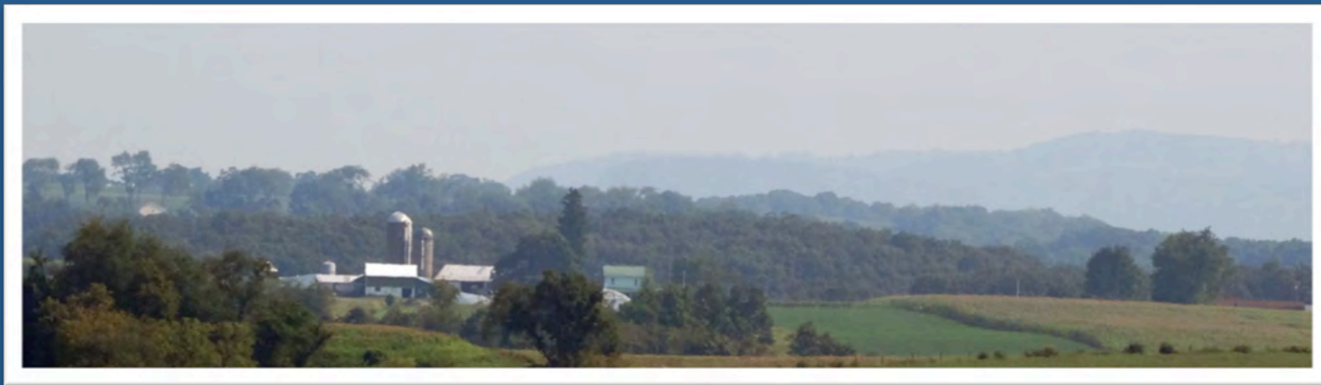

Farm Manure-to-Energy Initiative Final Report

Using Excess Manure to Generate Farm Income in the Chesapeake Bay Region's Phosphorus Hotspots

December 2015

Farm Manure-to-Energy Initiative | Final Report

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Written and produced by the Farm Manure-to-Energy Initiative.

Copies are available in Adobe Acrobat format (.pdf) at www.sustainablechesapeake.org and from the eXtension website at www.extension.org/68455 (under "Additional Resources").

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National Fish and Wildlife Foundation, Chesapeake Bay Funders Network, USDA Natural Resources Conservation Innovation Grant Program, and U.S. EPA Innovative Nutrient and Sediment Reduction Program, with matching fund contributions from project partners including technology vendors, farmers, and steering committee members.

Steering Committee

National Fish and Wildlife Foundation in partnership with the Chesapeake Bay Commission, Farm Pilot Project Coordination, Inc., International Biochar Initiative , Lancaster County Conservation District, Sustainable Chesapeake, University of Maryland Center for Environmental Science, University of Maryland Environmental Finance Center, Virginia Cooperative Extension, Virginia Tech Eastern Shore Agricultural Research and Extension Center, and members of the Chesapeake Bay Funders Network (including the Campbell Foundation and the Foundation for Pennsylvania Watersheds).

Farm Partners

Technology demonstrations were hosted by the Flintrock Farm of Lititz, PA; Mark Rohrer Farm of Strasburg, PA; Mike Weaver Farm of Fort Seybert, WV; Riverhill Farm of Port Republic, VA, and Windview Farm of Port Trevorton, PA. Additional support provided by the Earl Ray Zimmerman Farm of Ephrata, PA; Frye Poultry of Wardensville, WV; North Carolina State University Animal & Poultry Waste Management Center; Old Mill Farms of Melfa, VA; Robert, Brad, and J.B. Murphy of Rhodesdale, MD; Riverbank Farm of Dayton, VA; and Terra Blue Hen Farm of Delmar, DE.

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On the cover: The view from Windview Farm, Port Trevorton, PA.

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Executive Summary

The Farm Manure-to-Energy Initiative was launched in 2012 to demonstrate and objectively evaluate manure-based energy systems operating on several private farms in the Chesapeake Bay region. As a collaborative multi-state effort, the Initiative included farmers in Pennsylvania, Virginia, West Virginia, and Maryland, with project management and support from foundations, nonprofit organizations, academic institutions, government agencies, and private businesses. Over the course of four years, thermal manure-based energy systems were developed and installed on five farms, and each was assessed for its technical, environmental, and financial performance.

Livestock manure contains valuable nutrients and organic matter that can improve soil fertility and promote healthy crop production when used as a fertilizer. For most animal operations, on-farm or local use of manure as a fertilizer is a standard practice and considered appropriately protective of water quality when manure is applied according to nutrient management plan recommendations.

However, managing manure to protect water quality can be challenging in areas where animal production is concentrated. In these areas, long-term application of manure to fields has resulted in high levels of soil phosphorus and increased risk of transport to surface waters through stormwater runoff. Because manure is bulky and costly to transport long distances, opportunities to sell excess manure for use on nutrient-deficient fields outside of high-density production areas are limited.

Demonstrations and Evaluation Strategy

The Farm Manure-to-Energy Initiative focused on farm-scale thermochemical (thermal) systems. Thermal systems generate energy while producing nutrient rich co-products (ash and biochar) that could be more easily transported out of nutrient-dense areas and sold elsewhere as fertilizer. Four thermal technologies were selected for demonstration on five farms in the Chesapeake region:

- Ecoremedy ® gasifier (designed and installed by Enginuity Energy, with continuing support from Ecoremedy Energy) on Flintrock Farm in Lititz, PA
- Global Re-Fuel (designed and installed by Wayne Combustion Systems) on the Mark Rohrer Farm in Strasburg, PA, and on the Mike Weaver Farm in Fort Seybert, WV
- Bio-Burner 500 (by LEI Products) at Riverhill Farm in Port Republic, VA

- Blue Flame Boiler (designed and installed by Total Energy Solutions) on Windview Farm in Port Trevorton, PA

Additionally, Farm Manure-to-Energy Initiative partners helped to develop and secure funding for a demonstration of the Biomass Heating Solutions Ltd. (Bhsl) technology on a farm in Rhodesdale, MD. Construction for this project is anticipated in the spring of 2016. Partners have also support AHPharma Inc. efforts to demonstrate a thermal manure-to-energy system in their research farm in Tyaskin, MD.

Before installation, project partners worked closely with EPA Region 3 and state permitting agencies to determine permitting requirements for farm-scale systems in each of the Bay states. These conversations informed air emissions testing methodology and laid the foundation for the demonstration projects.

Each of the systems was evaluated for technical performance, environmental performance, and financial performance. Technical factors included the reliability of the system, how well the system integrated with the farm's existing heat delivery systems, and how well the technology succeeded in maintaining target temperature and relative humidity goals. To monitor environmental performance, project partners collected data on air emissions and documented the fate of nutrients as poultry litter moved through the system. Partners also evaluated the market potential of the ash co-product and compared its fertilizer value to raw poultry litter and traditional commercial fertilizers. Financial performance factors included the costs to install, operate, and maintain the system, and any reduced costs for propane or electricity.

Findings

Technical Performance

Performance varied considerably between the technologies. On one hand, the Global Re-Fuel technology failed to perform reliably and will need additional research and development before additional on-farm deployments. Alternatively, the Blue Flame boiler and Biomass Heating Solutions Ltd. technologies have been used successfully on poultry farms in the Chesapeake Bay region and Europe for up to 5 years. The Bio-Burner 500 and Ecoremedy gasifier are still in early phases of deployment. Additional data is needed on their performance before further deployments are recommended.

All of the technologies successfully integrated with existing propane heating systems and provided heat to poultry houses. However, the amount of heat produced (and propane offset) varied by the technology and the fuel quality of the poultry litter. The two technologies that have the longest track record for successful on-farm use (the Blue Flame boiler and BHSL system) are deployed on farms that completely clean out poultry houses between every flock. Most farms in the Chesapeake Bay region limit whole-house cleanouts and instead remove the top layer of poultry litter from the house at the end of each flock. Two farms that converted to organic production during this project period experienced an increase in litter moisture after the conversion. In one case, litter moisture was too high for the Global Re-Fuel system to use as a fuel. While the Ecoremedy gasifier successfully used higher moisture litter as a fuel, the heat output was reduced.

Environmental Performance

Air emissions were evaluated using a certified, third-party air emissions testing company to inform nutrient mass balance and permitting. The technologies demonstrated a range of air emissions. Because of the high potassium content of poultry litter, vendors will need to control particulate matter emissions. Particulate matter proved challenging for several of the vendors who were not able to demonstrate that the technologies would be feasible for installation in Bay states with low thresholds for particulate matter emissions. Only one vendor (BHSL) demonstrated the potential to meet all Bay state permitting requirements. Four of the technologies (Global Re-Fuel, Blue Flame boiler, Bio-Burner 500, and Ecoremedy gasifier) require additional controls for particulate matter to meet permitting thresholds in Maryland. Three of the technologies (Global Re-Fuel, Blue Flame boiler, and Bio-Burner 500) require additional reductions in nitrous oxides (NOx). System tuning for NOx emissions was recommended as the next step prior to consideration of NOx emissions controls. Two of the vendors demonstrated that, despite the nitrogen content of poultry litter, farm-scale thermal systems can be designed as low NOx emissions technologies.

The nutrient balance assessment suggests that much of the reactive nitrogen in poultry litter (primarily organic nitrogen and ammonia) is converted into non-reactive nitrogen in the thermal process. Reactive nitrogen in air emissions from thermal manure-to-energy systems was compared with reactive nitrogen (ammonia) lost from land application via various strategies (injection, shallow disking, and surface application without incorporation). Findings suggest that technologies with the lowest reactive nitrogen emissions will result in less reduced reactive nitrogen loss to the atmosphere than recommended practices for reducing nitrogen loss through land application (injection and immediate incorporation with a shallow disk). The technology with the highest nitrogen concentration in air emissions still reduced reactive nitrogen loss compared to surface application without incorporation.

The nutrient balance for phosphorus suggests that almost all of the phosphorus in poultry litter is sequestered in the ash (both bottom ash and fly ash from emission control systems). However, there was some loss of phosphorus in the emissions associated with particulate matter.

The nutrient balance also illustrated challenges with quantifying the fate of nutrients in farm-scale systems. Two of the analyses suggest that there is more phosphorus in the ash and air emissions than in the poultry litter used as a fuel. Since there is no known mechanism for creating phosphorus in on-farm thermal manure-to-energy systems, it is likely that variability in the fuel feed rate, ash production rates, and nutrient content of the poultry litter contributed to the variability of the results.

Financial Assessment

The financial assessment process was limited by the length of the performance period. However a simple analysis, considering just capital costs and energy savings, suggest that farm-scale systems can have a positive return on investment (ROI), even when they are not performing well. For example, despite technical problems, the Global Re-Fuel system has the potential to generate a 34% ROI over a 15-year period (or 26% over a 10-year period). The Blue Flame System would generate a 49% ROI over 15 years (or 38% over ten years). This analysis did not take into account operations and maintenance costs, cost-share program contributions, or allowances provided by the integrator for propane or electricity purchases. These allowances, which are common for organic or antibiotic-free integrators, can have a considerable impact on the ROI.

Although the available data, which was limited by the duration of the performance monitoring period, did not quantify the generated heat in a way that statistically correlates the technology with reduced propane use, farmers repeatedly observed and reported the trend toward reduced propane use while the systems were running. This saved energy and money for the growers and reduced their carbon footprint.

Fertilizer Value of Ash and Biochar Co-Products

Field row crop trials and laboratory analysis were used to evaluate the fertilizer value of ash and biochar co-products produced from a range of thermal systems, including combustion, gasification, and pyrolysis technologies. The fertility value of thermal co-products was compared with commonly used commercial phosphorus and potash fertilizers (triple super phosphate and muriate of potash), as well as untreated poultry litter.

Results suggest that, although not as concentrated, poultry litter co-products are feasible as a substitute for commercial fertilizer products for row crop production. Trace mineral content of the bottom ash also met state requirements for fertilizers.

Nutrient densification varied between pyrolysis, gasification, and combustion systems: phosphorus was concentrated between 4-12 times its original density, potassium was concentrated between 3-13 times its original density, and sulfur was concentrated between 2-5 times its original density. Thermal technologies that operate at higher temperatures densified nutrients more than lower temperature technologies (such as pyrolysis).

The nutrient densification and value of this material as a fertilizer indicates that cost-effective transport out of high-density production regions of the Chesapeake Bay is feasible and that this material could provide a new source of revenue for poultry growers. Although additional work is needed to establish markets, ash co-products have the potential to provide new sources of revenue for poultry growers through the sale of excess farm nutrients. One transaction that occurred during this project demonstrated this potential through the sale of poultry litter ash – at market prices for the phosphorus and potassium content – to soybean growers in Missouri.

Lessons Learned

This four-year project generated many important insights on the potential of these thermal systems and the remaining challenges for more widespread success. Some of the key lessons learned are:

1) On-farm thermal systems are not a good match for every farm. They require considerably more management than propane heating systems and, depending on the farm, they may not be cost effective. On-farm thermal systems also require more time to operate, especially because the technologies are still in the early phases of commercial deployment.

2) The success of a particular technology on one farm does not mean that it will succeed on another farm. The characteristics of poultry litter vary significantly between farms, requiring farm-specific adjustments to the system. Success requires collaboration between the vendor and the farmer.

3) Poultry litter ash and biochar are valuable plant nutrients. Depending on the process, poultry litter ash contains in the range of 14 to 18% phosphorus fertilizer and 13 to 24% potash fertilizer. Plant availability of the nutrients also varies by process but is in the range of 80 to 100%.

4) To support regulatory compliance, vendors should be prepared to supply data on air emissions. In states with strict particulate matter emissions thresholds, advanced air emissions controls may be needed to trap and remove fine particulate matter when poultry litter is used as a fuel.

5) State rules vary significantly with respect to on-farm thermal poultry litter-to-energy technologies. Only one technology supported through this initiative meets permitting requirements for all the Bay states.

6) Initial capital expenditures for installing systems to heat poultry houses currently range from $87,000 to over $300,000 per house to install. As these technologies mature, prices will likely come down over time.

7) Costs vary significantly, but a face-value comparison may not be the best way to determine value. A comparison that normalizes the cost may be a better way to evaluate different technologies. For example, a unit such as dollars-per-BTU-delivered is worth considering in addition to the total cost of the system. On-going operation and maintenance costs should also be considered.

8) Farm-scale thermal systems can improve cold weather ventilation and reduce relative humidity in poultry houses resulting in better in-house air quality and improved bird health. These potential production benefits warrant further investigation.

9) Organic poultry farms may offer the best opportunity for deploying farm-scale thermal systems. In the Chesapeake region, organic production requires 3 to 5 times more propane than conventionally produced poultry. If a thermal, manure-

based system can reduce propane use and improve bird health and feed conversion, organic integrators may especially stand to benefit.

Next Steps

The Farm Manure-to-Energy Initiative identified both opportunities and challenges associated with these emerging technologies. Recommended next steps are as follows:

- Continue to support technology vendor efforts to improve emissions controls for deployment in all the Bay states. The project team is working with air emissions experts to recommend next steps for emissions control design and installation.
- Build on fertility trials to develop markets for poultry litter ash that connect growers with ash or biochar to end users willing to pay a fair price for the nutrients.
- Continue to communicate results: partners will work with farm partners to host field day events when avian influenza risk is lower.

For More Information

- Visit the project website hosted by eXtension at www.extension.org/68455.
- View the video at www.extension.org/68455 (available in January 2016).
- Contact Kristen Hughes of Sustainable Chesapeake at kristen@susches.org.

1. Background and Objectives: Manure-Based Energy in the Chesapeake Region

Thermal, manure-based energy systems are drawing increasing interest from farmers, scientists, business owners, environmentalists, and policymakers. In the Chesapeake Bay region, manure-based energy technologies have been highlighted as a potential strategy for meeting multiple goals: improving farm productivity, reducing nutrient pollution in waterways, and diversifying sources of energy production. A 2012 report by the Chesapeake Bay Commission and its partners described how progressive farmers and their technology partners had begun to demonstrate these "triple benefits" and concluded that their success "should not be limited to the pioneering few."[1]

To further investigate this potential, the Farm Manure-to-Energy Initiative was launched in 2012 to demonstrate and objectively evaluate manure-based energy systems operating on several private farms in the Chesapeake Bay region. As a collaborative multi-state effort, the Initiative included farmers in Pennsylvania, Virginia, West Virginia, and Maryland, with project management and support from foundations, nonprofit organizations, academic institutions, government agencies, and private businesses. Over the course of four years, thermal manure-based energy systems were developed and installed on five farms, and each was assessed for its technical, environmental, and financial performance.

Steering Committee

National Fish and Wildlife Foundation
Chesapeake Bay Commission
Chesapeake Bay Funders Network
Farm Pilot Project Coordination, Inc.
International Biochar Initiative
Lancaster County Conservation District
Sustainable Chesapeake
University of Maryland Center for Environmental Science
University of Maryland Environmental Finance Center
Virginia Cooperative Extension
Virginia Tech Eastern Shore Agriculture Research & Extension Center
USDA Conservation Innovation Grant
U.S. EPA Innovative Nutrient and Sediment Reduction Program

Project Funders

Chesapeake Bay Funders Network
National Fish and Wildlife Foundation

Participating Farms and Technology Vendors

Flintrock Farm, Lititz, Lancaster County, PA; system by Enginuity Energy
Riverhill Farms, Port Republic, Rockingham County, VA; system by LEI Products
Rohrer Farm, Strasburg, Lancaster County, PA; system by Wayne Combustion
Weaver Farm, Fort Sybert, Pendleton County, WV; system by Wayne Combustion
Wind View Farm, Port Trevorton, Snyder County, PA; system by Total Energy

[1] *Manure to Energy: Sustainable Solutions for the Chesapeake Bay Region*. Chesapeake Bay Commission, Chesapeake Bay Foundation, Maryland Technology Development Corporation, and Farm Pilot Project Coordination, Inc. (January 2012)

1.1. Nutrient Imbalance in the Chesapeake Region

Livestock manure contains valuable nutrients and organic matter that can improve soil fertility and promote healthy crop production when used as a fertilizer. For most animal operations, on-farm or local use of manure as a fertilizer is a standard practice and considered appropriately protective of water quality when manure is applied according to nutrient management plan recommendations.

However, managing manure to protect water quality can be challenging in areas where animal production is concentrated. In these areas, long-term application of manure to fields has resulted in high levels of soil phosphorus in excess of crop fertilizer requirements. Nutrient management plans limit manure application of manure to fields with excessive soil phosphorus levels because high phosphorus levels increase the risk that manure phosphorus will be transported to surface waters through stormwater runoff. Today, areas in the Chesapeake Bay watershed that have the highest rates of phosphorus loading in their waterways correspond to areas where animal production is concentrated: Lancaster County, Pennsylvania; the Delmarva Peninsula; Virginia's Shenandoah Valley; and the eastern panhandle of West Virginia (see Figure 1).

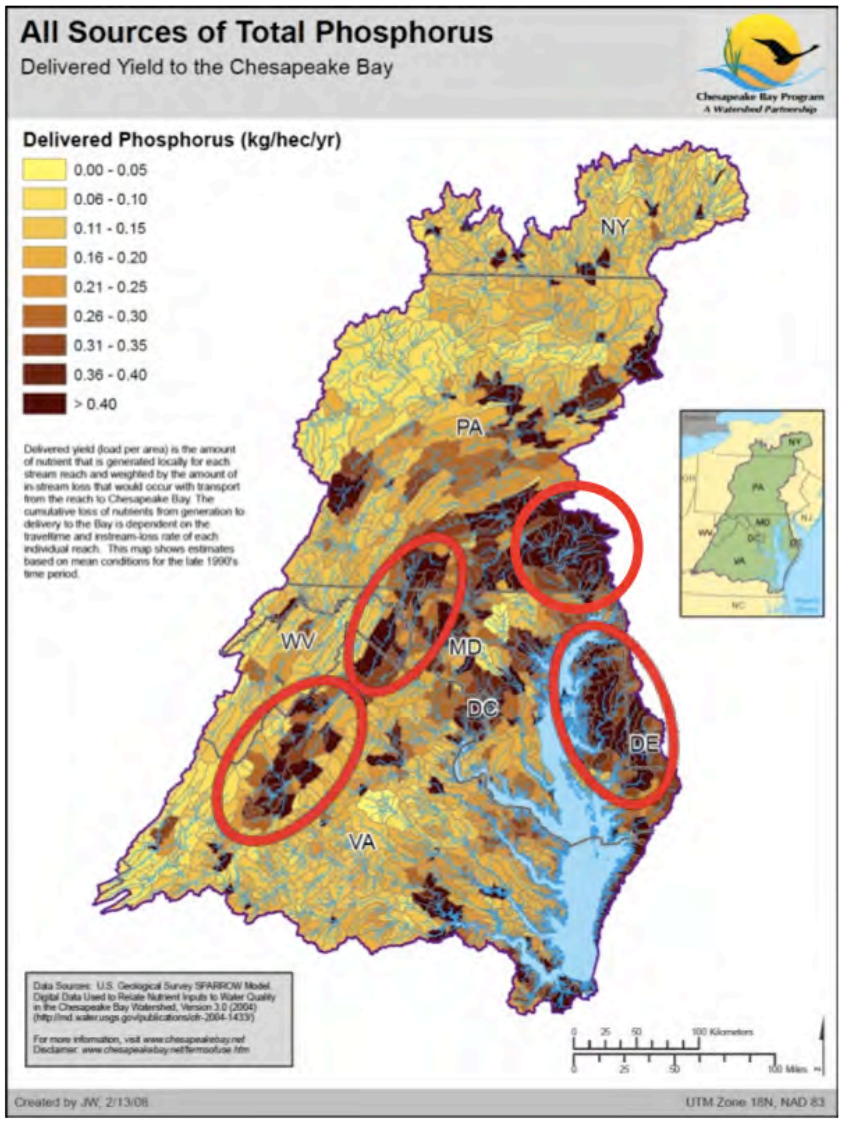

Figure 1. Nutrient "hotspots" in the Chesapeake Bay watershed.

In surface waters, the same nutrients that make manure a good fertilizer fuel the growth of algae in aquatic systems; noxious algal blooms caused by an overabundance of nutrients — nitrogen and phosphorus — are the primary cause of poor water quality in the Chesapeake Bay. Agriculture is the largest source of nitrogen and phosphorus pollution in the

Bay, and manure nutrients contribute about half of the nutrient load that originates from agriculture.

Because manure is bulky and costly to transport long distances, opportunities to sell excess manure for use on nutrient-deficient fields outside of high-density production areas are limited. In these high-density animal production areas, the market for manure nutrient is saturated, and farmers typically sell manure at a far lower price than they would receive in regions without concentrated animal production.

The goal of this project was to evaluate the feasibility of using manure-to-energy technologies to increase revenue farmers receive from manure nutrients and to generate on-farm energy, offsetting the use of non-renewable fuels.

1.2. The Technologies

Manure-to-energy systems fall into two categories: thermal systems, which use heat to convert biomass to energy, and anaerobic digestion systems, which use bacteria to convert organic carbon in manure to methane gas. A variety of techniques exist under both categories, using different types of manure.

Gasification is one type of a thermal system, shown here at Flintrock Farm in Pennsylvania.

Anaerobic digestion has been used successfully on larger farms for decades, using wet manure from cows or swine as feedstock. During the digestion process, microbes convert some of the organic nitrogen and phosphorus in the manure to an inorganic form that can be used as fertilizer. However, the total concentration of nitrogen and phosphorus is not changed in a digester. The process can reduce the volume of manure, but typically not enough for cost-effective transport over long distances. For drier manure like poultry litter, the digestion process – which requires the addition of water – may make transport of nutrients over long distances more expensive. Although some vendors are working on post-digestion treatment technologies that could facilitate transport of excess nutrients, anaerobic digesters are typically not used to address regional nutrient imbalance. [2]

[2] However, there are advanced solid-liquid separation technologies in the pilot phase of development that could facilitate concentration of phosphorus from liquid manures (including anaerobically digested manure). Several of the Farm Manure-to-Energy Initiative partners are engaged in or supporting evaluation of these technologies on dairy farms in the Chesapeake Bay watershed. The National Fish and Wildlife Foundation Chesapeake Bay Stewardship Fund program is sponsoring demonstration and evaluation of two advanced

Because of the Chesapeake region's emphasis on water quality and nutrients, the Farm Manure-to-Energy Initiative focused on technologies that had potential to expand the markets for excess manure nutrients by facilitating transport over long distances. To meet both energy and water quality goals, the project focused on thermal systems. Types of thermal systems include combustion, gasification, and pyrolysis; each of these systems captures energy from manure and, at the same time, concentrates excess nutrients in an ash or biochar. These co-products can be cost-effectively transported long distances and sold to farmers in nutrient-deficient regions. In addition, thermal processes destroy any pathogens associated with raw manure. The resulting ash or biochar can be used as a replacement for inorganic phosphorus and potash fertilizers for crops such as fruits and vegetables, where raw manures are typically not used as fertilizer (see Appendix F).

1.3. Goals and Objectives

The overarching goals of the Farm Manure-to-Energy Initiative are to:

1) Reduce the land application of manure in the Chesapeake region's nutrient hotspots
2) Displace imported fertilizer products with products derived from locally grown manure
3) Reduce phosphorus and nitrogen runoff to the Chesapeake Bay and its tributaries
4) Increase the viability of sustainable agriculture by transforming a manure liability into a farm asset
5) Increase private financing of manure-to-energy technologies in the region

To meet these goals, the steering committee focused on the following objectives:

1) Demonstrate manure-to-energy technologies on four working farms in phosphorus hotspots in the Chesapeake region and evaluate their technical, environmental, and economic performance.
2) Create a network of local, independent, manure-to-energy experts, as well as a web-based clearinghouse of data and resources, to help farmers and service providers compare differing technologies.
3) Expand local and regional markets for co-products that generate revenue for farmers.

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solid liquid separators used with liquid dairy manure. Pennsylvania State University is working with the USDA Agricultural Research Service on one demonstration project in the Lancaster County, Pennsylvania. Farm Pilot Coordination, Inc., is working with Virginia Tech on another technology demonstration in the Shenandoah Valley of Virginia. These technologies are still in development and not ready for widespread adoption.

4) Improve access to both public and private financing options by developing state-specific financing templates that identify existing funding options and innovative approaches for private financing.

1.4. The Project Steering Committee

Given the regional nature and ambitious goals of the Farm Manure-to-Energy Initiative, the National Fish and Wildlife Foundation (NFWF) established a steering committee to oversee the project. Members were recruited to provide direct assistance in project implementation (the project team) as well as members who worked collaboratively to make key decisions and share project findings with stakeholders. The steering committee met at least quarterly throughout the four-year project. Individual participants who served on the steering committee, along with a brief summary of their roles, are presented below:

- Jake Reilly, Elizabeth Nellums, Amanda Bassow, Mandy Chestnutt, and Mark Melino of NFWF provided overall project coordination, including contracting with project partners and coordinating funding. The NFWF team served as the lead applicant on the USDA Conservation Innovation Grant that provided critical support for this project, and brought additional funding via private and U.S. EPA funds to the project.
- Kristen Hughes Evans with Sustainable Chesapeake provided overall project management, including coordination among project partners and the steering committee, budget management, and sharing results with funders and stakeholders.
- Bob Monley, Preston Burnette, and Jane Corson-Lassiter (on detail from the USDA Natural Resources Conservation Service) with the Farm Pilot Project Coordination took the lead on contracting with technologies and farm partners, overseeing technology installation, and evaluating technical performance.
- Jill Jefferson, Naomi Young, and Sean Jefferson of the University of Maryland Environmental Finance Center (EFC) evaluated the financial feasibility of the projects. Dr. Dan Kugler, Allie Santacreu, and Michelle Arthur developed a financing inventory that identified funding resources for projects in the Chesapeake region. The EFC team also evaluated program-related investments, an innovative approach to private philanthropic support for these emerging technologies.
- Dr. Mark Reiter of the Virginia Tech Eastern Shore Agriculture Research & Extension Center led efforts to evaluate the fertilizer value of the ash and biochar co-products and track the fate of nutrients in the poultry litter as they moved through the system.

- Connie Musgrove of the University of Maryland's Center for Environmental Science headed up efforts to develop a clearinghouse website to share information.
- John Ignosh of the Virginia Cooperative Extension and Virginia Tech Biological Systems Engineering provided support for monitoring, air emissions testing, and performance evaluation.

Amanda Bassow and Preston Burnett, both members of the Steering Committee, view the thermal system installed at Riverhill Farm in Virginia.

- Don McNutt of the Lancaster County PA Conservation District helped connect the project's farm partners and facilitated project implementation in Pennsylvania.
- Bevin Buchheister of the Chesapeake Bay Commission helped to communicate lessons learned to policy makers in the Chesapeake region.
- Pat Stuntz of the Campbell Foundation lead outreach efforts with Maryland stakeholders and provided project financial support.
- John Dawes of the Foundation for Pennsylvania provided guidance and financial support for project implementation in Pennsylvania.
- Debbie Reed and Stefan Jirka of the International Biochar Initiative supported the project team in evaluating the potential of pyrolysis technologies.

2. Process: Getting Projects on the Ground

2.1. Selecting Farmers

The Farm Manure-to-Energy Initiative released a request for farm partners and relied on local conservation professionals for introductions to farmers who were interested in installing a manure-based energy system on their farm. The team looked for farms of various sizes that were a good fit for the technology and whose owners were committed to supporting the system both during the study period and beyond. The steering committee also sought to partner with farmers who would support efforts to share the project findings. Five farms were selected to demonstrate technologies funded by the Farm Manure-to-Energy Initiative. The project team also worked with a sixth farm (Double Trouble, Rhodesdale, MD) to secure funding for a technology demonstration (this project is still in the permitting and construction phase).

Farmers across the Chesapeake region worked with the Farm Manure-to-Energy Initiative to explore the potential of thermal technologies, including Mark Rohrer of Strasburg, PA.

2.2. Selecting Vendors

The project team solicited technology vendors through a request for information (RFI), which was distributed widely. Vendors were asked to provide information on technologies that not only convert manure to energy but also facilitate transport of nutrients out of high-density animal production regions. They were encouraged to provide information on costs (installation, operation, and maintenance), their experience using manure as a feedstock, and data that demonstrated environmental performance. Vendors were also asked to describe any financial and technical resources they were willing to contribute to a demonstration project.

Four vendors were selected as partners in the demonstration projects: Enginuity Energy, Total Energy, LEI Products, and Wayne Combustion. All had experience using poultry litter as a feedstock and financial resources they could contribute to developing the projects. Two of the vendors provided data on air emissions data available to facilitate permitting.

2.3. Pairing Technologies with Farm Partners

Four thermal technologies were selected for demonstration on five farms. The project team also worked with a sixth farm to secure funding for a fifth technology demonstration and with APHarma Inc. to pilot a poultry litter-to-energy system used with a radiant floor heating system. Demonstrations funded by the Farm Manure-to-Energy Initiative that have been installed on farms in the Chesapeake Bay region include:

- Ecoremedy ® gasifier (designed and installed by Enginuity Energy, with continuing support from Ecoremedy Energy) on Flintrock Farm in Lititz, PA
- Global Re-Fuel (designed and installed by Wayne Combustion Systems) on the Mark Rohrer Farm in Strasburg, PA, and on the Mike Weaver Farm in Fort Seybert, WV
- Bio-Burner 500 (by LEI Products) on Riverhill Farm in Port Republic, VA
- Blue Flame Boiler (designed and installed by Total Energy Solutions) on Windview Farm in Port Trevorton, PA

Demonstration projects in development with support from the Farm Manure-to-Energy Initiative:

- AHPharma, Inc. is working to demonstrate a farm-scale manure-to-energy technology used in conjunction with a radiant floor heating system at a poultry research farm in Tyaskin, MD.
- Biomass Heating Solutions Ltd. (Bhsl) is working with the Murphy's to demonstrate a farm-scale manure-to-energy system in Rhodesdale, MD.

2.4. Permitting

Before installation, project partners worked closely with EPA Region 3 and state permitting agencies to determine permitting requirements for farm-scale systems in each of the Bay states. These conversations informed air emissions testing methodology and laid the foundation for the demonstration projects.

In general, all but one of the technologies demonstrated fell under the purview of federal rules for Industrial, Commercial, and Institutional Boilers. One was not currently covered under a federal permit program because it was an air-to-air heat system rather than a boiler. In all cases, poultry litter used as a fuel met EPA fuel-legitimacy requirements, a critical test to satisfy criteria of Section 112 of the Clean Air Act. If these criteria had not been met, the systems would have been covered by Section 129 of the Clean Air Act, which applies to incineration regulations with associated permitting requirements that would not be feasible for a farm-scale project. However, all of the technologies fell below the size threshold that would require registration under the federal rules for boilers.

For these projects in which the only fuel was poultry litter produced on the farm, compliance with the federal Clean Air Act permitting requirements was relatively straightforward.[3] The project team was able to work closely with both the EPA the U.S. Department of Agriculture to help ensure that future farmers using these technologies understand the federal fuel legitimacy requirements. As a result, the team produced a federal permitting checklist for farmers interested in installing manure-based energy systems, available at www.extension.org/68455.

At the state level, the rules varied significantly. In the interim, both Virginia and West Virginia approved permits for running the systems as research projects. Air emissions testing results from this project will help to facilitate future permitting in these states. While exploring the potential for a demonstration project in Maryland, the project team supported efforts by the Maryland Department of the Environment to update its rules; the team learned that Maryland and Delaware have the strictest related emissions rules, with respect to nitrous oxides (NOx) and total particulate matter in the Chesapeake region. The project team challenged the technology vendors participating in this initiative to meet the permit requirements for all Bay states, including Maryland and Delaware, regardless of the state where the demonstration was installed.

3. Performance Evaluation

Each of the five systems installed through this initiative were evaluated for technical performance, environmental performance, and financial performance.

Technical performance was based on several factors, including the reliability of the system, how well the system integrated with the farm's existing heat delivery systems, and how well the technology succeeded in maintaining target temperature and relative humidity goals.

To monitor environmental performance, project partners collected data on air emissions and documented the fate of nutrients as poultry litter moved through the system. In addition, partners evaluated the market potential of the resulting ash, conducting laboratory

Emissions testing, shown here on Windview Farm in Pennsylvania, was conducted at three demonstration locations.

[3] The process is more complex for larger systems that import poultry litter from multiple farms.

analysis and field trials to determine the value of the fertilizer as compared to raw poultry litter and traditional commercial fertilizers. Air emissions data was collected by a third-party, certified testing company using EPA methodology. This data was used in conjunction with EPA-approved risk screening tools to determine whether emissions from on-farm manure-to-energy systems pose a threat to the health of farm families and surrounding communities.

Financial performance factors included the costs to install, operate, and maintain the system and the reduced costs of propane or electricity. The Environmental Finance Center also completed a review of financing options for on-farm manure-based systems in the Chesapeake region (http://efc.umd.edu/manuretoenergyinitiative.html#.Vngu32SDGko), as well as an evaluation of financing opportunities through program-related investments as a means of providing support for future technology deployment in the region.

4. Summary of Results

4.1. Technology Performance

Ecoremedy Gasifier

The Ecoremedy gasifier shown here was installed on Flintrock Farm in Pennsylvania to provide heat to four poultry houses.

- *Technical*: The Ecoremedy gasifier is a chain-grate, air-blown gasification system designed to deliver between 0.8 and 1.2 MBtu/hr of heat via hot water to four poultry houses. Installed on Flintrock Farm, the system uses poultry litter removed from the top surface of the bedding and is still in the early phases of commercial development. While the system is integrating well with the farm's existing propane heating system and controllers, Ecoremedy Energy is working to address several technical issues that have impacted system reliability. This system is capable of using "crust out" and wetter litter as fuels. However, the conversion from conventional to organic production during this project period resulted in high litter moisture and reduced heat output from the system. Flintrock Farm has implemented a number of strategies to improve fuel quality and has successfully reduced moisture and large rocks in the poultry litter used as a fuel for this system. Given that this technology is still in the early deployment phase, successful operation at Flintrock Farm is warranted prior to additional installations.

- *Environmental*: While this system meets NOx emissions thresholds for permitting in states with the strictest NOx permit requirements, additional particulate matter emissions controls will be needed for installation throughout the Chesapeake Bay region. A SCREEN3 analysis was used to predict maximum concentrations of pollutants from this system, and all pollutants evaluated were below established thresholds designed to protect public health. Nutrient balance suggests that most of the phosphorus is concentrated in the ash. Measured total reactive nitrogen in air emissions from the Ecoremedy gasifier are lower than best practices for land application of the same amount of poultry litter (e.g., lower than injection or immediate incorporation by shallow disking).

  This project has also demonstrated the potential for this technology to facilitate transport of manure phosphorus produced in excess of the farm's needs out of the Chesapeake Bay region. Enginuity Energy brokered a sale of the ash co-product to soybean growers in Missouri. The soybean grower was willing to pay market price for the phosphorus and potash content of the ash, based on previous experience using the product.

- *Financial*: The Ecoremedy system was the most expensive system to install. While it offers flexibility in terms of moisture content of poultry litter that other systems do not have, the higher moisture content of the poultry litter after the farm converted to organic production has resulted in reduced heat output and propane savings. A simple ROI analysis (looking at capital costs and propane savings) and current performance suggests that, based on energy savings alone, this system does not have a positive ROI over a 10- or 15-year period. Recent and planned improvements for the system may improve heat delivery and performance and thus financial feasibility.

  The sale of ash from this system at market prices to famers located outside of the Chesapeake Bay region demonstrates the potential for these technologies to increase the value of excess nutrients produced on farms in high-density animal production areas. Even considering transportation costs, the purchase price for the ash exceeded the locally available market price for untreated poultry litter.

Global Re-Fuel Poultry Litter Furnace (PLF-500) by Wayne Combustion Systems

- *Technical*: The Global Re-Fuel PLF-500 is combustion technology that delivers heat via hot air to poultry housing. It was installed on two farms in the region (the Mark Rohrer Farm in Strasburg, PA and the Mike Weaver Farm in Ft. Seybert, WV). One system was also installed on a farm in Port Republic, VA, with funding from the Eastern Shore of Virginia Resource Conservation & Development Council. Previously, the system had also been installed and operated on a poultry farm in Indiana.

The Global Re-Fuel system was installed on two farms, shown here on the Mike Weaver Farm in West Virginia.

  Despite the previous on-farm history, the Global Re-Fuel furnace did not perform well on farms in the Chesapeake Bay region. Both systems experienced multiple technical failures that compromised system reliability and required considerable time for repairs. Located in Indiana, Wayne Combustion Systems did not have local technicians and instead relied on the farmers to make almost all of the repairs.

  Currently, none of the Global Re-Fuel systems installed in the Chesapeake Bay are operational. In addition to technical problems that negate continuous operation, one farm converted to organic poultry production and now produces poultry litter with a moisture value too high for use as a fuel in the Global Re-Fuel Furnace. Both farmers participating in the Farm Manure-to-Energy Initiative have received funding to support decommissioning.

  However, when the system was working, it did successfully integrate with existing propane heating systems and house controllers. Despite the poor performance, the projects demonstrated the potential for a simple, direct air-to-air heating system to reduce propane use.

  Given the technical performance issues, this technology will need additional research and development before installation on farms. To support this effort, the project team developed step-by-step recommendations for improved performance on the existing units. Florida A&M University has secured funding to explore options for improving technical performance.

- *Environmental:* Wayne Combustion Systems was not able to meet air permitting requirements for the strictest Bay states because of high particulate matter. Opacity was also a concern. Improvements to the combustion chamber design are recommended as the first step in reducing emissions of particulate matter. Additional particulate matter emissions controls are also recommended. However, technical performance issues are the primary concern with this technology and should be addressed before additional investments in emissions controls.
- *Financial:* Even with performance that did not meet the design criteria, the Global Re-Fuel System realized propane savings and demonstrated that a low-cost, simple heat delivery system can have a positive ROI. A simple ROI analysis that considered only infrastructure and energy savings for the Mark Rohrer Farm demonstrated an ROI of 26% after 10 years and 34% after 15 years. An ROI for the Mike Weaver Farm, where propane use is lower than average because of energy conservation measures, yielded a lower ROI of 4% over 10 years and 5% over 15 years. This difference illustrates the importance of looking at all options for reducing energy use prior to investing in a farm-scale technology. Farm energy audits are designed to identify the most cost-effective strategies for reducing propane and electricity use and should be taken into consideration when evaluating the cost-effectiveness of on-farm manure-to-energy systems.

Blue Flame Boiler by Total Energy

- *Technical:* The Blue Flame boiler is designed to deliver 1.5 to 2.0 MBtu/hr of heat to poultry housing via hot water. This technology has the longest track record for using poultry litter as a fuel in the Chesapeake Bay region. The start of the 2015 cold weather season is the sixth year of use at Windview Farm in Port Trevorton, PA, and the fourth year in operation at the Earl Ray Zimmerman Farm in Ephrata, PA. After a fire in an electrical panel damaged the installation at Windview Farm, a new Blue Flame boiler was installed in the summer of 2015 with support from the Farm Manure-to-Energy Initiative. The new system improved the hot water distribution system and has to date been used successfully to heat one flock. Previous experience at both Windview Farm and the

The start of the 2015 cold weather season launched the sixth year of use for this Blue Flame Boiler at Windview Farm in Pennsylvania.

Earl Ray Zimmerman Farm suggests that, after an initial learning curve, the system performs as designed, integrated with existing propane heating systems and house temperature controllers, and results in significant propane savings.

An important consideration is that both farms using this technology remove all poultry litter from the houses between every flock. Most poultry growers in the region remove only the top crust from the poultry litter between flocks, as replacement bedding is expensive. Windview Farm grows antibiotic-free chickens and is required by their integrator to replace bedding between flocks, while the Earl Ray Zimmerman Farm adopted this approach to improve fuel quality and system performance.

- *Environmental*: Total Energy Solutions will need to reduce both NOx and particulate matter emissions from the Blue Flame boiler to meet all Bay state permitting requirements. Tuning of this system to improve NOx emissions is recommended as the first approach. Improved cyclones installed between the first and second round of emissions tests reduced particulate matter emissions by 31%, but emissions are still too high for installation in Maryland and Delaware. However, improvements to the cyclones reduced the maximum concentration of particulate matter as predicted by SCREEN3 to levels below thresholds established to protect public health.
- *Financial*: A simple ROI analysis focusing on capital costs and energy savings demonstrates a positive ROI for this technology on Windview Farm (38% ROI at 10 years and 49% ROI at 15 years). Although the ROI did not take this into consideration, both Windview Farm and the Earl Ray Zimmerman Farm receive a propane subsidy, which considerably improves the ROI for this system.

Bio-Burner 500 by LEI Products

The Bio-Burner 500 at Riverhill Farm in Virginia was modified to accept poultry litter as a fuel.

- *Technical*: The Bio-Burner 500 is a biomass combustion system that comes with a boiler. Use of hot water generated by the system is up to the end user (LEI does not design heat delivery systems). At Riverhill farm, funding from the Farm Manure-to-Energy Initiative was used in the summer of 2015 to modify an existing system previously fueled by woodchips to accept poultry litter. These modifications included the addition of a wet scrubber to control particulate matter emissions and poultry litter and ash handling. This unit is permitted with a biomass research permit, and the Farm Manure-to-Energy partners are currently working with the Virginia Department of Environmental Quality to finalize permitting so that this unit can be operated using poultry litter as a fuel on a regular basis. Currently, biomass research permits facilitate data collection only. Hence, long-term technical performance of this unit using poultry litter as a fuel is currently not available.

Previous experience at Riverhill Farm using this system with woodchips suggests that it operates reliably with less than 5% down time. At Riverhill Farm, hot water from the Bio-Burner 500 is used to heat a turkey poult house via a radiant floor heating system. The turkey brooder house, where poults spend the first five weeks, has a high heat demand compared to grow-out houses. The Bio-Burner 500 provides heat in conjunction with the house propane heating system.

