons processed is also reported in Table GAS.7 for each of the five size categories. As reported in Table GAS.7, the predicted cost per dry ton of loaded solids ranges from $87.42 to $122.77 across the five size categories. When factoring in the avoided costs of land application, the range of predicted costs per dry ton loaded falls to $81.29 to $99.39.

Table GAS.7 also presents predicted gasifier costs per ton of ash produced. Gasifier ash can be used as a fertilizer input or as a feed ingredient (replacing dicalcium phosphate as a phosphorus source), and therefore has a potential revenue stream associated with it. For this reason, the $ / ton of ash produced cost reported in Table GAS.7 can be interpreted as a breakeven cost for the gasifier technology. As mentioned in Section 2, 12.2% of dry matter swine solids loaded into the gasifier were recovered as ash. The predicted total amount of ash produced and recovered is reported in Table GAS.7 for each of the five representative finishing farms. The cost per ton of ash produced is calculated as the total annualized gasifier cost reported in Table GAS.4 divided by the total ash produced. This cost ranges from $717 to $1,006 per ton across the five farm size categories. After subtracting avoided land application costs, the predicted breakeven costs of the gasifier technology range from $666 to $815 per ton of ash. As discussed in Section 4.3, the estimated implied price of a ton of gasifier ash is $345.

5. Predicted Standardized Costs of a Continuous-Feed Gasifier (proposed technology, yet to be demonstrated)

5.1. Second Generation Gasification Technology

The version of gasifier that has been tested and demonstrated is a single-batch gasifier. All of the performance data reported in Tables GAS.1 and GAS.2 reflect this type of technology. The continuous-feed gasifier described in this section has yet to be tested by the technology providers. Its performance has not been demonstrated or verified. Therefore, the economic analyses in sections 5.2-5.5 are highly speculative.

The BGP gasification technology is still in developmental stages and not yet fully commercial. While the first generation gasifier technology is the previously described single-batch unit, a second generation technology is currently being tested. This second generation BGP gasifier is a continuous-feed unit, meaning that the gasification process can be sustained over long periods of time without stopping to load feedstock or remove ash. By operating the gasifier continuously, there is the potential for large energy savings. In fact, it is hoped that the need for supplemental energy (e.g., propane) will be eliminated except during the gasifier startup process. The second generation gasifier is expected to operate solely on the waste heat that it produces.

The second generation BGP gasifier technology separates the steps of the gasification process. Augers carry the feedstock from a hopper to the drying chamber, where it is heated at 200°C with radiant waste heat from the lower chamber. Then, the feedstock is conveyed to the gasification chamber which is heated to 600-900°C. With the second generation design, steam can be introduced from the drying chamber and product gases can potentially be formed and captured for conversion to liquid fuels or value-added chemicals. From the gasification chamber, the feedstock is carried to the carbon cycle chamber. Combustion in this chamber provides the requisite heat for the gasification chamber.

The technology providers are hopeful that the new design will help gasifier economics in three ways: 1.) by making better use of waste heat in order to eliminate or substantially eliminate propane usage and costs; 2.) by having the potential to form product gas; and 3.) by recovering waste heat from the flue in order to heat barns, generate steam, etc.

The following sections and economic analyses assume that the continuous-feed gasifier technology is able to sustain its steady-state operation by solely using waste heat. Propane or supplemental energy is still necessary during startup periods. It is assumed that there are 20 days per year of starting or re-starting the gasifier during which propane is required. Propane usage during these days is the same as demonstrated in the single-batch gasifier (0.057 gallons / DM lb. of 50% DM solids loaded or 0.025 gallons / DM lb. of 79% DM solids loaded). Because this technology has yet to be tested, it is uncertain whether the continuous-feed gasifier will actually be able to operate using only waste heat and, if not, what the necessary propane usage rates will be. The continuous-feed gasifier is a more complicated technology than the single-batch gasifier and therefore more costly. The technology providers and commercial collaborators have again provided the economics team with cost estimates for the second generation technology. A cost estimate was given for each of the five feeder-finish size categories. These cost estimates were based on the size of the gasifier that would be required to handle the average daily amount of solids produced at a representatively-sized finishing farm within each category.