- *Environmental*: The Bio-Burner 500 would need both NOx and particulate matter emissions reductions to meet all Bay state permitting requirements. The Farm Manure-to-Energy Initiative team recommends tuning this system to improve NOx as a first step. Improvements made between the first and second round of emissions testing reduced particulate matter emissions by 61%. However, SCREEN3 analysis used to predict the maximum concentration of pollutants suggests that, if all particulate matter is assumed to be fine particulate matter, the system exceeds National Ambient Air Quality Standards (NAAQS) for fine particulate matter. The short stack height and wide diameter, as configured during emissions testing, are likely contributing to this problem. Further SCREEN3 analysis with increased stack height resulted in maximum concentrations of fine particulate matter below NAAQS thresholds. Further analysis to determine the most cost-effective stack design for this system is warranted.
- *Financial*: Given the lack of performance data with poultry litter used as a fuel, an ROI analysis was not developed for this technology. However, the Bio-Burner 500 is one of the lowest cost units currently available on the market. If this technology successfully and reliably converts poultry litter to heat, it could provide a financially attractive option for smaller farms.

Biomass Heating Solutions Ltd (Bhsl) Fluidized Bed Combustion

- *Technical*: Bhsl manufactures a fluidized bed combustion system that delivers heat to poultry houses via hot water. This technology is not currently installed in the United States (the project planned for Rhodesdale, MD, is currently in development). However, several of the Farm Manure-to-Energy partners have visited Bhsl installations in the U.K. and observed that the technology works well as a source of heat for poultry housing. The Bhsl system is currently installed on three poultry farms in the U.K. with additional installations planned for 2016. The company has logged over 100,000 of operation for these units.

  The technology is available in varying sizes and, in addition to providing heating for poultry houses, also delivers electricity to the grid. Currently installations include two units that use 5 metric tons and one unit that uses 10 metric tons per day of poultry litter as a fuel.

One key difference between poultry litter management in the United States and Europe is that European poultry growers remove all poultry litter between flocks. As previously discussed, this is not a common practice in the United States. The Rhodesdale demonstration will be the first Bhsl system to use poultry litter typically of United States production systems.

- *Environmental*: Bhsl emissions for NOx and particulate matter are considerably lower than technologies demonstrated by the Farm Manure-to-Energy Initiative to date. To meet European air emissions standards, Bhsl has developed advanced emissions controls and focused on the system design to reduce NOx emissions. Third-party data collected by air emissions testing companies in Europe indicate that this technology is able to meet all Bay state permitting requirements.
- *Financial*: Bhsl offers one of the most expensive technologies for use with poultry litter, yet the company has a track record for performance and the lowest air emissions observed to date with poultry litter-fueled systems. The company is exploring strategies to reduce costs and is considering offering the technology via a managed system through which the farmer commits to purchasing energy from Bhsl, and Bhsl in turn owns, installs, and provides remote performance monitoring for the technology. While the farmer would need to provide fuel to the system, additional maintenance and repairs would be handled by Bhsl. Financial feasibility of this technology in the United States warrants further investigation and will be informed by the demonstration project planned for Rhodesdale, MD.

4.2. Environmental Performance

4.2.1. Fate of Poultry Litter Nutrients

An analysis of the fate of poultry litter nutrients was conducted for three of the technologies: the Bio-Burner 500, Ecoremedy gasifier, and Blue Flame boiler. Data suggests that the technologies reduce reactive nitrogen in poultry litter fuel by more than 90%. This nitrogen is likely converted to non-reactive nitrogen in the thermal conversion process.

All technologies reduced reactive nitrogen in air emissions compared to surface application of poultry litter, a standard land application practice in the region. Total reactive nitrogen from the technologies was also similar to or less than reactive nitrogen emissions associated with immediate incorporation via shallow disk.

The ash co-product, rich in phosphorus, collects in the system hopper.

Phosphorus was primarily concentrated in the ash, although a small amount was identified in air emissions. Efforts to reduce particulate matter emissions should also reduce atmospheric emissions of phosphorus. If this ash is transported out of the watershed or used to replace commercial phosphorus imported into the watershed, considerable reductions in phosphorus loading would be achieved.

4.2.2. Air Emissions and Permitting

The Farm Manure-to-Energy Initiative team consulted with federal and state air permitting regulators to design an emissions testing protocol to support permitting of demonstrations and future technology deployments. Criteria and comprehensive air emissions data was collected for three of the technologies: the Bio-Burner 500, Ecoremedy gasifier, and Blue Flame boiler. Criteria pollutants from third-party, certified air emissions testing companies were also provided by Bhsl and Wayne Combustion Systems.

Analysis of poultry litter fuel characteristics to support federal permitting suggests that poultry litter contaminants are within ranges for traditional solid fuels (coal and wood). This contaminant comparison is important for determining federal regulations associated with individual technology deployments.

Air emissions data suggests that all vendors, except for Bhsl, will need additional particulate matter emissions controls to qualify for installation in Maryland and Delaware. Additional NOx reductions are also needed for Maryland deployment for the Bio-Burner 500 and Blue Flame boiler. The Farm Manure-to-Energy Initiative team suggests that tuning these systems is the first step in reducing NOx emissions.

With support from the USDA Air Quality and Atmospheric Change Team, the Farm Manure-to-Energy Initiative reached out to Dr. Michael Buser (Oklahoma State University), an expert in emissions controls for agricultural systems. Dr. Buser designed cyclone emissions controls for two of the demonstration projects that resulted in reduced air emissions.

Environmental scanning electron microscopy (ESEM) of particulate matter in air emissions with energy-dispersive spectroscopy to assist in both the initial chemical analysis and preliminary particle size information demonstrated that a potassium species dominated particulate matter (potassium concentration of larger and smaller particles ranged from 36 to 50%).

Potassium volatilizes in thermal manure-to-energy species and can form compounds with chlorine and sulfur. Potassium-based particulate matter is often measured at below 2.5 um and is thus categorized as fine particulate matter.

A SCREEN3 analysis for three of the technologies (Bio-Burner 500, Ecoremedy gasifier, and Blue Flame boiler) was used to determine whether air emissions posed a potential threat to public health. The SCREEN3 model predicts that maximum concentration of pollutants produced by the system, which were then compared to established thresholds for criteria pollutants and air toxics. The analysis assumed that total particulate matter was classified as both PM10 and PM2.5.

Results form the SCREEN3 analysis found that emissions from the Ecoremedy gasifier and the Blue Flame boiler (after additional particulate matter emissions controls were installed) resulted in maximum concentrations of pollutants below public health thresholds. However, assuming all particulate matter is fine particulate matter, the Bio-Burner 500 predicted maximum concentration of PM2.5 exceeds the federal air quality standard. Further analysis suggested that the low height and wide diameter of the Bio-Burner 500 is likely contributing to this problem. For example, increasing the stack height by 12 feet reduced maximum concentrations of PM2.5 to levels below federal thresholds. As such, it is likely that stack modifications should be explored for this system. Additional particulate matter emissions controls to support expanded adoption throughout the region will also result in reduced maximum concentrations for these technologies.

The project team plans to continue working with vendors to improve particulate matter emissions controls, facilitating installation on farms throughout the Chesapeake Bay region.

4.2.3. Financial Performance

The financial performance analysis for the Ecoremedy gasifier and Global Re-Fuel systems was limited to data collected over one cold-weather season. However, Windview Farm provided data for energy use and savings associated with the Blue Flame boiler for 5 years of operation.

It is important to note that even when technical issues resulted in failure of the thermal technologies in delivering heat or electricity throughout an entire flock cycle, there were periods of successful energy production that reduced the use of propane for heating the poultry houses. While the data did not quantify the generated heat in a way that statistically correlates the technology with reduced propane use, farmers repeatedly observed and reported the trend toward reduced propane use while the systems were running. This saved energy and money for the growers and reduced their carbon footprint.

A sensitivity analysis to quantify and rank different farm characteristics or their ability to influence energy outcomes was also conducted. The analysis focused on the Mark Rohrer Farm, which provided the most detailed data and a side-by-side comparison of two poultry houses with and without manure-to-energy. Findings from the sensitivity analysis include:

- **A 25% increase in R-value results in an 18.5% decrease in the amount of propane saved by the manure-to-energy facility**. Farmers starting with a better insulated poultry house, with all other factors being constant, will save less propane by switching to manure-to-energy. As a rule of thumb in nearly all sectors of the economy, energy efficiency is more cost effective than switching to renewable sources of energy.
- **A 25% increase in boiler efficiency results in a 16.5% decrease in the amount of propane saved by the manure-to-energy system**. Farms with older, inefficient heating systems (e.g., boilers and furnaces) appear to have more to gain from installing a manure-to-energy heating system than a farm with a newer, high-efficiency heating system. For farms that can rely entirely on manure-to-energy

systems for their heating needs, the efficiency of the existing system becomes less important because of the complete fuel switch.

- **The switch from organic to conventional birds results in a 77% decrease in the amount of propane saved from the manure-to-energy system**. All else being equal, organic poultry operations consume more propane than conventional poultry operations because of the premium cost on organic feed and the fact that food and heat are close substitutes. A related finding is that colder climates require more heating. It would stand to reason that poultry operations in these environments have more to gain in energy savings from manure-to-energy heating systems than peer farms in warmer climates.

Given the limited availability of data, the demonstration projects illustrated a range of results for the potentials ROI. The ROI is the ratio of energy savings to capital investment; it helps describe the extent to which the energy savings can offset the equipment costs over the operating life span of the technology. The assessment was based on an "intermittent scenario" of propane and electricity usage, with the manure-to-energy technology delivering heat only 40% of the time on any given day. Obviously, in scenarios where the technology is delivering heat for longer durations, the ROI will be better.

Given a technology operation of 40% of the time, the ROI analysis yielded a range of results from 0 to 38% over 10 years, and 0 to 49% over 15 years. Windview Farm and the Mark Rohrer Farm offer positive return on the dollar invested. With the newly installed Blue Flame boiler on Windview Farm, it is reasonable to assume that the ROI will be even more favorable in the upcoming cold months, based on the increased size (an improved match to litter generated) and improved heat delivery system.

Due to lack of data or lack of transferability to other farms, the ROI analysis did not consider several financial components that would impact system performance. For example, propane allowances that some integrators (particularly organic) provide for farms will significantly improve the ROI. Windview Farm and the Earl Ray Zimmerman Farm both receive allowances for propane from their integrator, but conventional producers typically pay a larger portion (in many cases, most of) the propane costs out of pocket. When propane costs are shared between the integrator and the farmer, the willingness of the integrator to reimburse the grower for propane savings is an important component of financial feasibility.

Additionally, the ROI analysis did not address the potential change in revenue associated with poultry litter or ash sales. Markets for ash are not well established. While some vendors have had success in brokering purchases of ash at prices reflective of the market value of the nutrient, other farmers are still giving the ash way, thus incurring revenue loss from reduced poultry litter sales.

The project team recommends that, in the future, ROI analyses focus on flock health, whole-farm operations, and the social and environmental benefits gained from implementing manure-to-energy technology. For this reason, it is important not to focus on the value of co-products (ash and biochar) alone, and instead look at what the manure-to-energy technology does for farm operations and the greater community (which affects the role of public cost-share dollars).

The project team also noted that the unique circumstances of each of these farms raise questions about the ease and potential for using their varied experiences to construct meaningful cost ranges (capital and operational) that indicate financial impacts of the technology on a farm's bottom line. At the same time, these experiences illustrate the willingness of farmers to test new technologies with the potential to generate positive environmental and economic impacts.

5. Fertility Value and Market Potential of Poultry Litter Co-Products

The environmental potential of thermal manure-to-energy technologies hinges on the ability to use the ash and biochar as a fertilizer on fields in nutrient-deficient regions. Because these products are not currently produced in the Chesapeake region, end-user markets are not established. To facilitate market demand for excess phosphorus, the Virginia Tech Eastern Shore Agricultural Research and Extension Center set up field trials to evaluate the performance of ash and biochar as a replacement for commercial phosphorus for row crops (corn, soybeans, and wheat) and for fresh market fruits and vegetables (where raw manure is not used as fertilizer for health reasons). In addition, several vendors established end-user markets for ash outside of the Chesapeake Bay region. Partners are also exploring additional market opportunities for incorporation of ash into specialty fertilizers.

The ash co-product shows promise as a crop fertilizer and can be cost-effectively transported to fields in nutrient-deficient regions.

The research revealed that several factors impact the overall nutrient concentrations of poultry litter co-products and the degree to which the nutrients they contain (nitrogen, phosphorus, and potassium) are available for plant uptake. The thermal combustion system is one variable, which includes the temperature of combustion, fuel-to-oxygen ratio, residence time of the poultry litter feedstock, and whether or not the system has an exhaust scrubbing system to catch fly ash. Another major factor is the poultry litter: the initial concentration of nutrients, bedding material, and moisture content of the poultry litter impact the co-product.

Nutrient densification varied between systems: phosphorus was concentrated between 4-12 times its original density, potassium was concentrated between 3-13 times its original density, and sulfur was concentrated between 2-5 times its original density. Our comparisons between total nutrient digestions and water-soluble extractions found that the ash and biochar co-products were significantly less plant available than standard inorganic fertilizers. The biochar co-products had the least plant-available nutrients of the fertilizers in the study. Therefore, a greater amount of the co-products will have to be applied to achieve the same standards as traditional inorganic fertilizers or fresh poultry litter.

Still, results indicate that poultry litter co-products are feasible fertilizers. However, given the variability in nutrient content and availability, ash and biochar co-products should be individually analyzed for nutrient content before making application recommendations.

6. Summary of Lessons Learned

6.1. Technology

1) On-farm systems are not a good match for every farm. They require considerably more management than propane heating systems and, depending on the farm, they may not be cost effective. On-farm thermal systems require far more time to operate and maintain than traditional propane heating systems. Most require the addition of poultry litter to the feed hopper at least once per day. Growers can expect to spend considerable time getting a technology that is in the early phases of commercial deployment up and running properly. These technologies are only appropriate for use on farms where growers have the time and interest in maintaining them.
2) The success of a particular technology on one farm does not mean that it will succeed on another farm.
    - The characteristics of poultry litter vary significantly between farms. Moisture content, foreign material (i.e., rocks), energy value (i.e., Btu/lb), and particle size can each impact system performance. System design and adjustments should be specific to the farm.
3) Success requires collaboration between the vendor and the farmer.
4) Farmers should seek technology vendors with knowledge and real-world experience that matches their specific situation as closely as possible; this could be a challenge because few technology vendors have experience using poultry litter as a fuel.
    - Vendors should be willing to invest resources to resolve unexpected technical issues.

- When heat delivery for animal housing (e.g., poultry houses) is proposed, vendors should have experience or work with experienced partners to support the design process. Buildings for animal housing are not comparable to other industrial buildings when it comes to the design of heating and cooling systems.
- Industry-specific knowledge is key to ensuring that a poultry litter-to-energy technology delivers heat successfully to the poultry houses.

5) The complexity of the project will be reduced if one vendor oversees both the energy-generating technology (the thermal system) and the energy delivery system (heat or electricity to the grid).
6) To support regulatory compliance, vendors should be prepared to supply data on air emissions.
7) Some thermal manure-to-energy systems need to be sheltered from weather. NRCS standards for building construction may need to be met if the project uses federal cost-share dollars.
8) Rocks and other foreign objects (such as tools) are ubiquitous in poultry litter. Technologies that use poultry litter as a fuel need to be able to handle foreign objects without damaging the equipment, shutting down the system, or demanding unacceptable levels of operator time and attention.
9) In states with strict particulate matter emissions thresholds, advanced air emissions controls may be needed to trap and remove fine particulate matter when poultry litter is used as a fuel.
10) Growers expressed interest in both heat and electricity generation via net metering. However, poultry litter-to-energy technologies with a track record of delivering electricity to the grid are limited. Also, proximity to three-phase power as well as state net metering regulations may impact the feasibility of grid connection.

6.2. Environment

1) State rules vary significantly with respect to on-farm thermal poultry litter-to-energy technologies. In some Bay states, several of the technologies demonstrated through this project currently do not meet permitting thresholds for particulate matter and/or nitrous oxide. One technology supported through this process meets permitting requirements for all the Bay states.
2) Most states in the Bay region require data on air emissions to support the permitting process.
3) Design of advanced air emissions controls for use with on-farm systems in states with strict particulate matter emissions thresholds can be challenging. Off-the-shelf technologies may not be suitable without additional engineering and design modifications.

4) Good design is key to reducing air emissions. Examples of design issues that negatively impact air emissions include incomplete combustion and lack of temperature or combustion air flow through the system.

5) All vendors participating in this project except for Bhsl will need to reduce particulate matter emissions to facilitate adoption throughout the region. NOx emissions associated with two of the technologies also exceed Maryland permitting thresholds. Only Bhsl currently qualifies for installation on farms throughout the Chesapeake Bay region.

6) EPA's SCREEN3 was used to predict maximum concentrations of pollutants associated with the Bio-Burner 500, Ecoremedy gasifier, and Blue Flame boiler. Criteria and hazardous air pollutants fell below federal or state established pollutant thresholds for all pollutants except fine particulate matter associated with the Bio-Burner 500. Assuming all total particulate matter is fine particulate matter (<2.5 µm in diameter, or PM2.5), SCREEN3 predicted maximum concentrations for PM2.5 emissions would exceed federal National Ambient Air Quality Standards. Changes to the stack are recommended to partially address this problem. Additional emissions controls for particulate matter are recommended for all technologies except Bhsl.

6.3. Financial

1) Initial capital expenditures for installation can be high:
   - Systems for heating poultry houses currently range from $87,000 to over $300,000 per house to install.
   - As these technologies mature, prices will likely come down over time.
   - One vendor is proposing a "pay for service" arrangement, but most vendors sell the technology directly to the farmer.

2) Technologies vary significantly in terms of cost but face-value comparison is not always the best approach to determining value. A comparison that normalizes the cost may be a better way to evaluate technologies with different heat delivery mechanisms and efficiencies. For example, a unit such as dollars-per-BTU-delivered is worth considering in addition to the total cost of the system. On-going operation and maintenance costs should also be considered.

3) To reduce the size of the system (and therefore its cost), the farmer should first enact an energy conservation and energy efficiency plan for the farm.

4) Lack of a technology track record for on-farm performance increases risk for cost-share programs or farmer-financed systems. For example, EQIP funding for on-farm systems requires a 10-year contract. To date, no thermal poultry litter-to-energy systems have been deployed on any farm for 10 years.

5) Consistent determinations across states are important, if and when equipment can be housed in existing NRCS cost-shared poultry storage facilities.

6) Farm-scale thermal systems can benefit bird health and production. These potential benefits from warrant further investigation.

   - These systems deliver a drier heat to poultry houses than conventional propane heaters, as the by-products of combustion are exhausted outside of the poultry house. Drier heat can reduce both air and poultry litter moisture levels, which can in turn reduce emissions of ammonia.
   - Farmers with poultry litter-fueled heating systems can ventilate in the winter to support air quality via increased fresh air exchanges due to relatively lower unit energy costs of manure-to-energy systems.
   - Better air quality could result in improved flock performance, including key indicators such as weight gain, feed conversion, and mortality, but more work is needed in these areas to characterize any bird health improvements.

7) Organic poultry farms may offer the best opportunity for deploying farm-scale thermal systems. Organic poultry growers ventilate more frequently in the winter. In the Chesapeake region, organic production requires 3 to 5 times more propane than conventionally produced poultry. If there are improvements in bird health and feed conversion, these will be particularly important for organic integrators because organic feed is far more expensive than conventional.

8) For some technologies, based on a simple ROI analysis that considered only infrastructure costs and energy savings, energy production alone will likely not be sufficient to justify their widespread adoption from a financial standpoint. It is more likely that a combination of factors, including reduced energy costs, reduced need for nutrient pollution controls, improved production, and the added income, once markets are established, from a highly concentrated lightweight ash co-product, will be what moves these technologies toward commercialization.

6.4. Marketing Co-Products

1) Poultry litter ash and biochar are valuable plant nutrients. Depending on the process, poultry litter ash contains in the range of 14 to 18 % phosphorus fertilizer and 13 to 24% potash fertilizer. Plant availability of the nutrients also varies by process but is in the range of 80 to 100%.

2) On sandy loam soils in Virginia, row crops fertilized with ash and biochar from poultry litter produced yields similar to untreated poultry litter and commercial fertilizers.

3) Ash and biochar from thermal manure-to-energy technologies contain phosphorus that is 80 to nearly 100% soluble compared to triple super phosphate. In other words, thermal treatment converts much of the organic phosphorus — which is not immediately available for plant up-take — to phosphorus that is immediately plant available.

4) Connecting ash producers with end users will be critical for achieving the project goals of generating new sources of revenue for excess manure nutrients.

- One vendor has had success in establishing markets with Midwest soybean growers who are willing to pay market price for the phosphorus and potash components of the poultry litter ash. However, other participating farm hosts do not have established markets for ash they are currently producing.

7. Communicating Results

With support from the Livestock Poultry Environmental Learning Center, project partners developed a website to serve as a clearinghouse for information and third-party evaluations of farm-scale thermal manure-to-energy technologies. Located on the eXtension website at www.extension.org/68455, the website was designed to serve as a central repository for future Extension or Land Grant University-affiliated evaluation efforts.

In addition to the website, steering committee members have given more than 120 presentations to stakeholders (farmers, policy makers, conservation professionals, state and federal agency representatives, and environmental nonprofit organizations) throughout the Chesapeake region. The project team also supported presentations given at national Livestock, Poultry and Environmental Learning Center meetings as well as hosting a webinar available to conservation professionals around the country.

Although field day events at project demonstration sites were initially planned, concerns about avian influenza outbreaks during the fall of 2015 curtailed these important communication opportunities. As an alternative, project partners worked with The Downstream Project to create a video highlighting the farm demonstrations and results from the project. The video will be available at www.extension.org/68455 in January 2016.

8. Summary & Next Steps

In summary, the Farm Manure-to-Energy Initiative has identified both opportunities and challenges associated with these emerging technologies:

- Several of these technologies have been in operation on multiple farms for more than three years. However, others are still in the early demonstration phase. One technology that initially seemed promising proved not ready for further deployment.
- All require a greater investment of time and capital to manage and install than traditional propane heating systems.
- The technologies demonstrated reductions in reactive nitrogen and the potential to cost-effectively transport excess phosphorus to nutrient-deficient farms outside of high-density animal production areas. Most of the technologies reduced reactive nitrogen emissions to air resources compared to standard land application practices.

- All but one technology will need additional work on air emissions (particulate matter especially) before they can be installed in the Bay states with the strictest air permitting standards. The high potash content of poultry litter facilitates production of fine particulate matter. Only Bhsl met all criteria for installation throughout the Chesapeake Bay region.

Next steps are as follows:

- Continue to support technology vendor efforts to improve emissions controls for deployment in all the Bay states. The project team is working with air emissions experts to recommend next steps for emissions control design and installation.
- Build on fertility trials to develop markets for poultry litter ash that connect growers with ash or biochar to end users willing to pay a fair price for the nutrients.
- Continue to communicate results: partners will work with farm partners to host field day events when avian influenza risk is lower.
- Research on the impact of thermal farm manure-to-energy systems on in-house air quality and poultry health, feed conversion, and weight gain is also recommended.

Appendix A

Technical Performance: Global Re-Fuel Poultry Litter Furnace

A summary of preliminary technical performance findings funded by the
Farm Manure-to-Energy Initiative

December 2015

Contents

1. The Technology

The Global Re-Fuel poultry litter furnace (PLF-500), manufactured by Wayne Combustion Systems in Fort Wayne, Indiana, is designed to burn poultry litter on-site as a heat source for poultry housing (Figure 1). According to Wayne Combustion, the Global Re-Fuel system has a maximum feed rate of 180 pounds of poultry litter per hour, and the system is rated to generate 500,000 Btu/hour of heat.

The design of the Global Re-Fuel unit is unique. It is a two-stage, air-to-air combustion system that can be described as "a box within a box":

1. The combustion chamber is the inner chamber. It is a rectangular box comprised of mild steel that sits inside the outer chamber.
2. The outer chamber is the heat exchanger. A large HVAC fan (8,000-9,000 CFM) blows air around the outside of the combustion chamber where the heat from combustion transfers its energy to the air. The air is directed around the combustion chamber via baffles and ultimately exits through ductwork to the poultry house. The return air comes from the poultry house, creating a system that does not pressurize nor pull a vacuum on the poultry house.

The material handling system is comprised of a large bulk hopper that uses a drag chain to move the litter into a horizontal transfer auger. The bulk hopper has a series of "beaters" that are used to de-lump the litter before it exits the hopper and enters the transfer auger. The transfer auger takes the litter from the bulk hopper onto an inclined belt conveyor that is mostly enclosed. The belt conveyor moves the litter to a cone-shaped surge hopper located on top of the combustion unit. Another de-lumper is located between the belt conveyor and the surge hopper. The surge hopper has a material sensing switch that controls all prior material handling components in an on/off fashion. When the surge hopper is empty, the material handling components are energized and stay energized, enabling the flow of material until the surge hopper is full, thereby stopping material flow.

The surge hopper has a rotating assembly inside to keep the litter from bridging. An auger is mounted vertically in the surge hopper and is used to meter litter from the surge hopper onto the top distribution plate inside the combustion chamber. The surge hopper acts as an airlock as long as litter is inside. The top distribution plate has a sweep arm that rotates on top of the distribution plate. The top plate has holes in it so that the litter will only pass through the plate once the litter is small enough to go through the holes. This allows time for the litter to be dried and for some pyrolysis to take place before the litter falls on the combustion grate.

Another sweep arm is used to keep the litter moving on the bottom combustion grate. The concept is for the litter to combust quickly as it falls from the top plate to the bottom plate with little residence time on the bottom plate. The bottom plate acts as an air distribution grate and ash removal system. The bottom combustion grates consist of two plates that have identical slots. The bottom of the two plates remains stationary while an air cylinder is used to "shake" or rotate the top bottom grate a few degrees in a clockwiseto-counterclockwise motion to shake the ash through the holes in the grates and allow the ash to fall through the grates into an “ash pan” below. The ash pan also has a shake mechanism to keep the ash moving. The ash pan has two 3-inch flexible augers that are perpendicular to each other. They are used to remove the ash from the system. The combustion air is delivered via a blower through the bottom combustion grate slots. The combustion air blows vertically upwards through the grate, where it comes into contact with the litter and encounters volatile off-gassing from the litter, which is subsequently oxidized via combustion. On one side of the combustion chamber is a vertical steel wall that separates the combustion zone from the flue stack, located at the top on one side of the chamber.

The control system uses a programmable logic controller (PLC) to control the entire system. Turning the system on simply requires the operator to press the “GO” button. The system has safety features designed to prevent overheating and to detect problems in the system. If problems are detected, the system is designed to shut down to prevent damage.

By design, the only other things the farmer needs to do are load the large hopper and empty the ash barrel. In these case studies, it typically took 30-45 minutes to heat up with propane before the system started using litter as the fuel. It took another 30-60 minutes to reach full temperature.

This system operates in tandem with the poultry house’s existing propane heating system. The house controllers are then used to manage the propane-fueled unit heaters to provide supplemental heat for the houses. The two systems operate independently of each other; the Global Re-Fuel system operates continuously because the unit is not able to modulate to meet a varying thermal load. The propane burners can be set to turn on at any set temperature. This arrangement allows the systems to operate together but on separate controls. If the Global Re-Fuel system is not working, then the propane burners will heat the houses. When the Global Re-Fuel unit returns to operation, it will generate heat; the propane burners will only turn on when more heat is needed than what the Global Re-Fuel unit can provide.

The Global Re-Fuel furnace has an adjustable fuel feed rate. If the houses need less heat, then the Global Re-Fuel unit can be set to a lower feed rate with a press of a button. Currently, there is no mechanism to automatically reduce the temperature of hot air delivered to houses.

While the system is automated, the farmer needs to adjust the system from time to time. As previously mentioned, the system provides heat to the houses regardless of house temperature. If the houses do not need heat or if they need minimal heat, the system either has to be either turned off or the feed rate reduced. Other things that were not automated and needed periodic adjustment include:

- The combustion air, which is manually adjusted.
- The ash system is timed using the feed rate to set the time interval and could not be changed without PLC programming changes.

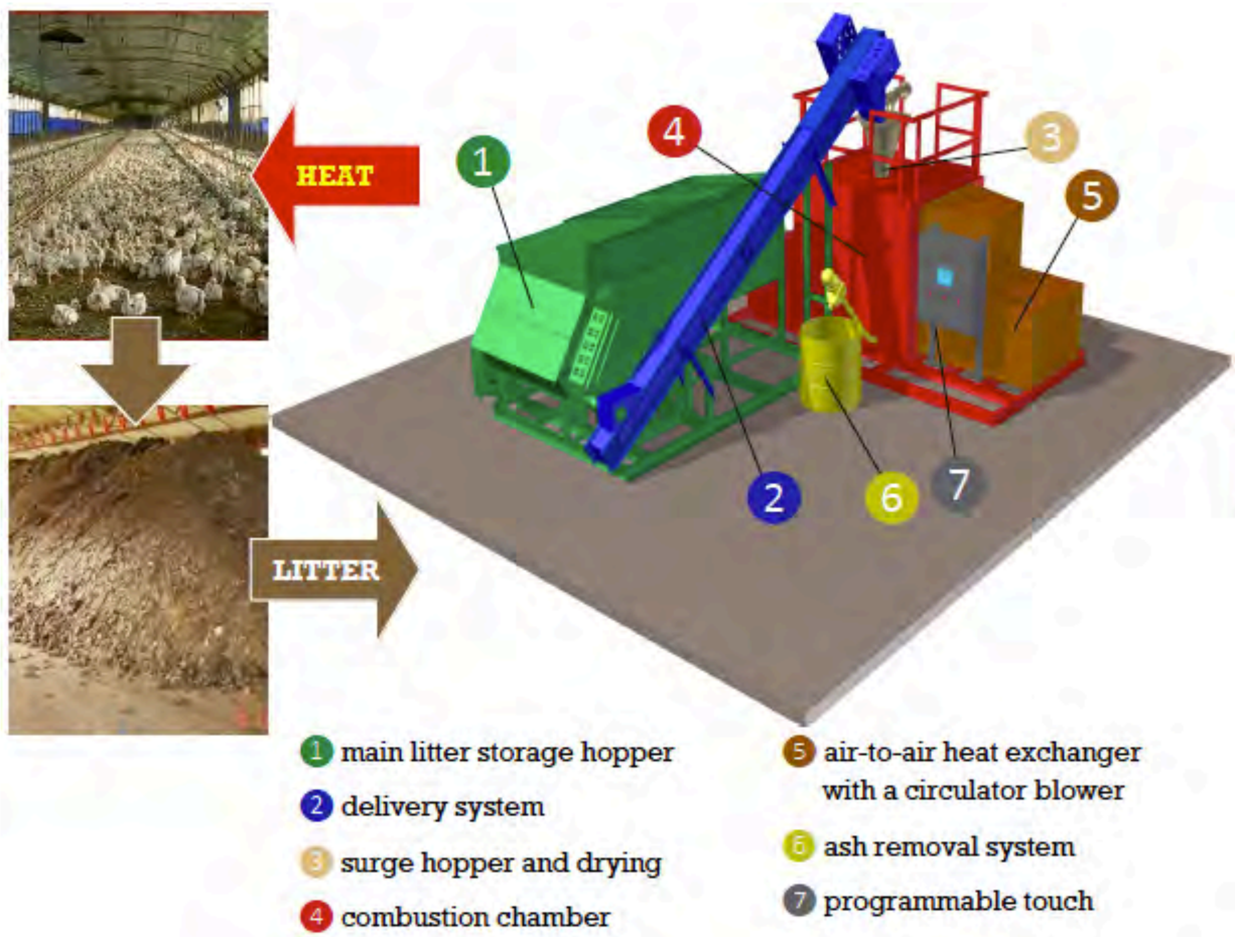


Figure 1. Configuration of the Global Re-Fuel poultry litter furnace, manufactured by Wayne Combustion.

Because hot air cannot be delivered long distances without sacrificing temperature, the Global Re-Fuel system must be located in close proximity to the load. It can be installed between two poultry houses (Figure 2) or alongside one house with duct work installed underground to heat two houses, maintaining vehicle access between the houses if necessary (Figure 3).

Figure 2. The Global Re-Fuel system at the Rohrer farm is located between two poultry houses to reduce length of ductwork.

Figure 3. The Global Re-Fuel system at the Weaver farm is placed on a concrete pad between two poultry houses. The farmer needed to maintain the road between the houses, so the system was installed adjacent to one house and the ductwork to the other house was buried under the road.

2. The Farms

Funding from the Farm Manure-to-Energy Initiative was used to install the Global Re-Fuel furnace on two farms in the Chesapeake Bay region: the Mike Weaver farm (Fort Seybert, West Virginia) and the Mark Rohrer farm (Strasburg, Pennsylvania). The Eastern Shore of Virginia Resource Conservation District also sponsored an installation on a turkey farm in Port Republic, Virginia. Prior to installation in the Chesapeake Bay area, the system had been previously demonstrated on a poultry farm in Indiana.

2.1 Mike Weaver Farm: Fort Seybert, West Virginia

Located in Fort Seybert, West Virginia, the Mike Weaver farm produces 585,000 broiler chickens per year for Pilgrim's Pride. Birds are grown to 4 pounds over a 36-day period in two poultry houses that measure 624 feet by 50 feet (31,200 ft^2 total area per house). In addition to poultry, the farm also produces 28 beef cattle on 60 acres of pasture. Twenty-five acres on the farm are planted in hay to produce winter forage for the cattle.

The broilers produce approximately 400 tons of poultry litter per year, which is stored under cover. Litter is "caked out" between every flock. Mr. Weaver does not use any of litter on the farm as a fertilizer. All of the farm's poultry litter is sold to farmers outside of the Chesapeake Bay watershed. Energy value and moisture content of the poultry litter produced on the farm is 4972 Btu/lb and 21%, respectively (see Appendix E for details on methods used for collection and analysis).

An energy audit was previously conducted for this farm. Based on the audit recommendations, Mr. Weaver replaced interior lighting with LED bulbs. Other energy-saving strategies in the poultry houses include attic inlets that provide solar heat to the house and high-efficiency motors for the house fans. Currently, the farm uses approximately 1,900 gallons of propane per year. At $1.30 per gallon, the total cost for propane is $2,500 per house (or $5,000 per year). Mr. Weaver pays for propane out of pocket.

The Global Re-Fuel system was intended to provide heat for both poultry houses. To maintain vehicle access between the houses, the system was installed alongside one of the poultry houses with ductwork installed under the road to deliver heat to the second house (Figure 3).

2.2 The Mark Rohrer Farm: Strasburg, Pennsylvania

Located in Strasburg, Pennsylvania, the Mark Rohrer farm began this project as a producer of conventional broiler chickens. The farm produced 296,000 broilers per year for Tysons, growing birds to 6 pounds in a 48-day period in two poultry houses measuring 48 feet by 500 feet. During the project timeframe, the Mark Rohrer farm converted to organic broiler production for Coleman Natural. Once the organic conversion took place, moisture content of the poultry litter increased beyond the specifications for the Global Re-Fuel unit. Because of higher moisture value of the poultry litter and other issues (described below) the unit has not been used since the farm converted to organic production.

The farm produces 320 tons of poultry litter per year, which is stored in a covered facility. All of the litter produced by the farm is exported for local use. Energy content of the poultry litter produced under conventional operation was 5,178 Btu/lb and 20 percent moisture (see Appendix E). After conversion to organic production, poultry litter moisture increased to 46 percent under the water lines and 38 percent elsewhere in the house.

In 2011, Mr. Rohrer installed solar panels on the poultry houses and annually generates approximately 80,000 kWhs of electricity and, via net metering, delivers 10,000 kWhs to the grid.

The Global Re-Fuel system is installed directly between the two houses (Figure 2). As vehicles can access the center lane from either side of the houses, installation in the center of two houses did not interfere with vehicle access.

3. Objectives and Methods

3.1 Overall Technical Performance Design Objectives

The objective of the performance evaluation was to determine the degree to which the Global Re-Fuel unit achieved the following design objectives:

- Use poultry litter as a fuel to reliably deliver heat to poultry houses
- Integrate seamlessly with the farm's existing propane-fired unit heaters and ventilation systems to maintain house temperature and relative humidity within industry-recommended (and grower established) targets
- Reduce propane use on the farm
- Run successfully with minimal operation and maintenance requirements (routine maintenance and daily addition of poultry litter fuel)
- Operate without negatively impacting bird production and ideally improve bird health and production by allowing for increased winter ventilation and improved air quality

3.2 Technical Performance Evaluation Methods

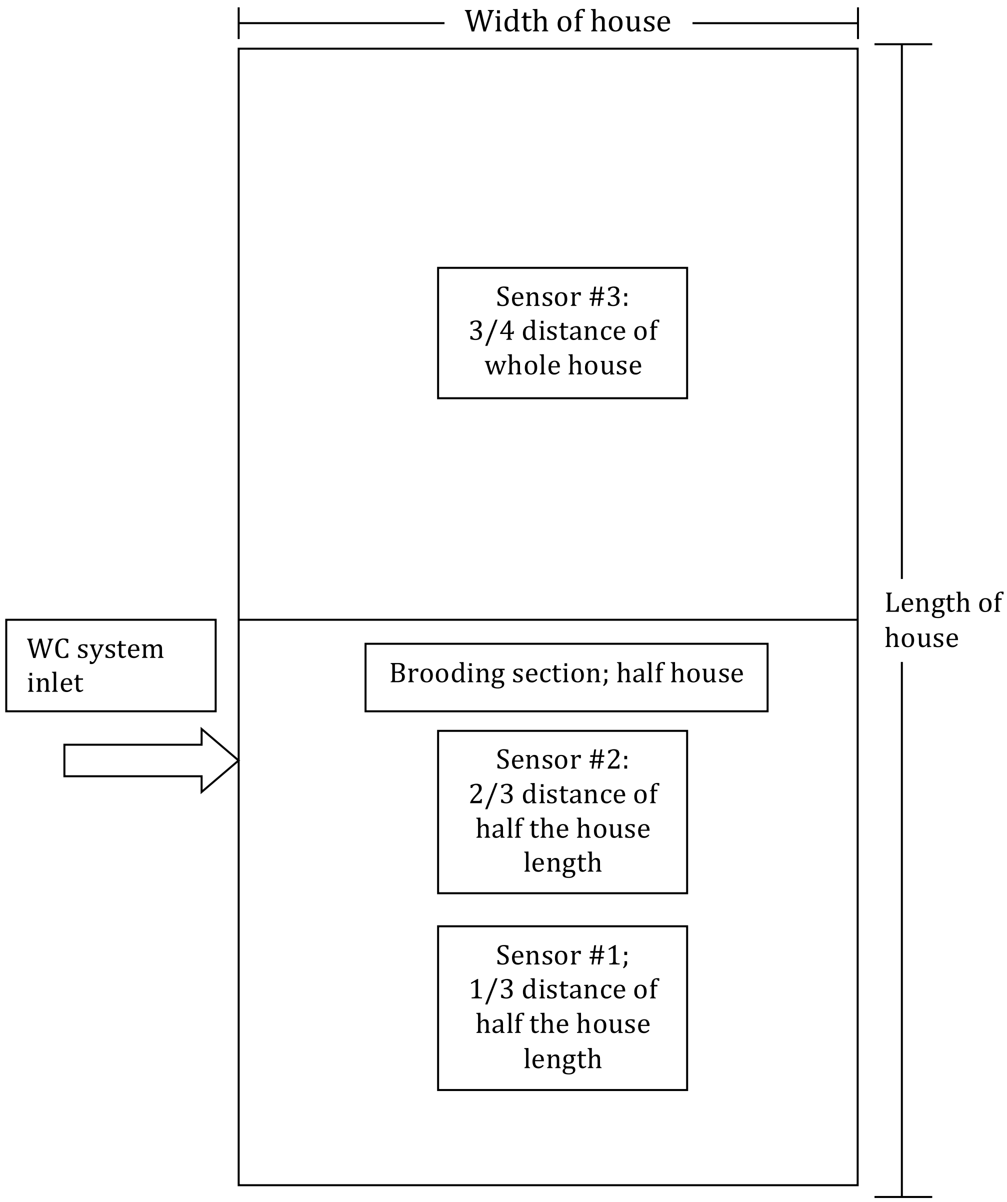
Temperature and humidity

To monitor in-house conditions, in January and September 2014, the project team installed three, 12-bit temperature/relative humidity sensors (HOBO, S-THB-MOO2) in each poultry house at the Rohrer and Weaver farms with an additional sensor installed outside of the house to monitor outdoor temperature and relative humidity. Figure 5 depicts the location of each of the sensors within the poultry houses. At the Mark Rohrer farm, temperature and humidity sensors were also installed in two similar poultry houses owned by Todd Rohrer that were located immediately adjacent to Mark Rohrer's two poultry houses. Data from the sensors was collected and stored using a HOBO data logger (U30-GSM-000-10-S100-001).

HOBO (S-THB-M002) temperature/relative humidity sensors were also installed in the inlet and outlet ducts to monitor system run time. On the Mike Weaver farm, these duct temperature sensors were installed in September 2014, while at the Mark Rohrer farm they were installed in November 2014. Whenever the inlet temperature (heat supply) was above 100 °F and there was a temperature difference of 10°F or greater between the inlet and return ductwork (with the supply ductwork having the higher temperature), the system was deemed to be "on."

In July of 2014, a smoke test was at the Mike Weaver farm to observe heat distribution in the house using the house's existing ventilation system. The propane heating system was turned off for this test.

Figure 5. Temperature and humidity sensor locations at the Mark Rohrer farm, the Todd Rohrer farm, and the Mike Weaver farm. The dimensions reflect Mark and Todd Rohrer's poultry houses, but the configuration also applies to the Mike Weaver Farm.



Energy use and/or savings (propane and electricity)

The project team measured electricity load requirements for the Global Re-Fuel unit as well as propane use. On the Mark Rohrer farm and the Todd Rohrer farm, a propane meter (American Meter AL-425TCH-CF) was installed in September 2014 to measure propane consumption of both the Global Re-Fuel unit (which uses propane as a starter fuel) and propane used for poultry houses. One meter was installed for Mark Rohrer's house #3 and one meter for Todd Rohrer's house #2. Utility meters were used to monitor whole-farm electricity consumption, while a GE I-210 electricity meter was used to monitor Global Re-Fuel system electricity consumption at the Mark Rohrer farm. Electricity consumption of the Global Re-Fuel unit at the Mike Weaver farm was measured via a submeter; however, the electric meter at the Weaver farm never operated correctly.

Farmer-supplied performance data

Both Mike Weaver and Mark Rohrer used weekly log sheets to track operation and maintenance requirements, system run time and performance concerns, flock age, and their observations of in-house conditions. Metrics documented on the log included:

- Flock status (number of days from placement)
- Portion of the house occupied by the flock (partial/whole)
- Hours the system was operational (hours/week)
- Hours of farm labor needed to run the system over the week (operation and maintenance)
- Reasons the system was not run (e.g., heat not needed, maintenance problems)
- Description of any problems that occurred
- Length of system down-time due to problems
- House conditions (heat distribution, dust level, ammonia odor)
- Propane meter readings

Data on flock performance was assessed via information supplied by the integrator in the farm's "settlement sheet." Settlement sheets include data on average bird weight, feed consumption, feed conversion, and bird health relative to other producers with similar flock placement timing.

Mark Rohrer also supplied information on previous farm energy use (propane and electricity), flock performance (via settlement sheets), and poultry litter production and use (on and off the farm).

4. Performance Results

4.1 Reliability

Both Global Re-Fuel units experienced numerous mechanical problems that required significant investment in time for both farmers and Wayne Combustion. These mechanical problems interfered with the operation of the units and reduced reliability and heat delivery. As of the conclusion of the monitoring period, many of these technical problems were not yet resolved. Because of these issues (and increased moisture of the poultry litter at the Mark Rohrer farm after conversion to organic production), neither of these units are currently operational. A summary of technical issues is included in Table 1.

Table 1. Summary of mechanical problems for both Global Re-Fuel units, time required to resolve, and recommended next steps

Mechanical Issue	Farmer Time to Resolve (hrs)	Recommended Next Steps
Mike Weaver Farm		
Hopper sensor problems (multiple times)	1.5 hours	Replace sensor or replace litter handling equipment.
Ash auger jam (multiple times)	18 hours total	Replace flexible ash auger with solid shaft auger and re-do ash catch pan to eliminate the need for two separate ash augers.
Combustion grate stuck	30+ hours	Increased force to the shake grate solved problem but created a new one. Combustion grate and air delivery need to be redesigned
Incomplete ash	On-going	The combustion grate problem was solved by increasing the amount of force shaking the grate, but it shook too hard and would allow unburnt litter to fall into the ash pan.
Burner distribution plate deterioration	On-going	Replaced plate once. Plate needs to be made out of different high-temperature alloy.
Excessive dust from material handling systems	On-going	Material handling system redesigned using sealed conveyers where possible and sealing off areas under main hopper.

Mark Rohrer Farm		
Main conveyor motor overload	4+ hours	Reset overload contactor. Belt conveyor needs to be replaced with different conveying mechanism.
Ash pan broke	12 hours	The ash pan and ash augers are overheating and need to be replaced with metals that can take the corrosive and high temperature conditions. No other Global Re-Fuel system has experienced this problem. Possible cause is that draft is too low, preventing the hot gases from being adequately pulled through the stack.
Ash auger jam (multiple times)	On-going	Replace flexible ash auger with solid shaft auger and re-do ash catch pan to eliminate the need for two separate ash augers.
Combustion grate stuck	On-going	Increased force to the shake grate solved problem but created a new one. Combustion grate and air delivery need to be redesigned
Incomplete ash	On-going	The combustion grate problem was solved by increasing the amount of force shaking the grate, but it shook too hard and would allow unburnt litter to fall into the ash pan.
Litter moisture too high	On-going	The litter from the organic birds was higher in moisture (>30%) and was too high for the unit to sustain combustion.

4.2 Capacity Factor

Capacity factor as defined for this project describes the actual operation of the unit compared to the potential operational time. Each farmer had different goals for running the units (to pre-heat houses and to provide heat for chicks), and these goals changed from flock to flock. In general, Mike Weaver's operational goal was to run the unit up to three days prior to flock placement and for approximately three weeks after flock placement. Mark Rohrer's operational goal was to run the unit up to three days prior to placement and for three to four weeks after flock placement. To facilitate comparison, a timeframe of three days before flock placement and three weeks after flock placement was used as the potential operational time.

Table 2. Capacity factor performance for the Global Re-Fuel systems at the Mark Rohrer and Mike Weaver Farms

Farm Name	Flock 1 [September - November]	Flock 2 [November - January]	Flock 3 [January - March]
Mike Weaver Farm (9/26/14 – 3/5/15)	52.1%[1]	25.3%	39.3%
Mark Rohrer Farm (9/18/14 – 3/10/15	48.8%	68.2%	0[2]

[1]The percent of time the Global Re-Fuel system ran 3 days prior to flock placement, and 3 weeks after flock placement (24 days).

[2]The Global Re-Fuel unit did run prior to the third flock for Mark Rohrer; however, it only ran for a few days approximately one week prior to the flock being placed and thus that runtime was not counted.

4.3 Heat Delivery, Temperature, and Relative Humidity

Heat delivery, propane use, and electricity use are presented in Table 3. Over a three-flock period, the Globl Re-Fuel unit at the Mike Weaver farm delivered between 56.66 and 114.85 MBtu of heat to two poultry houses. During this timeframe, estimated propane heat delivery was estimated 135.5 MBtu for Flock 1 and 3 (no data on propane use for Flock 2 was available). At the Mark Rohrer farm, the Global Re-Fuel heat delivery ranged from 25.52 to 156.29 MBtu per flock over a three-flock period, while propane heat delivery ranged from 139.50 to 741.24 MBtu.

The Global Re-Fuel system consumes propane fuel to provide heat for start-up and electricity to run controllers and mechanical components. Data from both farms suggests this propane start-up fuel ranges between 0.25 and 6.78 gallons of propane/MBtu. At the Mike Weaver farm, total propane use was 0.026 MBtu propane/MBtu poultry litter heat delivered. At the Mark Rohrer farm, total propane use was 0.023 MBtu propane/MBtu poultry litter heat delivered. Over a three-flock period on the Mark Rohrer farm, the Global Re-Fuel system used 3,903 kWh of electricity to deliver a total of 291.85 MBtu of heat, or 13.37 kWh/MBtu heat.

Table 4 and Figures 6 and 7 describe the performance of the system with respect to achieving target temperature and relative humidity goals compared to operation of the poultry houses using propane fuel only. These goals were set based on the farmer's preferences. Mark Rohrer and Todd Rohrer have a goal that the temperature in the houses will be within three degrees of the house controller sensors located. Mike Weaver has a goal of only 2 degrees temperature difference between the sensors. The goal for relative humidity was to keep it under 60 percent. Performance for periods when the system was running (with Global Re-Fuel) and not running (without Global Re-Fuel) are included for comparison. Also, Table 4 includes data from two poultry houses on the Todd Roher farm that are located immediately adjacent to the Mark Rohrer farm and are included for comparison purposes.

Table 3. Operational performance data for the Global Re-Fuel unit on the Mike Weaver and Mark Rohrer farms

<table>
<tr><th></th><th colspan="6">Global Re-Fuel</th><th colspan="2">Propane Heating System</th></tr>
<tr><th></th><th>Hours in Operation</th><th>Poultry Litter Feed Rate (lbs/hr)</th><th>Propane Use (gallons)</th><th>Propane Use (MBTUs)</th><th>Electricity Use (kWh)</th><th>Heat Delivered to Houses (MBTU)*</th><th>Propane Use (gallons)</th><th>Propane Use (MBTU)</th></tr>
<tr><td colspan="9">Mike Weaver Farm</td></tr>
<tr><td>Flock 1</td><td>300</td><td>100-180</td><td>14.9</td><td>1.34</td><td>n/a</td><td>114.85</td><td rowspan="2">1,659</td><td rowspan="2">135.50</td></tr>
<tr><td>Flock 2</td><td>148</td><td>100-180</td><td>29.3</td><td>2.64</td><td>n/a</td><td>56.66</td></tr>
<tr><td>Flock 3</td><td>226</td><td>100-180</td><td>31.1</td><td>2.80</td><td>n/a</td><td>86.52</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Total</td><td>674</td><td>100-180</td><td>75.3</td><td>6.78</td><td>n/a</td><td>258.04</td><td>1,659</td><td>135.50</td></tr>
<tr><td colspan="9">Mark Rohrer Farm</td></tr>
<tr><td>Flock 1</td><td>276</td><td>100-180</td><td>27.8</td><td>2.50</td><td>1395</td><td>110.04</td><td>1,550</td><td>139.50</td></tr>
<tr><td>Flock 2</td><td>392</td><td>100-180</td><td>44.5</td><td>4.01</td><td>2284</td><td>156.29</td><td>4,461</td><td>401.49</td></tr>
<tr><td>Flock 3</td><td>64</td><td>100-180</td><td>2.8</td><td>0.25</td><td>224</td><td>25.52</td><td>8,236</td><td>741.24</td></tr>
<tr><td>Total</td><td>732</td><td>100-180</td><td>75.1</td><td>6.76</td><td>3903</td><td>291.85</td><td>14,247</td><td>1,282.23</td></tr>
</table>

* Based on 140 lbs/hr feed rate and the Btu/lb value of the litter collected at the beginning of the project (5,178 Btu/lb for Rohrer and 4,972 Btu/lb for Weaver) times the estimated efficiency of the Global Re-Fuel unit (55%).

Table 4. Temperature and relative humidity performance in houses heated with the Global Re-Fuel system for the duration of the monitoring period (three flocks). Performance for periods when the system was running (with Global Re-Fuel) and not running (without Global Re-Fuel) are included for comparison. Also, data from two poultry houses on the Todd Rohrer farm that are located immediately adjacent to the Mark Rohrer farm are included for comparison purposes.

Farm Name (Monitoring Period)	**Temperature Target**			**Relative Humidity Target**		
	Achieved for the entire flock	Achieved with Global Re-Fuel	Achieved without Global Re-Fuel	Achieved for the entire flock	Achieved with Global Re-Fuel	Achieved without Global Re-Fuel
Mike Weaver Farm (9/26/14 – 3/5/15)	27%	28%	28%	4%	16%	3%
Mark Rohrer Farm (9/18/14 – 3/10/15	72%	71%	87%	10%	37%	45%
Todd Rohrer Farm (10/22/14 – 3/10/15)	75%	n/a	n/a	14%	n/a	n/a

Figure 6. Temperature as measured by inside and outside sensors, compared to target temperature during Flock 1. Periods when the Global Re-Fuel system was operational (Global Re-Fuel on) are denoted by a straight green line at bottom of the graph.

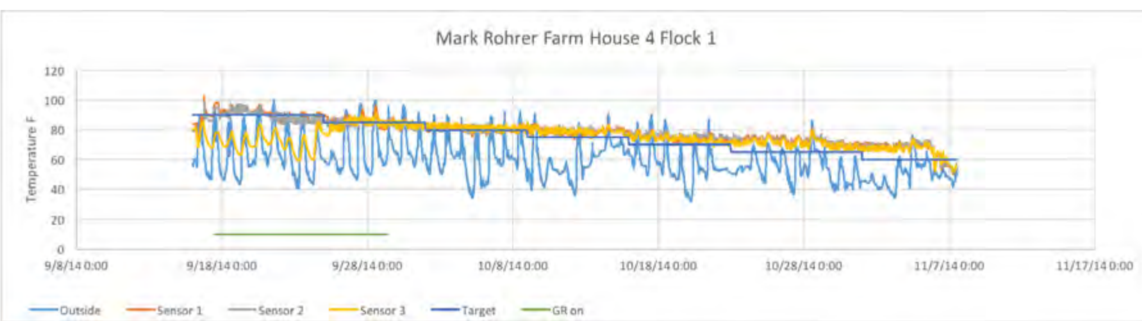
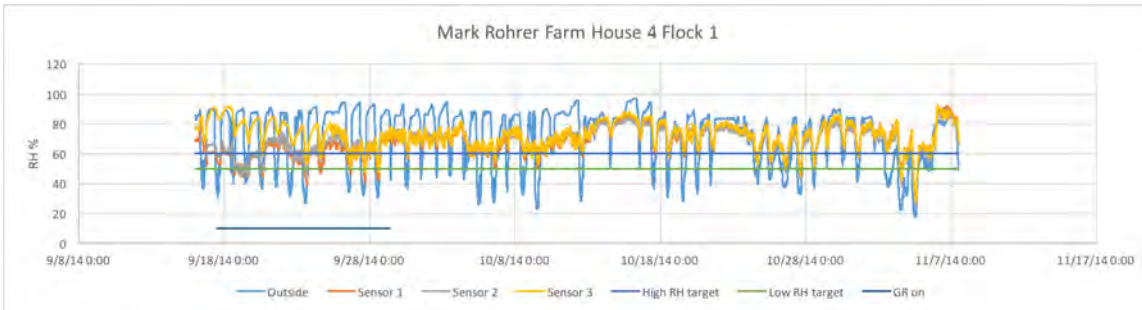


Figure 7. Relative humidity (RH) as measured by in-house and outdoor sensors at the Mark Rohrer farm for House 4 during Flock 1 compared to the target RH. The period when the Global Re-Fuel unit was operational (Global Re-Fuel on) is denoted by a straight line at the bottom of the graph.



4.4 Operation and Maintenance Requirements

Time spent by both Mr. Weaver and Mr. Rohrer for non-routine maintenance on the Global Re-Fuel unit was much higher than anticipated. For example, Mr. Weaver's time investment during one flock, primarily for maintenance, was 10% of the total run time for the unit (32 hours of labor for 304 hours of runtime). Mr. Rohrer kept detailed records of his time operating and maintaining the unit. On weeks when the system was operational, he spent 3 to 3.5 hours in routine maintenance. Overall, for the period of time when the unit operated, he spent 50 hours operating and maintaining the unit for 695 hours of operation. At 695 hours (or 4.12 weeks) of operation, routine operation should have required 13 hours.

5. Performance Discussion

5.1 Reliability and Capacity Factor

Multiple technical performance issues resulted in considerable negative impacts to the Global Re-Fuel system reliability and capacity. These technical performance problems (summarized in Table 1) will need to be addressed before the system should be deployed on additional farms. At the conclusion of this project, the units on the Mike Weaver farm and the Mark Rohrer farm are not operational. Note that the Mark Rohrer farm has since converted to organic production and now produces poultry litter with moisture content above 30%. This moisture value exceeds the design specifications for the Global Re-Fuel unit. Hence, in addition to addressing technical problems with the unit, litter moisture would also need to be addressed for successful operation on the Mark Rohrer farm. Both Mike Weaver and

Mark Rohrer have been provided with funding from the Farm Manure-to-Energy Initiative to support decommissioning of the system.

5.2 Heat Delivery, Temperature, and Relative Humidity

When the Global Re-Fuel systems were operational, initial performance suggests that it did successfully integrate with the farm's existing propane heating systems on the Mike Weaver farm. Data is less conclusive at the Mark Rohrer farm, where there is an apparent improvement in performance when the Global Re-Fuel system is off, although it is not possible to determine whether the Global Re-Fuel system is the contributing fact to the decrease in performance or whether other factors are a function (larger birds and whole house heating later in the flock, for example).

One technical problem that impacted temperature delivery on the Mike Weaver farm was observed. It was discovered that the Global Re-Fuel unit's louvers that control the air flow through the ductwork and into the poultry houses malfunctioned and were partially closed. This caused the temperature for the supply air to reach over 200^0 F with a significantly reduced airflow. This caused the sensor in the middle of the barn to be a few degrees higher when the Global Re-Fuel system operated, causing the percent time of the sensors were within 2 degrees of each other to be very low. This failure of the Global Re-Fuel system's louvers was not detected by the Global Re-Fuel controls and will need to be addressed in the future.

Farmers noted that they needed to adjust their circulation fans and house vents to adjust for the Global Re-Fuel system. This area of heat distribution can be studied in the future projects.

Relative Humidity is the amount of water vapor present in air expressed as a percentage of the amount needed for saturation at the same temperature. Zero percent relative humidity means the air is completely dry; 100% relative humidity means the air is saturated and any more water vapor added to the environment would "fall out" as rain or condensation. A target of 50-60% relative humidity is considered comfortable for humans and good for bird health.

Relative humidity for both farms fell within acceptable industry ranges for a small percent of the time (Table 4). Table 4 indicates that the Mike Weaver farm showed improved relative humidity performance when the Global Re-Fuel system was operational, while the Mark Rohrer farm had the opposite experience. Hydronic heat or air-to-air heating systems (as provided by the Global Re-Fuel system) should provide a drier heat than propane, which releases 0.8 gallons of water as moisture for every gallon of propane burned. Therefore, it is unclear why the Mark Rohrer farm experienced worse relative humidity performance without the Global Re-Fuel system, particularly since the system primarily operated in the beginning of the flock, when the birds were smaller and therefore producing less moisture in the form of manure and respiration.

5.3 Operation and Maintenance Requirements

Operation and maintenance requirements for these two units greatly exceed the amount of time that farmers anticipated. Despite the time Mr. Rohrer and Mr. Weaver invested in equipment repairs, the units did not consistently perform as designed. In addition to design issues as previously discussed, Wayne Combustion did not have technical staff available on an as-needed basis to support equipment repairs during the commissioning period. Often, technical staff would provide guidance to the farmers over the phone, and the farm partners would then implement the repairs on their own. While this was sometimes successful in the short-term, ultimately these systems needed far more technical repair and support than Wayne Combustion was able to provide, resulting in an unacceptably high labor investment required of the farm partners.

6. Recommendations and Next Steps

Given the Global Re-Fuel Furnace's technical performance issues, this technology is currently not ready for widespread adoption. Research and development investments are needed before this technology is ready for further deployment on farms. Wayne Combustion Systems, a company that specializes in gas-powered burners rather than farm equipment, has decided not to continue investments in developing and commercializing this technology.

However, given the low price-point and compelling design, project partners suggest that this technology has the potential to provide a low-cost option for on-farm poultry litter-generated heat. To support the additional research and design needed to bring this technology to market, the Farm Manure-to-Energy Initiative team has consulted with Wayne Combustion Systems and the Global Re-Fuel technology inventor to identify strategies to address these technical problems. Detailed, step-by-step recommendations have been developed to support this process including specific engineering and mechanical recommendations, the order of implementation, and an approximate budget.

With support from the Natural Resources Conservation Service, Florida A&M will begin implementing these strategies and will look at how changes in operational parameters such as combustion air, litter moisture, and draft conditions effect the performance of the system and the emissions (focusing on carbon monoxide, nitrogen oxides, and particulate matter). This project will involve members of the Farm Manure-to-Energy Initiative to implement a testing protocol to look at the changes in combustion on the Global Re-Fuel unit located near Harrisonburg, VA.

Appendix B

Technical Performance:
Ecoremedy® Gasifier Poultry Litter Furnace

A summary of preliminary technical performance findings funded by the Farm Manure-to-Energy Initiative

December 2015

Contents

1. The Technology

Installed on the Flintrock Farm in the summer of 2014, the Ecoremedy® gasification system is a fixed feed rate system with a designed output of 0.8 -1.2 MBtu/hr. This system is designed to accept the poultry litter in the "as-is" condition. In theory, the system can use poultry litter with moisture levels up to 50%, although lower moisture content increases heat delivery.

The Ecoremedy gasifier is a chain-grate, air-blown gasification system in which fuel enters an oxygen-starved gasifier. Syngas generated from the gasification process enters a separate oxidation chamber where it is combusted. Heat gases from the combustion chamber then pass through a boiler used to heat water.

The Ecoremedy system consists of four primary components: 1) the gasifier; 2) the boiler; 3) the material handling system for fuel and ash; and 4) the hydronic heating system. The litter is loaded into a standard litter spreader modified with an electric motor to move the litter into the gasifier (figure 1). Prior to entering the gasifier (figures 2 and 3), the litter passes through a de-lumper, which breaks up the clumps in the litter (figure 1). After the de-lumper, the litter moves via a conveyor belt to a surge hopper on the gasifier, which also acts as an airlock.

The gasifier uses a chain grate to convey the litter through the gasification zone. The residence time is controlled by the speed of the conveyer belt, and the feed rate is controlled by a slide gate that adjusts the bed depth and the conveyor belt speed. The chain rides over perforated cast iron plates. Underfire air is blown through these holes and through the moving bed of litter. There are three separate underfire zones so the amount of air can be controlled independently (via manual controls) in each zone to fine tune the gasification to accommodate changes in the litter. Although the system is designed to operate at a constant feed rate, manure controls provide options for changing the feed rate if necessary.

Gate height and grate speed are independently adjusted to achieve the desired feed rate. These adjustments also allow for consideration of the litter bed depth and residence time. Proper adjustment of feed rate is critical for complete gasification of the fuel. For example, if bed depth is too high or the grate speed to fast, then gasification of the poultry litter could be incomplete, reducing the energy output and increasing the carbon and volume of the ash.

The litter that has been converted to ash falls into an ash bin at the end of the chain grate, where the ash is augered automatically outside of the gasifier, and into a dump hopper. Ash is stored in concrete walled structure to ensure complete cooling prior to bagging for off-farm transport.

The syngas created in the gasification zone flows into a separate chamber above the gasification chamber where secondary combustion air is blown in at different locations to completely oxidize the fuel. This two-stage system allows for complete control of the combustion process and complete oxidation of the fuel.

From the secondary combustion chamber, hot gases flow into a three-pass fire tube boiler (figure 2). This boiler is a standard off-the-shelf boiler (Superior Boil Works, Inc. Model #MS3-OB-270-W30) with the entrance modified to bolt to the gasifier. The flue gases leave the boiler and are pulled through the system by an exhaust fan. There are two cyclones in series that are designed to control particulate matter emissions. After the flue gases leave the cyclone they are vented to the atmosphere.

The hydronic heating system uses standard plumbing components to each of the four houses. Each house has three Landmeco heaters (model number 94-900), for a total of twelve heaters. Each heater has a thermostat to control the amount of heat the Landmeco will pull from the hot water. The gasifier output does not modulate according to the heat demand from the four houses, always running at 100% for a given feedrate. Any excess thermal energy not used in the houses is released to the atmosphere by a large radiator near the gasifier. A bypass valve, controlled by a thermostat near the boiler, activates the heat dump equipment if the incoming water temperature is above a certain threshold.

Figure 1. Litter starts in the litter spreader (white piece of machinery) that goes through a lump breaker (grey piece labeled "Danger") and then is conveyed to a hopper above the gasifier (hopper not pictured).

Figure 2. The gasifier is the gray colored device and the boiler is the blue colored equipment at the top. The litter flows through the unit from left to right.

Figure 3. Flame from the combustion of the gasifier-generated syngas inside the combustion chamber.

2. The Farm

Along with contributions from Enginuity Energy LLC and Flintrock Farm, funding from the Farm Manure-to-Energy Initiative (from private foundations) and the Pennsylvania Natural Resources Conservation Service's Environmental Quality Incentives Program was used to install the Ecoremedy gasifier at Flintrock Farm in Lititz, Pennsylvania. Flintrock Farm produces organic broiler chickens in twelve poultry houses. At the start of the project, the farm produced conventionally-raised broilers. In January of 2014, the farm began producing organic broiler chickens for Coleman Natural. Birds are grown to 6.3 pounds over a fifty-day period.

The gasifier was installed to heat four poultry houses; two of the houses are 44 feet by 500 feet, and the other two houses are 54 feet by 600 feet (108,800 ft^2 total area). There are also an additional eight poultry houses, each 44 feet by 500 feet, located on a separate tract of land down the hill that are also part of this farm (but not part of the gasifier heat distribution system). In addition to poultry, the farm offers horse stabling and a riding arena. The farm also has forty acres planted in hay.

Depending on the farm's whole-house clean out schedule, the four houses heated by the gasifier produce between 750 to a little more than 1,000 tons of poultry litter per year, which is stored in a covered storage facility. Litter is "caked out" between every flock. Based on the farm's comprehensive nutrient management plan recommendations, between 2 and 3 tons of poultry litter (80 to 120 tons per year) are applied to the farm's hay acreage. Prior to installation of the gasifier, the remainder of the litter was exported off the farm, often for use in the mushroom industry. The gasifier uses 4.5 tons of poultry litter per day. If the system is operated for both heat and litter moisture control, the system would use all of the farm's exported poultry litter. An October 2015 poultry litter sample indicated that litter used as a fuel on the farm had an energy value of 4627 Btu/lb, an ash content of 23.73%, and a moisture value of 25.11% (see Appendix E for details on methods used for collection and analysis).

Solar panels (200 kW) also contribute to renewable energy production on the farm. Excess generation from the utility-interactive system is delivered to the grid via a net-metering program with the electric utility.

3. Objectives and Methods

3.1 Overall Performance Design Objectives

The objective of the performance evaluation was to determine the degree to which the Ecoremedy gasification unit achieved the following design objectives:

- Use poultry litter as a fuel to reliably deliver heat to poultry houses.
- Integrate seamlessly with the farm's existing propane-fired unit heaters and ventilation systems to maintain house temperature within industry-recommended (and grower established) targets.

- Reduce propane use on the farm.
- Run successfully with minimal operation and maintenance requirements (routine maintenance and daily addition of poultry litter fuel).
- Operate with no negative impacts on bird production and ideally improve bird health and production by allowing for increased winter ventilation and improved air quality.

3.2 Technical Performance Evaluation Methods

Temperature and humidity

Houses 9 and 10 were the smaller houses and had only three temperature sensors in each house. Houses 11 and 12 had five temperature sensors each and one relative humidity sensor. The farmer's house controllers and its sensors (Hired Hand Evolution computer controllers) were used for this data.

Energy consumption (propane and electricity) and delivery

The project team measured electricity load requirements for the Ecoremedy gasfier as well as farm propane use and energy delivered to the poultry houses. Propane meters (American Meter AL-425TCH-CF) were previously installed by the farmer to measure propane consumption for poultry houses. The Ecoremedy gasifier had its own propane tanks, and the bills were used to determine the amount of propane used during start-up. Utility meters were used to monitor whole-farm electricity consumption, while a GE I-210 electricity meter was used to monitor Ecoremedy gasifier system electricity consumption. The heat transfer is calculated every second using measured thermal fluid flow, the specific heat and specific volume of the thermal fluid, and the temperature difference across the boiler. The real time heat transfer is displayed on the control panel.

3.3 Farmer-supplied performance data

Farm staff used weekly log sheets to track operation and maintenance requirements, system run time and performance concerns, flock age, and their observations of in-house conditions. Metrics documented on the log included:

- Flock status (number of days from placement)
- Portion of the house occupied by the flock (partial/whole)
- Hours the system was operational (hours/week)
- Hours of farm labor needed to run the system over the week (operation and maintenance)
- Reasons the system was not run (e.g. heat not needed, maintenance problems)
- Description of any problems that occurred
- Amount of down-time due to system problems
- House conditions (heat distribution, dust level, ammonia odor)
- Propane meter readings

The farm owner also supplied information on previous farm energy use (propane and electricity), flock performance (via settlement sheets), and poultry litter production and use (on and off the farm).

Figure 4. Temperature sensor locations at Flintrock Farm for the two houses sized 44 feet x 500 feet (Houses 9 and 10)

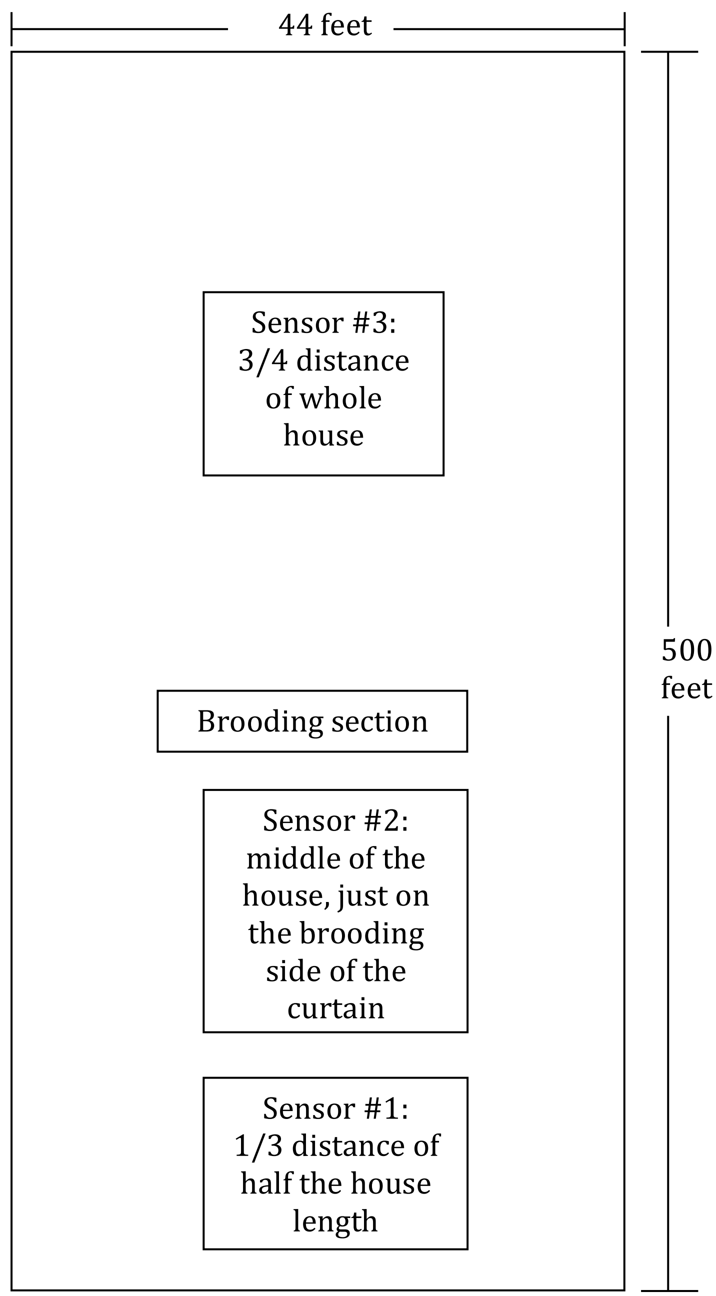
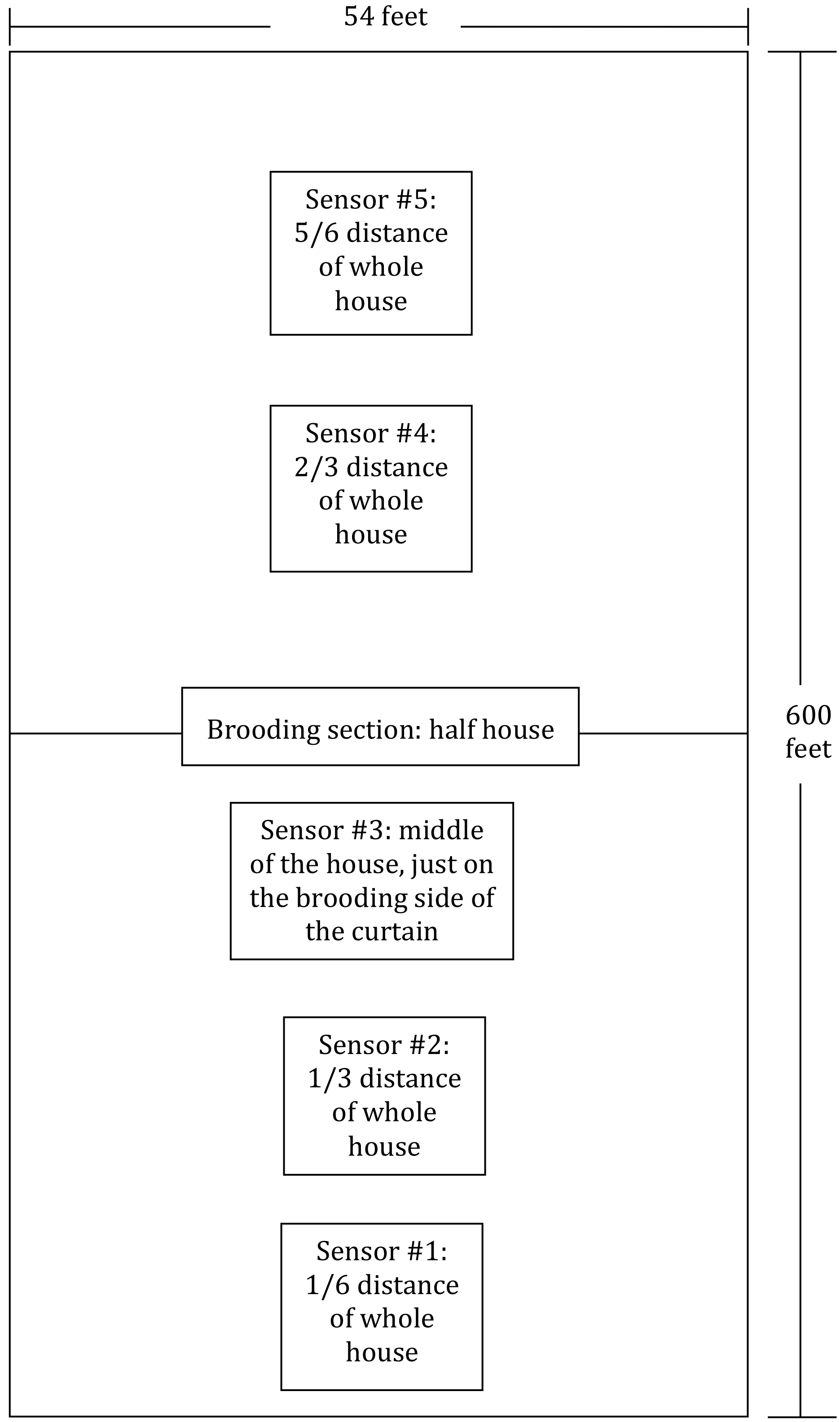


Figure 5. Temperature sensor locations at Flintrock Farm for the two houses sized 54 feet x 600 feet (Houses 11 and 12)



4. Performance Results

The system was installed during the summer of 2014, and the initial commissioning phase of the project started in late 2014. The project team defined commissioning as continuous operation without technical problems for one complete flock. As of November 2015, the vendor is still working with Flintrock Farm to achieve uninterrupted operation over a complete flock.

4.1 Reliability

Overall, the system will run for several weeks during a flock, but it requires several hours during operation and after shutdown for maintenance before the next flock, as shown in Table 2. Since installation, many of the issues have been resolved to reduce maintenance. However, there are still key technical challenges that impact system reliability (and steps that have taken to address them):

1. The screen on the chain grate routinely required repair between flocks, if not during a flock, and the under-fire grates clogged after approximately two of weeks of continuous use. To address this problem, the chain grate was redesigned to overlay the load bearing belt with a fine mesh screen to prevent the ash and litter from contacting the under-fire air holes. This change has improved air distribution and reduced clogging of holes in the perforated plates.
2. Rocks in the poultry litter resulted in repeated system shutdowns during the initial start-up phase. Rocks jammed in the de-lumper and/or jammed in the ash auger, causing damage to auger. Two strategies were used to address this problem. First, clean-out of the houses is done in a way that avoids the introducing rocks into the litter from the earthen floor. Also, the ash auger system was re-designed to reduce jamming and associated damage to the flighting. The flight thickness was doubled and the ash removal frequency was increased.

Table 2. List of technical major problems during the project and farm labor required to resolve

Description of Mechanical Issue	Farmer Time to Resolve (hrs)	Resolution and/or Recommended Next Steps
Boiler tubes fouling	Several weeks	Installed thermostats on heaters to keep boiler return temperature above 150°F to reduce condensation of flue gas in boiler tubes.
Ash auger damaged	1-2 weeks	Ash auger flights were bent due to part of chain grate screen coming off and wrapping around flights. Replaced auger. Initially removed screen altogether, but recently reinstalled screen with a better quality attachment system
Rocks jamming de-lumper and ash auger	Happened several times, typically less than 1 hour to resolve; on-going	Initially, large rocks (1” diameter and larger) jammed the de-lumper and ash auger. Careful litter removal and ash auger redesign have helped, with only 1-2 interruptions per week max.
Baghouse clogging	Several weeks	Initial baghouse used for particulate matter removal clogged very quickly (hours to days) and was taken out of the system and replaced with two cyclones in series.
Incomplete ash	Several days/on-going	The system could not process the high moisture material (above 40% moisture) and the under-fire plates were becoming clogged. The litter is now drier, typically between 25-30% moisture. The under-fire plates still become clogged, and a final solution has not been implemented yet. The system runs, but the plates have to be cleaned between flocks.
Leaking connections on house heaters	2 weeks	The heaters had leaking fittings. The heaters had European fittings, which were not known at the time of installation. New fittings were installed and solved the leaks.
System not reaching designed output of 1.2 MBtu/hr (output is typically at 0.8 -1.0 Mbtu/hr)	On-going	Initial issue was high moisture litter with low Btu. Litter is now drier. Under-fire grates and chain grate also limited firing at higher feed rates. Newly designed screen is addressing this problem. Installation of emissions controls initially reduced output due to ID fan capacity. However, planned improvements to the system are expected to result in full capacity operation.
Screen on chain grate	On-going	A screen is used on the chain grate to help prevent clogging of the underfire grates. The screen material needs repairing or replaced after each flock or sometimes during the flock. A new screen design has improved air distribution and reduced clogging of holes in the perforated plates.

4.2 Heat Delivery, Temperature, and Relative Humidity

Table 3 shows the percentage of time that the system was providing heat to the poultry houses during five flocks. This capacity factor was calculated by adding up the total time the system ran during each flock and dividing it by the total flock time. Flock 4 only had 28% runtime as the system had a major failure in the chain grate system. Once a solution was found, the system ran more consistently during Flock 5. Flock 5 had only 45% run time, but the system did not need to run the entire flock time because the weather was much warmer and the houses didn't need heat. However, the amount of time that the houses did not need heat was not known and therefore was not used in this calculation.

Table 3. Capacity factor (percent of the time the unit was functioning correctly during each flock)

Farm Name	Flock 1 [9/15/14 – 11/3/14]	Flock 2 [12/5/14 – 1/26/15]	Flock 3 [2/3/15 – 3/24/15]	Flock 4 [4/2/15 – 5/21/15]	Flock 5 [6/8/15 – 7/27/15]
Flintrock Farm	0%	64%	57%	28%	45%

4.3 Energy Consumption (Propane and Electricity) and Delivery

Energy consumption and production for the Ecoremedy gasifier as compared to the propane heating system is provided in Table 4. Over the five-flock demonstration period, 25,082 MBtu of heat from both the in-house propane heaters and the gasifier was provided to the four poultry houses. The gasifier, which was not operated continuously through this period due to technical issues, contributed 6.6% of that total. Heat was delivered to poultry houses at an average rate of 0.66 MBtu/hour over the five-flock period. This heat output was 34-44 percent less heat output than originally planned (1.0-1.2 MBtu/hour).

To produce 1,661 MBtus of heat, the gasifier consumed 33.1 MBtu's of propane and 31,511 kWh of electricity. Electricity consumption consistently averaged 12.6 kW/hour of operation. Propane use was more variable, since propane is associated with start-up (e.g., the more often the gasifier is started during one flock the higher the propane consumption will be). Propane use varied over the course of flocks 2-5 (when the system was operational) from 0.04 to 0.19 gallons of propane/hour of gasifier operation.

Table 4. Operational performance data (propane and electricity consumption compared to heat delivery) for the Ecoremedy gasifer unit on Flintrock Farm compared to the existing propane heating system

	Ecoremedy Gasifier						Propane Heating System	
	Hours in Operation	Poultry Litter Rate (lbs/hr)	Propane Use (gallons)	Propane Use (MBTUs)	Electricity Use (kWh)	Heat Delivered to Houses (MBTU)	Propane Use (gallons)	Propane Use (MBTU)
Flintrock Farm								
Flock 1	0	200-300	93.7	8.5	0	0	n/a	n/a
Flock 2	868	200-300	34.8	3.2	10,936	678.3	2019	183.7
Flock 3	727	200-300	135.0	12.3	9,160	468.6	14,053	1,278.8
Flock 4	372	200-300	48.8	4.4	4,687	157.7	6,844	622.8
Flock 5	534	200-300	52.1	4.7	6,728	361.5	500	45.5
Total	2501		364.4	33.1	31,511	1,666.1	23,416	23,416.0

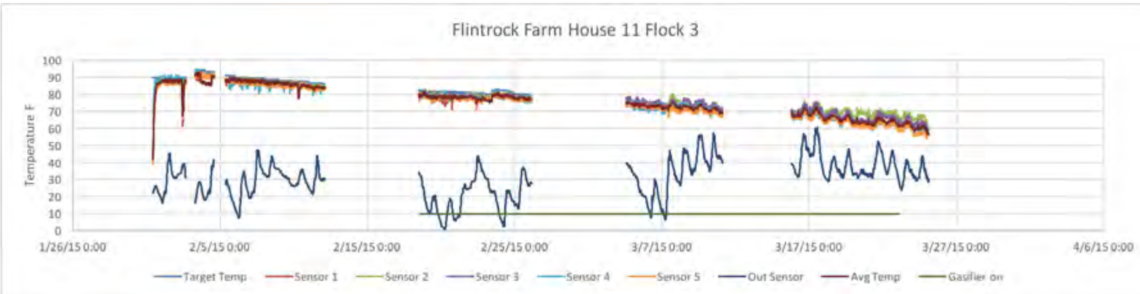
Data comparing the percentage of time the target temperature was achieved in the poultry houses when the gasifier was operational and when it as not is provided in Table 5. Performance for periods when the system was running (with the Ecoremedy gasifier) and not running (without the Ecoremedy gasifier) are included for comparison. Houses 9 and 10, the two smaller houses, were grouped together because they were the same size, as well as Houses 11 and 12 (the two larger houses). An example of temperature recorded by the sensors in one of the poultry houses is shown in Figure 6, which depicts sensor temperature readings and outside temperature over the course of one flock during a period of time when the gasifier system ran intermittently.

Table 5. Temperature and relative humidity performance in houses heated with the Ecoremedy system for the duration of the monitoring period (5 flocks). Houses are grouped by size (9 and 10 are 44 ft x 500 ft., and 11 and 12 are 54 ft x 600 ft.)

Farm Name (9/15/14 – 7/27/15)	Temperature Target			Relative Humidity Target		
	Achieved for the entire flock (%)	Achieved with Ecoremedy	Achieved without Ecoremedy	Achieved for the entire flock	Achieved with Ecoremedy	Achieved without Ecoremedy
H9 &10 *	55%	71%	44%	n/a	n/a	n/a
H11 &H12	61%	65%	58%	31%	47%	44%

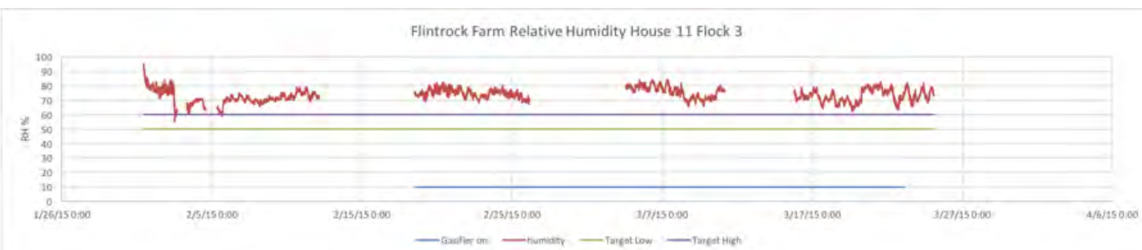
* Houses 9 and 10 did not contain relative humidity sensors.

Figure 6. Temperature readings from House 11 temperature sensors (five inside and one outside) compared to target temperature for periods when the gasifier ran intermittently



Relative humidity for the poultry houses fell within acceptable industry ranges 31% of the time (Table 5) for the entire flock with or without operation of the Ecoremedy gasifier. Figure 7 shows relative humidity over one flock from House 11.

Figure 7. Relative humidity in House 11 compared to target ranges over the course of one flock when the gasifier ran intermittently



4.4 Operations and maintenance

Estimated daily labor for filling the fuel hopper and checking the system is 1 to 1.5 hours. However, this is an estimate, as the system has had considerable start-up issues since installation that have required additional farm labor to address (Table 2). From November 29, 2014, through October 2, 2015, farm staff invested 564 hours in operations and maintenance.

5. Discussion

5.1 Reliability

The Ecoremedy gasifier installation at Flintrock Farm has had a longer than expected start-up period. While many of these have been addressed, this system is still in the early phases of demonstration. Many of the experiences that Flintrock Farm and the vendor have addressed provide valuable insight for future projects. For example:

- The conversion of the farm from conventional to organic production at the beginning of 2014 increased the moisture content of the poultry litter. The Ecoremedy gasifier system was designed to handle litter with up to 50% moisture, but the combination of the wetter litter, which has lower energy content, contributed to problems during the commissioning period. To address this issue, Flintrock Farm changed the way the litter is removed from the poultry houses. Specifically, litter below the water lines, which had much higher moisture than litter from the rest of the house, was scraped out and stored separately from litter used as fuel for the gasifier. This practice lowered the moisture content over the overall litter from the mid-40s to around 30%.
- The initial problems related to the boiler fouling — a common problem for biomass-fueled combustion systems — was addressed by increasing the temperature of the water in the boiler. Thermostats were installed at the house heaters to limit their use if the return boiler water was too low (around 150°F). After the thermostats were installed and after a few adjustments, the boiler fouling problem was solved. One important lesson was to keep the water temperature in the boiler above 150°F to prevent condensation from occurring on the gas side of the boiler tubes.
- Rocks (or other solid debris) in poultry litter are a ubiquitous problem and will impact material handling systems for most manure-to-energy projects. Both equipment design and on-farm management strategies were used at Flintrock farm to minimize equipment shut-down and damage. Like most poultry houses in the region, poultry litter on Flintrock Farm is placed over a bare dirt floor. During whole-house clean out, they now leave about ½ inch of litter in the houses to avoid scraping the dirt floor. Also, litter from the center of the house, which has fewer rocks than litter from the house perimeter, is used for fuel. Heavy equipment traffic has packed the dirt floor of the center of the house (whereas stones are more likely to mix with litter closer to the house walls where the floor dirt is more loosely packed). Also, the vendor doubled the thickness of the flights of the ash auger and increased the frequency of ash removal. This resolved problems previously experienced with flights being folded flat by rocks.