5.2. Predicted Annualized Costs for a Continuous-Feed Gasifier Loaded with 50% DM Separated Swine Solids (Table GAS.8)

Table GAS.8 shows the annualized costs associated with installing and operating a continuous-feed gasifier on representatively-sized North Carolina finishing farms. The predicted costs shown in this table assume that 50% DM swine solids are loaded into the gasifier. The total gasifier cost listed in the first row is based on estimates provided by the principal investigators and commercial collaborators. The bottom line of Table GAS.8 lists the total annualized costs of the continuous-feed gasifier. These annual costs range from $20,254 for the smallest size category to $115,834 for the largest size category of finishing farms. Propane costs account for only 12% to 28% of total annualized costs across various size categories reflecting more efficient use of waste heat.

5.3. Per-Unit and Breakeven Costs for a Continuous-Feed Gasifier Loaded with 50% DM Separated Swine Solids (Table GAS.9)

Table GAS.9 reports the total annualized costs for a continuous-feed gasifier loaded with 50% DM swine solids (as calculated in Table GAS.8) using several denominators. The first metric used is $ per 1,000 pounds steady state live weight (SSLW). Predicted costs range from $50.07 to $120.99 per 1,000 pounds SSLW and decrease as farm size increases. Gasification of separated solids also implies an avoided land application cost. In the belt systems report, it was assumed that belt-separated solids were land applied. If, instead, the solids were loaded into the gasifier, then the cost of land applying the solids would be avoided. The second row of Table GAS.9 shows the avoided land application costs associated with the gasifier technology. Avoided costs are greater for larger farms, as larger farms produce more solids and incur more machine application hours and higher application costs (see Appendix C in the Combined Appendices Report for a more detailed description of land application of solids). After subtracting avoided land application costs, the range of predicted costs becomes $40.91to $86.06 per 1,000 lbs. SSLW across farm size categories.

The second denominator used in Table GAS.5 is dry tons of separated solids processed. This metric represents the gasification costs associated with processing one dry ton of loaded swine solids. The predicted total annual number of dry tons processed is also reported in Table GAS.9 for each of the five size categories. As reported in Table

GAS.9, the predicted cost per dry ton of loaded solids ranges from $33.50 to $80.94 across the five size categories. After subtracting avoided costs of land application, the range of costs per dry ton loaded falls to $27.31 to $57.57.

Table GAS.9 also presents gasifier costs per ton of ash produced. Gasifier ash can be used as a fertilizer input or as a feed ingredient (replacing dicalcium phosphate as a phosphorus source), and therefore has a potential revenue stream associated with it. For this reason, the $ / ton of ash produced cost reported in Table GAS.9 can be interpreted as a breakeven cost for the gasifier technology. As mentioned in Section 2, 12.2% of dry matter swine solids loaded into the gasifier were recovered as ash. The predicted total amount of ash recovered is reported in Table GAS.9 for each of the five representative finishing farms. The cost per ton of ash produced is calculated as total annualized gasifier costs reported in Table GAS.8 divided by total ash production. This predicted cost ranges from $275 to $663 per ton of ash across the five far size categories. After subtracting avoided land application costs, the breakeven costs of the gasifier technology range from $224 to $472 per ton of ash. As discussed in Section 4.3, the implied price of a ton of gasifier ash as a feed ingredient is $345.

5.4. Predicted Annualized Costs for a Continuous-Feed Gasifier Loaded with 79% DM Separated Swine Solids (Table GAS.10)

Table GAS.10 shows the annualized costs associated with installing and operating a continuous-feed gasifier on representatively-sized North Carolina finishing farms. The costs shown in this table assume that 79% DM swine solids are loaded into the gasifier. The total gasifier cost listed in the first row is based on estimates provided by the principal investigators and commercial collaborators. The bottom line of Table GAS.10 lists the total annualized costs of the continuous-feed gasifier. These annual costs range from $21,322 for the smallest size category to $100,039 for the largest size category of finishing farms. Propane costs account for between 5% to 14% of predicted total annualized costs across the various size categories due to the more efficient use of waste heat and the more efficient gasification of higher DM solids.