According to Dan Heller, owner of the Flintrock Farm, "this is a process and a journey, and we definitely haven't arrived at a final destination yet… We are continuing to invest in refining the system with the hope that we can continue to improve the system. We are making progress. The technology does work. The question is, can we make it reliable enough so that it is worth the effort? We have days where it runs great, but days where it requires maintenance. We are hopeful that changes they are making will result in smooth, uninterrupted operation."

5.2 Heat Delivery, Temperature, and Relative Humidity

Variation in temperature between the sensors suggests that, over the course of five flocks, there were periods in which the Ecoremedy gasifier had better temperature performance than when the gasifier was not operational (71% versus 44 % in Houses 9 and 10, and 65% versus 58% in Houses 11 and 12) (Table 5). Relative humidity results were similar for periods when the Ecoremedy gasifier was operating (47%) and when the system was not operating (44%).

However, these results are not sufficient to determine whether these observed improvements are the result of the gasifier heating system, or some other contributing factor. Over this performance monitoring period, technical and material handling issues compromised performance so that the gasifier provided only 6.7% of the total Btu's delivered to the poultry houses over a five-flock period. Additional monitoring would help to determine whether heat delivery improves with design modifications, and whether temperature and relative humidity results are consistent over time and with changes in the percentage of the total heat delivered by the gasifier.

5.3 Energy (Propane and Electricity) Use and Delivery

Even with intermittent operation and performance below design goals, the Ecoremedy gasifier produced far more energy than it consumed via electricity and start-up propane. However, start-up issues previously discussed (technical and material handling) undermined heat output of the gasifier system.

5.4 Operation and Maintenance

Farm labor requirements were far higher than anticipated, despite the vendors' dedication to resolving issues in a timely manner. This is similar to what the Farm Manure-to-Energy Initiative team has observed with other first-time demonstration projects, and it is something both farmers and technology vendors should be aware of. For this project, close proximity of the vendor to the farm, as well as the vendor's commitment to the project helped to facilitate repairs. If technical and material handling issues are resolved on this farm in such a way that translates to other projects, this initial labor investment should be minimized on future projects.

6. Vendor Comments

Each manure-to-energy technology vendor was provided with the opportunity to provide comments for inclusion in this report. The following comments are authored by Ecoremedy Energy:

Enginuity Energy is appreciative of the opportunity to work with Flintrock Farm and the Farm Manure-to-Energy Initiative to install the Ecoremedy advanced gasification system. We thank all parties for their cooperation and patience throughout the project.

We've learned a great deal through this project and have improved the equipment design for easier maintenance and longer operation without incident. Specific improvements include:

- A revised gasifier chain grate design that supports the fine particles of litter and tiny gravel size stones on top of the load-bearing belt. This simple change dramatically improved the belt integrity and reduced clogging of under fire air perforations.
- Although the new grate design dramatically reduced clogging of the under fire gasification air nozzles, future air perforations will be tapered to prevent bridging of any tiny stones within the air hole.
- In an effort to reduce equipment cost for farm-scale application, we elected to remove the gasification air preheater from the original scope of supply. Years of operating history in GA and at our R&D facility installed on the Harrisburg Area Community College campus in Harrisburg, PA, provided reason to believe we did not need an air preheater. We learned an air preheater is paramount when dealing with aged litter and other composted manure fuel feedstock.
- Automatic ash removal augers will be installed under the return chain to eliminate the need to temporarily empty ash from under the gasifier than has been deposited during the return trip of the chain grate.
- An improved guillotine gate assembly that includes a motor driven actuator with dual drive screws.

The above mentioned design changes will significantly improve operational uptime. Some lessons learned regarding the overall system for farm scale installations:

- Careful management of litter collection is mandatory. We experienced many large rocks the size of a fist or a cell phone that caused downtime due to a jammed lump buster, often resulting in damage to equipment. Rocks that are smaller than golf balls are processed without problem.
- Nutrients in aged litter are concentrated compared to litter that is removed after each flock. The concentrated levels of potassium chloride (KCl) in aged litter results in higher levels of fly ash <u>precipitate</u> than in single flock litter. It is important to note the distinction between precipitate fly ash and carry over fly ash. Precipitate fly ash actually precipitates out of the flue gas stream when it cools within the boiler compared to a mechanical carryover of fly ash due to combustion or improper

gasification. The higher KCl precipitate fly ash levels require extreme care to operate the oxidizer below the ash fusion temperatures to avoid fouling within the boiler. Our operational uptime dramatically improved when we learned to keep the oxidizer below 1700°F.

- A baghouse is a poor selection for a farm-scale project where shutdowns occur between flocks. The high moisture content of the feedstock coupled with an outdoor installation resulted in condensation within the baghouse and immediate fouling of filter media. Operational costs to properly preheat the baghouse before start-up and again during shutdown are cost prohibitive for farm scale operations.
- Mechanical collecting using cyclone collectors is a nice primary dust collection method but not sufficient as the only collection method. Our fly ash particle size is less than 5 microns, which is very difficult to capture with a mechanical cyclone.
- Indoor installation in a controlled environment is absolutely necessary. Our gasification system is an outdoor installation exposed to the weather and other problematic elements. Controls and equipment do not perform well in such extreme temperatures and corrosive conditions. We will not make this mistake again. Flintrock has enclosed the gasifier/boiler and controls room since the initial installation.

The Ecoremedy technology successfully performed under challenging conditions:

- Although designed originally for litter with different properties, we are successfully gasifying aged litter from organic chickens with higher moisture content, lower energy content, and higher bulk density than originally specified.
- Our system is exposed to the outside elements. Installed within the litter storage facility, the prevailing wind blows across the litter metering equipment and conveyors covering all equipment and controls with fine litter and dust. We operated in temperatures below 0° F for many consecutive days. This was poor judgement to attempt to install and operate in such an environment.

We wish to make two comments regarding the overall performance levels of the Ecoremedy gasifier and the Enginuity Energy LLC team:

- The outdoor installation created many problems for the equipment. Particularly damaging was the historic cold temperatures during the 2013 and 2014 winters. The outdoor installation without gasification air preheater coupled with below zero temperatures made it extremely difficult to achieve targeted performance levels. We have subsequently installed a small heat exchanger around our boiler exhaust stack in an attempt to raise the gasification air temperature by 100°F. This has proven to improve the unit performance. Flintrock Farm has recently enclosed the boiler room, increasing the temperature within the room and protecting the controls from frigid temperatures and corrosive dust. We anticipate this will result in further performance and maintenance improvements.

- AFTER all the equipment was ordered and delivered to site, we were notified that our previously approved location for installation was no longer approved requiring an addition to be built onto the existing litter storage barn to house the gasifier and boiler system. This delay resulted in the expiration of all equipment warrantees BEFORE commissioning. When we experienced problems that were rightfully covered under OEM warranty, all claims were denied due to expired warranty period. Enginuity Energy was forced to incur significant out-of-pocket expense not anticipated to repair/replace equipment that would have otherwise been covered, or partially covered, under warranty. This resulted in longer response time and repair time.

7. Recommendations and Next Steps

The Ecoremedy gasification system on Flintrock Farm is still in the early phases of demonstration and warrants additional monitoring. Successful demonstration should be achieved at Flintrock Farm before the system is installed on additional farms.

In the vendor comment section, Ecoremedy Energy identifies a number of strategies planned for implementation on this farm that will improve technical performance. Next steps for air emissions control equipment are discussed in Appendix E of the final report.

Appendix C

Technical Performance: LEI Bio-Burner 500 Biomass Heating System

A summary of preliminary technical performance findings by the
Farm Manure-to-Energy Initiative

December 2015

Contents

1. The Technology

After several years of research and development, in August of 2015, LEI Products adapted the LEI Bio-Burner 500, originally installed on Riverhill Farm in 2012 for use with woody biomass, so that the unit could be fueled with poultry litter. The Bio-Burner 500 is a fixed-grate combustion boiler system packaged unit that consists of three main components: the feed handling equipment, combustion unit and boiler, and emissions abatement technology.

The feed handling equipment consists of a large cylindrical hopper that uses a sweep arm and augers to convey the feedstock into the combustion chamber (Figure 1). The hopper's fuel feedrate modulates according to the combustion control system and will automatically increase or decrease the fuel feedrate as needed.

The hopper is designed to handle a wide variety of biomass feedstocks by preventing bridging, a common problem with biomass. The fuel is augered into the combustion chamber where it falls onto a hot combustion grate and is mechanically stirred. A propane-fired burner is used to pre-heat the combustion chamber to start the combustion of the fuel. A stir arm keeps the fuel moving, exposing it to hot surfaces and combustion air. Combustion air enters into the chamber at the grate surface and swirls around the combustion chamber, creating turbulence needed for combustion. The combustion chamber and passage to the heat exchanger are refractory lined, which keeps the combustion chamber hot enough to sustain combustion.

Hot flue gases from the combustion chamber flow through an integrated double-pass boiler into the emissions control system, which includes a cyclone followed by a wet scrubber.

This unit has four points for ash removal:

1. The combustion grate has a notch on the outer edge that allows the ash to fall into a trough where an auger will continuously remove the ash.
2. The boiler tubes are vertical and have turbulators inside the tubes that must be manually moved to keep the boiler tubes clean.
3. The ash falls to the bottom where a push arm is manually operated to move the ash into an auger for removal.
4. Any ash removed by the cyclone can be removed manually with an auger.

The boiler is designed to heat water to a set temperature controlled by a system controller. LEI Products provides the heating system without heat delivery components. How the hot water is utilized is up to the end user. The Bio-Burner 500 reviewed in this report sent the hot water to a heated radiant concrete floor in the brooding house. Pancake-style propane heaters are also used in the brooder house.

The emissions controls use cyclones followed by a wet scrubber designed to reduce particulate matter and opacity. The flue gases pass through a cylinder housing rotating vanes. These vanes rotate through a liquid bath of water and glycerin. As the vanes rotate through the liquid bath, they deposit captured particulate matter and coat themselves with new liquid. Once the vanes exit the liquid and rotate through the flue gas stream, the wet vanes pick up particulate matter and rotate back through the bath. This process is continuous.

The flue gases are cooled to below 140^{0}F and the heat is removed by an external heat exchanger. Heat from the exchanger is not used on site and is discharged to the atmosphere. The purpose of cooling the flue gases is to make the capture of particulate matter and condensable particulate matter more effective. High flue gas temperature would result in evaporation of the wet scrubber liquid, interfering with performance. After the emissions control system, the resulting flue gases go through a blower and up the flue stack, venting to the atmosphere.

With respect to routine operations and maintenance, the liquid bath requires fresh liquid to be added to maintain the correct level of fluid. The wet scrubber will also require periodic flushing to remove the captured particulate matter. Additionally, the farmer must fill the hopper, manually clean the boiler tubes, and manually empty the ash.

A system controller allows the system to be almost fully automated. Adjustments and monitoring can take place remotely.

LEI Products offers this system in different sizes, ranging from 100,000 to 500,000 Btu/hr output. The unit evaluated is rated for 500,000 Btu/hr output. Initially designed for use with woody biomass fuels, this system has been used on the farm with wood chips for the past three years.

Based on design research conducted using poultry litter as a fuel over the past two years, LEI Products recently modified this unit to be fueled by poultry litter instead of wood chips. This is the first unit in the field to use poultry litter as a fuel. The modifications focused on material handling and, in particular, the higher ash production expected with poultry litter compared to woody biomass. Wood has an ash content of 1-3% by weight. Poultry litter has an ash content of 10-20% by weight. Additional ash removing augers were installed to increase the rate of ash removal from the combustion chamber, where most of the ash is produced. The gear motors on the material handling augers were upgraded to three-phase motors with stronger gearboxes. A stand-alone, skid-mounted wet scrubber was added to remove particulate matter from the flue gases. The wet scrubber requires electricity for operation. No changes were made to the combustion chamber, but the boiler received a different type of cleaning mechanism to help keep the tubes clean from particulate matter deposits.

Figure 1. The silver cylinder with the wooden "A" frame cover is the litter storage hopper. It has a sweep arm that feeds the litter into an auger that meters the litter into the combustion chamber.

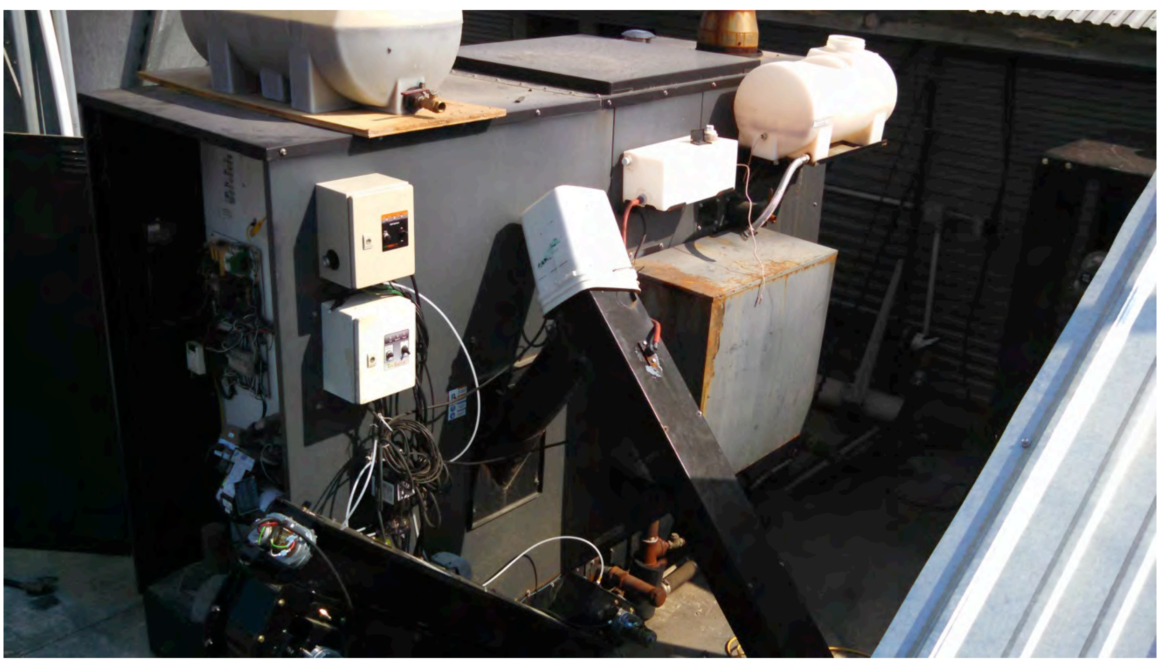


Figure 2. The rectangular tube in the middle of the picture is an auger that is metering the litter into the combustion chamber from the litter storage unit that is to the left of the picture.

Figure 3. This is the entire system without the scrubber. It is capable of sitting outside without a shelter as long as the litter and ash bins are covered.

Figure 4. This is the wet scrubber before it was connected to the exhaust of the combustion unit.

2. The Farm

Glenn Rodes, owner of Riverhill Farm in Port Republic, Virginia, grows eight flocks of 35,000 turkeys or 280,000 turkeys per year for Cargill. Turkeys spent the first five weeks on the farm in a brooding house and are then moved to the farm's four poultry grow-out houses for an additional eight weeks. The turkey brooding house has a high heat demand compared to traditional turkey housing for larger birds. In addition to the 0.5 MBtu/hour rated Bio-Burner 500, the house propane heating system (88, 48 inch Sibley Convention Brooder stoves, at 31,000 Btu each) supplies about 0.5 MBtu/hour (Figure 5).

The brooder house litter is cleaned out between each flock and litter is replaced with new bedding (soft wood shavings, mostly pine). Over all, including poultry litter from the brooder house and the four grow-out houses, the Riverhill Farm poultry operation produces 1,600 tons of poultry litter per year. According to the farm's nutrient management plan recommendations, almost all of the poultry litter is exported off the farm (via a poultry litter broker). Much of the litter is transported to the Rocky Mount area of Virginia, a nutrient-deficient region outside of the Chesapeake Bay watershed. Energy value of the litter is 4030 Btu/lb and moisture content is 24.4% (see Appendix E for details on methods used for collection and analysis).

Riverhill Farm also has 500 acres of cropland, which produces corn, soybeans, alfalfa, hay, barley, and canola.

Figure 5. Brooder house with newly placed poults.

3. Objectives and Methods

Because installation of this system occurred in the last year of the project (August 2015), technical performance data is primarily limited to Mr. Rodes' previous experience fueling the unit with wood chips. The system is permitted under a Biomass Research Permit, which allows for use of the system for data collection purposes (for example, air emissions testing), but not for routine use. Once the research permit has been reviewed and finalized by the permitting agency, the system will begin operation using poultry litter as a fuel, allowing for additional performance evaluation.

In the meantime, in addition to air emissions testing (discussed in Appendix E), determination of the Bio-Burner 500 heat output was calculated using a paddle wheel flow meter and water temperatures sensors located at the inlet and outlets of the boiler.

4. Results to Date

4.1 Reliability

The Bio-Burner 500 has been in operation on the farm using wood chips as fuel since the spring of 2012. Riverhill Farm places an average of eight flocks during the year in the brooding barn: approximately four flocks during the warmer months and four flocks during the colder months. Typically, the wood chip-fueled Bio-Burner 500 would operate continuously for 1-2 weeks for each flock during the warmer months and approximately 3-4 weeks for each flock during the colder months. This totaled approximately 20 weeks of run time during each year.

Since 2012 (while using wood chips as the primary fuel), the Bio-Burner 500 did experience some failures that were resolved quickly as indicated in table 2. According to Riverhill Farm, when used with wood chips as a fuel, the LEI Bio-Burner operates reliably with less than 5% downtime.

Table 2. Description of the failures with wood as fuel

Description of Mechanical Issue	Farmer Time to Resolve (hrs)	Recommended Next Steps
Fuel auger motors failed	2 hours to replace	DC drive gearmotors failed approximately once a year. More robust AC gearmotors with variable frequency drives (VFDs) will be installed that will be more robust.
DC transformer failed	Few hours to replace	This was used to power the DC drive gearmotors. VFDs will replace the DC system.
Touchscreen control panel	Few hours	Dead spots would develop in the screen. This has been replaced twice.
Heat exchanger tube failure	1 week for parts and 1 day for replacement	Some of the tubes rusted, potentially due to poor water quality. LEI replaced the tubes.
Thermocouple in combustion chamber failed	Few hours	A thermocouple failed and was replaced.
Fuel stir arm failed	Few hours	The original design had combustion air going through the stir arm, and the stirm arm would only last for one year. The new stir arm does not have combustion air going through it.
Fuel stir arm driveshaft failure	Several hours	New design is much easier to replace where older design was much harder and took longer.
Flue gas fan failure	Several hours	Motor failure.

4.2 Temperature and Propane Savings

The Bio-Burner 500 heat delivery system demonstrated successful integration with the farms existing propane heating systems. The brooding house uses pancake-style propane heaters to deliver heat from the top down, while the radiant floor heat delivers heat from the bottom up.

The Bio-Burner 500 heat output has been variable, but typically falls in the range of 375,000 and 400,000 Btu/hr. Mr. Rodes estimates that he saves approximately 500-800 gallons per flock during the summer months and about 2,000 gallons per flock during the winter months, or approximately 10,000 gallons during one year.

4.3 Operation and Maintenance Requirements

Mr. Rodes estimates that he spends about five minutes a day checking on the unit while it is running and about 30 minutes a week to clean the boiler tubes and remove the ash when the unit is using wood chips for fuel. Miscellaneous maintenance and repairs require about three hours a month. The hopper is filled about 2-3 times a week and it requires 10 minutes per filling. Mr. Rodes estimates these numbers will be similar when the unit is operating with poultry litter instead of wood. He suggests that the unit may need to be cleaned more frequently.

5. Discussion

Most of the system failures were associated with components that were easily replaced, such as motors and electronic parts that are prone to wearing out over time. Some of these parts have been redesigned or upgraded to increase service life.

According to Mr. Rodes, with woodchips as a fuel, the unit has been reliable to date. However, he suggests that any biomass unit requires design and maintenance. Early adopters can expect to run into problems that require design changes, as he experienced with the Bio-Burner (for example, the combustion fuel stir bar needed replacing). Overall, he's been very happy with the unit to date.

Initial research and development and initial operation on Riverhill Farm suggests that the system, with modifications as discussed, will work with poultry litter as a fuel.

However, due to the increase in ash content when used with poultry litter, the entire ash handling system will need to be modified in the future. Currently the ash removal from the combustion chamber is automated, and a larger final container for the ash will be needed. The boiler tubes and cyclone are secondary sources of ash and are currently manual. These systems could be modified to automatically empty into the main ash collection area so that there is only one source of ash for the farmer to manage. This system is ideally suited for one to two poultry houses.

6. Recommendations and Next Steps

The project team recommends the following modifications to the unit to facilitate ease of use with poultry litter as a fuel:

- Modify ash removal in the boiler tubes to automate and streamline ash removal from the system.
- The ash hopper size should be increased to accommodate the increased amount of ash.
- LEI may want to consider building a larger unit that can provide heat to multiple poultry houses.

Appendix D

Technical Performance: Total Energy Blue Flame Boiler Heating System

A summary of preliminary technical performance findings funded by the
Farm Manure-to-Energy Initiative

December 2015

Contents

1. The Technology

The Blue Flame Boiler Heating System by Total Energy Solutions uses three main components for a complete manure-to-energy hydronic heating system:

1. The material handling equipment for litter and ash
2. A Blue Flame Stoker Boiler combustion unit that uses poultry litter as the feedstock
3. A hydronic heating system using CUBO brand heaters in the poultry houses

The system uses an off-the-shelf litter spreader (BBI, 24 ft. truck-mount spreader box without the spinners and the drive) converted to an electric drive. The litter is then conveyed from the litter spreader via an auger to the Blue Flame's surge hopper.

The Blue Flame stoker and boiler unit (Model CGS-W-M700) is a standard off-the-shelf combustion unit initially designed to be fueled with wood or coal, but which is now being fueled by poultry litter. With a maximum output capacity ranging from 1.5–2.0 MBtu/hr, this unit has approximately an 8:1 turn-down ratio, meaning it uses the poultry house temperatures to control the feed rate of the boiler, which in turn controls the heat output. When the houses call for more heat, the boiler ramps up; when the houses call for less heat, the boiler ramps down.

Within the Blue Flame stoker unit, a twin-screw feeding system meters the litter onto the moving chain combustion grate. Combustion is facilitated by a combination of underfire and overfire air, controlled by a programmable logic controller (PLC) to maximize efficiency and reduce emissions. The combustion process takes place all in one chamber above the chain grate. The oxidized flue gases then travel through a triple pass boiler where hot water is heated.

In this case study, hot water exiting the boiler is piped into two poultry houses heated by previously installed Modine (V/VN-279) downdraft hot water heaters (three heaters in the 10,000 square foot barn and four heaters in the 20,000 square foot barn).

From the boiler, the flue gasses pass through a set of cyclones to control emissions. The ash from the combustion chamber and the fly ash from the cyclones are automatically removed from the system and emptied into a dump hopper that the farmer must empty periodically.

This system was installed in the summer of 2015. It replaces and improves upon an older Blue Flame stoker and boiler heating system originally installed with funding from the National Fish and Wildlife Foundation in 2009; it delivered heat until 2014, when an electrical fire in the electrical distribution panel (not associated with the Blue Flame system) damaged this unit beyond repair. Insurance covered the replacement cost, and funds from the Farm Manure-to-Energy Initiative, Total Energy Solutions, and Windview Farm were used to improve system performance, based on lessons learned over the previous years.

The 2015 installation included design improvements that enhanced the system:

- The combustion section is now separate from the boiler section, which improves combustion efficiency and heat transfer to the water. The new boiler also has a remote monitoring capability — the programmable logic controller (PLC) — allowing updates from the factory and remote monitoring of the boiler performance.
- Mr. Curtis requested that the ash auger system be designed with an open U-trough (instead of a closed tube) to facilitate flow of rocks or other larger material (often associated with poultry litter) through the system. Previously, rocks would get jammed in the ash auger and shut down the system.
- The original hot water distribution system was completely removed and replaced. The original system used independent supply and return water lines and pumps to deliver hot water from the boiler to each Modine heater. The original demonstrated problems associated with pump and pipe sizing, which significantly compromised delivery of hot water to heaters located at the end of the poultry houses.
- The new design uses one sensorless, variable-speed pump located in the boiler room along with a single supply and return line to each poultry house. Each heater is now individually tapped off of the supply-and-return line. He also replaced underground piping to the houses with a heavy duty, pre-insulated, large-bore PEX pipe (3 in., Logstor).

Currently, the pump operates on a continual basis supplying hot water to the heaters at a steady rate. However, the farmer is considering installation of actuator valves that will allow for variable pump speed based on the heat requirements of the house. This change will improve energy efficiency. For example, energy requirements will be reduced from 5 HP to ¾ HP during periods of low heat-demand.

Figure 1. Litter spreader emptying into auger (left of picture).

Figure 3. Blue Flame stoker and boiler. The boiler sits on top of the combustion system.

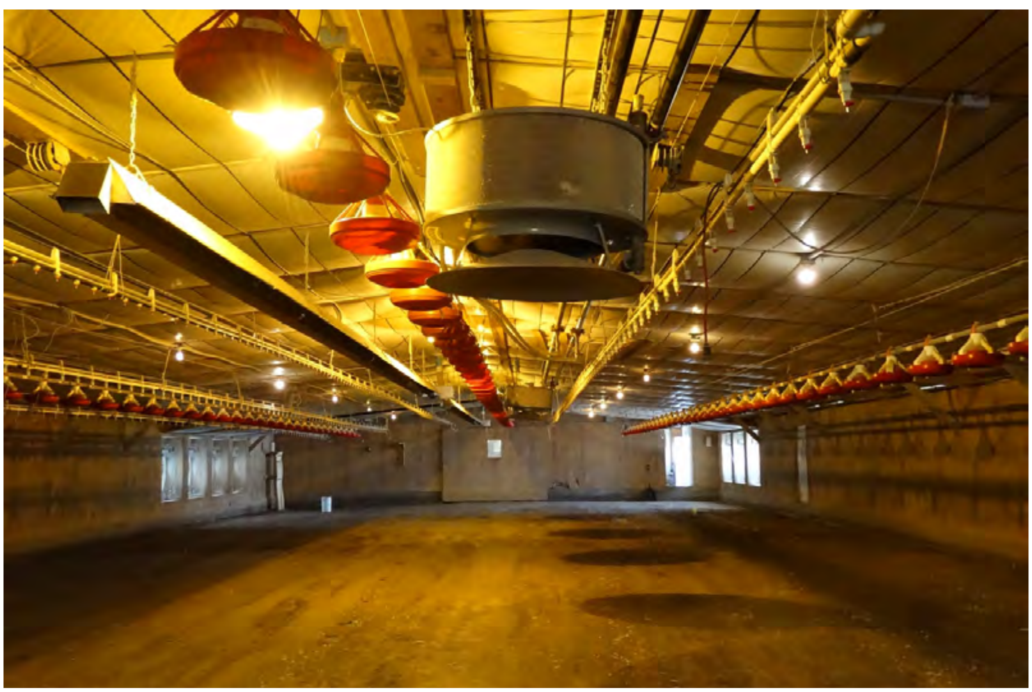


Figure 3. Modine heaters used in poultry houses.

2. The Farm

Windview Farm in Port Trevorton, Pennsylvania, grows approximately 440,000 anti-biotic free broiler chickens per year for Sullivan's Natural in two poultry houses. Each building consists of a 10,000 ft^2 section and a 20,000 ft^2 section, for 30,000ft^2 per building, or 60,000 ft^2 total. The farm places six to seven flocks per year with an average flock cycle of 40 days. Broilers are grown to varying weights depending on market demand.

The operation produces approximately 375 tons of poultry litter a year. Based on the farm's nutrient management plan recommendations, up to 2 tons per acre (for corn) are applied to 40 acres owned by the farm and an additional 100 acres of rented land. The application rate varies according to the crop production cycle, with corn and soybeans planted in rotation. Remaining poultry litter is exported off the farm.

Analysis of the poultry litter indicates that the energy value is 5,635 Btu/lb, the ash content is 12.53%, and the moisture value is 29.75% (for details on collection and analysis methods, see Appendix E). As required by the farm's integrator, the poultry houses are completely cleaned out between each flock, and old litter is entirely replaced with fresh litter. This is unusual, as most poultry growers scrape or "crust" out the top layer of litter between flocks, limiting whole house clean outs to once every very years to reduce costs associated with purchasing replacement bedding.

3. Objectives and Methods

3.1 Overall Performance Objectives

- Using poultry litter as a fuel, reliably deliver heat to poultry houses.
- Integrate seamlessly with the farm's existing propane and ventilation systems to keep house temperature within industry-recommended guidelines.
- Reduce propane use on the farm.
- Run successfully with minimal operation and maintenance requirements (routine maintenance and daily addition of poultry litter fuel).
- Operate with no negative impacts on bird production, and ideally improve bird health and production by allowing for increased winter ventilation and improved air quality.

3.2 Evaluation Method

Because installation of the new Blue Flame system took place during the summer of the last year of the project, the Farm Manure-to-Energy Initiative team was not able to collect monitoring data. However, the previous system had been used successfully on the farm for five years prior to being damaged in a fire. The technical performance discussion is based on prior operational history and one flock of operation during the 2015 cold weather season.

4. Performance Results

4.1 Reliability

The original Blue Flame boiler and heating system has operated for just over five years without any major problems. However, Mr. Curtis advises that it took a few flocks for him to learn how to operate the system and how to manage his litter in order to produce a good quality fuel for the boiler. The system has had only one failure in five years (a fan motor that had to be replaced).

The new system has been operated for one complete flock since the system was installed. According to Mr. Curtis, the changes made to the system have improved performance. He says they have plenty of hot water. He also observed that the U-shaped ash auger has reduced system downtime associated with rocks getting caught in the ash removal system.

4.2 Temperature and Propane Reductions

During the first few flocks of full time operation of the Blue Flame boiler, the amount of propane used was reduced by 90 percent. Even with 20-degree nighttime temperatures, the system generated 100% of the heat needed by the houses.

4.3 Operations and Maintenance

Mr. Curtis estimates that the system requires about 45 minutes per day to operate, including loading four bucket loads of poultry litter into the fuel feed hopper and unloading the ash. On colder days, operational time increases to one hour. This also includes removal of foreign debris from the litter.

According to the Mr. Curtis, the key to reliable operation of the system is managing the litter for good fuel quality. The drier the fuel, the better it will burn. Currently, the farm's integrator requires whole house clean outs between every flock. However, Total Energy Solutions recommends this approach for all farms using this system to improve performance and reliability.

Mr. Curtis also notes that while he has become very good at managing his litter, he has not been able to eliminate foreign objects like large rocks completely. Hence, on occasion, additional maintenance is required to remove a stone from the ash auger.

While the boiler system requires very little maintenance for things like greasing, the house heaters do require cleaning because of dust on the heat exchanger surfaces. Compressed air is used to blow the fans off a few times a week.

The system also requires attention upon shutdown to keep the boiler water temperature and the flue gas temperature close to each other to prevent condensation in the boiler tubes. A slow controlled shutdown is preferred, which takes a couple of days, but it only requires an extra 1-2 hours of monitoring by the farmer.

5. Discussion

With five years of operational time, the Blue Flame stoker and boiler heat delivery system is the longest-running poultry litter-fueled energy system in the Chesapeake Bay region. With this system, Mr. Curtis has realized significant fuel savings. For the newly installed system, now run for one flock, Mr. Curtis says that he is “extremely impressed.” He notes that “the litter is dry and the foot pads are good” and that “I don’t know that I would change anything. It is working extremely well.”

However, the requirement for whole house clean-out between every flock will likely be a concern for some growers. Because wood shavings used as bedding are expensive, most poultry farms in the region “scape out” or “crust out” between every flock, which entails removing the top layer of the litter only. Additional time and expense associated with whole house clean-outs between every flock would need to be taken into account in the operations and maintenance requirements for this system.

Blue Flame does offer a range of units as small as 1.0 to as much as 16.0 Mbtu output with poultry litter, making this system adaptable to farms of various sizes. Because the system delivers heat via hot water, there is some flexibility with respect to where the unit is located with respect to the poultry houses, although minimizing the distance reduces infrastructure costs.

As discussed in the air emissions chapter of the final report (Appendix E), Total Energy Solutions is working with emissions control experts to reduce particulate matter and nitrogen oxide emissions so that this technology can be installed in all the Bay states. They are focusing on emissions controls that are cost effective while meeting current permitting thresholds throughout the region.

6. Recommendations and Next Steps

Based on feedback from experts in poultry ventilation, this system is ideally suited to support improved cold-weather ventilation and house air quality, as well as providing a source of dry heat. There is currently very little published data on the impacts of this type of thermal manure-to-energy heating system on bird production. Because each of the Windview Farm poultry houses has two separate sections, this farm would be ideally suited for on-farm research to evaluate the impact of a poultry litter-fueled heating system on key poultry production metrics. These metrics could include growth rate, feed conversion, bird health, litter quality, paw quality, in-house air quality, etc.

As previously discussed, Total Energy Solutions will continue to work with project partners to improve air emissions and support expanded adoption throughout the region.

Appendix E

Air Emissions and Permit Compliance

A summary of findings from the Farm Manure-to-Energy Initiative

December 2015

Contents

1. Introduction

Characterizing air emissions of farm manure-to-energy technologies supported both environmental performance evaluation objectives and permitting for current and future installations. The Farm Manure-to-Energy Initiative team focused on states with concentrated poultry production in the Chesapeake Bay region, including Pennsylvania, Delaware, Maryland, Virginia, and West Virginia, and worked with state and federal agencies, including the USDA and EPA, to develop the emissions testing protocols to support permitting requirements. Regardless of where the technology demonstration was located, the Farm Manure-to-Energy steering committee challenged the vendors to demonstrate that their technology could meet permitting requirements for all five Bay states.

This report includes criteria and comprehensive air emissions data from three technologies currently installed in the region with funding from the Farm Manure-to-Energy Initiative (the Ecoremedy ® gasfier, Blue Flame boiler system, and LEI Bio-Burner 500). Because of technical issues with the Global ReFuel system and the need for further research and development (R&D) prior to additional installations (see Appendix A for more information), emissions from this technology were not characterized with funding from the Farm Manure-to-Energy Initiative. The vendor has provided third-party certified air emissions testing data to support the R&D process, which should include changes to the combustion and air emissions controls that would be expected to reduce air emissions. Additionally, although the Biomass Heating Solutions Limited (Bhsl) unit planned for an installation in Rhodesdale, MD, is not yet constructed and thus not available for emissions testing, Bhsl did provide third-party emissions test results for criteria pollutants from the Uphouse Farm Ltd. installation located in Norfolk, United Kingdom.

For the Ecoremedy gasifier, Blue Flame Boiler system, and Bio-Burner 500, air emissions of nitrogen and phosphorus species were also used to determine the fate of poultry litter nitrogen and phosphorus. Results from this analysis are included in Appendix G.

1.1 State Permitting Requirements

All five of these states have different permitting requirements for farm-scale thermal manure-to-energy technology systems (see Table 1), but all require data on air emissions for state regulatory compliance.

Table 1. Summary of Chesapeake Bay state permitting requirements for farm-scale thermal manure-to-energy technologies using manure or poultry litter as a fuel

State	State Permitting Requirements
Delaware	Delaware permits all farm-scale systems. To be eligible for operation in Delaware, the system must be on a farm, using only farm manure or litter as a fuel. The system cannot process over 3,000 lbs/hour, and combustion temperatures must meet or exceed 1,400°F. Thresholds for particulate matter (PM) are set based on fuel feed rate. For more information, see: http://regulations.delaware.gov/AdminCode/title7/1000/1100/1107.shtml#TopOfPage
Maryland	Maryland permits all farm-scale systems and sets thresholds for permit eligibility based on PM and oxides of nitrogen (NOx) emissions rates. Thresholds for PM and NOx vary by the location and fuel feed rate (Btu/hour). Although thresholds are set for PM and NOx, the Maryland Department of Environment also requests data on emissions of other criteria and hazardous air pollutants. For the biomass permitting regulations, see http://www.dsd.state.md.us/comar/comarhtml/26/26.11.09.12.htm. For a description of permit areas, see http://www.dsd.state.md.us/comar/comarhtml/26/26.11.01.03.htm.
Pennsylvania	Pennsylvania requires a plan approval (analogous to a construction permit in other states) and an operation permit. However, smaller farm-scale systems (< 2.5 MBtu/hour fuel input) can apply for a plan approval exemption. Thresholds are established for criteria pollutants above which a Title V permit may be required. For more information see: http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-96215/275-2101-003.pdf
Virginia	Virginia sets thresholds for criteria pollutants below which farm-scale manure-to-energy projects would be exempt from permitting. Projects that fall above the thresholds are eligible for permitting under the Minor New Source Review program. Virginia also has established a Biomass Pilot Test Facility General Permit that allows for construction and minimal operation for the purposes of collecting performance data necessary to determine permit requirements. For more information, see: http://www.deq.virginia.gov/Programs/Air/PermittingCompliance/Permitting/BiomassPermittingRequirements.aspx
West Virginia	West Virginia farm-scale manure-to-energy installations may need two permits to operate: one for solid waste management (to meet requirements of Title 33 Series 1 Solid Waste Management Rule §33-1-5) and one for air emissions (to meet requirements of Title 45 Series 13). West Virginia may also issue a research permit for pilot projects to support the permitting process. For more information, see: http://www.dep.wv.gov/pio/Documents/Rules%202011/DWWM/Solid%20Waste/Waste%20Mgt.%2033-1.%20Solid%20Waste%20Management%20Rule.pdf and http://www.dep.wv.gov/daq/planning/Documents/45-13.pdf.

1.2 Federal Regulatory Compliance

Air emissions data (NOx emissions specifically) and poultry litter fuel characteristics were used to support federal Clean Air Act compliance. When the Farm Manure-to-Energy Initiative project began in the fall of 2011, federal rules for determining how farm scale poultry litter-to-energy technologies would be permitted were still in the draft stage. The project team worked closely with EPA Region 3 staff in the Air Toxics and Non-Hazardous Secondary Materials program to understand these rules and ensure that the demonstration projects would comply with the regulations.

At this time, the federal rules for farm-scale systems have been finalized. In summary, two sections of the Clean Air Act potentially apply to hazardous air pollutant (HAP) emissions from on-farm thermal technologies using manure or poultry litter as a fuel source. These rules fall under Section 129 of the Clean Air Act, which addresses HAP emissions from combustion of solid waste (i.e., incineration), and Section 112 of the Clean Air Act, which addresses emissions of air toxics from the combustion of fuel in systems used to produce and capture energy. Both Section 112 and Section 129 cover combustion technologies, but Section 129 requirements for combustion of solid waste are much stricter than Section 112 requirements for the combustion of fuel in systems used to produce energy. Projects that fell under the purview of Section 129 would not be appropriate for deployment at the farm-scale.

The key to ensuring the proposed farm-scale thermal system falls under the purview of Section 112 (for combustion of fuels) and not Section 129 (for incineration of solid waste) is to ensure that the farm's manure or poultry litter meets EPA's "fuel legitimacy criteria." Although manure and poultry litter are not considered by EPA to be traditional fuels like coal and wood, EPA recognized that they can have legitimate fuel value in some circumstances. The EPA Non-Hazardous Secondary Materials (NHSM) rule (Title 40 Part 241 Subpart B § 241.3) details the process for determining whether a non-hazardous secondary material (like manure or poultry litter) meets EPA's fuel legitimacy criteria. For farm-scale thermal systems that will be fueled only by manure or poultry litter produced on the farm, the NHSM rule is designed to be self-implementing. In other words, the farmer determines, without any EPA or other regulatory agency involvement, whether the manure meets EPA's fuel legitimacy requirements when combusted in the proposed thermal technology. (Upon request, EPA will review these determinations and issue a written opinion, but that process is not required.)

Partners in the Farm Manure-to-Energy Initiative developed a checklist to help farmers participating in the project self-determine whether their poultry litter met EPA's fuel legitimacy criteria. The checklist was developed with feedback from USDA and EPA staff (in particular, with support from U.S. EPA Region 3 staff), but it is not an official EPA or USDA guidance document. Farmers who are interested in using this approach for the NHSM fuel-legitimacy process should contact their regional EPA office to determine whether this is acceptable in their region or to request more information on the self-determination or non-waste determination process.

The NHSM rule also notes that farmers who choose to use the self-determination approach should keep records documenting the rationale for their decision, including any documents used in the decision-making process (such as lab analysis of poultry litter heat value and contaminant levels). Written justification for the determination decision and any other documents justifying the decision process would also be appropriate.

Once the determination has been made that the farm's manure or poultry litter meets federal fuel legitimacy requirements, the next step is to determine whether the unit must be registered. The farm-scale technologies demonstrated with funding from this project were not required to register because they were either: 1) not a boiler (e.g., the Global ReFuel air-to-air heating system), or 2) defined as a hot water heater with heat delivery capacity below 1.6 MBtu/hour (see 40 CFR § 63.11237 definition of "hot water heater"). For larger hot water boiler systems, federal rule compliance involves registration and biennial tune-ups (for more information, see EPA's website on Boiler Compliance at Area Sources[1]). EPA oversees this program in Delaware, Pennsylvania, Virginia and West Virginia, while the Maryland Department of Environment is responsible for implementing this program in Maryland.

1.3 Improving on Air Emissions Controls

Based on initial performance data and visual observations, it was apparent that some vendors would have difficulty meeting all Bay state permitting requirements for particulate matter, while at least one vendor (Bhsl) identified an engineering solution. Vendors used a variety of approaches to reduce particulate matter emissions including:

- LEI Products (Bio-Burner 500) addressed this issue by conducting in-house R&D to develop a wet scrubber system to complement an existing cyclone to improve particulate matter removal. This system has been evaluated over the last 1-2 years at their facility in Kentucky using poultry litter as a fuel and was installed at Riverhill Farm for demonstration with funding from this project.
- Blue Flame (Blue Flame Boiler System offered in the United States by Total Energy Solutions) conducted in-house R&D to improve the performance of the air emissions controls (cyclones) that come with their system.
- Wayne Combustion used a stepwise approach focusing on reducing cost and complexity of the emissions control system. They evaluated options for improved stack design, cyclone emission controls, and baghouses. With respect to baghouses, they observed clogging of bag pores with system shutdown. As cooler air passed through the baghouse, moisture condensed with fine particulate matter and clogged the bag pores.
- Enginuity Energy also proposed baghouses for particulate matter emissions control. They observed the same clogging issue with system shutdown.

[1] http://www3.epa.gov/boilercompliance/ - areasource

- Biomass Heating Solutions Ltd. uses baghouses successfully for farm-scale poultry litter-to-energy emissions controls and has deployed these emission control systems on three farms in the United Kingdom (Figure 1). However, considerable research and development was invested to adapt baghouses for use with their fluidized bed combustion system.

Figure 1. Baghouse emissions control system used by Biomass Heating Solutions Ltd. at the Uphouse Farm in Norfolk, United Kingdom

To support Enginuity Energy, Total Energy Solutions, and Wayne Combustion Systems in their efforts to reduce air emissions for particulate matter, the project team reached out to air emissions experts for advice and support. The first expert consulted was Greg Zwicke, with the USDA-NRCS Air Quality and Atmospheric Change Team. Mr. Zwicke connected the team with Dr. Michael Buser, associate professor at Oklahoma State University. Dr. Buser specializes in air emissions controls for agricultural production systems and worked directly with Enginuity Energy (Ecoremedy gasifier), Total Energy Solutions (Blue Flame's Stoker Boiler), and Wayne Combustion (Global Re-Fuel) to improve the design of emissions control systems.

Dr. Buser recommended cyclones as the first approach to reducing particulate matter emissions. Cyclones have several advantages, which include the following:

- Low capital costs
- No moving parts, therefore low maintenance requirements and operating costs
- Minimal space requirements[2]

Dr. Buser worked with the project team to design a system with two cyclones operated in a series to reduce particulate matter emissions (Figure 2). Based on testing results, the plan is to refine the design as necessary to meet state permitting requirements. Even if advanced emissions controls are needed (baghouses, for example), well-designed cyclones will improve performance and reduce maintenance costs of additional emissions control systems.

Figure 2. Cyclones installed to treat emissions for the Blue Flame stoker boiler at Windview Farm

2. Air Emissions Performance Objectives

The project team defined appropriate technologies as those that:

[2] EPA Air Pollution Control Technology Fact Sheet (EPA-452/F-03-005).

1) Meet all Bay state air permitting requirements
2) Are safe for farm workers and surrounding communities
3) Reduce nonpoint source nutrient pollution loading to aquatic resources relative to land application of excess poultry litter

3. Project Approach and Methods

3.1 Developing the Emissions Testing Plan

The air emissions monitoring component of the project was developed in consultation with air emissions experts from USDA, EPA, and Chesapeake Bay state air permitting agencies to facilitate use of the data to inform air permitting decisions in all high-density animal production areas of the Chesapeake Bay region (Delaware, Maryland, Pennsylvania, Virginia, and West Virginia). In addition to permitting agency staff, project partners consulted with representatives from the environmental community to solicit their feedback on the air emissions monitoring strategy.

3.2 Tested Systems and Locations

Based on this emission testing plan, the Farm Manure-to-Energy Initiative funded comprehensive emissions testing for three manure-to-energy systems in region: the Blue Flame boiler at Windview Farm (Port Trevorton, PA); the Ecoremedy gasifier at Flintrock Farm (Lititz, PA); and the LEI Bio-Burner 500 at Riverhill Farm (Port Republic, VA).

In addition to comprehensive testing at these three farms, a second round of testing was conducted at each location focusing only on particulate matter. This second test followed improvements made to emissions control systems based on results from the first round of tests.

3.3 Characterizing System Fuel Feed Rate

To support reporting of air emissions for state permitting requirements, project partners also characterized the fuel feed rate (lb/hr) as well as the fuel energy input feed rate, reported in units of MBtu/hr for the LEI Bio-Burner, Ecoremedy gasifier, and Blue Flame boiler. Energy value of the poultry litter was measured “as-is” using ASTM-D (Table 2). Bhsl provided data on fuel feed rate and analysis results of the poultry litter energy value for the Uphouse Farm installation.

For the Ecoremedy gasifier, Blue Flame boiler, and Bio-Burner 500, the rate of feed rate throughout the testing period varied according to the system designs. The Ecoremedy gasifier is a fixed feed rate system so the rate stayed the same throughout the duration of both emissions tests. The Bio-Burner 500 maintains a relatively constant feed rate over time, but the system does modulate the feed rate based on the combustion temperature. The Blue Flame boiler feed rate modulates based on house temperature and thus has the highest potential for feed rate variability.

For the first round of emissions testing of the Bio-Burner 500 (at Riverhill Farm) and the Ecoremedy gasifier (at Flintrock Farm), the project team used the total volume of the litter hopper, density of the litter, and start and stop time of when the hopper was filled and emptied to calculate the feed rate. The calculated feed rate using this method matched the feed rate predicted by the Ecoremedy gasifier to within 10 lbs per hour. The system using the Blue Flame boiler (at Windview Farm) included a BBI fuel hopper with four truck scales located under the hopper. Scale readings were taken when the hopper was loaded and periodically as the hopper emptied. Using this information, a time-weighted average feed rate was calculated for this site.

For the second round of particulate matter testing, the testing interval was too short to allow for complete emptying of the fuel feed hopper. Hence, the system-predicted feed rates for the Blue Flame boiler and Ecoremedy gasifier displayed on the control panel during the test duration were used. Although the system is designed to adjust the feed rate based on house heat demand, Total Energy maintained a steady feed rate through the Blue Flame boiler system for the duration of this shorter test. For the Bio-Burner 500, change of depth in fuel in the feed hopper bin during the duration of the test along the bulk density of the litter was used to calculate the fuel feed rate.

In addition to feed rate, poultry litter fuel characteristics from Riverhill Farm, Flintrock Farm, and Windview Farm were analyzed to support federal Clean Air Act compliance. In addition to poultry litter samples from these farms, samples from 8 other farms participating in the project and/or that were considering participating in the project were also collected. Over the course of the project, a total of 11 samples were collected from poultry litter storage sheds according to methods described in Peters et. al (2003). At each location, 10 samples were collected from various locations throughout the pile, at least 18 inches below the surface and thoroughly mixed in a clean, 5-gallon pail. One-pound subsamples were collected from the pail and sent to Brookside Laboratories and the Clemson Agricultural Services Laboratory for moisture, energy value, trace metals, non-metal elements (nitrogen, sulfur, chlorine, fluorine) and 16 polycyclic hydrocarbons (PAH) analysis. Additionally, some of the samples were analyzed for ash content. The sample analysis plan was designed with guidance from EPA staff to support federal Non-Hazardous Secondary Material (NHSM) fuel legitimacy determinations. Table 2 summarizes the poultry litter components analyzed and analysis methods. Ash content was analyzed using samples from Flintrock Farm, Riverhill Farm, and Windview farm only.

Table 2. Poultry litter sampling constituents including unit, method, and analytical laboratory

Constituent	Unit	Method	Analytical Laboratory
Moisture	%	Clemson: Wolf, Wolf and Hoskins 1997, SERA6/NEC-67 Brookside: ASTM D4006	Clemson* and Brookside**
Energy Value	Btu/lb	ASTM D	Brookside
Ash	%	EPA Method 160.4	Brookside
Bulk Density	grams/cubic centimeter	ASABE S269.4	Clemson
Organic nitrogen	%	Adapted from AOAC 990.3	Clemson
Ammonia nitrogen	%	Adapted from AOAC 973.49 & EPA 350.2	Clemson
Nitrate-nitrogen	%	Peters et. al. (2003)	Clemson
Sulfur	%	Adapted from EPA 3050	Clemson
Chloride	mg/L	EPA 300.0	Brookside
Fluoride	mg/L	EPA 300.0	Brookside
Calcium Carbonate Equivalency	%	Adapted from AOAC Method 955.01	Clemson
pH		Adapted from AOAC 973.04	Clemson
Aluminum	ppm	Adapted from EPA 3050	Clemson
Arsenic	ppm	Adapted from EPA 3050	Clemson
Antimony	mg/L	EPA 3050B (Prep) EPA 6020B (Analytical)	Brookside
Beryllium	mg/L	EPA 3050B (Prep) EPA 6020B (Analytical)	Brookside
Boron	ppm	Adapted from EPA 3050	Clemson
Cadmium	ppm	Adapted from EPA 3050	Clemson
Calcium	ppm	Adapted from EPA 3050	Clemson
Chromium	ppm	Adapted from EPA 3050	Clemson
Cobalt	mg/L	EPA 3050B (Prep) EPA 6010B (Analytical)	Brookside
Copper	ppm	Adapted from EPA 3050	Clemson
Iron	ppm	Adapted from EPA 3050	Clemson
Lead	ppm	Adapted from EPA 3050	Clemson
Magnesium	ppm	Adapted from EPA 3050	Clemson
Mercury	mg/L	EPA 245.1 (Prep) EPA 7471A (Analytical)	Brookside
Manganese	ppm	Adapted from EPA 3050	Clemson
Molybdenum	ppm	Adapted from EPA 3050	Clemson
Nickel	ppm	Adapted from EPA 3050	Clemson
Phosphorus	%	Adapted from EPA 3050	Clemson
Phosphorus, Soluble	%	Adapted from EPA 3050	Clemson
Potassium	%	Adapted from EPA 3050	Clemson
Selenium	ppm	Adapted from EPA 3050	Clemson
Sodium	ppm	Adapted from EPA 3050	Clemson
Zinc	ppm	Adapted from EPA 3050	Clemson
16-PAH*			Brookside
acenaphthene	ug/L	EPA Method 8270	Brookside

acenaphthylene	ug/L	EPA Method 8270	Brookside
anthracene	ug/L	EPA Method 8270	Brookside
benzo[*a*]anthracene	ug/L	EPA Method 8270	Brookside
benzo[*b*]fluoranthene	ug/L	EPA Method 8270	Brookside
benzo[*k*]fluoranthene	ug/L	EPA Method 8270	Brookside
benzo[*ghi*]perylene	ug/L	EPA Method 8270	Brookside
benzo[*a*]pyrene	ug/L	EPA Method 8270	Brookside
chrysene	ug/L	EPA Method 8270	Brookside
dibenzo(a,h)anthracene	ug/L	EPA Method 8270	Brookside
fluoranthene	ug/L	EPA Method 8270	Brookside
fluorene	ug/L	EPA Method 8270	Brookside
indeno(1,2,3-cd)pyrene	ug/L	EPA Method 8270	Brookside
naphthalene	ug/L	EPA Method 8270	Brookside
phenanthrene	ug/L	EPA Method 8270	Brookside
pyrene	ug/L	EPA Method 8270	Brookside

* Clemson Agricultural Services Laboratory
** Brookside Laboratory

3.4 Air Emissions Testing Strategy and Methods

A third-party, certified air emissions testing company was selected through a request-for-proposal process that considered bids and company qualifications to characterize emissions from three farm-scale manure-to-energy systems. Environmental Source Samples, Inc., based in Wilmington, NC, was selected for all three projects.

The pollutants tested and testing methods were developed based on feedback from Virginia, Pennsylvania, Maryland, Delaware, West Virginia, and the San Joaquin Valley Air Pollution Control District (who were consulted because of their past experience with gasification emissions). Federal agency air emissions experts with the USDA Natural Resources Conservation Service Air Quality and Atmospheric Change Team and the EPA Air Toxics program were also consulted. The project team also sought feedback from Mr. Walter Smith, a former EPA air permitting specialist.

Based on these recommendations and the constraints of the project budget, the EPA methods for criteria air pollutants, ammonia (NH_3), and hazardous air pollutants listed in Table 3 were selected for evaluation.

Table 3. Air emissions parameters and methods proposed for evaluation

Parameter Type	Method	Parameter
Criteria Pollutants	EPA Method 7E	NOx
	EPA Method 6C	SO_2
	EPA method 10	CO
	EPA Method 5*	Particulate matter
	EPA Method 202	Filterable particulate matter
	EP Method 25(a)	VOC
Air Toxics	EPA Method 18	Aldehydes (acetaldehyde, acrolein,)
	EPA Method 316	Formaldehyde
	EPA Method 18	Organic compounds (benzene, styrene, xylene, and trichloroethylene)
	EPA Method 26a	Hydrogen halides (HCl/HFl)
	EPA Method 29	Metals[5] (Ref. Method 29)
	EPA Method 23	PAH (incl. napthalene)
	EPA Method 23	Dioxins and furans (total mass and TEQ)
Other	EPA Method 9	Stack height and opacity (Ref. Method 9)
	EPA Method CTM-027	NH_3
	EPA Method 1,2, and 3A, 4	Exhaust flow rate, sampling points, velocity, molecular weight, moisture content, O_2, CO_2

3.5 Characterizing Particulate Matter

Scanning electron microscopy (SEM) was used to further characterize the particulate matter captures on filter media during the source emission work in executing EPA Method 5 and EPA Method 202. EPA Methods 5 and 202 each isokinetically collect particulate matter on a media filter for subsequent gravimetric analysis. In the case of EPA Method 5, the collected particulate matter is identified as filterable particulate matter (FPM) and was collected on a glass media filter. For EPA Method 202, the collected particulate matter is identified as condensable particulate matter (CPM) and was collected on polytetrafluoroethylene (PTFE) filter media. The summation of FMP and CPM is the total particulate emission rate. On November 5, 2015, analysis was conducted at Virginia Tech's Institute for Critical Technology and Applied Science's Nanoscale Characterization and Fabrication Laboratory (VT-ICTAS-NCFL) and performed using the FEI Quanta 600 FEG Environmental Scanning Electron Microscope (ESEM). The analysis was performed with the assistance and expertise of Stephen McCartney, senior research associate at VT-ICTAS-NCFL, and John Ignosh. The ESEM, coupled with energy-dispersive spectroscopy (EDS), assisted in both the initial chemical analysis and preliminary particle size information for selected particles viewed in the ESEM.

3.6 Evaluating Health Impacts

Based on recommendations from USDA and state regulatory agency air emissions experts, the project team planned to use data collected via air emissions monitoring to run EPA's SCREEN3 model. The SCREEN3 model is a single- source Gaussian plume model, which provides maximum ground-level concentrations for point sources. These concentrations can then be compared to the National Ambient Air Quality Standards (NAAQS) for criteria pollutants or the Significant Ambient Air Concentration (SAAC) for air toxics. The SAAC is the concentration of a toxic pollutant in the air that may have adverse health impacts if it exceeds the threshold. For NAAQS that include 24-hour and annual concentration standards, SCREEN3 procedures document (U.S. EPA, 1995) recommended adjustment factors were applied to predicted maximum 1-hour concentrations to generate maximum 24-hour and annual concentrations. Pollutants for which established NAAQS or SAAC thresholds were identified are listed in Table 4.

Table 4. Pollutants analyzed using SCREEN3 and the sources of thresholds used for comparison. National Ambient Air Quality Standards (NAAQS) or Significant Ambient Air Concentration (SAAC) for air toxics

Pollutants	Threshold Source	Pollutants	Threshold Source
NO x (lbs/hr)	NAAQS	HCl (lbs/hr)	SAAC
SO2 (lbs/hr)	NAAQS	HF (lbs/hr)	SAAC
CO (lbs/hr)	NAAQS	Antimony (lbs/hr)	SAAC
Total FPM (lbs/hr)*	NAAQS	Arsenic(lbs/hr)	SAAC
Total CPM (lbs/hr)*	NAAQS	Beryllium(lbs/hr)	SAAC
Total PM (lbs/hr)*	NAAQS	Cadmium(lbs/hr)	SAAC
		Chromium(lbs/hr)	SAAC
		Lead(lbs/hr)	SAAC
		Manganese (lbs/hr)	SAAC
		Mercury (lbs/hr)	SAAC
		Nickel (lbs/hr)	SAAC
		Phosphorous (lbs/hr)	SAAC
		Selenium (lbs/hr)	SAAC
		Biphenyl	SAAC
		Napthalene	SAAC
		Formaldehyde	SAAC
		Acetaldehyde	SAAC
		Acrolein	SAAC
		Benzene	SAAC
		Styrene	SAAC
		Trichloroethylene	SAAC
		Total Xylene	SAAC

*For the purpose of SCREEN3 analysis, filterable, condensable, and total PM was compared to the NAAQS for PM10 and PM2.5

Also, because EPA methods for measuring fine particulate matter emissions from stationary sources (i.e., EPA Method 201A) were not applicable to the demonstration projects (due to their smaller stack size), the analysis assumed that all particulate matter is fine particulate matter (less than 2.5 um in size). This is a conservative approach but also the most likely to identify public health concerns.

4. Results

4.1 Fuel Feed Rate and Characterization

Results from fuel feed rate and energy value calculations are presented in Table 5. BHSL data on the poultry litter used to fuel the Bhsl Uphouse installation indicated that the fuel had a lower heating value proximate analysis of 11, 595 kJ/Kg (or 4,984 Btu/lb). The fuel feed rate for the Bhsl Uphouse system was 10 Metric tons/day, or 917 lb/hour).

Table 5. Fuel feed rate and energy value for poultry litter used for the Ecoremedy gasifier, LEI Bio-Burner 500, Blue Flame boiler, and Bhsl system

Technology	Sample Date	Feed Rate	Feed Rate	Energy Value	Fuel Input Rate
		lb/h	tons/yr	Btu/lb	MBtu/hr
Blue Flame Boiler	8/17 to 8/18/15	333	1,459	5,667	1.89
Blue Flame Boiler	10/22/15	244	1,069	5,635	1.37
Ecoremedy Gasifier	8/13 to 8/15/15	260	1,139	4,920	1.28
Ecoremedy Gasifier	10/7/15	234	1,025	4,637	1.09
Bio-Burner 500	9/2 to 9/4/15	73	320	4,030	0.29
Bio-Burner 500	10/8/15	104.5	458	5,957	0.62
Bhsl	11/10/15	917	4,016	4,984	4.57

Results from poultry litter analysis of 11 farms in the region (the Riverhill Farm, the Flintrock Farm, and Windview Farm, as well as 8 other farms in the region) suggest that contaminant values fall well within ranges typical for coal and wood, fuels that in most cases could also be used in thermal farm scale manure-to-energy systems (Table 6). Based on Brookside Laboratory concerns about organic acid interference with fluoride detection with EPA Method 300.0, only results from EPA method SM 4500-C are reported. Ash content ranged between 12.5 and 23.7%.

Table 6. Contaminant values in poultry litter from 11 farms in the Chesapeake Bay region (conventional, organic, and antibiotic free) compared to contaminants found in traditional fuels (coal and wood)

Contaminant	Units	Traditional solid fuel range	Lowest Value in 11 Poultry Litter Samples	Highest Value in 11 Poultry Litter Samples
		As-Is		
Energy Value*	Btu/lb	>5,000	3,255	5,909
		Dry Basis		
Antimony (Sb)	ppm	ND - 26	ND	ND
Arsenic (As)	ppm	ND - 298	ND	7.73
Beryllium (Be)	ppm	ND - 206	ND	ND
Cadmium (Cd)	ppm	ND - 19	ND	0.26
Chromium (Cr)	ppm	ND - 340	1.97	9.57
Cobalt (Co)	ppm	ND - 213	ND	ND
Lead (Pb)	ppm	ND - 229	ND	5.82
Manganese (Mn)	ppm	ND – 15,800	420	686
Mercury (Hg)	ppm	ND - 3.1	ND	ND
Nickel (Ni)	ppm	ND - 730	8.11	70.74
Selenium (Se)	ppm	ND - 74.3	ND	ND
Chlorine (Cl)**	ppm	ND – 9,080	83	8,769
Flourine (F)**	ppm	ND - 300	ND	26
Nitrogen (N)**	ppm	200 - 54,000	42,296	52,473
Sulfur (S)**	ppm	ND - 61,300	4,098	15,382
16-PAH	ppm	6 - 253	ND	ND

*For proposed fuels below 5000 Btu/lb, cost-effectiveness of energy production is a critieria for EPA fuel legitimacy determination.

**For contaminant comparison purposes, EPA's final non-hazardous secondary material rule notes that EPA did not intend to consider chlorine, flourine, nitrogen and sulfur contaminants if they do not result in the formation of air pollutants. For more information, see page 9141-9142 of Commercial and Industrial Solid Waste Incineration Units: Reconsideration of Final Amendments; Non-Hazardous Secondary Materials that are Solid Waste (http://www3.epa.gov/epawaste/nonhaz/define/rulemaking.htm - 122012)

For more information on federal permitting for farm-scale thermal systems, see: http://www.extension.org/pages/70264/start-up-questions-and-considerations-for-manure-to-energy-projects - .VfLrT2TBzRY

4.2 Characterization of Air Emissions

Emissions Testing

Third party, certified emissions test results for criteria and hazardous air pollutants, as well as data from the second particulate matter emissions test, is included in Table 7. Figure 2 shows the change in total particulate matter emissions between the first and second tests.

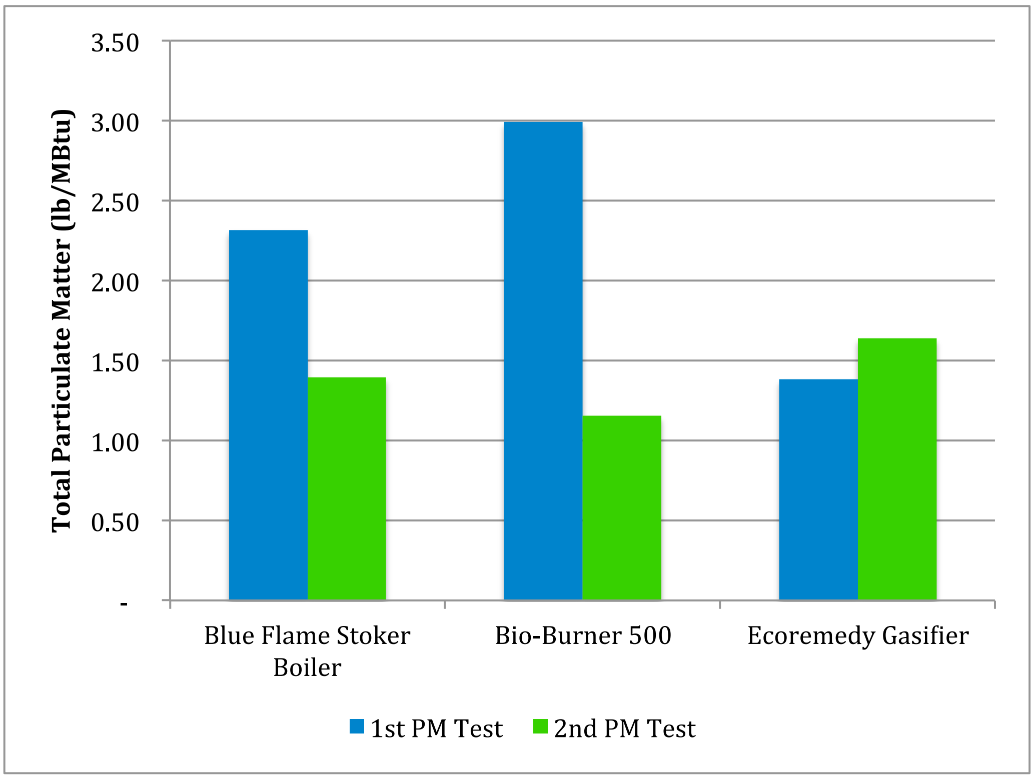


Figure 2. Change in total particulate matter emissions rate between the first and second emissions test

Table 7. Third-party, certified air emissions test results from poultry litter-to-energy fueled technologies (Environmental Source Samplers, Inc.)

Parameter	Blue Flame Boiler				EcoRemedy Gasifier				LEI Bio-Burner 500				Biomass Heating Solutios Limited			
	lb/h**	lb/yr	tons/yr*	lb/MMBtu	lb/h	lb/yr	tons/yr*	lb/MMBtu	lb/h	lb/yr	tons/yr*	lb/MMBtu	lb/h	lb/yr	tons/yr*	lb/MMBtu
	August 17 to 18th, 2015				August 13-15, 2015				September 2-4, 2015				10-Nov-15			
NOx	1.36	11914	5.96	0.72	0.13	1139	0.57	0.10	0.16	1402	0.70	0.54	0.14	1236.00	0.62	3.09E-02
SO2	0.32	2803	1.40	0.17	0.90	7884	3.94	0.70	0.00E+00	0.00	0.00	0.00	3.86E-05	0.34	1.69E-04	8.44466E-06
CO	1.04	9110	4.56	0.55	0.21	1840	0.92	0.16	4.00E-02	350	0.18	0.14				
Total Filterable PM	4.37	38281	19.14	2.32	1.67	14629	7.31	1.31	0.87	7621	3.81	2.96	1.83E-03	16.03	8.01E-03	4.01E-04
Condensable PM	8.80E-02	771	0.39	4.66E-02	0.10	902	0.45	0.08	6.00E-03	53	0.03	0.02				
Total PM	4.46	39070	19.53	2.36	1.77	15505	7.75	1.38	0.88	7709	3.85	2.99				
VOC	1.53E-02	134	6.70E-02	8.11E-03	1.05E-06	9.20E-03	4.60E-06	8.21E-07	1.00E-03	8.76	4.38E-03	3.40E-03				
Hydrogen Chloride	0.36	3127	1.56	0.19	0.49	4317.80	2.16	0.39	1.68E-02	147	7.36E-02	5.71E-02				
Hydrogen Fluoride	2.40E-03	21.02	1.05E-02	1.27E-03	6.30E-03	55.19	2.76E-02	4.92E-03	1.00E-04	0.88	1.00E-04	3.40E-04				
Ammonia (NH3)	1.20E-03	10.51	5.26E-03	6.36E-04	3.10E-03	27.16	1.36E-02	2.42E-03	1.00E-04	0.88	4.33E-03	3.40E-04				
Phosphorus	1.99E-02	174.32	8.72E-02	1.05E-02	1.30E-03	11.39	5.69E-03	1.02E-03	4.33E-03	37.9	1.90E-02	1.47E-02				
Formaldehyde	4.86E-05	0.43	2.13E-04	2.57E-05	1.07E-05	9.37E-02	4.69E-05	8.36E-06	6.20E-06	5.43E-02	2.72E-05	2.11E-05				
Acetaldehyde	8.95E-05	0.78	3.92E-04	4.74E-05	5.70E-05	0.50	2.50E-04	4.46E-05	5.48E-05	0.48	2.40E-04	1.86E-04				
Acrolein	4.68E-05	0.41	2.05E-04	2.48E-05	3.02E-05	0.26	1.32E-04	2.36E-05	4.64E-05	0.41	2.03E-04	1.58E-04				
Benzene	0.11	972	0.49	5.88E-02	2.10E-02	184	9.20E-02	1.64E-02	3.75E-02	329	0.16	0.13				
Styrene	0.12	1016	0.51	6.15E-02	2.63E-04	2.30	1.15E-03	2.06E-04	3.97E-02	348	0.17	0.13				
Trichloroethylene	0.18	1612	0.81	9.75E-02	4.37E-04	3.83	1.91E-03	3.42E-04	6.41E-02	562	0.28	0.22				
Total Xylene	0.22	1936	0.97	1.17E-01	4.28E-02	374.93	1.87E-01	3.35E-02	7.37E-02	646	0.32	0.25				
Antimony	9.90E-06	0.09	4.34E-05	5.25E-06	3.19E-06	0.03	1.40E-05	2.49E-06	2.39E-07	0.00	1.05E-06	8.12E-07				
Arsenic	4.56E-05	0.40	2.00E-04	2.42E-05	2.77E-05	0.24	1.21E-04	2.17E-05	4.50E-04	3.94	1.97E-03	1.53E-03				
Beryllium	1.91E-06	0.02	8.37E-06	1.01E-06	7.97E-07	0.01	3.49E-06	6.23E-07	5.99E-07	5.25E-03	2.62E-06	2.04E-06				
Cadmium	2.25E-05	0.20	9.86E-05	1.19E-05	2.33E-05	0.20	1.02E-04	1.82E-05	5.25E-06	4.60E-02	2.30E-05	1.78E-05				
Chromium	4.25E-05	0.37	1.86E-04	2.25E-05	6.34E-05	0.56	2.78E-04	4.96E-05	1.20E-04	1.05	5.26E-04	4.08E-04				
Lead	1.49E-04	1.31	6.53E-04	7.90E-05	1.07E-04	0.94	4.69E-04	8.36E-05	4.11E-05	0.36	1.80E-04	1.40E-04				
Manganese	9.96E-04	8.72	4.36E-03	5.28E-04	9.92E-05	0.87	4.34E-04	7.75E-05	9.78E-05	0.86	4.28E-04	3.32E-04				
Mercury	1.00E-06	0.01	4.38E-06	5.30E-07	9.81E-07	0.01	4.30E-06	7.67E-07	4.47E-07	3.92E-03	1.96E-06	1.52E-06				
Nickel	5.50E-05	0.48	2.41E-04	2.91E-05	3.61E-05	0.32	1.58E-04	2.82E-05	1.67E-05	0.15	7.31E-05	5.68E-05				
Selenium	1.04E-04	0.91	4.56E-04	5.51E-05	4.71E-05	0.41	2.06E-04	3.68E-05	5.99E-06	5.25E-02	2.62E-05	2.04E-05				
Total PAH (inc. napthalene)	3.29E-05	0.29	1.44E-04	1.74E-05	7.72E-06	0.07	3.38E-05	6.04E-06	1.96E-05	0.17	8.57E-05	6.65E-05				
Napthalene	2.06E-05	0.18	9.01E-05	1.09E-05	2.86E-06	0.03	1.25E-05	2.24E-06	1.22E-05	0.11	5.35E-05	4.15E-05				
Total Dioxins & Furans	2.59E-08	0.00	1.14E-07	1.37E-08	1.22E-08	0.00	5.33E-08	1.83E-08	2.46E-08	2.16E-04	1.08E-07	8.38E-08				
WHO TEQ	2.40E-05	0.21	1.05E-04	1.27E-05	9.64E-06	0.08	4.22E-05	7.54E-06	2.17E-05	0.19	9.50E-05	7.37E-05				
	October 22, 2015				October 7, 2015				October 8, 2015							
Total Filterable PM	1.86	16294	8.15	1.35	1.70	14892	7.45	1.57	0.67	5869	2.93	1.08				
Condensable PM	0.06	517	0.26	0.04	0.08	710	0.35	0.07	0.05	412	0.21	0.08				
Total PM	1.92	16819	8.41	1.40	1.78	15593	7.80	1.64	0.72	6307	3.15	1.16				

* Annual calculations assume continuous operation (24 hours, 365 days per year, or 8,760 hours per year. However, thermal manure-to-energy systems on farms are not used continuously. Most farms do not operate them between flocks, and they may not operate them as birds get larger and demand less heat. They would not be used at all during high temperature periods when houses are cooled with tunnel ventilation.

Environmental Scanning Electron Microscopy (ESEM) Analysis

Results from the energy-dispersive spectroscopy (EDS) generated during the ESEM analysis are presented in Table 8. The analysis was completed for five samples. These consisted of three sets of filterable particulate matter collected on glass media filters in execution of EPA Method 5 for the Ecoremedy gasifier, Bio-Burner 500, and Blue Flame boiler. The analysis was also performed on two sets of condensable particulate matter collected on polytetrafluoroethylene (PTFE) media filters in execution of EPA Method 202 for the Ecoremedy gasifier and Bio-Burner 500. The five filters were products from the second campaign of source emission testing, which focused on particulate matter only. However, at the time of the ESEM analysis, the condensable particulate matter filter for the Blue Flame unit were not yet available, and therefore not included in this analysis. It should be noted that, as reported in Table 6, EPA Method 202-derived condensable particulate matter represents approximately 3%, 4%, and 7% of total particulate matter for the Blue Flame boiler, Ecoremedy gasifier, and Bio-Burner 500 technologies, respectively. Additionally, the EDS generated for the CPM filters appeared to primarily characterize the chemical species found in the filter substrate itself (i.e., polytetrafluoroethylene), as no CPM was identifiable within the selected areas of interest during this initial ESEM analysis. As such, Table 8 focuses on the filterable particulate matter.

ESEM-derived photos of filterable particulate matter are provided in Figures 3-6 for the Bio-Burner 500, Ecoremedy gasifier, and Blue Flame boiler. Generally, the filterable particulate matter identified in the ESEM was comprised of two types of particulate matter. The first consisted of relatively larger and more well defined particulate matter. The second consisted of relatively smaller and less defined agglomerations of particulate matter. Therefore, two areas of interest were identified on each FPM-filter, one for each region. Figure 3 below shows an ESEM-derived photo featuring the two particulate matter classes and associated areas of interest for the Blue Flame boiler. Table 7 provides the EDS-derived chemical analysis, as a mass percentage, for each of the two regions (i.e., larger particulate, smaller particulate) for each of the three FPM filters, as well as an average composition for each unit.

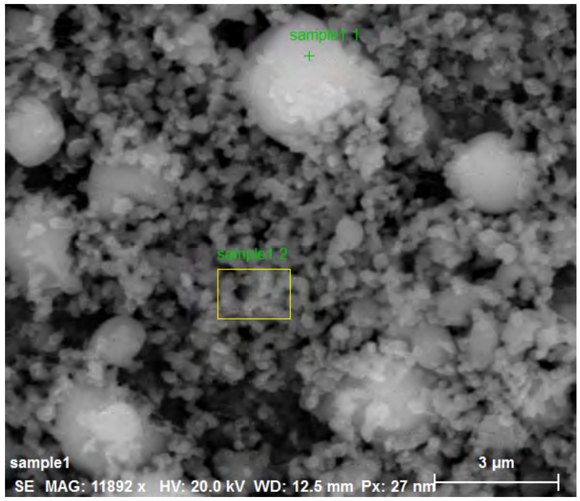


Figure 3. ESEM-derived photo featuring the two particulate matter classes (larger and smaller) and associated areas of interest for EDS of FPM from the Blue Flame technology

Table 8. Results from energy-dispersive spectroscopy (EDS) analysis for filterable particulate matter from the LEI Bio-Burner 500, Ecoremedy gasifier, and Blue Flame boiler

Technology		EDS Chemical Analysis – Mass Percent (%)				
		O	Na	S	Cl	K
Blue Flame	Larger Particulate	26.15	1.66	4.54	24.51	43.14
	Smaller Particulate	38.48	3.86	8.74	11.59	37.33
	Average	32.31	2.76	6.64	18.05	40.24
LEI Bio-Burner 500	Larger Particulate	42.89	4.43	12.66	3.93	36.09
	Smaller Particulate	46.20	2.67	9.81	6.26	35.05
	Average	44.55	3.55	11.24	5.10	35.57
Ecoremedy Gasifier	Larger Particulate	27.20	0.42	16.38	2.83	53.16
	Smaller Particulate	21.22	1.80	9.05	20.16	47.77
	Average	24.21	1.11	12.72	11.50	50.47

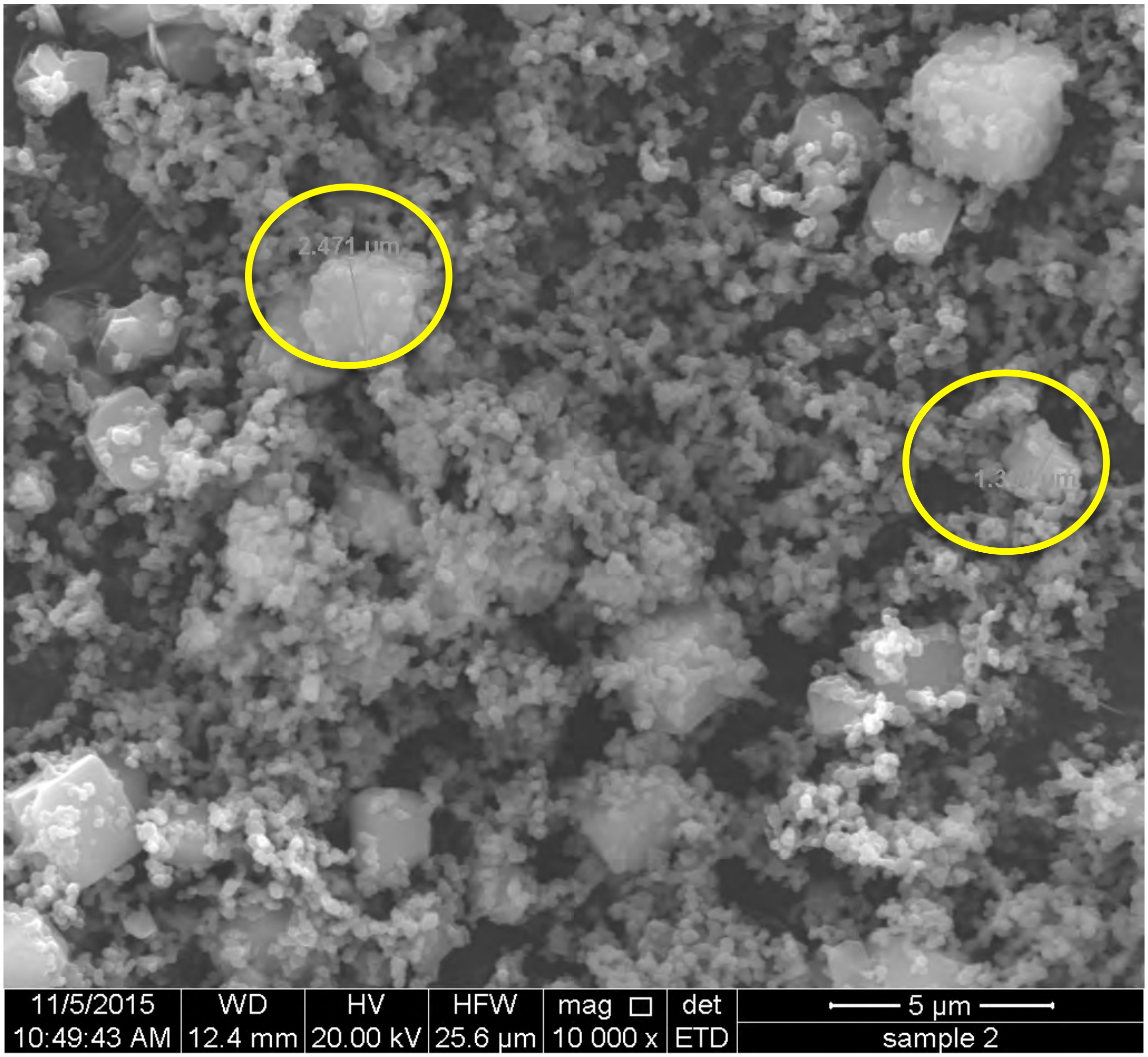


Figure 4. SEM (10,000x) photo of filterable particulate matter from the LEI Bio-Burner 500. Note indicated sizes of selected particulates range from 2.471 um to 1.368 um.

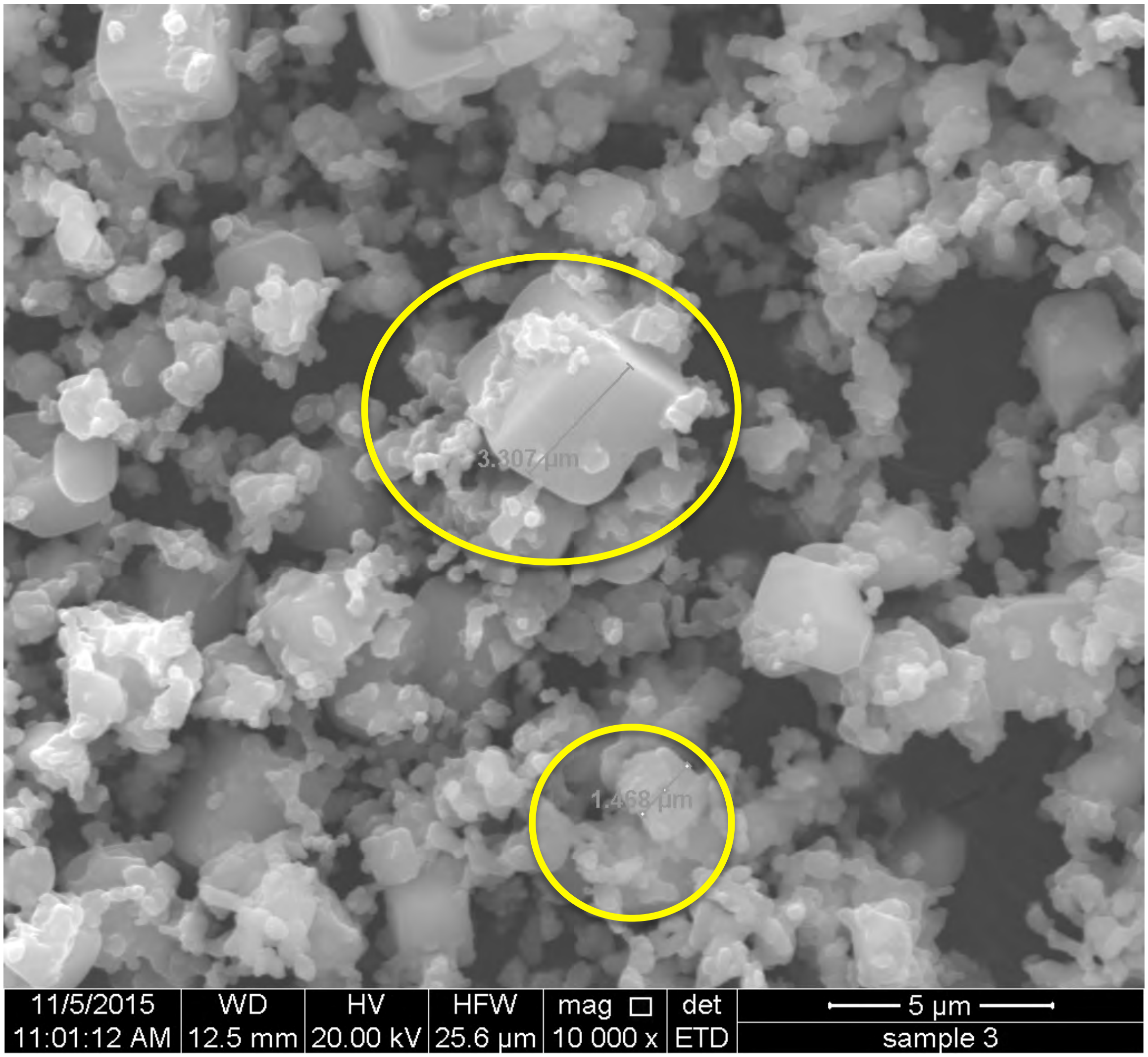


Figure 5. SEM photo (10,000x) of filterable particulate matter from the Ecoremedy gasifier. Note indicated sizes of selected particulates range from 3.307 um to 1.468 um.

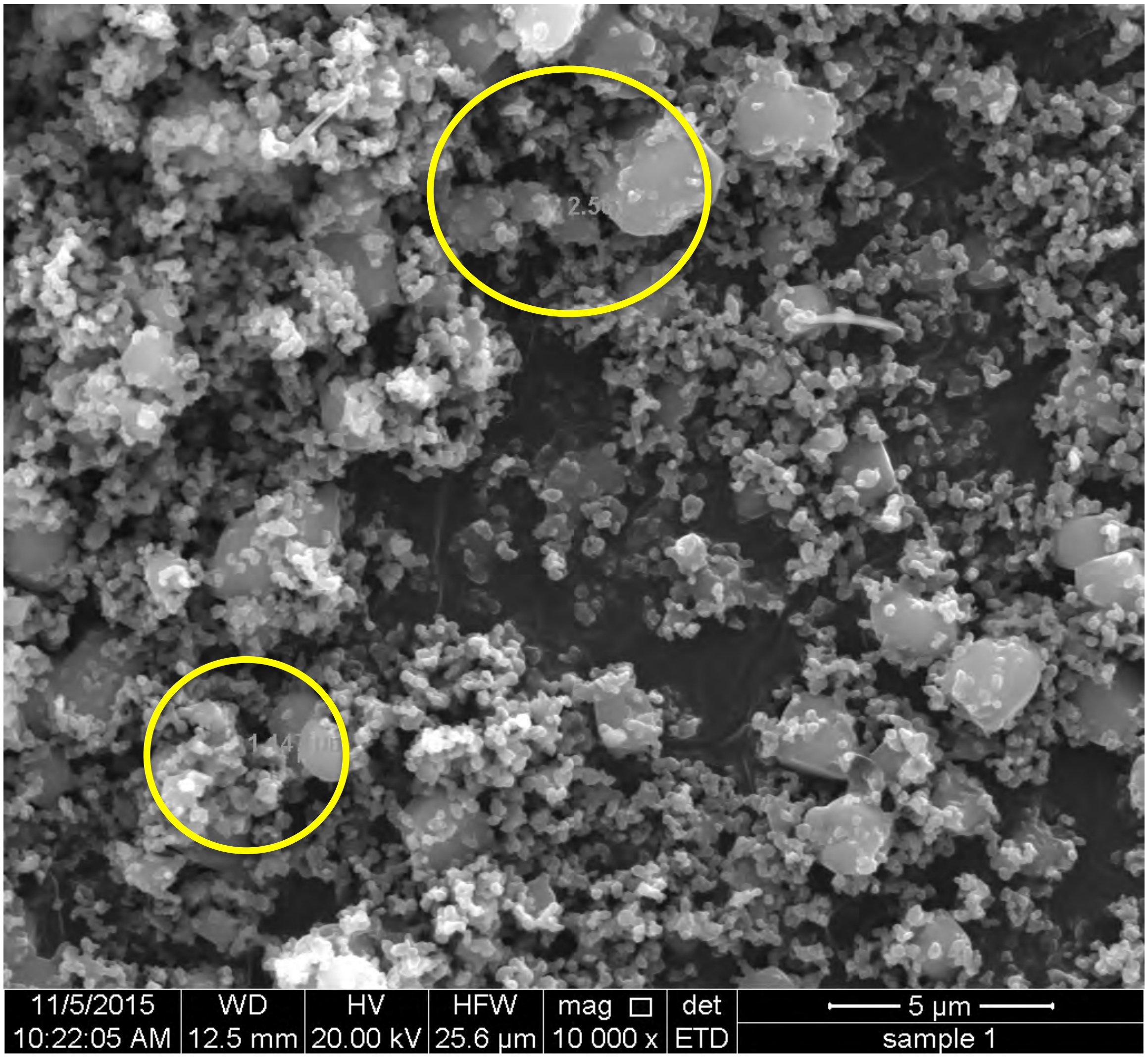


Figure 6. SEM photo(10,000x) of filterable particulate matter from the Blue Flame stoker boiler. Note indicated sizes of selected particulates range from 2.56 um to 1.147 um.