5.5. Per-Unit and Breakeven Costs for a Continuous-Feed Gasifier Loaded with 79% DM Separated Swine Solids (Table GAS.11)

Table GAS.11 reports predicted total annualized costs for a continuous-feed gasifier loaded with 79% DM swine solids (as calculated in Table GAS.10) using several denominators. The first metric used is $ per 1,000 pounds steady state live weight (SSLW). These costs range from $43.24 to $127.37 per 1,000 pounds SSLW and decrease as farm size increases. Gasification of separated solids also implies an avoided land application cost. In the belt systems report, it was assumed that belt-separated solids were land applied. If, instead, the solids were loaded into the gasifier, then the cost of land applying the solids would be avoided. The second row of Table GAS.11 shows the avoided land application costs associated with the gasifier technology. Avoided costs are greater for larger farms, as larger farms produce more solids and incur more machine application hours and higher application costs (see Appendix C in the Combined Appendices Report for a more detailed description of land application of solids). After subtracting avoided land application costs, the range of costs becomes $34.08 to $92.44 per 1,000 lbs. SSLW across farm size categories.

The second denominator used in Table GAS.11 is dry tons of separated solids processed. This metric represents the gasification costs associated with processing one dry ton of loaded swine solids. The predicted total annual number of dry tons processed is also listed in Table GAS.11 for each of the five size categories. As reported in Table GAS.11, the predicted cost per dry ton of loaded solids ranges from $28.93 to $85.21 across the five size categories. After subtracting avoided costs of land application, the range of costs per dry ton loaded falls to $22.80 to $61.84.

Finally, Table GAS.11 presents gasifier costs per ton of ash produced. Gasifier ash can be used as a fertilizer input or as a feed ingredient (replacing dicalcium phosphate as a phosphorus source), and therefore has a potential revenue stream associated with it. For this reason, the $ / ton of ash produced cost reported in Table GAS.11 can be interpreted as a breakeven cost for the gasifier technology. As mentioned in Section 2, 12.2% of dry matter swine solids loaded into the gasifier were recovered as ash. The predicted total amount of ash produced and recovered is reported in Table GAS.11 for each of the five representative finishing farms. The cost per ton of ash produced is calculated as the total annualized gasifier costs reported in Table GAS.10 divided by total ash production. This cost ranges from $237 to $698 per ton of ash across the five categories of farm size. After subtracting avoided land application costs, the breakeven costs of the gasifier technology range from $187 to $507 per ton of ash. As discussed in Section 4.3, the estimated implied price of gasifier ash as a feed supplement is $345 per ton.

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Tables GAS.1-GAS.3: Gasifier Operating and Performance Data

Table GAS.1. Trial Processing Efficiency of the Gasifier (Koger, et al)

Feedstock	Set Temp. (°C)	Pounds of DM Processed	% DM (as loaded)	Propane Usage (ft.^{3})	Run Time (hrs.)	DM Processing Rate (lbs. / hr.)	Propane Usage Rate (gal. / lb.)*
Separated swine solids	800	68.9	48	144	3.75	18.4	0.057
Separated swine solids	800	70.4	79	65	2.50	28.2	0.025

* Assuming a propane density of 36.39 cu. ft. / gallon

Table GAS.2. Nutrient Content of Ash from Gasification of Selected Feedstocks (Koger, et al)

Feedstock	P	K	Ca	Mg	Zn	Cu
	% nutrient content (corrected to 100% mineral ash)					
Separated swine solids	13.07	10.25	13.41	9.80	0.31	0.16
Chicken litter	4.98	2.83	25.54	1.20	0.09	0.02
Swine mortalities	17.45	5.49	27.40	1.22	0.16	0.04
Turkey litter	6.15	3.38	9.76	1.98	0.06	0.14

Table GAS.3. Assumed Total Solids Produced and Collected at Standardized SF/PSF Feeder-Finish Farms (Combined Appendices Report)

	1,240	**5,100**	**8,800**	**12,246**	**17,136**
	(number of head)				
Total solids production rate* (lbs. DM / head / day)	1.105	1.105	1.105	1.105	1.105
Daily amount of DM solids produced (lbs.)	1,370	5,636	9,724	13,532	18,935
Daily amount of solids entering the gasifier** (lbs.)	2,740	11,271	19,448	27,064	37,871