4.3 Health Impacts

For air toxics, SCREEN3 maximum 1-hour air concentrations fell below established Virginia-based SAACs threshold levels. For criteria pollutants measured in the second round of emissions testing (after additional pollution control devices were installed), all SCREEN3 maximum 1 hour concentrations fell below established NAAQS (including 1 hour, 24 hour, and annual concentrations where appropriate) except filterable and total particulate matter for the Bio-Burner 500, which exceeded the established 24-hour and annual NAAQS threshold for fine particulate matter (Table 9) for both testing dates. Also, prior to emissions control improvements, SCREEN3 analysis of the first round of emissions testing predicted that filterable and total particulate matter emissions from the Blue Flame

Boiler would also exceed 24-hour and annual NAAQS for fine particulate matter. Note that SCREEN3 is highly conservative with respect to predicting maximum pollutant concentrations and analysis with a more refined model (AERMOD for example) is the next step to determine if there is actually a problem. This analysis was outside the scope of this project.

Table 9. SCREEN3-predicted maximum concentrations and distance to maximum concentration for filterable and total particulate matter (PM) compared with NAAQS thresholds for fine particulate matter (<2.5 um). Actual PM2.5 emissions rates were not measured because stack diameters for these technologies are too small to measure fine particulate matter according to approved EPA methods. A conservative approach is to assume all measured PM is fine PM.

Test Site and Technology	Emissions Test Date	Distance to Maximum Concentration	SCREEN3 Predicted 24-hour Maximum Concentration of PM	NAAQS for 24-hour Concentration for PM2.5	SCREEN3 Predicted Annual Maximum Concentration of PM	NAAQS for Annual Concentration for PM2.5
		(m)	(ug/m^3)	(ug/m^3)	(ug/m^3)	(ug/m^3)
Blue Flame Boiler						
Filterable PM	8/17/15	177	46.6	35	9.3	12
Total PM	8/17/15	177	47.5	35	9.5	12
Filterable PM	10/2/15	167	29.6	35	5.9	12
Total PM	10/2/15	167	30.6	35	6.1	12
Bio-Burner 500						
Filterable PM	8/13/15	78	86.0	35	17.2	12
Total PM	8/13/15	78	87.0	35	17.4	12
Filterable PM	10/8/15	78	66.2	35	13.2	12
Total PM	10/8/15	78	71.2	35	14.2	12
Ecoremedy Gasifier						
Filterable PM	8/13/15	193	30.0	35	6.0	12
Total PM	8/13/15	193	31.8	35	6.4	12
Filterable PM	10/7/15	163	28.1	35	5.6	12
Total PM	10/7/15	163	29.4	35	5.9	12

5. Discussion

5.1 Poultry Litter Contaminants

Results from poultry litter analysis indicates that potential air contaminants in poultry litter from 11 farms in the region fall within ranges for traditional fuel (coal and wood). Note that for nitrogen, EPA indicated in the NHSM rule that contaminant comparison could be based on actual NOx emissions rates, as they did not intend to characterize nitrogen that does not form NOx as a contaminant.

One anomaly observed in the data were the values initially reported for the poultry litter fluoride content. Brookside Laboratory initially used EPA Method 300.0, which produced unexpectedly high results. Further analysis with via Method 4500-F-C resulted in lower numbers (see Table 6). Brookside Laboratory staff suggested that the project team disregard the results from the initial analysis using ICP due to potential interference with organic acids and only use results from analysis via Standard Method 4500-F-C.

For more information on federal permitting for farm-scale thermal systems, see http://www.extension.org/pages/70264/start-up-questions-and-considerations-for-manure-to-energy-projects - .VfLrT2TBzRY.

5.2 Air Emissions and Permitting

Only the Bhsl technology met the air emissions performance objective of potentially meeting permit thresholds for all Bay states with concentrated poultry production. For installation in Maryland, three of the four technologies considered would require additional particulate matter controls, and two would require additional NOx reductions. Only the Bhsl technology would meet Maryland and Delaware's particulate matter thresholds (Figures 7 and 8), while both the Ecoremedy gasifier and Bhsl system met Maryland NOx thresholds (Figure 9).

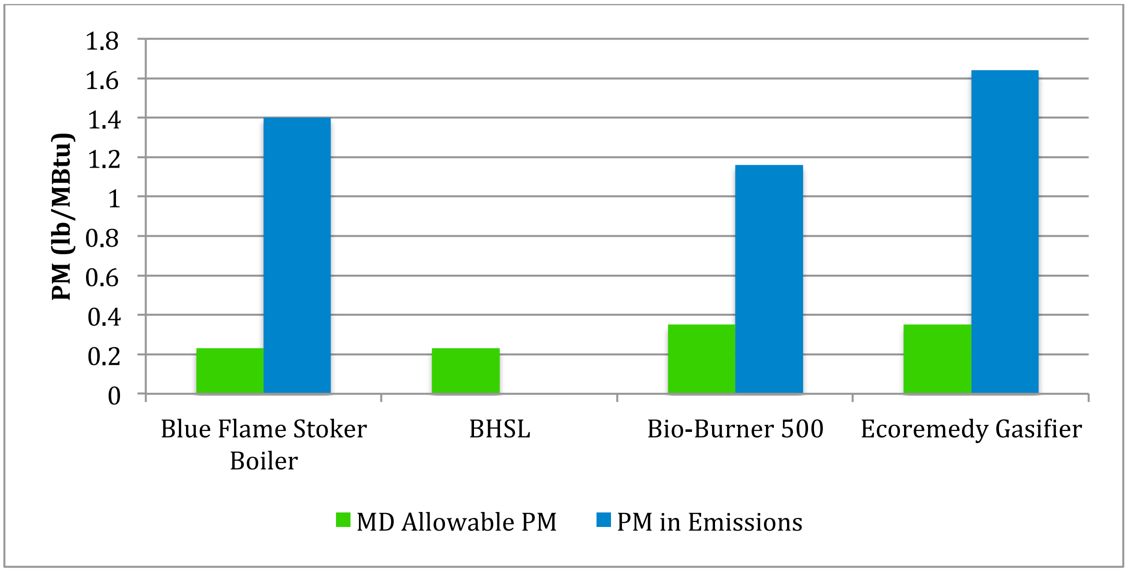


Figure 7. Maryland particulate matter permitting thresholds (assuming the project is located on the Eastern Shore) compared to measured particulate matter emissions

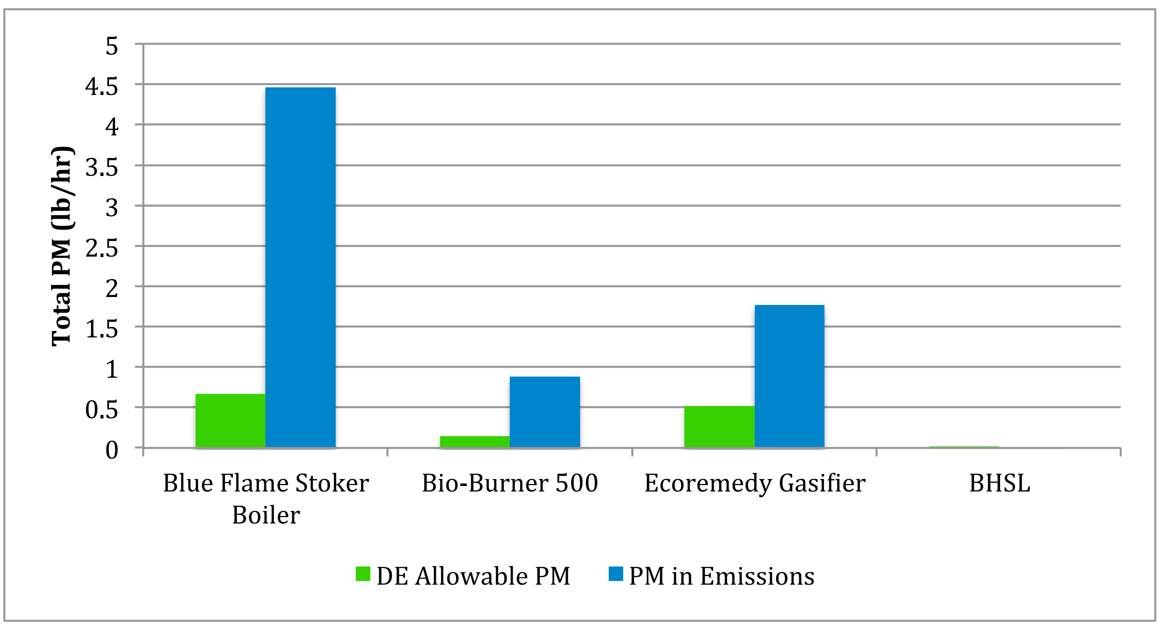


Figure 8. Delaware allowable total particulate matter emissions compared to measured total particulate matter emissions

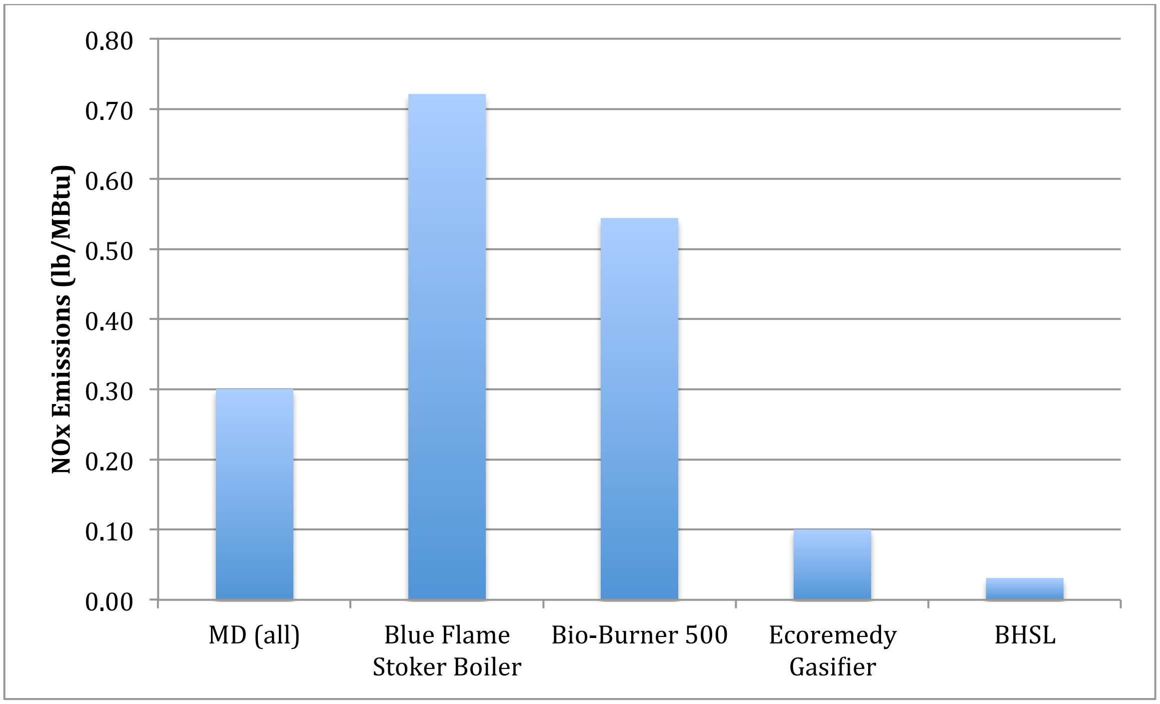


Figure 9. Maryland NOx emission thresholds (assuming the project is located on the Eastern Shore) compared to measured NOx emissions from four manure-to-energy technologies.

In Pennsylvania, on-farm units less than 2.5 MBtu/hr in size can request a waiver for plan approval permits. However, they may be subject to operating permit requirements if they exceed established thresholds. Table 10 presents performance of the technologies compared to these established thresholds.

One consideration with respect to permitting farm-scale thermal manure-to-energy systems is that feed rate can be challenging to accurately quantify. Maryland and Delaware set the air pollutant emissions thresholds based on the fuel feed rate and energy value (e.g., pound of pollutant per million Btus (MBtu). Despite careful attention to quantifying both the feed rate (as described in the methods section) and ash production rate (methods described in Appendix G), initial results suggested discrepancies between nutrients in poultry litter used as fuel and nutrients in the poultry litter ash and air emissions. In summary, initial estimates for phosphorus concentration in poultry litter, minus phosphorus concentration in air emissions, varies from reported phosphorus concentration in the ash, taking into account estimated ash production rates. This issue is discussed in more detail in Appendix G. Note that feed rates vary for two of the technologies based on either house temperature (Blue Flame boiler) or internal combustion chamber temperature (Bio-Burner 500). For the one system with a fixed feed rate (the Ecoremedy gasifier), quantified feed rate differed from system-predicted feed rate by only 8 lbs per hour, or approximately 3 percent variation.

Table 10. Pennsylvania potential-to-emit and actual emissions rate thresholds for operational permits. Sources above these limits may be required to secure an operational permit. All particulate matter as reported in “total PM” is assumed be PM10 or smaller.

Pollutant	Potential to Emit <	Bio-Burner 500	Blue Flame Boiler	Eco-remedy Gasifier	Actual Emissions Rate <	Bio-Burner 500	Blue Flame Boiler	Eco-remedy Gasifier	Bhsl
		100% Run-time				40% Run-time			
	tons/year								
CO	100	0.18	4.56	0.92	20	0.07	1.82	0.37	
NOx	100	0.70	5.96	0.57	10	0.28	2.38	0.23	0.62
SOx	100	0.00	1.40	3.94	8	-	0.56	1.58	1.69E-04
PM10	100	3.81	8.41	7.80	3	1.26	3.36	3.12	0.01
VOCs	50	4.38E-03	0.07	4.60E-06	8	0.00	0.03	0.00	
Single HAP	10				1	-	-	-	
Multiple HAPs	25	0.94	2.77	0.28	2.5	0.38	1.11	0.11	

Target for particulate matter in PA: If 3 TPY is the limit for actual run time, assuming 40% operation is the actual run-time, 1.71 lb/hour is maximum PM10 emissions rate. Highlighted cells show where 40% run time exceeds the actual emissions rate limit.

Virginia and West Virginia permitting thresholds are based on uncontrolled emissions and assume continuous operation throughout the year. Partners in the Farm Manure-to-Energy Initiative are working with project vendors to estimate the efficiency of emissions control equipment to determine if the technologies require permitting in Virginia. Tables 11 (Virginia) and 12 (West Virginia) compare permit exemption thresholds (based on uncontrolled emissions rates and assuming continuous operation) and measured emissions from on-farm thermal systems with control technologies.

Table 11. Virginia minor source permit exemption thresholds (based on uncontrolled emissions rates and assuming continuous operation) compared with measured, controlled thermal manure-to-energy technologies (also assuming continuous operation)

Pollutant	New Source	Modified Source	Bio-Burner 500	Blue Flame Boiler	Ecoremedy Gasifier	Bhsl
	Uncontrolled		Controlled			
PM	25	15	3.15	8.41	7.8	0.01
PM-10	15	10	3.15	8.41	7.8	0.01
PM 2.5	10	6	3.15	8.41	7.8	0.01
CO	100	100	0.18	4.56	0.92	
NOx	40	10	0.70	5.96	0.57	0.62
SO2	40	10	0.00	1.40	3.94	1.69E-04
VOC	25	10	4.38E-03	0.07	4.60E-06	

Table 12. West Virginia criteria pollutant thresholds (based on potential to emit, uncontrolled emissions, and continuous operations) compared to measured emissions from manure-to-energy technologies with emissions controls (also assuming continuous operation)

	PTE Thresh-old*	Bio-Burner 500	Blue Flame Boiler	Eco-remedy Gasifier	Bhsl	PTE Thresh-old*	Bio-Burner 500	Blue Flame Boiler	Eco-remedy Gasifier	Bhsl
	lb/hr					tons/yr				
NOx	6	0.16	1.36	0.13	2.87E-04	10	0.70	5.96	0.57	0.62
SO2	6	0.00	0.32	0.9	1.98E-03	10	0.00	1.40	3.94	1.69E-04
CO	6	0.04	1.04	0.21		10	0.18	4.56	0.92	
Total PM	6	0.88	4.46	1.77	3.90E-03	10	3.15	8.41	7.8	0.01
VOC	6	1.00E-03	0.015	1.05E-06		10	4.38E-03	0.067	4.60E-06	

*PTE = potential to emit, based on uncontrolled emissions

West Virginia also establishes potential-to-emit thresholds for hazardous air pollutants. The Ecoremedy gasifier, LEI Bio-Burner 500, and Blue Flame boiler measured hazardous air emissions all fell well below these thresholds.

5.3 Particulate Matter Characterization

Results from the SEM analysis indicate a predominance of potassium, chlorine, and sulfur in the filterable particulate matter entrained on the filters used in the EPA Method 5 analysis from all test sites. Larger and smaller particulate matter species have similar chemistry except for the Ecoremedy gasifier, where this is more of a difference between the two. Also at the Ecoremedy gasifier location, particulate matter from the second cyclone was moist compared to the fly ash removed from the first cyclone as well as all of the fly ash removed from cyclones for the LEI Bio-Burner 500 and Blue Flame boiler.

One hypothesis is that potassium bonds with sulfur until sulfur is depleted, forming K_2SO_4. Once sulfur is depleted, potassium bonds with chloride forming KCl. Nielsen et al. (2000) discuss the fate of potassium, sulfur, and chlorine in biomass fuels used in high-temperature combustion systems, including the potential for corrosion problems associated with burning biomass fuels in high-temperature systems.

5.4 Health Impacts

SCREEN3 analysis indicates that maximum pollutant concentrations for filterable and total particulate matter exceed NAAQS 24 and annual concentration standards for fine particulate matter at the distance of maximum concentration from the source. While it is likely that a portion of the total particulate matter includes particle sizes great than 2.5 um, given the lack of EPA-approved methodology for fine particulate matter emissions from small stacks, the most conservative approach is to assume all particulate matter is fine particulate matter for the purposes of this analysis.

Improvements to the Blue Flame boiler emissions controls between the first and second round of emissions testing reduced emissions of filterable and total particulate matter to levels below the NAAQS PM2.5 threshold. However, while improvements to the Bio-Burner 500 emissions controls reduced total particulate matter emissions (Figure 1), SCREEN3 predicted maximum concentration values for filterable and total PM still exceed the NAAQS 24-hour and annual standards for fine PM2.5.

The lower height (20 feet) and wide diameter (1.15 feet) of the Bio-Burner 500 stack, as tested, appears to be contributing to this problem, resulting in low exit temperature and velocity. Subsequent SCREEN3 analysis that added 12 feet to the stack height resulted in fine and total particulate matter emissions below NAAQS for 24-hour and annual PM2.5. Likely, a more optimal stack configuration could achieve similar results in practice, especially in combination with any abatement improvements for further removal of fine particulate matter. Alternatively, because SCREEN3 is a highly-conservative screening model, more refined air quality dispersion modeling analysis may be needed to determine whether PM2.5 concentrations can, in fact, be expected to meet the NAAQS. More refined air quality dispersion modeling is outside the scope of this project.

6. Next Steps

The project team is currently in the process of sharing results from air emission testing and particle speciation analysis with emissions control experts and will continue to work with LEI Products (Bio-Burner 500), Ecoremedy Energy (Ecoremedy gasifier), and Total Energy Solutions and Blue Flame (Blue Flame boiler) to reduce particulate matter emissions. In addition to improving emissions controls, the project team recommends the following:

- Evaluation of Bio-Burner 500 emissions with a more refined dispersion model (like AERMOD) to determine to determine maximum PM concentrations.
- Pending the outcome of more refined dispersion models, evaluation of how stack configuration impacts maximum concentration for particulate matter from the Bio-Burner 500 may be warranted. For example, SCREEN3 predicts that increasing the stack height by 12 feet reduces maximum concentrations of filterable and total particulate matter to levels below the NAAQS 24-hour and annual fine particulate matter thresholds. However, there may be less costly options (reducing the stack diameter for example) that would achieve similar results.
- The Bio-Burner 500 and Blue Flame boiler should be "tuned" to reduce NOx emissions. This is the first step in reducing NOx and should be implemented before consideration of NOx emissions controls. Biennial tuning is required for larger boilers, but these results indicate that it should also be used by smaller boiler systems to minimize NOx emissions.
- After tuning, additional NOx controls may be necessary for the Bio-Burner 500 and Blue Flame boiler for installation in Maryland.

For permitting in all the Bay states, emission control efficiencies for the control equipment will be needed, especially for permitting in Virginia and West Virginia. Specifically, the Virginia Department of Environmental Quality will need to know the efficiency of the control systems on the Bio-Burner 500 to make a permit determination for the Riverhill Farm system.

The project team also recommends additional analysis on pollution emissions as impacted by fuel feed rate. Because feed rates in the systems change with either farmer adjustments or, for the Blue Flame boiler, with in-house temperatures, subsequent analysis on the effect of feed rate and emissions would be helpful. In particular, these analyses should explore the impact of fuel feed rate and emissions as they relate to permitted thresholds.

7. References

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Appendix F

Nutrient Availability from Poultry Litter Co-Products

A summary of findings funded by the Farm Manure-to-Energy Initiative

December 2015

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Contents

Abstract

Phosphorus is a nutrient of concern in the Chesapeake Bay watershed, largely due to nutrient imbalances in areas with confined animal feeding operations. By converting poultry litter to an ash or biochar, nutrients are concentrated into a form that can be economically shipped out of nutrient-dense areas to nutrient deficient regions, such as the corn belt. In nutrient deficient regions, these poultry litter co-products have potential use as fertilizer with less impact on water quality.

The Virginia Tech Eastern Shore Agricultural Research and Extension Center initiated a study to compare poultry litter co-products to industry standard fertilizers. Seven poultry litter ash products, derived from different sources using different combustion techniques, and two biochar products were characterized. Both were compared to fresh poultry litter, as well as industry standard fertilizers for inorganic phosphorus (triple super phosphate or TSP) and inorganic potassium (muriate of potash or KCl).

There was variability between all ashes and biochars based on the thermal conversion system and the composition of the original poultry litter. On an elemental level, the inorganic fertilizers had the highest concentrations of nutrients, the ash products were the best complete fertilizers, and the biochars had less nutrients available for plant up-take than the ashes. Nutrient density in the ash and biochars varied between systems: phosphorus was concentrated between 4-10 times its original density; potassium was concentrated between 2.5-5 times its original density, and sulfur was concentrated between 2-3 times its original density. Additional, water-soluble based extractions found deceased solubility of the ash and biochar products compared to the industry standard fertilizers.

In conclusion, nutrient concentrations in the ash and biochar derived from poultry litter indicate that these co-products are comparable sources of phosphorus and potash fertilizer. However, further testing is needed to determine plant availability and nutrient uptake.

1. Introduction

Phosphorous and nitrogen are both nutrients of concern to water quality (US EPA, 1988) and are most often connected with eutrophication (Levine and Schinder, 1989; Pote et al., 1996). Areas of intensive animal production often have the greatest potential for eutrophication due to non-point nutrient sources (Pote et al., 1996; Duda and Finan, 1983). Phosphorus is also an important because it is an extremely valuable agronomic nutrient and is considered a non-renewable resource. Current research estimates that within 50 to 100 years we will have mined all of our current known phosphorus supplies (Lynch et al. 2013).

Poultry litter, which contains phosphorus, has been well researched and vetted as a satisfactory fertilizer (Reiter et al., 2013; Sharpley et al., 2007; Revell et al., 2012). However, in regions with intensive animal production, land application of poultry litter is not a viable option due to high residual nutrient levels in the soil. Historically, most manure applications were applied to crop lands at a rate that correlates with the nitrogen requirements of the crops, which typically leads to an over application of phosphorus (Maguire et al., 2007; Sims et al., 1998). The over application of phosphorus is often due to the nitrogen-to-phosphorus ratio. The phosphorus content of manure is typically higher than the ratio that plants require, leaving a surplus of phosphorus (Pote et. al 1996). The average nitrogen-to-phosphorus ratio plants require is approximately 8:1 (Zhang et al., 2002; Bryson et al., 2014), and the average range of poultry litter is 1:1 (Zhang et al., 2002). When applying poultry litter to meet the nitrogen requirements of a crop, you will be providing 8 times more phosphorus than required. In a study by Sharpley (2007) on the effects of poultry litter applications on bermudagrass [*Cynodon dactylon* (L.)], applying poultry litter to meet nitrogen requirements resulted in an excess of 365 kg phosphorus ha^{-1} that was not removed by the bermudagrass.

Due to nutrient management regulations (VA-DCR, 2014), poultry litter is often transported off of the farms. Transportation from nutrient-rich areas is difficult, though, because poultry litter has a low nutrient density in a large, bulky volume of poultry litter. A solution to this issue is the thermal conversion of poultry litter into co-products: ash and biochar. The combustion of poultry litter is a viable approach to alternative energy generation, while at the same time reducing the total volume of the product into an easily transportable ash that remains high in key crop nutrients like phosphorus and potassium (Sharpley et al., 2007; MacDonald, 2007).

Poultry litter ash has proposed agronomic value as a fertilizer. There is significant research describing the analysis of wood-based ash co-products, but very little for manure-based ash. Crozier (2009) studied a granulated manure ash in three different experimental systems (greenhouse low-phosphorus soil, long-term phosphorus research sites with established phosphorus gradients, and agricultural fields with prior phosphorus fertilization at agronomic rates); when compared to industry standard fertilizer for inorganic phosphorus (triple super phosphate or TSP), source differences were infrequent and relativity minor. Codling (2002) compared the effectiveness of poultry litter ash as a fertilizer with an industry standard fertilizer for potassium phosphate, as a phosphorus source for wheat. The two fertilizers were applied at three rates (0, 39, and 78 kg P ha^{-1}) in a wheat-based [*Triticum aestivum* (L.)] trial. No significant difference was found between the two fertilizers. A study by Reiter et al. (2004) comparing poultry litter ash to traditional fertilizer in a rice [*Oryza sativa*(L.)], wheat, and soybean[*Glycine max*(L.)] rotation found that the ash had slightly less short-term availability but increased residual soil phosphorus. In studies by Pagliari (2006, 2008), turkey [*Meleagris gallopavo*(L.)] manure ash was found to have no statistical differences in plant yield and uptake when compared with TSP in corn [*Zea mays*(L.)] and alfalfa [*medicago sativa*(L.)] trials. These studies are a step in proving that poultry litter ash co-products have a similar value to farmers as traditional fertilizers. Research indicated that ash could be a viable phosphorus source, but needs further testing to explore optimum application rates. Ash applications act not only as fertilizers but also as soil amendments. Demeyer et al. (2001) found that ash worked as a liming agent increasing the pH of the soil from 4.5 to 7.0 with the highest application rate of 44 Mg ha^{-1}, stimulated the microbial activities and increased water holding capacity by increasing soil aeration.

Biochar is another co-product of the thermal conversion of fresh poultry litter. There is interest in biochar for a multitude of uses, including bioenergy, carbon sequestration, soil amendment, and fertilizer (Maguire and Agblevor, 2010). Biochar is voluntarily regulated by the International Biochar Initiative, which established regulations for creating, sampling, testing, and using biochar worldwide. Biochar is defined by the International Biochar Initiative (2015) as the carbon-rich product that results from heating biomass with little or no oxygen. After pyrolysis, the inorganic components of poultry litter are significantly concentrated, although less concentrated than ash, and the densification increases the co-product's value as an agronomic nutrient source (Revell et al., 2012b; Agblevor et al., 2010). The main difference between biochar and ash is the creation temperature, as variations in temperature during production will impact the quantity and quality of the end product (Maguire and Agblevor, 2010). Biochar is the product of a lower burning temperature during combustion at 400-500°C, as compared to ashes that are produced at temperatures greater than 1000ºC (Gaskin et al., 2008).

Studies proposed that biochar can be used to improve soil productivity and sequester carbon (Atkinson et al., 2010; Laird, 2008). It has been found, mainly by scientists in the tropics, that biochar and charcoal created by pyrolysis will improve soil health and crop production (Chan et al., 2007; Lehmann et al., 2003; Oguntunde et al., 2004; Steiner et al., 2007; Yamato et al., 2006). This process forms hydrogen and organic carbon bonds that will sequester carbon for more than 100 years (International Biochar Initiative, 2015). By increasing the active surface area of the soil, its capacity to retain nutrients and water increases water holding capacity and nutrient uptake (Maguire, 2010). In a study by Revell et al. (2012b), biochar was found to decrease the bulk density of the soil by increasing aeration, the water holding capacity increased linearly with rates of (0, 4.5, and 9 Mg ha^{-1}), pH was increased, and the cation exchange capacity of the soil increased only when applied above agronomic rates. Increased water holding capacity is one of the major benefits to using biochar, as drought is a major reason for decreased crop production in non-irrigated lands (Revell et al., 2012a; Havelin et al., 2005). A study by Schomberg et al. (2012) reported that soil parameter improvements greatly depended on biochar quality, temperature and speed of pyrolysis, and the soil. Laboratory incubations with various biochar amendments were conducted in the long and short term to explore the effects of biochar on changes in soil pH, ammonia losses, and soil carbon effects. Biochar additions resulted in a reduction of NO_3^- leaching and large increases in mineralizable nitrogen were not observed, meaning most soil carbon in the biochar was not available to micro-organisms. The study suggested that development of standards and guidelines would allow better usage of biochar by matching the biochar to specific soils and land use situations (Schomberg et al., 2012).

A review by Kelleher et al. (2002) discussed the advances in poultry litter conversion technologies by analyzing the most common techniques: composting, anaerobic digestion, direct combustion, and pyrolysis. The goals of using these technologies are to make the products safer for land application, reduce the total volume, increase the nutrient density, and increase the value of the product.

The process of composting is an aerobic process that occurs relatively quickly (4-6 weeks) and produces a material that is odorless, fine-textured, and has low moisture content (Kelleher et al., 2002). Moisture content is an important factor in composting. The moisture should be between 40-60% to allow for evaporation during the metabolic heating process (Kelleher et al., 2002; Rynk et al., 1991). Higher moisture content will inhibit the composting process, resulting in higher ammonia volatilization rates; lower moisture rates will inhibit decomposition (Kelleher et al., 2002). At the end of the process, the composted material will be granular with moisture content of 20% or less (Elwell et al., 1998). The composted material will be pathogen free and easy to handle, but disadvantages include odor, the loss of nitrogen (47-62%), phosphorus not being reduced or concentrated, and a cost for equipment and labor inputs (Kelleher et al., 2002; Sweeten, 1988).

Anaerobic digestion is commonly used around the world as a way to dispose of numerous agricultural and industrial waste products. Anaerobic digestion has two basic stages. The first stage is acid fermentation, which breaks down the organic material into organic acids, alcohols, and bacterial cells. The second stage involves the conversion of the hydrolysis products to gases (carbon dioxide and methane) (Kelleher et al., 2002; Williams, 1999). The gas mixture (60% methane) produced by this process is collected and used in bioreactors, as fuel, as a natural gas alternative, or in generators to create electricity (Kelleher et al., 2002). Disadvantages to digestion include high equipment costs, added volume without concentrating phosphorus, the need for added nutrients to correct for the carbon-to-nitrogen ratio, and the need for nitrogen to drive microbial metabolism and reactions. Other added costs include measures taken to enhance digestion because poultry litter has a high pH and ammonia content, which inhibits methane production (Krylova et al., 1997; Kelleher et al., 2002).

Direct combustion, a high oxygen thermal conversion technique, is the most promising new technology available to farmers. Numerous studies showed that thermal conversion of poultry litter to a bio-fuel is possible through multiple techniques, including combustion (>1100ºC and high O_2), gasification (700-1000ºC and minimal O_2), liquefaction, and pyrolysis (350-650ºC and depleted O_2) (Mante and Agblevor, 2010; Çaglar and Demirbas, 2000; McKendry, 2002; Cantrell et al., 2007; Farm Manure-to-Energy Initiative, 2015). Direct combustion tends to be most feasible for the farm-scale conversion of poultry litter. Some models employ a technique called localized fluidized bed combustion units to gasify the poultry litter at 700-1000°C with moisture content at approximately 25% (Kelleher et al., 2002; Williams, 1999). The advantages of combustion are the concentration of nutrients to 6 or 7 times that of the original feedstock and an increase of 1.5 to 2.5 times the bulk density of the poultry litter (Bock, 2004). The main disadvantage of an ash product is the loss of nutrients during the combustion process; however, if the litter is combusted at a much lower temperature some losses can be avoided (Faridullah et al., 2009; Steiner et al., 2010). The majority of nutrients from the fresh poultry litter is released from the systems in the form of non-reactive nitrogen gas (N_2) but the reactive forms may also be released in the forms of nitrogen oxides (NO_x) and ammonia (NH_3) (Farm Manure-to-Energy Initiative, 2015). The emissions differ system to system, but the reactive emission typically range from less than 2 to less than 1 percent due to the presence of NH_3 and organic nitrogen in poultry litter. At higher temperatures they will react with NO_x to form the non-reactive N_2 gas and water vapor, minimizing the reactive nitrogen emissions (Farm Manure-to-Energy Initiative, 2015). It is generally known that the land application of fresh poultry litter results in much higher emissions of atmospheric nitrogen (approximately 50-90%), so the thermal conversion of poultry litter may actually reduce atmospheric emissions of reactive nitrogen (Farm Manure-to-Energy Initiative, 2015).

Pyrolysis is the thermal decomposition of biomass in a depleted oxygen environment that uses a fluidized bed reaction between 350-650°C (Farm Manure-to-Energy Initiative, 2015; Mante and Agblevor, 2010), but differs from direct combustion by using lower heat and lower oxygen concentrations. The lower temperature helps lower nitrogen losses, but a substantial amount is lost or converted to atmospheric nitrogen (Knicker, 2007). Pyrolysis also concentrates the amounts of nutrients from the original substrate, including phosphorus and potassium, while reducing the total mass by approximately 60%, which increases the nutrient density (Kim et al., 2009; Revell et al., 2012).

The majority of research for manure-based fertilizers has been related to nitrogen availability because nitrogen is typically the most yield-limiting nutrient in row crops (Slaton et al., 2013). The plant availability of nitrogen, phosphorus, and potassium are all vital to plant health and growth and interrelated in their respective cycles (Brady and Weil, 1996). A study by Sharpley and Sisak (1997) proposed that the bioavailability of phosphorus from manure sources may differ from traditional inorganic fertilizer and suggested that application recommendations be tailored to the unique fertilizer source. Studies have shown that the phosphorus in manure is generally found to be 60-100% of the availability of commercial fertilizers depending on the source over multiple years (Barbazan et al., 2009); the first-year bioavailability of phosphorus was similar to inorganic fertilizer (Sneller and Laboski, 2009), and most potassium is highly water soluble and plant available (Jackson et al., 1975).

Both organic and inorganic phosphorous is present in the solid phase of poultry litter and is normally present in the acid-soluble fraction. However, nutrient levels can vary widely due to husbandry and diet practices, such as the type of bedding material, number of birds in a flock, and number of flocks between clean-outs (Lynch et al., 2012). Soils tend to strongly hold phosphorus due to clay, iron oxide, and aluminum oxide, so there is little to no risk of leaching in soils that test low for phosphorus (Sims et al., 1998; Brady and Weil, 1996). Phosphorous fixation occurs at both ends of the pH spectrum, in acidic low pH soils (<5.0) and basic, high pH soils (>8.0) (Brady and Weil, 1996). In the low ranges, phosphorus will react to aluminum, iron, and manganese oxides. In the high ranges, phosphorus will react with calcium, fixing the phosphorus into insoluble compounds (Brady and Weil, 1996). But under long-term applications of phosphorus, in excess of crop removal rates, the soil concentrations will rise (Maguire and Sims, 2002). When tested levels of phosphorus in the soil are high or excessive, an increased chance of nutrient leaching and agricultural runoff can be expected (Moore and Edwards, 2007; Maguire and Sims, 2002). Soil pH also affects the availability of phosphorus.

Traditionally in Virginia, the primary test for soil phosphorus has been Mehlich-I, which is also known as the dilute double acid method (Sims, 2000; Mehlich, 1953). Other methods discussed in literature pertaining to the Mid-Atlantic region are water extraction and dilute salt extraction at varying ratios of 1:10 and 1:100 (Aslyng, 1964; Olsen and Sommers, 1982; van Diest, 1963). Many phosphates in the soil have formed insoluble compounds that are no longer plant available (Brady and Weil, 1996). There is some criticism that the Mehlich acid-based extraction is too harsh and extracts more than the plant available phosphorus (Self-Davis and Moore, 2000), which leads to unreliable recommendations and leads many to recommend water or dilute salt extractions over the traditional Mehlich-I extraction (Self-Davis and Moore, 2000; Pote et al., 1996; Luscombe et al, 1979).

While there is no single recommended protocol for measuring water extractable phosphorus (WEP), there are some commonly recommended protocols (Self-Davis and Moore, 2000; Kleinman et al., 2007). The dilute salt (0.1M $CaCl_2$) and water extractions (1:10 and 1:100) are tests that extract the readily available portions of the nutrients that will be available for plant uptake. These tests produce lower concentrations of nutrients as compared to acid extractions and are used in the industry to make recommendations for phosphorus management systems on farms (Self-Davis and Moore, 2000). The dilute salt extraction is used in place of water to obtain a clearer filtrate, but the amount of soluble phosphorus will be smaller due to Ca^{2+} ions enhancing phosphorus sorption in the soil (Aslyng, 1964). Water extraction ratios have been discussed in the literature since the mid-1980s. A study by Kleinman et al. (2007) looked at WEP extraction ratios with help from 10 laboratories across the country. They compared extracts at 3 different ratios (soil: extractant): 1:10, 1:100, and 1:200. They found the 1:10 level was the most problematic out of the 3 ratios of soil to extractant. At the 1:10 ratio, the results were inconsistent, they had trouble obtaining sufficient extract for analysis, and the extracts were relatively dark in color causing many problems for colorimetric analysis, including the clogging of instrumentation tubing (Kleinman et al., 2007). They also found a consistent trend, with greater quantities of WEP being recovered as the extraction ratio increased. However, due to the experimental variability no proportional relationship could be determined between the ratios. The study recommended the usage of the 1:100 ratio as the middle ground because it offered the most reasonable balance of precision and practicality (Kleinman et al., 2007).

This project evaluated removing excess phosphorus from nutrient-dense areas by repurposing ash and biochar co-products of the poultry industry into a marketable fertilizer that can be exported out of the watershed and used by farmers in the phosphorus-deficient areas of the country or within the watershed where fresh poultry litter is not an option. The objective of this project was to characterize and analyze the composition of poultry litter co-products in comparison to traditional inorganic fertilizers and fresh poultry litter.

2. Characterization of Poultry Litter Ash Co-Products

2.1 Materials and Methods

This study was initiated to evaluate the chemical characteristics of poultry litter co-products (ash and biochar) (Table 2.1) compared to triple super phosphate and muriate of potash. The fertilizers were arranged in a randomized complete block design (RCBD) with 4 replications.

2.1.1 Elemental Analysis

Fertilizer samples (0.5 g) were digested in nitric acid and hydrogen peroxide using method 3050B (USEPA, 1996), and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011). Using dilute salt and water extraction testing protocols for 0.1M $CaCl_2$ (Aslyng, 1964), 1:10 water (Olsen and Sommers, 1982), and 1:100 (van Diest, 1963) the correct ratio of sample to solution was placed in 60 ml straight-walled plastic extracting beakers. The samples were shaken for 1 hour on a reciprocating shaker (Eppindorf, Enfield, CT, 06082) set at 200 oscillations per minute. The extracts were filtered through Whatman no. 2 filter paper into plastic vials and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011). A total nitrogen, carbon, and sulfur combustion procedure was conducted for the samples using the Dumas method with a Vario EL Cube (elementar Americas, Mt. Laurel, NJ, USA) (Bremner, 1996).

2.1.2 Balance Comparison

Balance comparisons of the poultry litter going in and ash coming out of poultry litter burners took place as litter burners began running at the farm locations. Each thermal system was unique to the farm, including its physical construction, operating conditions, residence time, and initial feedstock (Table 2.2); individual system sampling methods are listed below. Samples were tested for percent moisture (Wolf and Haskins, 2003), calcium carbonate equivalent (Wolf and Haskins, 2003), and elemental concentration using the EPA method 3050B. Densification was calculated by taking the ash nutrient concentration percentage and dividing by the corresponding nutrient concentration percentage in the poultry litter feedstock (times concentrated = ash nutrient percentage/ poultry litter nutrient percentage)

- Wayne Combustion Global Refuel: ASH3 and ASH6

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter going in, the main bulk ash auger, and the fly ash auger from the side at the heat exchanger. The residence time was observed to be 30 minutes from the start to the main bulk ash auger and the fly ash auger. The time and temperature of the combustion chamber was recorded for each sampling.

- Total Energy Blue Flame Stoker: ASH4

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter entering the system, the main ash auger, and the end ash auger. The residence time was observed to be 60 minutes from start to the main bulk ash auger and 70 minutes from start to the end auger with the bulk ash and fly ash mixture. The time, stack temperature, and water heating set point was recorded for every sample. The combustion temperature was not available on this system.

- Enginuity Energy: Energy Ecoremedy Gasifier: ASH7

  Samples were taken at two sampling locations in accordance to the residence time of the systems: fresh poultry litter entering the system and the bulk ash auger at the end of the system. The residence time was observed to be 157 minutes from the start to the end of the system. The time and chamber temperature was recorded at two locations within the system at a residence time of 55 minutes (gas burner #1) and 147 minutes (gas burner #2). The water boiler set temperature was also recorded for each sample.

2.1.3 Total Carbon Content

Total carbon content of the ash co-products were determined using a total nitrogen, carbon, and sufur dry combustion procedure was conducted for the samples using the Dumas method with a Vario EL Cube (elementar Americas, Mt. Laurel, NJ, USA) (Bremner, 1996).

2.1.4 Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA), SAS PROC MIXED procedures and Fisher's LSD with an alpha level of 0.10 using SAS 10.1 statistical software (SAS Institute, 2007).

2.2 Results and Discussion

2.2.1 Elemental Analysis

Acid Digestion

The nitric acid/hydrogen peroxide digestion is a complete elemental digestion that quantified the total concentrations of elements (Table 2.3a; Table 2.3b). The industry standard triple super phosphate (TSP) had the highest phosphorus concentration (201.81 g kg^{-1}) and a significant concentration of Ca (168.22 g kg^{-1}). Muriate of potash (KCl) had the highest potassium concentration (493.11 g kg^{-1}) as expected. When comparing the ash co-products to each other, ASH3 was the superior fertilizer because it had the highest concentrations of nutrients across the board, which was followed by ASH4 as a close second (Table 2.3a). BIOCHAR3 had the worst concentration of micro-nutrients; meaning that, although it has a significant concentration of macro elements (phosphorus, potassium, sulfur), it was lacking in the micro, which would make it the least complete fertilizer (Table 2.3a). The biochar co-products had the lowest concentrations of nutrients across the board. The ASH5 fertilizer was superior for potassium, but low as a complete fertilizer (Table 2.3a).