* See Appendix A, Table A.25 of the Combined Appendices Report

** Assuming 50% DM content of belt-separated solids (see Belt System Report)

Tables GAS.4-GAS.7 : Predicted Standardized Costs and Returns for the Single-Batch Gasifier Technology

Table GAS.4. Predicted Standardized Costs for a Single-Batch Gasifier Loaded with 50% DM Separated Swine Solids

	1,240	**5,100**	**8,800** (number of head)	**12,246**	**17,136**
Cost of gasifier unit	$40,000	$75,000	$100,000	$135,000	$170,000
Annualized cost of gasifer	$5,961.18	$11,177.21	$14,902.95	$20,118.98	$25,335.01
Contractor & engineering services and overhead	$2,569.27	$4,817.38	$6,423.17	$8,671.28	$10,919.39
Total Annualized Construction Cost	*$8,530.45*	*$15,994.59*	*$21,326.12*	*$28,790.26*	*$36,254.40*
Maintenance cost	$800.00	$1,500.00	$2,000.00	$2,700.00	$3,400.00
Property taxes	$203.20	$381.00	$508.01	$685.81	$863.61
Propane cost*	$42,783.56	$176,005.94	$303,669.58	$422,589.14	$591,318.75
Secondary blower electricity costs*	$35.06	$35.06	$35.06	$35.06	$35.06
Total Operating Costs	*$43,821.82*	*$177,922.00*	*$306,212.65*	*$426,010.01*	*$595,617.42*
Total Annualized Cost of Gasifer Technology	**$52,352.27**	**$193,916.59**	**$327,538.77**	**$454,800.27**	**$631,871.82**

* Assuming a propane cost of $1.50 / gallon and a propane usage rate of 0.057 gal. / DM lb. of feedstock loaded

** The secondary blower has a 50-watt motor and is always on during gasification.

Table GAS.5. Predicted Per-Unit and Breakeven Costs for a Single-Batch Gasifier Loaded with 50% DM Separated Swine Solids

	1,240	**5,100**	**8,800** (number of head)	**12,246**	**17,136**
$ / 1,000 lbs. SSLW	$312.73	$281.65	$275.71	$275.10	$273.14
Avoided annual land application costs*	$5,848	$10,365	$13,628	$16,629	$21,198
$ / 1,000 lbs. SSLW less avoided land application costs	$277.80	$266.60	$264.23	$265.04	$263.98
Dry tons of swine solids processed per year	250.23	1,029.18	1,775.85	2,471.25	3,458.06
$ / dry ton processed	$209.22	$188.42	$184.44	$184.04	$182.72
$ / dry ton processed less avoided land application costs	$185.85	$178.35	$176.77	$177.31	$176.59
Tons of ash produced per year**	30.53	125.56	216.65	301.49	421.88
$ / ton of ash produced (breakeven cost of gasifier)	$1,714.78	$1,544.41	$1,511.83	$1,508.51	$1,497.75
$ / ton of ash produced less avoided land application costs	$1,523.23	$1,461.86	$1,448.93	$1,453.35	$1,447.51

* Assuming nitrogen-based application to forage of belt-separated solids—see Appendix C in the Combined Appendices Report for more detail on land application of solids

** 12.2% of the DM swine solids loaded into the gasifier is recovered as ash.

Table GAS.6. Predicted Standardized Costs for a Single-Batch Gasifier Loaded with 79% DM Separated Swine Solids

	1,240	5,100	8,800 (number of head)	12,246	17,136
Cost of gasifier unit	$40,000	$75,000	$100,000	$135,000	$170,000
Annualized cost of gasifer	$5,961.18	$11,177.21	$14,902.95	$20,118.98	$25,335.01
Separated solids storage tank	$1,490.29	$1,490.29	$1,490.29	$1,490.29	$1,490.29
Contractor & engineering services and overhead	$3,211.59	$5,459.70	$7,065.49	$9,313.60	$11,561.71
Total Annualized Construction Cost	*$10,663.06*	*$18,127.20*	*$23,458.73*	*$30,922.87*	*$38,387.02*
Maintenance cost	$1,000.00	$1,700.00	$2,200.00	$2,900.00	$3,600.00
Property taxes	$254.00	$431.80	$558.81	$736.61	$914.41
Propane cost*	$18,767.46	$77,188.74	$133,188.41	$185,343.78	$259,354.16
Secondary blower electricity costs*	$35.06	$35.06	$35.06	$35.06	$35.06
Total Operating Costs	*$20,056.52*	*$79,355.60*	*$135,982.28*	*$189,015.45*	*$263,903.63*
Total Annualized Cost of Gasifer Technology	**$30,719.58**	**$97,482.80**	**$159,441.01**	**$219,938.32**	**$302,290.65**