When compared to the industry fertilizer standards no co-product was similar to TSP for phosphorus concentration (Table 2.3a, 2.4, 2.5, 2.6). For potassium concentration, no co-products were similar to KCl, but all co-products had concentrations greater than or similar to the fresh poultry litter standard (Table 2.3a, 2.6). In the dilute salt extraction and the 1:10 water extraction, BIOCHAR1 had a concentration less than both KCl and poultry litter (Table 2.4, 2.5). Poultry litter had the greatest sulfurS concentration, and all co-products had significant less sulfur but were similar to each other (Table 2.3a)

Micro-nutrients or trace elements were present in all of the co-product samples (Table 2.3a; Table 2.3b). With the exception of ASH5, all of these concentrations were below the level of environmental concern according to the fertilizer law (USDA-NRCS, 2015). Micro-nutrients such as boron, manganese, copper, and inc are vital to growth in plants. In highly managed and high-yielding farming systems, farmers are looking to supplement these nutrients to crops. By using a poultry litter co-product, these farmers will get the extra benefit of these nutrients not normally found in inorganic fertilizers. ASH5 had the highest concentration of trace elements (Table 2.3b) and was over the threshold to be applied as a commercial fertilizer due to its arsenic levels. This is most likely due to being created from poultry litter that was more than 10 years old. Since, there have been many regulation and pharmaceutical changes that have significantly reduced the trace elements in poultry litter. The biggest change has been in residual arsenic concentration, which was prevalent with the usage of the pharmaceutical known as Roxersone. Roxersone was used in poultry production to help prevent coccidiosis, a parasitic disease that infects the intestinal tracts in poultry and can lead to death in poultry (US-FDA, 2015). After a FDA study in 2009 found significant concentrations of arsenic in poultry meat, the industry voluntarily shifted away from the use of Roxersone (US-FDA, 2015).

Dilute Salt and Water Extractions

While there is no single recommended protocol for measuring WEP, we analyzed our sources using three of the most recommended protocols (Kleinman et al., 2007). The dilute salt extraction is used in place of water to obtain a clearer filtrate, but the amount of soluble phosphorus will be smaller due to Ca^{2+} ions enhancing phosphorus sorption in the soil (Aslyng, 1964). Our results found known significant differences between the three extractions for phosphorus concentration. There was a significant difference for potassium concentration; the 1:100 water extractions produced higher concentrations than the others. Trends show that although no significant differences were produced from our data the 1:10 $CaCl_2$ extraction concentrations (Table 2.4) were tended to be slightly less than the 1:10 water extract concentrations (Table 2.5).

The results from the WEP testing reaffirmed our results from the complete acid extractions in terms of which system produced superior fertilizer products, although it showed they were potentially less plant available. The ash co-products were all similar in their nutrient concentrations (Table 2.4, 2.5, 2.6). ASH5, the only fly ash tested, had the highest potassium and sulfur concentrations. Potassium and sulfur are likely to volatilize and exit the system through the exhaust stack (Kelleher et al., 2002) and would therefore likely be present in the fly ash. BIOCHAR1 had the lowest nutrient concentration, and BIOCHAR2 was similar.

2.2.2 Balance Comparison

The characterization of poultry litter from four different farms showed many differences in moisture, calcium carbonate equivalent (CCE), and elemental concentrations (Table 2.6), which was expected. The composition of poultry litter varies greatly from location to location depending on the practices of the individual poultry producer (Bolan et al., 2010; Kelley et al., 1996; Tasistro et al., 2004). Thus, the resulting ash from the different thermal combustion systems is influenced by not only the unit, but by the starting material (Table 2.7). The ASH7 system had much higher moisture concentrations than the other locations, and thus produced an incomplete burn (Table 2.8). The incomplete burn of the ASH7 system resulted in the lowest densification of nutrients (Table 2.9). The ASH4 location had the highest concentration of nutrients from the densification across the board; this system had the superior mix of burn temperature (1000ºC), oxygen levels, and feedstock moisture content (25.24%). This is supported by the literature, which stated that the ideal conditions for combustion are at 700-1000°C with a moisture content of approximately 25% (Kelleher et al., 2002; Williams, 1999). The literature also states that the typical concentration factor is 6 or 7 times that of the original feedstock nutrients (phosphorus, potassium, and sulfur) of the poultry litter (Bock, 2004). Our study found that this varied between systems based on moisture, but falls well within our range of 4-10 times concentration for phosphorus (Table 2.9). The systems tested in our balance comparison trials were not equipped with cyclones or bagging units, so the majority of potassium and sulfur escaped the systems through the exhaust (Kelleher et al., 2002) and resulted in lower concentrations (2.5-5) for potassium (Table 2.9), and for sulfur (2-3) (Table 2.9).

2.2.3 Ash Co-Product Carbon Content

The carbon content of poultry litter co-products also varies greatly based on the thermal conversion system and the initial poultry litter feedstock. ASH7 had the highest carbon content, followed by ASH3 and ASH4 (Table 2.10). The feedstock of ASH7 had the highest moisture content and thus the most incomplete burn, having less carbon removed from the system.

2.3 Conclusion

Overall, our data has determined that nutrient concentrations of poultry litter co-products are highly dependent on the conditions of their feedstock. The thermal combustion system is the greatest variable; this includes the temperature of combustion, the fuel-to-oxygen ratio for combustion, the residence time of the poultry litter, and whether or not the system has an exhaust scrubbing system to catch fly ash. Another major factor is the poultry litter from which the co-product is formed; the initial concentration of nutrients, bedding material, and moisture content of the litter impact the co-product.

Our study found that nutrient densification varied between systems: phosphorus concentration fell within a range of 4-10 times concentrated, potassium concentration was 2.5-5 times concentrated, and sulfur was 2-3 times concentrated. Our comparisons between total nutrient digestions and water soluble extractions found that the ash products were significantly less plant available than the standard fertilizers, which means that a greater amount of the co-products will have to be applied to meet the same nutrient availability of the standards. Overall, if all ideal combustion criteria are met (700-1000ºC; 25% moisture), then poultry litter co-products are a feasible form of fertilizer. However, the co-products will need to be individually analyzed for nutrient content before application recommendations can be made.

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2.5 Tables

Table 2.1 Descriptions of poultry litter co-product sources used in all studies

Source	Co-Product Type	Farm Name	Thermal Conversion System
Ash1	Bulk Ash	BHSL	Gasification
Ash2	Bulk Ash	MOO	Gasification
Ash3	Bulk Ash	RHO	Combustion
Ash4	Bulk Ash	ZIM	Combustion
Ash5	Fly Ash	MOK	Combustion
Ash6	Bulk Ash	ROR	Combustion
Ash7	Bulk Ash	HEL	Gasification
Ash8	Bulk Ash	WVR	Combustion
Biochar1	Biochar	NCB	Pyrolysis
Biochar2	Biochar	JFB	Pyrolysis
Biochar3	Biochar/Ash	FPPC	Combustion

Table 2.2 Source information and background information for poultry litter co-product thermal conversion systems

Source	Location	System	Burn Temp	Residence Time	Mode of Energy Dispersal	Poultry Litter Type	Co-Product Type
ASH1	Limerick, Ireland	Bhsl-Ireland Fluidized bed system	85ºC water set temp	N/A†	Hot Water	Broiler	Ash
ASH2	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	157 min	Forced Air	Broiler	Ash
ASH3§	Port Republic, VA	Wayne Combustion Global Refuel	593ºC in chamber	30 min	Forced Air	Turkey	Ash
ASH4§	Lancaster County, PA	Total Energy Blue Flame Stoker	82ºC water set temp 171ºC exhaust temp	60 min	Hot Water	Organic Broiler¶	Ash
ASH5	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	167 min	Forced Air	Broiler	Fly Ash
ASH6§	Lancaster County, PA	Wayne Combustion Global Refuel	593ºC in chamber	30 min	Forced Air	Broiler	Ash
ASH7§	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	157 min	Forced Air	Organic Broiler	Ash
ASH8	Pendleton County, WV	Wayne Combustion Global Refuel	593ºC in chamber	30 min	Forced Air	Broiler	Ash
BIOCHAR1	North Carolina State University	Coaltec Unit	400ºC in chamber	5 min	Forced Air	Broiler	Biochar
BIOCHAR2	Hardy County, WV	Westfiber by PHG Energy	450ºC	360 min	Forced Air	Broiler	Biochar
BIOCHAR3‡	Cheraw, SC	BGP	871ºC in chamber	60 min	Forced Air	Broiler	Biochar/Ash

†N/A. Information not available at this time.
‡When the system capacity is overload with feedstock, unit will produce biochar (our sample) but is designed to produce ash.
§Thermal conversion systems used in the balance comparison study.
¶Organic broiler operations clean the litter out the poultry house with every flock, meaning fewer nutrients will be present in the poultry litter feedstock.

Table 2.3a Total elemental concentration of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	S	Ca	Mg	Mn	Na	Fe	Al	B	Zn	Cu
	g kg^{-1}									mg kg^{-1}		
ASH1	81.89d†	114.30e	24.33b	138.42c	37.19b	3.12b	31.55b	9.56cde	10.56c	249.19c	2670.55b	1222.61d
ASH2	52.72f	71.27f	13.59b	77.33d	27.48d	2.16e	33.74a	9.11de	9.52d	139.41e	1510.43d	1089.3e
ASH3	104.90b	129.77d	28.42b	162.58a	36.59b	4.60a	25.24c	16.88b	2.15f	220.56d	2888.41a	3429.68a
ASH4	90.22c	145.78c	16.95b	131.82c	46.42a	2.94c	23.57d	14.98b	17.94b	383.45b	2515.92b	1861.01c
ASH5	9.40i	202.35b	41.49b	51.86e	8.93f	0.86g	13.98g	70.95a	2.53ef	98.10f	2879.72a	809.23f
ASH8	77.21e	116.57e	34.20b	133.04c	34.26c	2.45d	31.36b	13.24bc	19.82a	242.27c	1793.99c	3252.34b
BIOCHAR1	34.37g	32.03g	9.20b	147.19b	10.18f	0.86g	6.56i	6.01ef	9.31d	38.21g	948.90e	84.10hi
BIOCHAR2	30.81h	67.15f	13.64b	45.80e	14.92e	1.19f	17.22f	10.28cd	8.85d	108.81f	1081.55e	1848.22c
BIOCHAR3	37.08g	66.30f	9.06b	47.82e	7.36g	0.58h	21.81e	4.81f	2.82ef	45.39g	39.35g	155.80h
KCl	0.03j	493.11a	0.25b	0.72g	0.88i	NDi‡	15.01g	0.22g	0.07h	0.73h	0.15g	0.16j
Poultry Litter	12.51i	29.06g	370.92a	23.64f	174.73g	1.39h	9.38h	0.04g	1.02g	43.66g	588.35f	519.43g
TSP	201.81a	1.70h	247.95a	168.22a	4.54h	0.11i	3.03j	2.55fg	3.08e	643.96a	425.41f	22.56ij
$LSD_{0.10}$	3.44	9.62	166.85	8.44	1.84	0.14	1.13	3.96	0.77	16.84	173.78	79.84

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.3b Total elemental concentration of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	As	Be	Cd	Co	Cr	Hg	Mo	Ni	Pb	Sb	Se	Si
	--					mg kg^{-1} --						
ASH1	2.87ef†	0.92c	NDc	9.21d	41.96cd	ND‡	37.08c	37.60def	9.48b	1.21d	2.77c	44.09bc
ASH2	15.07c	0.34e	NDc	12.00c	169.69ab	ND	25.51d	108.86ab	7.18c	1.87c	1.88cd	29.59cde
ASH3	13.51c	0.12h	NDc	8.97d	15.45d	ND	48.84a	50.00cde	5.58d	1.07de	4.59b	35.04bc
ASH4	4.48de	1.37b	NDc	19.68b	33.11d	ND	25.14d	67.17cd	5.14d	1.60cd	2.51c	56.51ab
ASH5	51.87a	0.17g	4.91b	27.05a	237.07a	ND	36.32c	146.33a	56.89a	4.26a	20.29a	24.15cdef
ASH8	3.79de	0.44d	NDc	6.98f	31.09d	ND	42.20b	60.82cde	5.88d	0.35f	1.33de	32.63bcd
BIOCHAR1	0.87fg	0.45d	NDc	7.59ef	13.33d	ND	4.52g	7.47f	5.14d	0.22f	NDf	22.68cdef
BIOCHAR2	19.46b	0.31f	NDc	6.37f	12.86d	ND	21.37e	22.72ef	6.21d	0.38f	2.03cd	8.77def
BIOCHAR3	1.83efg	0.35e	NDc	3.46g	104.11bc	ND	13.90f	86.38bc	2.54e	0.54ef	NDf	4.07ef
KCl	0.27fg	NDi	NDc	0.04i	0.05d	ND	NDh	0.24f	NDf	NDf	NDf	19.64cdef
Poultry Litter	NDg	0.14gh	NDc	1.25hi	4.83d	ND	1.19h	3.35f	2.02e	NDf	0.67ef	NDf
TSP	5.99d	1.59a	8.28a	1.71h	159.13b	ND	4.57g	26.58ef	3.08e	2.53b	NDf	81.92a
$LSD_{0.10}$	2.81	0.03	0.67	1.50	69.94	---------	1.59	38.17	1.25	0.65	0.92	25.59

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.4 Weak Salt (0.1 M $CaCl_2$) Extraction of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	S	Mg	Mn	Zn	B
	--------------------g kg^{-1}	--------------------		--------------------------------mg kg^{-1}	-------------------------------		
ASH1	0.054b†	60.29e	28.94c	679.47de	0.02c	ND‡c	29.65c
ASH2	0.06b	48.25f	27.45d	1865.64b	0.22c	0.32c	10.75fg
ASH3	0.08b	72.81d	30.06c	646.97e	0.17c	NDc	21.10e
ASH4	0.02b	60.15e	19.95e	4.42g	NDc	NDc	50.13a
ASH5	0.01b	211.95b	50.35a	1287.03c	0.73c	1.35c	10.06g
ASH8	0.01b	88.64c	39.21b	218.03fg	0.05c	NDc	26.13d
BIOCHAR1	0.14b	13.25i	2.44i	259.99f	0.73c	0.30c	4.39h
BIOCHAR2	0.26b	42.32g	10.14h	927.81d	7.05c	12.01c	13.82f
BIOCHAR3	11.64b	74.74d	11.71g	5.17g	NDc	NDc	1.73hi
KCl	0.28b	483.89a	0.27j	563.96e	0.28c	NDc	0.90i
Poultry Litter	0.82b	26.07h	13.11f	567.07e	21.43b	79.93b	25.00d
TSP	219.57a	1.64j	3.09i	5138.78a	112.70a	443.26a	38.74b
$LSD_{0.10}$	16.56	3.89	1.13	250.89	8.07	20.65	3.29

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.5 Water Extraction (1:10) of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	Ca	S	Mg	Mn	Zn	B
	-------------------------g kg^{-1}------------------------				---------------------------------mg kg^{-1}----------------------------			
ASH1	0.13c†	62.60e	0.12c	25.53c	150.16e	0.02d	ND‡d	30.63c
ASH2	0.10c	48.06f	0.19c	23.21d	1293.29b	0.95d	1.35d	11.12g
ASH3	0.27c	70.31d	0.12c	25.23c	167.43e	0.29d	0.05d	20.85e
ASH4	0.11c	63.95e	0.05c	17.48e	8.81f	NDd	NDd	42.86a
ASH5	0.03c	194.39b	6.72b	44.25a	1243.33b	0.56d	0.91d	8.54h
ASH8	0.06c	89.54c	0.34c	33.16b	136.86e	NDd	NDd	23.45d
BIOCHAR1	0.59c	11.39i	0.08c	1.98i	90.92ef	0.37d	0.76d	3.86i
BIOCHAR2	0.40c	37.85g	0.18c	8.47g	436.85cd	5.72c	16.14c	13.53f
BIOCHAR3	11.82b	67.90de	0.02c	9.83f	6.17f	NDd	NDd	1.42j
KCl	0.02c	516.14a	0.30c	0.23j	503.46c	0.03d	NDd	1.49j
Poultry Litter	0.82c	22.52h	0.48c	10.94f	346.69d	16.78b	77.39b	23.50d
TSP	209.68a	1.80j	132.40a	3.37h	4158.25a	108.80a	294.95a	38.96b
$LSD_{0.10}$	5.23	5.40	3.40	1.24	109.58	4.41	3.90	1.17

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.6 Water Extraction (1:100) of ash co-products, fresh poultry litter, and standard fertilizers (KCl and TSP)

	P	K	Ca	S	Mg	Mn	Zn	B
	----------g kg^{-1}----------				----------mg kg^{-1}----------			
ASH1	1.95d†	72.52def	0.23c	27.04c	1189.50c	0.32e	ND‡e	31.49c
ASH2	1.43de	57.15fg	0.50c	24.43c	2080.35b	2.42de	2.42e	14.28f
ASH3	1.97d	86.56cd	0.35c	28.40bc	1063.69c	2.94de	NDe	25.26d
ASH4	0.77def	70.02ef	0.21c	18.48d	603.55de	NDe	NDe	48.88a
ASH5	0.21ef	265.59b	18.31b	65.73a	1871.13b	5.44d	32.93c	17.77ef
ASH8	0.26ef	92.93c	1.03c	32.03b	487.48e	0.15e	NDe	26.19d
BIOCHAR1	1.36de	28.80hi	0.37c	5.21f	535.72c	5.45d	9.59de	8.49g
BIOCHAR2	1.52d	44.93gh	0.63c	8.35ef	893.33cd	11.66c	18.68d	14.31f
BIOCHAR3	12.61b	77.70cde	0.08c	10.60e	134.29f	0.04e	NDe	NDh
KCl	0.06f	479.70a	0.41c	0.23g	571.76de	0.67e	0.28e	1.06h
Poultry Litter	3.55c	27.23i	0.85c	11.44e	990.78c	25.93b	74.21b	22.08de
TSP	190.42a	1.54j	133.86a	12.01e	4571.50a	118.17a	359.51a	43.20b
$LSD_{0.10}$	1.25	16.53	3.40	4.27	344.82	4.40	13.28	5.09

† A different letter within the column designates significance at the 0.10 level.
‡ ND = Non-detectable, below the detectable limit of the instrumentation (<.0001 mg L^{-1}).

Table 2.7 Characterization of fresh poultry litter samples from four different thermal conversion systems in the Mid-Atlantic

	Moisture	CCE†	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	K_2O‡	P_2O_5‡
	%								mg kg^{-1}							%	
ASH3	22.56d§	0.29d	4.58b	1.70a	2.19c	0.88a	0.59b	2.64b	5696c	678	116c	749a	616a	620b	57c	2.02c	3.04
ASH4	25.24c	1.78c	3.91d	0.76d	2.26c	0.38c	0.53b	1.65b	3769d	231	308b	420d	175c	565c	52c	2.03c	3.61
ASH6	28.9b	2.36b	4.04c	1.20c	3.00b	0.81b	0.64b	2.02b	6220a	665	603a	540c	226b	423d	706a	2.57b	1.97
ASH7	40.35a	3.46a	5.54a	1.41b	5.14a	0.86a	2.09a	5.14a	6018b	808	312b	663b	146d	909a	636b	3.67a	1.93
$LSD_{0.10}$	1.25	0.66	0.17	0.13	0.30	0.03	0.60	1.47	176	NS	72	37	23	36	24	0.20	NS

† CCE = calcium carbonate equivalent.
‡Available fertilizer equivalent.
§A different letter within the column designates significance at the 0.10 level.

Table 2.8 Characterization of poultry litter ash samples from three different thermal conversion systems in the Mid-Atlantic

	Moisture	CCE†	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	K_2O‡	P_2O_5‡
	%								mg kg^{-1}							%	
ASH3	0.20b§	22.54c	0.30b	10.70a	11.04b	2.32a	3.83	17.68a	33980a	10320b	1806d	4102a	3262a	2170b	261c	13.26	24.50a
ASH4	0.09b	31.13a	0.15c	7.20b	11.52b	1.24c	3.93	11.77b	20211c	12600a	18622a	2751b	1115b	2099b	316c	13.83	16.50b
ASH6	0.50b	28.90b	0.35b	6.09c	11.30b	2.30a	3.11	9.76c	28000b	9780b	13200b	2330c	1060c	1620c	2590a	13.40	13.90c
ASH7	17.76a	12.71d	2.36a	5.46d	12.47a	1.85b	5.96	7.29d	17400d	5336c	4036c	2177c	396d	2496a	1770b	12.33	10.27d
$LSD_{0.10}$	1.28	1.96	0.20	0.40	0.63	0.11	NS	1.22	1518	610	617	220	52	143	87	NS	0.80

† CCE = calcium carbonate equivalent.
‡Available fertilizer equivalent.
§A different letter within the column designates significance at the 0.10 level.

Table 2.9 Concentrations of nutrients from the densification of poultry litter entering the thermal conversion unit and poultry litter ash exiting the unit from four different units in the Mid-Atlantic

	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	K_2O	P_2O_5
	---Times Concentrated†---														
ASH3	0.07b‡	6.41b	5.04a	2.63b	6.62b	6.93b	5.98a	22.93b	15.71c	5.54b	5.36b	3.52b	4.61b	6.55b	8.26b
ASH4	0.04c	10.22a	5.12a	3.26a	7.49a	7.25a	5.41b	55.54a	65.44a	6.63a	6.48a	3.79a	6.05a	6.83a	11.36a
ASH6	0.09b	5.08c	3.77b	2.84b	4.86c	4.83c	4.50c	14.71c	21.89b	4.31c	4.69c	3.83a	3.67c	5.21c	7.06b
ASH7	0.43a	4.07c	2.48c	2.15c	3.12d	2.44d	2.90d	14.53c	16.58c	3.30d	2.80d	2.74c	2.77d	3.41d	5.54c
$LSD_{0.10}$	0.04	1.22	0.21	0.21	0.51	0.76	0.41	5.39	7.09	0.48	0.46	0.28	0.28	0.25	1.78

†Times Concentrated = ash nutrient concentration percentage/feedstock poultry litter nutrient concentration percentage).
‡A different letter within the column designates significance at the 0.10 level.

Table 2.10 Differences in carbon content of poultry litter ash and fresh poultry litter by thermal conversion system

	Bulk Poultry Litter Ash	Fresh Poultry Litter
	---C---	
	---%---	
ASH3	5.30b†	37.95b
ASH4	2.31c	38.43a
ASH7	13.03a	36.98c
$LSD_{0.10}$	1.11	0.39

†A different letter within the column designates significance at the 0.10 level.

3. Incubation of Poultry Litter Co-Products for Phosphorous and Potassium Availability

3.1 Abstract

Phosphorus and nitrogen are nutrients of concern in the Chesapeake Bay watershed due to nutrient imbalances in areas with confined animal feeding operations. By converting poultry litter to an ash or biochar, nutrients are concentrated into a form that can be economically shipped out of nutrient-dense areas to nutrient deficient regions, such as the corn belt. In nutrient deficient regions, these poultry litter co-products have potential use as fertilizer with less impact on water quality.

A non-leached aerobic incubation study was conducted on a Bojac sandy loam soil to test phosphorus and potassium availability from poultry litter ash. Four poultry litter ash products, derived from different sources using different combustion techniques, and 2 biochar products were surface broadcast applied at a rate of 85 mg P kg^{-1} and the corresponding potassium rate was recorded. Poultry litter co-products were compared to a no-fertilizer control and inorganic phosphorus (TSP) fertilizers at similar rates. A dilute salt extraction (phosphorus and potassium) was used to analyze the characteristics and availabilities of the poultry litter co-products under a controlled soil incubation environment to determine how they compare to the current industry standards in terms of potential bioavailability.

Overall, standard fertilizers (TSP and poultry litter) had the greatest initial availability for phosphorus (55.50% TSP; 9.13% poultry litter) and K (97.99% poultry litter) respectively. The poultry litter co-products varied in availabilities based on thermal conversion system from 1.60- 8.63% for phosphorus to 8.14- 88.10% for potassium. One ash co-product (ASH4) produced similar availabilities to the industry standard fertilizers after 56 days.

In conclusion, co-products from combustion thermal conversion systems were found to be superior to gasification and pyrolysis systems when the desire was to produce co-products with the most plant available phosphorus and potassium. As new thermal conversion systems are designed, the ash co-products will need further evaluation as temperature and oxygen during the combustion process significantly alters water-soluble nutrient availability.

3.2 Materials and Methods

The objective of this study was to analyze the characteristics and availabilities of the poultry litter co-products under a controlled soil incubation environment to determine how they compare to the current industry standards in terms of potential bioavailability.

3.3 Experimental Design

A non-leached aerobic incubation study was conducted with a Bojac sandy loam soil (Table 3.1) (Coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) (USDA-NRCS, 2012) with a bulk density of 1.14 g cm^{-3} (Table 3.2) to evaluate the phosphorus and potassium mineralization characteristics of poultry litter co-products. To evaluate the phosphorus and potassium mineralization of 4 ash co-products (ASH1, ASH2, ASH3, and ASH4) and 2 biochar co-products (BIOCHAR1 and BIOCHAR2) (Table 3.3) compared to TSP and KCl applied at a rate of 85 mg P kg^{-1} and the amount of potassium applied per co-product was recorded. The fertilizers were arranged in a randomized complete block design with 4 replications and incubated for 0, 3, 7, 14, 28, 56, 84, 112, and 140 days as described by (Reiter et al., 2014). The fertilizers were mixed in 50 g of air-dried soil in 500 ml plastic bottles. Bottles were then raised to approximately 60% water-filled pore space (0.15 g water g $soil^{-1}$; Schomberg et al., 2011) with double de-ionized water. Final weights were taken so the water content could be adjusted on an as-needed basis. Uncapped bottles were placed into incubation chambers at 80% humidity and 25°C.

3.3.1 Sample Analysis

At each sampling day, 4 replications were extracted per treatment source. For extraction, each bottle was filled with 500 mL of 0.01 M $CaCl_2$ solution (Aslyng, 1964) and shook for 1 hour at 200 opm (Kuo, 1996). The suspension settled for an hour and the supernatant was decanted and filtered through Whatman 42 filter paper into 25 mL scintillation vials and stored at 4°C until analyzed. Samples were analyzed for phosphorus and potassium concentrations using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire, R. O. and S. E. Henkendorn, 2011). The phosphorus and potassium concentrations of the untreated control soil samples were averaged and subtracted out. The percent remaining in the sample was calculated by the concentration of the sample divided by the original amount of fertilizer added and multiplied by 100.

$$\left(\frac{\text{Sample Concentation}}{\text{Original Amount Added}} \times 100 = \%\ \text{remaining}\right)$$

3.3.2 Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA), SAS PROC MIXED procedures and Fisher's LSD with an alpha level of 0.10 using SAS 10.1 statistical software (SAS Institute, 2007).

3.4 Results and Discussion

Overall availability of soil phosphorus from fertilizer sources was low due to the acidic nature of the soil. Water pH readings from the incubation soil averaged 5.4 (Table 3.2), which would decrease overall recoverable phosphorus. Phosphorous fixation occurs rapidly in the acidic pH ranges reacting with Al, Fe, and Mn ions and oxides to form insoluble compounds that are not plant available (Brady and Weil, 1996). When comparing the percentage phosphorus recovered/ phosphorus fertilizer applied over time for each fertilizer source (Figure 3.1), a significant phosphorus interaction was observed between fertilizer source and incubation sampling day (Table 3.5). As expected, the standard fertilizer TSP was initially the most available and water soluble at 0 d (55.50%), followed by fresh poultry litter (9.13%). Triple super phosphate became less available over time as Fe-oxides and Al-oxides in the soil absorbed phosphorus (Sims et al., 1998; Brady and Weil, 1996). Fresh poultry litter decreased in availability until day 28 (4.35%) and began significantly increasing in availability, 56 d (6.36), until peak availability at 112 d (7.19%). The increase in availability over time is likely from microbial activity, as the fresh material releases the phosphorus from poultry litter organic matter (Sharpley et al., 2007). Fresh poultry litter was found to be far less available (9.13%) than the 60-100% bioavailability range the literature field studies suggested (Slaton et al., 2013; Barbazan et al., 2009; Sneller and Laboski, 2009).

In comparing ash co-products, ASH4 has the highest water-soluble phosphorus (5.84 % at 0 d) and experienced a similar increase in availability to poultry litter at 14 d (5.95%) and 56 d (8.63%). The remaining co-products remained at a consistent solubility across time and had a range of approximately 2-4% available phosphorus, which was lower than the TSP and fresh poultry litter standards. Trends showed that ASH2 and the biochars had the least phosphorus availability.

The characteristics and solubility of the ash co-products vary due to the differences in their formation. All of the sources were derived from different thermal conversion systems and were combusted at different temperatures and had varying oxygen rates (Table 2.2). It seems that the ASH4 system had the optimal ratio of temperature to oxygen for soluble phosphorus availability in a growing season, and the ASH2 system would lead to the lowest solubility. The ASH2 system was gasified at higher temperatures for a longer period of time than the ASH4 system. The biochars were found to have a lower phosphorus availability rate, which was expected as biochars are formed in low heat with the intention of creating a slow-release product from which the full nutrient release may not be seen for years (Maguire and Agblevor, 2010).

When comparing the percentage of potassium recovered/ potassium fertilizer applied over time by each of the sources (Figure 3.2), a significant potassium interaction was observed between fertilizer source and incubation sampling day (Table 3.6). Fresh poultry litter had the greatest initial potassium availability at 0 d (97.99%). Our results for potassium availability were closer to the estimated availability in the literature, which stated that potassium should be highly soluble and should be 100% plant available (Jackson et al., 1975; Slaton et al., 2013). At 56 d, the potassium availability of ASH4

(88.19%) became similar to poultry litter (88.19%) and remained consistent until then end of the study. Also at 56 d, there was a significant increase in potassium availability for 4 of the co-products: ASH1 (46.37%), BIOCHAR2 (78.65%), ASH3 (54.54%), and ASH4 (81.04%). Out of all the co-products, ASH2 had the least water-soluble potassium at 0 d (10.89%).

Fresh poultry litter was by far the highest supplier of water-soluble potassium, which was expected as the standard unprocessed material, but over time ASH4 produced similar potassium availabilities after 56 d. Similar to the phosphorus release, ASH2 had the lowest nutrient availability; it did not change over time and remained within a range of 8.14-12.63%. The difference in these sources can once again be explained by differences in initial feedstock and system of thermal conversion (temperature and oxygen ratios). The potassium availability results further reiterate the ASH4 system's optimal conditions for creating a nutrient-dense and plant-available fertilizer.

3.5 Conclusion

The industry inorganic phosphorus fertilizer (TSP) and fresh poultry litter had the greatest initial availability for phosphorus and potassium. Over time, some of the ash co-products reached similar availabilities comparable to the industry standards but differed due to the variability in their systems of formation. The ASH4 thermal conversion system produced an ash co-product that was the most similar to the standards and provided an ideal fertilizer that was both nutrient dense and plant available. The ASH2 system converted the feedstock at higher temperatures and had longer residence times, creating a nutrient-dense product that was not readily water soluble. The biochar co-products were among the least available of the fertilizers in the study; this was expected because the biochars are formed with a slow-release product in mind to strongly hold and remove nutrients and carbon from the soil system for many years. Further ash research will be needed for each thermal conversion system and feedstock as the burning process significantly alters the overall nutrient water solubility over time.

3.6 References

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3.7 Tables

Table 3.1 Mehlich-I background analysis of nutrients of the Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) used in the incubation studies

	P	K	Ca	Mg	Zn	Mn	Cu	Fe	B
	---------------------------kg ha^{-1}------------------------				-----------------------------------mg kg^{-1}--------------------------------				
Soil	194	146	832	95	1.4	25.4	1.3	25.0	0.2

Table 3.2 Chemical and physical properties of the Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) used in the incubation studies

	pH	Buffer Index	Estimated CEC†	Bulk Density	Acidity	Base Saturation
			---meq 100 g^{-1}---	g cm^{-3}	----------------------%-------------------	
Soil	5.4	6.14	3.9	1.136	39.5	60.6

†CEC = Cation exchange capacity

Table 3.3 Nutrient content of poultry litter co-products, fresh poultry litter, and standard fertilizer (TSP) for phosphorus and potassium incubation study

Source	N	P	K	S
	--------------------	--------%--------	--------------------	
ASH1†	0.256	1.08	12.77	2.98
ASH2†	0.542	6.07	33.13	3.18
ASH3†	0.280	10.39	11.25	2.29
ASH4†	0.141	6.38	8.40	1.45
BIOCHAR1‡	1.44	2.29	1.71	0.40
BIOCHAR2‡	2.51	2.59	4.87	1.25
Poultry Litter	3.55	1.08	1.91	1.10
TSP	0.00	20.09	0.00	0.00

Table 3.4 Phosphorus (P) availability as a percentage of total P recovered or total P applied over a 140 d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products, fresh poultry litter, and standard phosphorus fertilizer (TSP)

	--Incubation Day--								
	0	3	7	14	28	56	84	112	140
	--% P Recovered--								
ASH1	3.69†	4.43	3.89	3.30	4.13	3.48	3.89	3.85	4.33
ASH2	1.89	2.58	2.32	1.78	2.71	2.29	2.78	2.29	2.20
ASH3	2.44	3.40	3.24	2.72	2.72	3.12	3.75	3.95	3.45
ASH4	5.84	6.74	5.99	5.95	6.45	8.01	8.63	7.75	7.51
BIOCHAR1	1.60	2.19	2.04	1.76	2.69	1.74	2.25	2.11	2.11
BIOCHAR2	3.28	3.34	3.23	2.75	3.70	3.50	3.17	3.51	3.95
Poultry Litter	9.13	4.50	5.21	4.64	4.35	6.36	6.65	7.19	5.25
TSP	55.50	15.12	12.32	11.31	11.36	7.43	6.68	5.25	5.88

† Phosphorus source x incubation time interaction $LSD_{0.10}$=1.99%.

Table 3.5 Potassium (K) availability as a percentage of total K recovered or total K applied over a 140-d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products and fresh poultry litter

	----------Incubation Day----------							
	0	3	7	14	56	84	112	140
	----------% K Recovered----------							
ASH1	36.00†	43.12	40.36	33.70	46.37	45.60	47.74	43.44
ASH2	10.89	11.39	12.10	8.14	12.63	12.15	10.81	10.42
ASH3	41.29	53.59	51.17	39.48	54.54	62.74	61.77	57.59
ASH4	58.76	66.91	67.41	60.44	81.04	88.10	76.73	81.95
BIOCHAR1	63.58	72.23	73.92	49.53	71.54	76.31	66.80	59.64
BIOCHAR2	64.19	69.55	67.83	59.61	78.65	82.18	80.68	74.20
Poultry Litter	97.99	88.58	88.36	87.94	88.19	93.24	92.75	87.73

†Potassium source x incubation time interaction $LSD_{0.10}$=8.99%.

3.8 Figures

Figure 3.1 Phosphorus (P) availability as a percentage of total P recovered or total P applied over a 140 d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products, fresh poultry litter, and standard phosphorus fertilizer

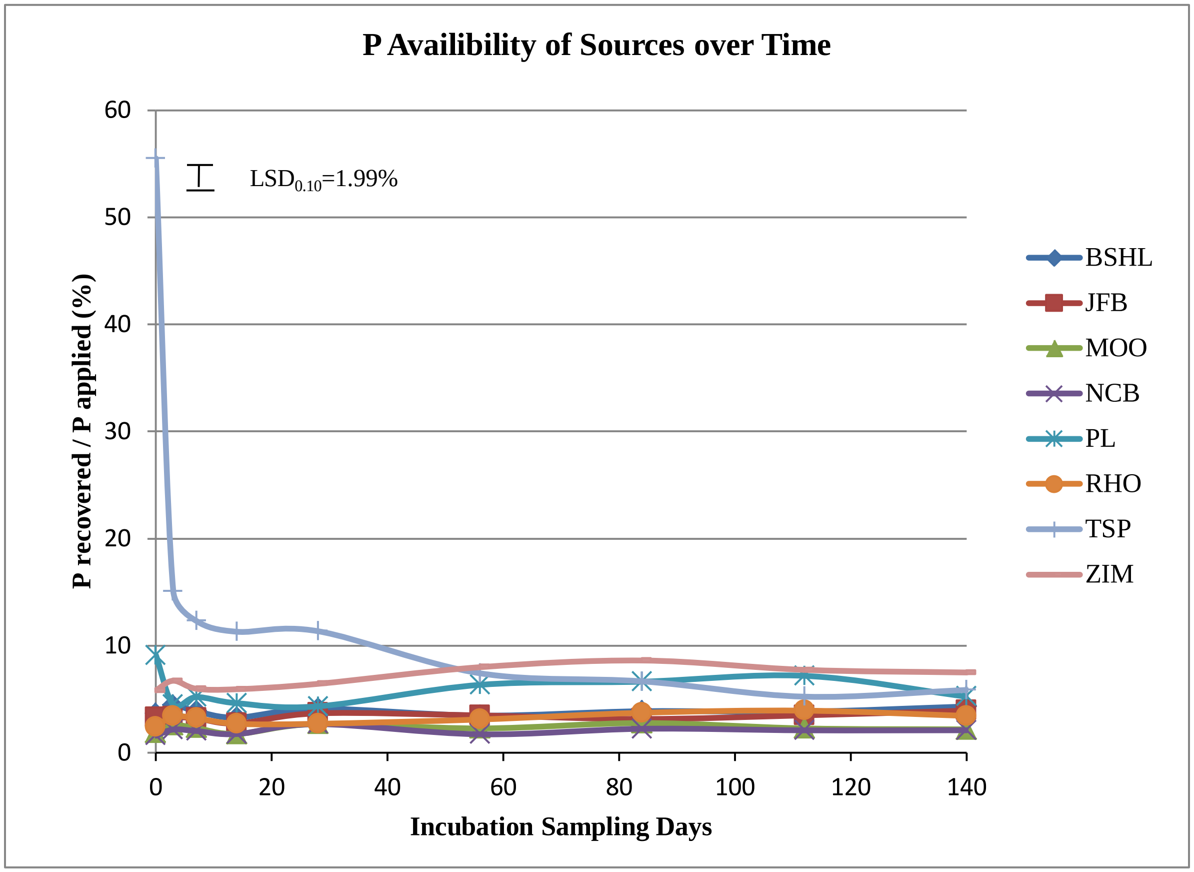
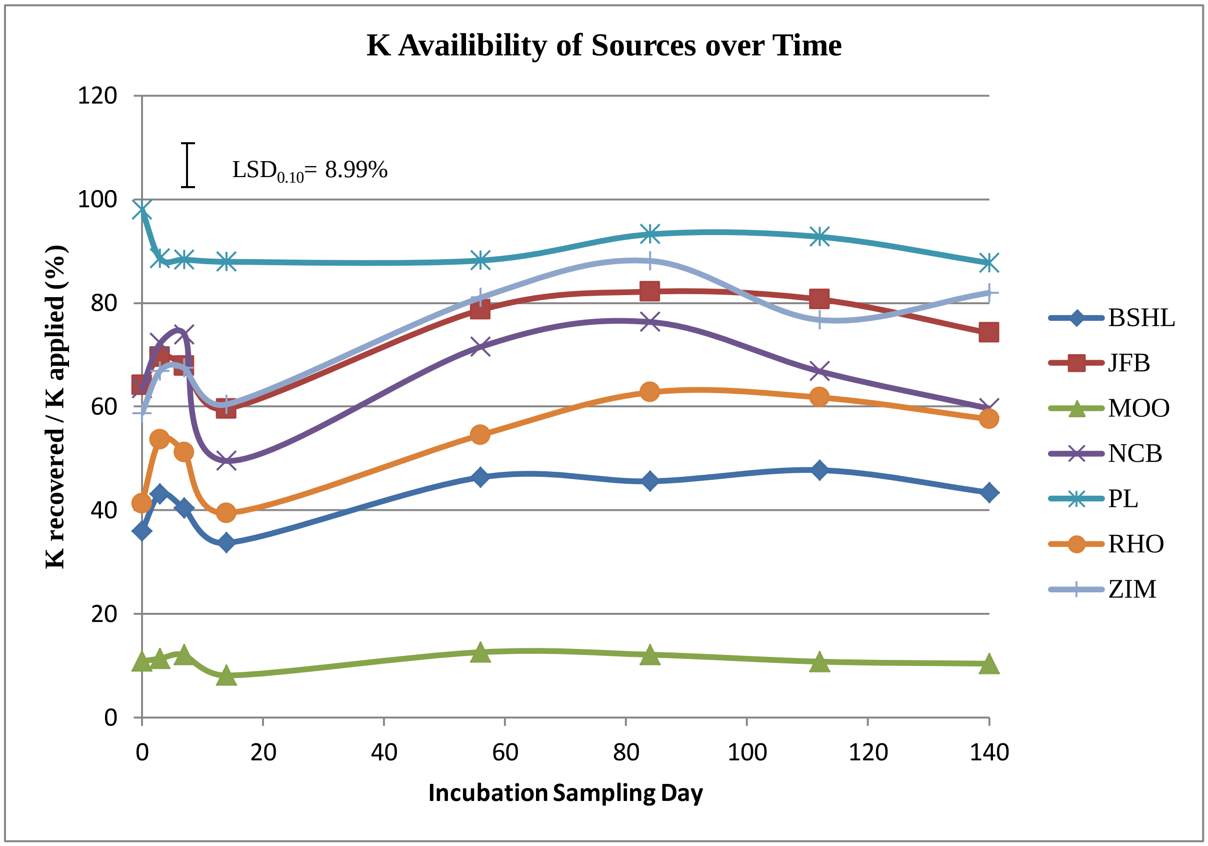


Figure 3.2 Potassium (K) availability as a percentage of total K recovered or total K applied over a 140 d incubation study with a Bojac sandy loam soil (coarse, loamy, mixed, semi-active, thermic, Typic Hapludult) for poultry litter co-products and fresh poultry litter



4. Nutrient Availability of Poultry Litter Co-Products in Field Trial Applications

4.1 Abstract

Phosphorus is a nutrient of concern in the Chesapeake Bay watershed due to nutrient imbalances in areas with confined animal feeding operations. By converting poultry litter to an ash or biochar, nutrients are concentrated into a form that can be economically shipped out of nutrient-dense areas to nutrient deficient regions, such as the corn belt. In nutrient deficient regions, these poultry litter co-products have potential use as fertilizer with less impact on water quality.

We initiated field studies (corn [*Zea mays* (L.)], soybean [*Glycine max* (L.)], and wheat [*Triticum aestivim* (L.)]) on sandy loam soils to test phosphorus and potassium availability from poultry litter ash. Four ash co-products, derived from different sources using different combustion techniques, and 2 biochar products were surface broadcast applied at varying phosphorus and potassium rates. Poultry litter co-products were compared to a no-fertilizer control and industry standard inorganic phosphorus (TSP) and inorganic potassium (KCl) fertilizer at similar rates. Yield, Mehlich-I extractable soil nutrients, plant tissue and grain samples, and organic matter content were used to compare treatments. In general, poultry litter was the superior fertilizer source. Poultry litter ash co-products were highly variable due to the variations in thermal conversion systems and feedstock of formation. However, when applied at the proper rate, the poultry litter co-products appear to be comparable to standard fertilizers in corn, soybeans, and wheat field studies.

4.2 Materials and Methods

4.2.1 Experimental Design

We initiated a study on sandy loam soils (Table 4.1) to test phosphorus and potassium availability from poultry litter ash on corn, soybean, and wheat. Overall, three corn phosphorus studies, two full-season soybean potassium studies, three double-crop soybean potassium studies, three wheat potassium studies, and three wheat potassium studies were conducted.

Corn studies were conducted at the Virginia Tech Eastern Shore Agriculture Research and Extension Center (AREC) in Painter, Virginia (2013, 2014) and at the Virginia Tech Tidewater AREC in Suffolk, Virginia (2014). Studies consisted of 4 replications and 25 total fertilizer treatments arranged in a randomized complete block design (RCBD). Four ash co-products (ASH1, ASH2, ASH3, and ASH4), derived from different sources using different combustion techniques, and 2 biochar products (BIOCHAR1 and BIOCHAR2) (Table 4.2) were surface broadcast applied at 3 phosphorus rates (22, 44, and 88 kg P_2O_5 ha^{-1}). Potassium was applied with a balanced application using KCl to ensure all plants had identical total potassium rates. Poultry litter co-products were compared to a no-fertilizer control and inorganic phosphorus (TSP) fertilizer at similar rates.

Full-season soybean studies were conducted at the Virginia Ag Expo location in the Land of Promise, Virginia (2013) and Lottsburg, Virginia (2014) (Table 4.1). Double-crop soybean studies were conducted on the Eastern Shore of Virginia at 2 sites in Accomack County (2014) (Table 4.1). The studies consisted of 4 replications and 10 total fertilizer treatments arranged in a RCBD. Five ash co-products (ASH1, ASH2, ASH3, ASH4 and ASH5), derived from different sources using different combustion techniques, and 2 biochar products (BIOCHAR1 and BIOCHAR2) (Table 4.2) were surface broadcast applied at one potassium rate (67 kg K_2O ha^{-1}) and phosphorus was applied with a balanced application using TSP. Poultry litter co-products were compared to a no-fertilizer control and potassium (KCl) fertilizer at similar rates.