* Assuming a propane cost of $1.50 / gallon and a propane usage rate of 0.025 gal. / DM lb. of feedstock loaded

** The secondary blower has a 50-watt motor and is always on during gasification.

Table GAS.7. Predicted Per-Unit and Breakeven Costs for a Single-Batch Gasifier Loaded with 79% DM Separated Swine Solids

	1,240	5,100	8,800 (number of head)	12,246	17,136
$ / 1,000 lbs. SSLW	$183.51	$141.59	$134.21	$133.04	$130.67
Avoided annual land application costs*	$5,848	$10,365	$13,628	$16,629	$21,198
$ / 1,000 lbs. SSLW less avoided land application costs	$148.58	$126.53	$122.74	$122.98	$121.51
Dry tons of swine solids processed per year	250.23	1,029.18	1,775.85	2,471.25	3,458.06
$ / dry ton processed	$122.77	$94.72	$89.78	$89.00	$87.42
$ / dry ton processed less avoided land application costs	$99.39	$84.65	$82.11	$82.27	$81.29
Tons of ash produced per year**	30.53	125.56	216.65	301.49	421.88
$ / ton of ash produced (breakeven cost of gasifier)	$1,006.21	$776.38	$735.94	$729.50	$716.53
$ / ton of ash produced less avoided land application costs	$814.66	$693.83	$673.03	$674.35	$666.29

* Assuming nitrogen-based application to forage of belt-separated solids—see Appendix C in the Combined Appendices Report for more detail on land application of solids

** 12.2% of the DM swine solids loaded into the gasifier is recovered as ash

Tables GAS.8-GAS.11 : Predicted Standardized Costs and Returns for the Continuous-Feed Gasifier Technology

Table GAS.8. Predicted Standardized Costs for a Continuous-Feed Gasifier Loaded with 50% DM Separated Swine Solids

	1,240	**5,100**	**8,800**	**12,246**	**17,136**
			(number of head)		
Cost of gasifier unit	$75,000	$150,000	$200,000	$275,000	$350,000
Annualized cost of gasifer	$11,177.21	$22,354.42	$29,805.90	$40,983.11	$52,160.32
Contractor & engineering services and overhead	$4,817.38	$9,634.76	$12,846.34	$17,663.72	$22,481.10
Total Construction Cost	*$15,994.59*	*$31,989.18*	*$42,652.24*	*$58,646.83*	*$74,641.42*
Maintenance cost	$1,500.00	$3,000.00	$4,000.00	$5,500.00	$7,000.00
Property taxes	$381.00	$762.01	$1,016.01	$1,397.01	$1,778.02
Propane cost*	$2,343.04	$9,636.71	$16,628.04	$23,139.43	$32,379.33
Secondary blower electricity costs*	$35.06	$35.06	$35.06	$35.06	$35.06
Total Operating Costs	*$4,259.10*	*$13,433.78*	*$21,679.11*	*$30,071.50*	*$41,192.41*
Total Annualized Cost of Gasifer Technology	**$20,253.69**	**$45,422.96**	**$64,331.35**	**$88,718.33**	**$115,833.83**

* Assuming a propane cost of $1.50 / gallon and a propane usage rate of 0.057 gal. / DM lb. of feedstock loaded during start-up periods (assumed to be 20 days per year)
** The secondary blower has a 50-watt motor and is always on during gasification.

Table GAS.9. Predicted Per-Unit and Breakeven Costs for a Continuous-Feed Gasifier Loaded with 50% DM Separated Swine Solids

	1,240	**5,100**	**8,800**	**12,246**	**17,136**
			(number of head)		
$ / 1,000 lbs. SSLW	$120.99	$65.97	$54.15	$53.66	$50.07
Avoided annual land application costs*	$5,848	$10,365	$13,628	$16,629	$21,198
$ / 1,000 lbs. SSLW less avoided land application costs	$86.06	$50.92	$42.68	$43.61	$40.91
Dry tons of swine solids processed per year	250.23	1,029.18	1,775.85	2,471.25	3,458.06
$ / dry ton processed	$80.94	$44.14	$36.23	$35.90	$33.50
$ / dry ton processed less avoided land application costs	$57.57	$34.06	$28.55	$29.17	$27.37
Tons of ash produced per year**	30.53	125.56	216.65	301.49	421.88
$ / ton of ash produced (breakeven cost of gasifier)	$663.40	$361.76	$296.94	$294.27	$274.57
$ / ton of ash produced less avoided land application costs	$471.85	$279.21	$234.03	$239.11	$224.32

* Assuming nitrogen-based application to forage of belt-separated solids—see Appendix C in the Combined Appendices Report for more detail on land application of solids
** 12.2% of the DM swine solids loaded into the gasifier is recovered as ash.

Table GAS.10. Predicted Standardized Costs for a Continuous-Feed Gasifier Loaded with 79% DM Separated Swine Solids

	1,240	**5,100**	**8,800** (number of head)	**12,246**	**17,136**
Cost of gasifier unit	$75,000	$150,000	$200,000	$275,000	$350,000
Annualized cost of gasifer	$11,177.21	$22,354.42	$29,805.90	$40,983.11	$52,160.32
Solids storage tank	$1,490.29	$1,490.29	$1,490.29	$1,490.29	$1,490.29
Contractor & engineering services and overhead	$5,459.70	$10,277.07	$13,488.66	$18,306.04	$23,123.42
Total Construction Cost	*$18,127.20*	*$34,121.79*	*$44,784.85*	*$60,779.44*	*$76,774.03*
Maintenance cost	$1,700.00	$3,200.00	$4,200.00	$5,700.00	$7,200.00
Property taxes	$431.80	$812.81	$1,066.81	$1,447.81	$1,828.82
Propane cost*	$1,027.65	$4,226.63	$7,293.00	$10,148.87	$14,201.46
Secondary blower electricity costs*	$35.06	$35.06	$35.06	$35.06	$35.06
Total Operating Costs	*$3,194.51*	*$8,274.50*	*$12,594.87*	*$17,331.74*	*$23,265.34*
Total Annualized Cost of Gasifer Technology	**$21,321.71**	**$42,396.29**	**$57,379.72**	**$78,111.18**	**$100,039.37**

* Assuming a propane cost of $1.50 / gallon and a propane usage rate of 0.025 gal. / DM lb. of feedstock loaded during startup periods (assumed to be 20 days per year)
** The secondary blower has a 50-watt motor and is always on during gasification.

Table GAS.11. Predicted Per-Unit and Breakeven Costs for a Continuous-Feed Gasifier Loaded with 79% DM Separated Swine Solids

	1,240	**5,100**	**8,800** (number of head)	**12,246**	**17,136**
$ / 1,000 lbs. SSLW	$127.37	$61.58	$48.30	$47.25	$43.24
Avoided annual land application costs*	$5,848	$10,365	$13,628	$16,629	$21,198
$ / 1,000 lbs. SSLW less avoided land application costs	$92.44	$46.52	$36.83	$37.19	$34.08
Dry tons of swine solids processed per year	250.23	1,029.18	1,775.85	2,471.25	3,458.06
$ / dry ton processed	$85.21	$41.19	$32.31	$31.61	$28.93
$ / dry ton processed less avoided land application costs	$61.84	$31.12	$24.64	$24.88	$22.80
Tons of ash produced per year**	30.53	125.56	216.65	301.49	421.88
$ / ton of ash produced (breakeven cost of gasifier)	$698.39	$337.66	$264.85	$259.08	$237.13
$ / ton of ash produced less avoided land application costs	$506.84	$255.11	$201.95	$203.93	$186.88

* Assuming nitrogen-based application to forage of belt-separated solids—see Appendix C in the Combined Appendices Report for more detail on land application of solids
** 12.2% of the DM swine solids loaded into the gasifier is recovered as ash