Phosphorus wheat studies were conducted at three locations on the Eastern Shore of Virginia in Accomack County (2014) (Table 4.1). The studies consisted of 4 replications and 13 total fertilizer treatments arranged in a RCBD. One ash co-product (ASH3) (Table 4.2) was surface broadcast applied at 4 phosphorus rates (34, 67, 101, and 134 kg P_2O_5 ha^{-1}) and potassium was applied with a balanced application using KCl. Poultry litter co-product was compared to a no-fertilizer control and inorganic phosphorus (TSP) fertilizer at similar rates.

Potassium wheat studies were conducted at three locations on the Eastern Shore of Virginia in Accomack County (2014) (Table 4.1). The studies consisted of 4 replications and 13 total fertilizer treatments arranged in a RCBD. One ash co-product (ASH3) (Table 4.2) was surface broadcast applied at 4 potassium rates (34, 67, 101, and 134 kg K_2O ha^{-1}) and phosphorus was applied with a balanced application using TSP. Poultry litter co-product was compared to a no-fertilizer control and inorganic potassium (KCl) fertilizer at similar rates.

4.2.2 Sample Analysis

Yield, grain moisture, and grain test weight were collected at the time of harvest. Grain weight was captured in field by the combine's software (ALMACO Seed Spector LRX, Nevada, IA). Sample moisture and grain test weight was collected using a GAC® 2100 Agri DICKEY John Moisture Tester (Churchill Industries, Minneapolis, MO). Yield was corrected for percent moisture to industry bushel standards: 25.4 kg (56 lbs) per bushel for corn at 15.5% moisture, 27.2 kg (60 lbs) per bushel for soybeans at 13% moisture, and 27.2 kg (60 lbs) per bushel for wheat at 13.5% moisture (Murphy, 1993).

Plant tissue samples were dried until a constant weight at 55°C. Samples (corn ear leaf, corn grain, soybean tissue at V3 and V5, soybean whole plant at R2, soybean grain, wheat whole plant prior to bloom, and wheat grain) were coarse ground to pass a 2 mm sieve. Ground samples (0.5 g) were digested in nitric acid and hydrogen peroxide using method 3050B (USEPA, 1996) and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011) for phosphorus and potassium.

Mehlich-I extractable nutrients were analyzed with ICP-OES (Mehlich, 1953). Soil samples were taken pre-fertilization at 3 depths: 0-15 cm, 15-30 cm, and 30-60 cm and at harvest at the 0-15 cm depth. Soils were air-dried and ground using a hammer mill to pass through a 2 mm screen. Using the Mehlich-I soil testing protocols, 8 grams of soil were extracted with 40 ml of Mehlich I solution (1:5 soil to extractant ratio) in 60 ml straight-walled plastic extracting beakers. The samples were shaken for 5 minutes on a reciprocating shaker set at 180 opm. Extracts were filtered through Whatman no. 2 filter paper into plastic vials and was then analyzed by ICP-OES for nutrient concentration.

To estimate phosphorus currently available in soil solution, 4 grams of soil were extracted with 40 ml of 0.01 $CaCl_2$ solution (1:10 soil to extractant ratio) in 60 ml straight-walled plastic extracting beakers (Aslyng, 1964; Olsen and Sommers, 1982). The samples were shaken for 1 hour on a reciprocating shaker set at 200 opm. Extracts were filtered through Whatman no. 2 filter paper into plastic vials. The solution was analyzed by ICP-OES for nutrients.

Soil organic matter samples were determined using the Loss-On-Ignition (LOI) Method as described by Ben-Dor and Banin (1989). The sample was air-dried at 105°C for 24 hours, cooled in a desiccator and weighed. The sample was then placed in a muffle furnace and ignited at 400°C for 16 hours, cooled in a desiccator and weighed. Organic matter is assumed to equal the % LOI. The LOI was determined by the equation % LOI = ($Weight_{105}$ - $Weight_{400}$ / $Weight_{105}$) x 100 (Ben-Dor and Banin, 1989).

4.2.3 Statistical Analysis

Statistical analysis was conducted using analysis of variance (ANOVA), SAS PROC MIXED procedures and Fisher's LSD with an alpha level of 0.10 using SAS 10.1 statistical software (SAS Institute, 2007).

4.3 Results and Discussion

4.3.1 Corn

There were significant differences between site year, so data is presented separately and the phosphorus source x phosphorus rate interaction was not significant. For the phosphorus rate main effect, yield increased in a linear relationship with phosphorus rate in the first year (Painter 2013) (Figure 4.1), averaged across phosphorus fertilizer sources. Phosphorus was limited in this experiment because a plateau was not reached due to the initial low phosphorus testing soil (9 mg kg^{-1}). Yield increased linearly in the second year (Suffolk 2014), until it reached a plateau at 22 kg ha^{-1} (Figure 4.1). After this point, no further benefit to phosphorus fertilizer was realized due to high initial soil phosphorus concentrations (29 mg kg^{-1}). Yield data from Painter 2014 was omitted due to significant deer damage across all replications.

Overall, for phosphorus source, Suffolk 2014 data indicated that poultry litter was significantly the highest yielding source (7891 kg ha^{-1}), averaged over phosphorus rate. We speculate that heavy rains during the early growing season leached or denitrified significant amounts of nitrogen fertilizer, and the slow-release nitrogen from poultry litter was available to the corn crop and gave a significant yield advantage. The ash co-products were similar to TSP but higher than the no-phosphorus fertilizer control (Table 4.3). Overall, our data agrees with Slaton et al. (2013) who, found that poultry litter provided an additional yield benefit above that of commercial fertilizer at one of their eight responsive sites and similar yields at the other sites. The cause of the yield benefit was unknown and could not be attributed to another essential nutrient present in the poultry litter but not in the commercial fertilizer (Slaton et al., 2013). The Painter 2013 site was not significant and the average yield was 4565 kg ha^{-1}.

When averaged by site year and phosphorus fertilizer source, corn grain moisture had a significant linear response to phosphorus rate. Moisture increased with phosphorus rate at Suffolk 2014 ($y= 0.0049x + 13.5$; p=0.0640) and the no-fertilizer control had the lowest grain moisture (15.85%). No-fertilizer plots matured more quickly with lower yields and lower available nutrient concentrations, resulting in lower grain moisture concentrations at harvest.

Corn grain test weight varied with location and phosphorus source. Test weight by phosphorus source, averaged over phosphorus rate, was significantly different with one biochar co-product, BIOCHAR1 (673.0 kg m^{-3}), having lower corn grain test weight than all the other treatments (Table 4.4). The lower test weight could be explained by the biochar removing nutrients from the soil system and preventing them from being immediately available to plants (Maguire and Agblevor, 2010) as BIOCHAR1 had lower grain test weight than the no-fertilizer control.

There were no observed significant differences of phosphorus concentration in the corn ear leaf. The ear leaf concentrations averaged (2.2 g kg^{-1}) across all treatments and site years; which is below the optimal range of 2.5-.5.0 g kg^{-1} for tissue P (Bryson et al., 2013).

Averaged across site year, grain phosphorus concentrations varied with phosphorus rate and phosphorus source. For phosphorus rate, the highest rate (88 kg ha^{-1}) had the greatest concentration, which increased linearly ($y= 1.589x + 2129$; p= 0.0578). For phosphorus source, TSP (2.33 g kg^{-1}) had the highest grain phosphorus concentration and was significantly similar to ASH4 (2.29 g kg^{-1}) (Table 4.4). ASH4 was also comparable to TSP in yield, moisture, test weight, and grain phosphorus concentration indicating similar phosphorus availability. BIOCHAR2 tended to have the lowest yield, moisture, test weight, and grain phosphorus concentration, indicating that the biochar co-product had the least available in the first growing season following application as a phosphorus fertilizer source.

4.3.2 Soybeans

Full Season Soybeans

Full season soybean yield, moisture, and test weight varied only with location and potassium fertilizer source was not significant. The Promise 2013 (2858 kg ha^{-1}) location had a statistically lower yielding crop than Lottsburg 2014 (5115 kg ha^{-1}).

The Lottsburg 2014 had statistically higher moisture concentrations (15.8%) than Promise 2013 (13.1%). The Lottsburg 2014 grain test weight (1839 kg m^{-3}) was statistically denser than Promise 2013 (709 kg m^{-3}). Therefore, the ash co-products were tested under variable growing conditions around Virginia, but source did not matter. Similar data and results were seen in other Virginia studies conducted during these same years at the same locations, as ample growing conditions did not necessitate additional potassium fertility (Stewart, 2015).

All V3 tissue concentrations averaged across all treatments and site years (27.0 g kg^{-1}) were above or within the optimal range of 17.0-25.0 g kg^{-1} for tissue potassium (Bryson et al., 2013). Tissue potassium concentration of V5 and R2 tissue varied with location. Lottsburg 2014 (21.0 g kg^{-1} and 25.0 g kg^{-1} for V5 and R2, respectively) had statistically higher concentrations than Promise 2013 (19.0 g kg^{-1} and 14.0 g kg^{-1}, respectively). All V5 and R2 tissue concentrations were within the optimal range of 18.0-25.0 g kg^{-1} for V5 tissue potassium and 15.0-22.5 g kg^{-1} for R2 tissue potassium (Bryson et al., 2013). The only significant result from potassium fertilizer source occurred at the Promise 2013 site location for grain potassium concentration. All ash co-products were statistically similar to the fresh poultry litter and TSP standards with the exception of ASH4 (17.5 g kg^{-1}), which had lower grain potassium concentrations.

Double Crop Soybeans

The Willis Wharf A site location had significant differences between potassium sources. The fly ash co-product ASH5 (1824 kg ha^{-1}) underperformed fresh poultry litter, KCl and most ash co-products, averaged across potassium rate. Interestingly, the fly ash has the highest potassium concentration (202.4 g kg^{-1}) of all ash co-products (Table 2.3a) tested. The fly ash is a fine particulate that exhausts from the thermal conversion units as they burn poultry litter, but appears to have lower water solubility than the bulk ash from the same systems and poultry litter as those treatments yielded 2435 kg ha^{-1} (ASH2). The ASH5 fly ash yields were actually lower than the no-fertilizer control plots (2222 kg ha^{-1}). Similarly, BIOCHAR1 was also lower yielding than the standard fertilizer treatments and several ash sources (Table 4.5).

For grain moisture, averaged over location, BIOCHAR1 and BIOCHAR2 were statistically similar to fresh poultry litter and KCl; the rest of the co-products were significantly drier than the standards, with ASH4 being the driest (Table 4.6). For test weight averaged over site year, there was a significant difference between potassium sources. BIOCHAR1, ASH3, ASH4, and ASH5 were similar to applying no fertilizer at all (Table 4.6). Low test weight results were similar to yield, and potassium availability may not be available from the biochar and fly ash co-products compared to other technologies that produce more soluble ash sources.

For the R2 tissue concentration of potassium averaged across location, Willis Wharf B site had significant differences between potassium sources. Poultry litter had the highest tissue potassium concentration at R2 (28.0 g kg^{-1}) than other co-products. All other co-products were similar to the no-fertilizer control. However, all R2 tissue concentrations were within the optimal range of 15.0-22.5 g kg^{-1} for R2 tissue (Bryson et al., 2013). Muriate of potash (18.4 g kg^{-1}) had the highest grain potassium concentrations.

4.3.3 Wheat Phosphorus

Overall, there were no major differences between ash co-products for wheat yield. Average yield by location for Gospel Temple was 4133 kg ha^{-1}, Cheriton was 3722 kg ha^{-1}, and Quinby was 3360 kg ha^{-1}. Grain moisture was only significant at the Cheriton site in phosphorus rate main effect, averaged over phosphorus source. Grain moisture content increased linearly with phosphorus addition ($y= 0.0025x +13.8$; $p= 0.0100$). Similarly, grain test weight decreased linearly with the addition of P ($y= -0.0712x + 766$; $p= 0.0351$).

For tissue phosphorus concentration averaged across phosphorus rate, the Gospel Temple site had a significant phosphorus source effect. ASH3 (2.5 g kg^{-1}) was statistically similar to TSP (2.8 g kg^{-1}), but had lower concentrations than poultry litter (3.0 g kg^{-1}). However, all tissue phosphorus samples were within the range of 2.0-5.0 g kg^{-1} (Bryson et al., 2013). Codling et al. (2002) found that poultry litter ash treatments produced higher tissue phosphorus concentrations than the standard, although their concentrations were below the optimum range due to initial low soil phosphorus concentrations. Overall, there were no major differences between ash co-products grain phosphorus concentration and averaged 3.9 g kg^{-1} for Quinby, 3,8 g kg^{-1} for Gospel Temple, and 3.7 g kg^{-1} for Cheriton.

4.3.4 Wheat Potassium

Averaged across location and potassium fertilizer rate, poultry litter was statistically the highest yielding (3744 kg ha^{-1}). Muriate of potash and ASH3 were similar to the no-fertilizer control treatments (3398 kg ha^{-1}) (Table 4.7). Therefore, the poultry litter provided additional yield benefit just as in a soybean study by Slaton et al. (2013), although the source of the additional benefit was unknown. Moisture exhibited similar results to yield when averaged over potassium rate, as poultry litter (13.8%) was statistically the driest source and KCl and ASH3 were statistically similar to each other and drier than the control plot (14.3%) (Table 4.7).

The tissue potassium concentration increased linearly with increasing fertilizer rate ($y = 21.29x + 13051$; $p = 0.0017$) (Figure 4.2), which is indicative of potassium availability and plant uptake from the fertilizer sources. Averaged across location and potassium rate, tissue potassium concentration from fresh poultry litter (16.2 g kg^{-1}) was statistically higher than KCl and ASH3 (Table 4.6). Only the poultry litter source had tissue potassium concentrations within the optimal range of 15.0-30.0 g kg^{-1} for tissue potassium (Bryson et al., 2013). Quinby had a significant difference between potassium fertilizer sources, averaged across potassium rates. ASH3 (4.3 g kg^{-1}) was statistically similar to poultry litter (4.3 g kg^{-1}) and had higher grain potassium concentrations than KCl (4.1 g kg^{-1}) and the control plot (4.1 g kg^{-1}) Therefore, the co-product was equally plant available compared to the standard sources.

4.3.5 Soil Mehlich-I and Soil Organic Matter

Following harvest, the phosphorus and potassium concentrations in the soil increased linearly with rate of fertilizer application, averaged over fertilizer source. Soil phosphorus concentrations increased linearly with the addition of fertilizer at the Painter 2014 corn location ($y = 0.0549x + 3.8$; $p = 0.0115$) (Figure 4.3) and soil potassium concentration for the wheat potassium locations ($y= 0.1873x + 81.7$; $p= 0.0088$) (Figure 4.4).

For the Gospel Temple site year phosphorus source main effect, poultry litter (32.5 mg P kg^{-1}) had higher phosphorus concentrations than the TSP standard (29.7 mg P kg^{-1}); this was most likely due to its greater residual phosphorus, although not significantly different than ASH3 (29.7 mg P kg^{-1}) or the no-fertilizer control (27.7 mg P kg^{-1}). At the Painter 2014 corn location, BIOCHAR2 (87.8 mg K kg^{-1}) had the greatest concentration of potassium in the soil while, the other sources were statistically similar (Table 4.8). This supports the yield data that the biochar sources are less plant available and will remain in the soil for future years (Maguire and Agblevor, 2010).

The vast majority of micro-elements increased linearly with increasing rate of fertilizer application and was observed with Al, Ca, Cu, B, Mg, and Zn. The overall Fe concentration in the soil made it difficult to see an Fe response from the application of the fertilizers. Overall, Zn tended to be less concentrated in the soil fertilized by ash co-products leading us to believe that Zn is more plant available in the ash form. Soil B concentration trended to be higher following poultry litter applications. Soil Cu concentrations tended to be higher following poultry litter and ash, as Cu is typically absent from inorganic fertilizers. None of the soil-applied elements exceeded concentrations that would cause environmental concern based on comparison of background concentrations in US soils according to the elemental limit recommendation charts from the USDA-NRCS (2015).

No significant differences were found for organic matter content after a single year application of ash and biochar. No significant difference was expected because at our greatest rate (88 kg ha^{-1}) we applied biochar at a rate of 1.7 Mg ha^{-1}and a study by Revell et al. (2012) found that after two years of applying biochar at a rate of 9 Mg ha^{-1}, 3 field sites showed significant increases in soil C (0.51, 0.39, and 0.36%; respectively). More research is need for multi-year usage to know when a change in organic matter will present.

4.4 Conclusion

Overall, poultry litter ash and biochar sources are suitable and comparable phosphorus and potassium fertilizers for crops on sandy loam soils in the Mid-Atlantic.

Poultry litter co-products vary greatly based on thermal conversion system and initial feedstock. If all ideal combustion criteria are met, then poultry litter co-products are feasible fertilizers, but need to be individually analyzed for nutrient content before making application recommendations. In our study, we found that the combustion systems seemed to have those ideal conditions and produced co-products that were highly plant available. However, a greater amount of the co-products will have to be applied to meet the same nutrient availability of the standards due to their lower plant availability. Fresh poultry litter tends to be the better fertilizer due to its added nitrogen content, which is lost in thermal conversion systems and would have to be supplemented with the ash co-products. Biochars tend to be less plant available than their ash counter parts. More research using the water-soluble availabilities instead of the total concentration nutrients of the co-products are needed to be able to identify stronger relationships with standard fertilizers.

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4.6 Tables

Table 4.1 Locations, soil types, and soil characterization for all field trial site locations

Year	Location	Crop	Texture	Classification	CEC†	pH	P	K	Ca	Mg
					--meq 100 g^{-1}--		------------mg kg^{-1}----------			
2013	Painter, VA	C‡	SL§	Typic Hapludults	5.6	5.7	9	71	641	92
2014	Painter, VA	C	SL	Typic Hapludults	5.4	6.1	5	60	686	95
2014	Cheriton, VA	W	FSL	Typic Hapludults	4.2	6.3	37	87	460	117
2014	Quinby, VA	W	SL	Typic Hapludults	4.8	5.6	36	109	473	71
2014	Willis Wharf, VA	SB/W	SL	Typic Hapludults	6.0	5.3	86	128	646	49
2014	Gospel Temple, VA	W	SL	Typic Hapludults	5.3	5.7	31	143	592	63
2014	Keller, VA	SB	LS	Typic Hapludults	4.2	6.0	14	102	569	55
2013	Land of Promise, VA	SB	L	Typic Hapludults	8.6	5.8	48	54	958	145
2014	Suffolk, VA	C	LS	Typic Hapludults	2.8	5.0	29	94	247	51
2014	Lottsburg, VA	SB	FSL	Aquic Hapludults	5.9	6.6	84	108	783	207

† CEC = cation exchange capacity
‡ C = corn, W = wheat, SB = soybean
§SL= sandy loam, L = loam, FSL= fine sandy loam, LS = loamy sand

Table 4.2 Nutrient content of ash and biochar treatment sources for field studies

Source	N	P	K	S
	---------------------------%	-------------------------		
ASH1†	0.256	1.08	12.77	2.98
ASH2†	0.542	6.07	33.13	3.18
ASH3‡	0.280	10.39	11.25	2.29
ASH4‡	0.141	6.38	8.40	1.45
ASH5†		0.66	37.10	
BIOCHAR1§	1.44	2.29	1.71	0.40
BIOCHAR2§	2.51	2.59	4.87	1.25
Poultry Litter	3.55	1.08	1.91	1.10
TSP	0.00	20.09	0.00	0.00
KCl	0.00	0.00	53.57	0.00

† Gasification
‡ Combustion
§ Pyrolysis

Table 4.3 Corn yield at the Suffolk 2014 site year comparing poultry litter co-product fertilizers to industry standard fertilizers (TSP)

Source	Suffolk 2014
	------------------kg ha^{-1}------------------
ASH1	6862b
ASH2	7083b
ASH3	6476b
ASH4	6978b
BIOCHAR1	6773b
BIOCHAR2	7062b
Poultry Litter	7891a
TSP	6871b
Control	5566c
$LSD_{0.10}$	834†

† A different letter within the column designates significance at the 0.10 level.

Table 4.4 Average corn grain test weight and grain phosphorus concentration across 3 site locations comparing poultry litter co-products, fresh poultry litter, and standard fertilizers (TSP)

Source	Test Weight	Grain P Concentration
	---------------kg m^{-3}-------------	-----------------g kg^{-1}------------------
ASH1	689.4a	2.22b
ASH2	682.5a	2.25b
ASH3	686.1a	2.16c
ASH4	685.5a	2.29a
BIOCHAR1	673.0b	2.02d
BIOCHAR2	685.3a	2.07d
Poultry Litter	688.3a	2.26b
TSP	690.9a	2.32a
Control	688.9a	2.16c
$LSD_{0.10}$	8.5	0.06

†A different letter within the column designates significance at the 0.10 level.

Table 4.5 Double crop soybean yield response to potassium source for WWA site location comparing poultry litter co-products, fresh poultry litter, and standard fertilizers (KCl)

Source	Yield
	----------------kg ha^{-1}---------------
ASH1	2435a
ASH2	2435a
ASH3	2397a
ASH4	2133abc
ASH5	1824c
BIOCHAR1	2020bc
BIOCHAR2	2237ab
Poultry Litter	2414a
KCl	2195ab
Control	2222ab
$LSD_{0.10}$	321

†A different letter within the column designates significance at the 0.10 level.

Table 4.6 Double crop soybean moisture, test weight, and grain potassium concentration by source over 3 site locations comparing poultry litter co-products, fresh poultry litter, and standard fertilizers (KCl)

Source	Grain Moisture	Test Weight	Grain K Concentration
	------------------%----------------	--------------kg m^{-3}-------------	----------------g kg^{-1}-------------
ASH1	12.9bcd	715.4abc	17.5cd
ASH2	12.9bcd	718.6abc	17.4cd
ASH3	12.9cd	714.7cd	17.3d
ASH4	12.8d	715.1bcd	17.6cd
ASH5	12.9bcd	712.8d	17.4cd
BIOCHAR1	12.9abc	713.7d	17.7bc
BIOCHAR2	13.0ab	718.7ab	17.8bc
Poultry Litter	13.1a	718.1abc	18.0b
KCl	13.0a	721.4a	18.4a
Control	13.0a	713.8d	17.9bc
$LSD_{0.10}$	0.1	3.9	0.4

†A different letter within the column designates significance at the 0.10 level.

Table 4.7 Wheat yield, grain moisture, and tissue potassium (K) concentration response to K source across 3 site locations comparing ash co-product, fresh poultry litter, and standard fertilizers (KCl)

Source	Yield	Grain Moisture	Tissue K Concentration
	----------------kg ha^{-1}-------------	-----------------%----------------	--------------g kg^{-1}--------------
ASH3	3214b	14.0b	14.1b
Poultry Litter	3744a	13.8c	16.2a
KCl	3319b	14.0b	14.2b
Control	3397b	14.3a	12.8c
$LSD_{0.10}$	222	0.1	0.7

†A different letter within the column designates significance at the 0.10 level.

Table 4.8 Soil potassium concentration by fertilizer source for the Painter 2014 corn site location

Source	Painter 2014
	---------------------------- Potassium ---------------------------
	---------------------------------mg kg^{-1}----------------------------
ASH1	71.8bc
ASH2	76.5bc
ASH3	77.0b
ASH4	73.3bc
BIOCHAR1	66.8c
BIOCHAR2	87.8a
Poultry Litter	74.9bc
TSP	69.4bc
Control	74.4bc
$LSD_{0.10}$	10.0

†A different letter within the column designates significance at the 0.10 level.

4.7 Figures

Figure 4.1 Corn yield by phosphorus (P) rate for 2 corn site locations

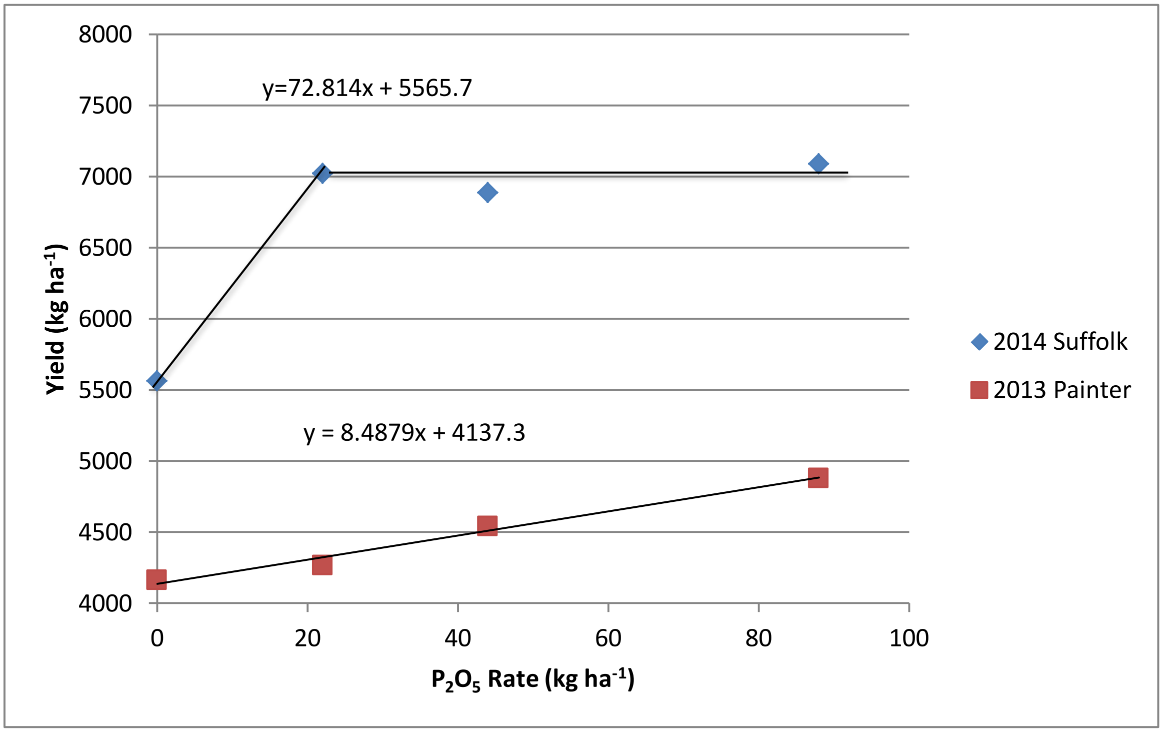


Figure 4.2 Wheat potassium (K) tissue K concentration response to rate of K across 3 site locations

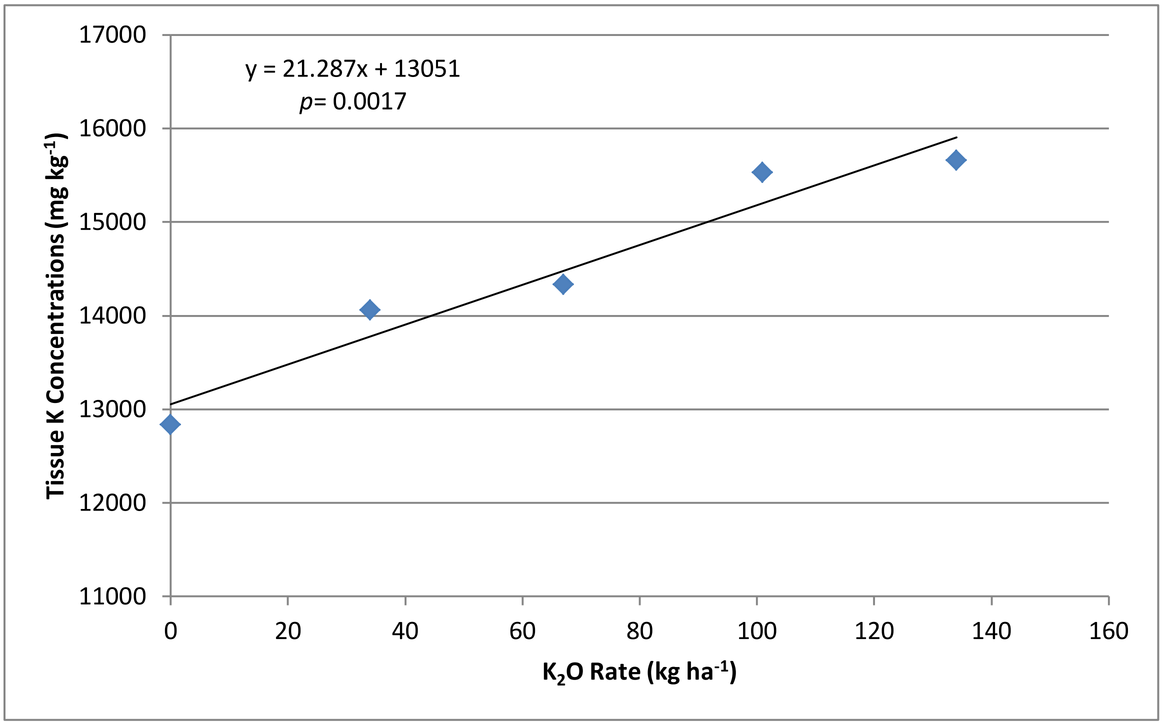


Figure 4.3 Soil phosphorus (P) concentration by treatment rate for the Painter 2014 site location

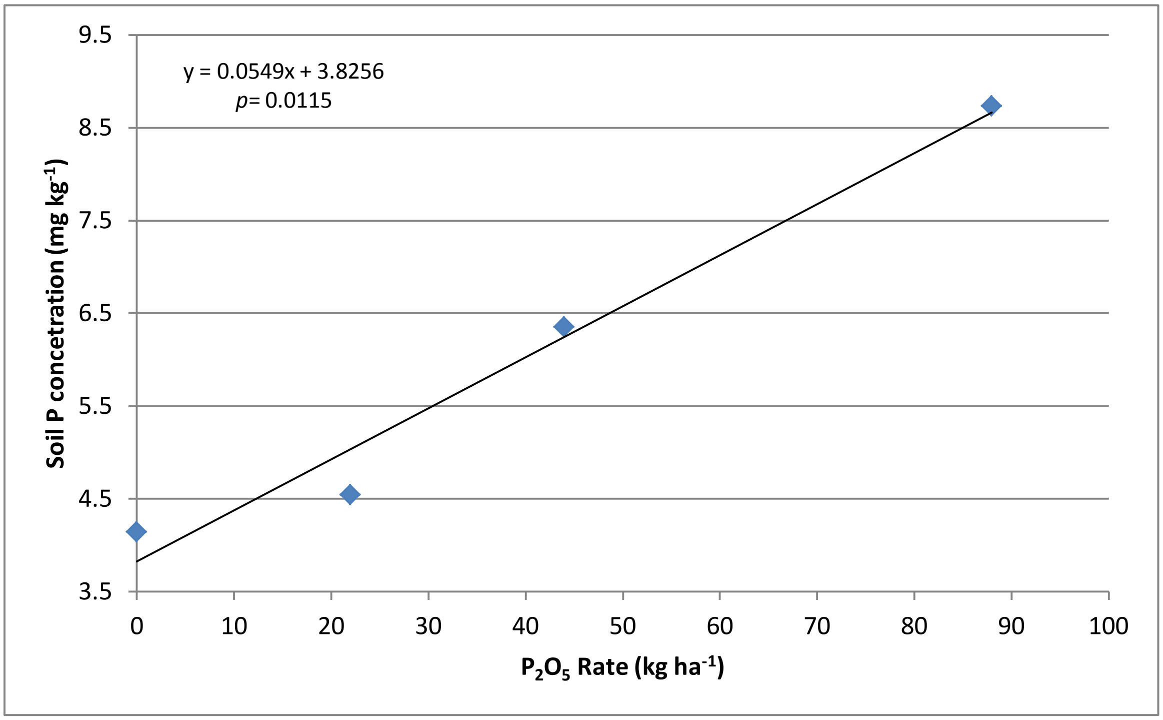
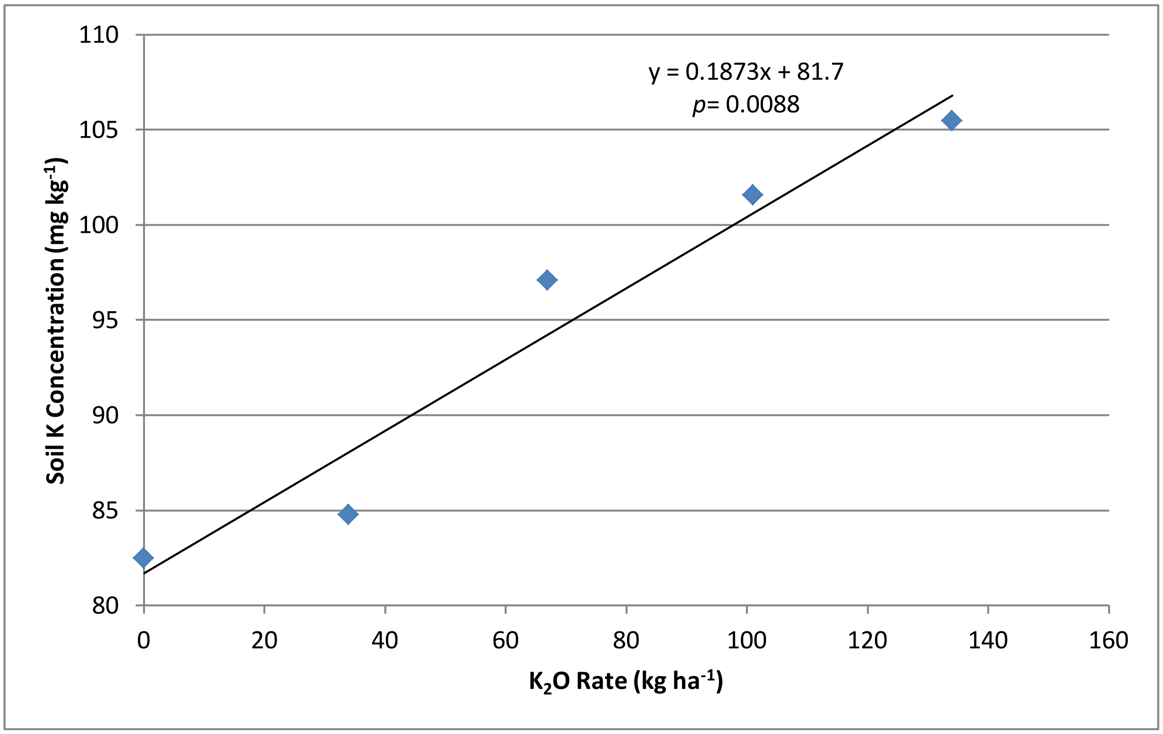


Figure 4.4 Soil potassium (K) concentration by treatment rate for Wheat K site locations



5. Comparison of Poultry Litter Input versus Ash Output During Emissions Testing

5.1 Abstract

Creating ash co-products from the thermal conversion of poultry litter concentrates nutrients in the ash and also releases nutrients to the atmosphere. We initiated a sampling study to compare poultry litter going into thermal conversion units to poultry litter ash that corresponded to air quality emissions testing. Three different systems were tested with varying scales of heat production and poultry litter feed rates. Overall, the macro-nutrients nitrogen and sulfur were significantly reduced in the resulting ash and were likely lost via the stack during gasification and combustion. Potassium in the bulk ash was reduced in gasification system bulk ash, but not impacted in the combustion systems. Stable nutrients, such as phosphorus, were concentrated 4.5 to 12.2 times when calculated on an "as-is" basis. This concentration effect would allow phosphorus to be shipped greater distances from the fresh poultry litter source, based on the nutrient value. In conclusion, elemental data from poultry litter and poultry litter ash can be combined with air emissions data to establish a complete nutrient mass balance for manure-to-energy projects.

5.2 Materials and Methods

5.2.1 Balance Comparison Sampling

Each thermal conversion system was unique to the farm location in its physical construction, operating conditions, residence time, and initial poultry litter feedstock (Tables 5.1 and 5.2); individual system sampling methods are listed below. Samples were tested for percent moisture (Wolf and Haskins, 2003), calcium carbonate equivalent (Wolf and Haskins, 2003), and elemental concentration using the EPA method 3050B. Air emissions testing occurred during each of these sampling times.

- Enginuity Energy: Energy Ecoremedy Gasifier: ASH7 and ASH9

  Samples were taken at two sampling locations in accordance to the residence time of the systems: fresh poultry litter entering the system and the bulk ash auger at the end of the system. Fly wash was collected at the bottom of the cyclone. Residence time was observed to be 299 minutes from the start to the end of the system. The time and chamber temperature was recorded at two locations within the system at a residence time of 134 minutes (Gas burner #1) and 239 minutes (Gas burner #2). The water boiler set temperature was also recorded for each sample.

- Total Energy Blue Flame Stoker Version 2.0: ASH10 and ASH11

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter entering the system, the main ash auger, and the end ash auger. The residence time was observed to be 120 minutes from start to the main bulk ash auger, and 100 minutes from start to the end auger with the bulk ash and fly ash mixture. The time, stack temperature, and boiler temperature were recorded for every sample.

- LEI Bio-Burner: ASH12 and ASH13

  Samples were taken at three sampling locations in accordance to the residence time of the system: fresh poultry litter entering the system, the main ash auger, and the bottom of the stack. The residence time was observed to be 15 minutes from start to the main bulk ash auger. The fly ash was sampled at the end of the day as the unit had to be opened. The time, stack temperature, poultry litter feed rate, and boiler temperature were recorded for every sample.

5.2.2 Elemental Analysis

Fresh poultry litter and ash samples (0.5 g) were digested in nitric acid and hydrogen peroxide using method 3050B (USEPA, 1996), and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011).

5.3 Results and Discussion

5.3.1 Elemental Analysis

The nitric acid/hydrogen peroxide digestion is an elemental digestion that quantified the total elemental concentration expected to be plant available; this is typically a complete digestion with fresh poultry litter (Tables 5.3a and 5.3b). Total nitrogen, phosphorus, and potassium fertilizer ratios for each poultry litter feedstock used was 2.8-1.8-5.5, 2.4-1.8-1.8, and 2.8-2.6-2.1 as %N-%P_2O_5-%K_2O (Table 5.3a); this is in the range of typical feedstocks found in the Mid-Atlantic region. Moisture ranges were from 23.2 to 25.7%, which is on the dryer side of fresh poultry litter sources. All micro-nutrient concentrations were within range of expected values (Table 5.3b). Typically, poultry litter composition varies greatly from location to location depending on the practices of the individual poultry producer (Bolan et al., 2010; Kelley et al., 1996; Tasistro et al., 2004).

5.3.2 Nutrient Concentration

The nutrient concentration impact varied widely across the study locations; it was calculated by the ash nutrient concentration being divided by the feedstock poultry litter nutrient concentration on an "as-is" basis. On average, total nutrients were concentrated 5.2, 7.3, and 12.1 for ASH12, ASH7, and ASH10, respectively (Table 5.4). Literature stated that the typical concentration factor is 6 or 7 times that of the original feedstock nutrients (phosphorus, potassium, and sulfur) for fresh poultry litter (Bock, 2004). Our study found that concentrations varied between systems based on moisture, but also varied for each specific nutrient source. For instance, the most stable nutrient, phosphorus, demonstrated a concentration effect of 4.5 to 12.2 (Table 5.4). Phosphorus is typically easily digested using the methodology used and is not typically lost via stack emissions. Other nutrients, such as nitrogen and sulfur, were greatly reduced after combustion due to stack emissions. Potassium reacted differently based on energy system being used. For instance, the gasification system had significant potassium loss via the stack, as potassium was only 3.2 times concentrated versus the 10.0 concentration of phosphorus (Table 5.4). However, the two combustion systems had nearly identical concentration effects for phosphorus and potassium (12.2 vs. 12.9 and 4.5 versus 4.9 for ASH10 and ASH12, respectively). Conversely, the ASH9 fly ash had nearly 4 times the amount of potassium than the two combustion sources (662.0 vs. 157.0 and 124.0 g K kg^{-1}, respectively) (Table 5.3a). Micro-nutrients, such as Fe and Al demonstrated a much higher concentration as they are more difficult to extract via the US-EPA 3050B digestion and were made significantly more available and extractable after being heated in the manure-to-energy systems.

5.4 Conclusion

Our study found that nutrient densification varied between systems and poultry litter feedstocks, with an average densification between 5.2 to 12.1 when averaged across all micro- and macro-nutrients. Densification varied between each nutrient as each nutrient reacted differently to the heating process and/or was lost from the system via air emissions. For instance, the unit producing ASH10 lost 100% of its nitrogen, but concentrated and increased aluminum availability up to 29.4 times. The gasification system that produced ASH7 lost more potassium via the stack than the combustion systems that produced ASH10 and ASH12. Regardless of the system, phosphorus was concentrated significantly (4.5 to 12.2 times) and would allow greater movement of phosphorus manure sources from the fresh poultry litter due to nutrient value alone; this would help move excess phosphorus out of watersheds. Overall, elemental data from poultry litter samples going into the energy system can be used alongside poultry litter ash elemental concentration and air emissions data to establish a complete manure-to-energy nutrient mass balance.

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5.6 Tables

Table 5.1 Descriptions of poultry litter co-product sources used for input/output comparisons

Source	Co-Product Type	Farm Name	Thermal Conversion System
ASH7	Bulk Ash	HEL	Gasification
ASH9	Fly Ash	HEL	Gasification
ASH10	Bulk Ash	CUR	Combustion
ASH11	Fly Ash	CUR	Combustion
ASH12	Bulk Ash	RHO	Combustion
ASH13	Fly Ash	RHO	Combustion

Table 5.2 Source information and background information for poultry litter co-product thermal conversion systems

Source	Location	System	Burn Temp	Residence Time	Mode of Energy Dispersal	Poultry Litter Type	Co-Product Type
ASH7 & ASH9	Lancaster County, PA	Enginuity Energy: Energy Ecoremedy Gasifier	593ºC at beginning of bed 204ºC at end of bed	299 min	Hot Water	Organic Broiler	Ash
ASH10 & ASH11	Snyder County, PA	Total Energy Blue Flame Stoker V2.0	82ºC water set temp 171ºC exhaust temp	120 min	Hot Water	Organic Turkey	Ash
ASH12 § ASH13	Port Republic, VA	LEI Bio-Burner	884ºC	15 min	Hot Water	Organic Turkey	Ash

Table 5.3a Total elemental concentration of ash co-products and corresponding fresh poultry litter on an "as-is" basis

Source	Product	Moisture	CCE†	N	NH_4-N	NO_3-N	P	K	S	Mg	Ca
		----------g kg^{-1}----------									
ASH7 & ASH9	Fresh Poultry Litter	257	41	27.9	7.1	0.384	7.9	46.0	8.0	6.3	20.4
ASH7	Bulk Ash	4	300	6.0	0.0	0.004	79.7	146.3	22.9	34.5	103.4
ASH9	Fly Ash	93	126	9.7	10.7	0.000	53.9	662.0	65.7	22.9	68.8
ASH10 & ASH11	Fresh Poultry Litter	232	16	23.9	4.6	0.047	7.8	14.8	3.2	3.6	13.5
ASH10	Bulk Ash	5	350	0.8	0.0	0.011	95.1	190.3	15.5	48.6	157.0
ASH11	Fly Ash	13	290	1.8	0.0	0.007	66.9	157.0	26.5	39.7	111.0
ASH12 & ASH13	Fresh Poultry Litter	246	20	28.4	7.5	0.108	11.2	17.9	6.1	10.3	38.9
ASH12	Bulk Ash	16	210	11.0	0.0	0.000	50.6	87.2	9.6	17.0	100.6
ASH13	Fly Ash	4	273	0.2	0.0	0.002	109.1	124.0	23.0	46.3	175.0

†Calcium carbonate equivalent.

Table 5.3b Total elemental concentration of ash co-products and corresponding fresh poultry litter on an "as-is" basis

Source	Product	Na	Fe	Al	Mn	Cu	Zn	B
		----------g kg^{-1}----------						
ASH7 & ASH9	Fresh Poultry Litter	4597	415	557	498	125	614	790
ASH7	Bulk Ash	26900	10667	10320	2387	566	2540	3253
ASH9	Fly Ash	19800	8030	4500	1690	598	5120	3490
ASH10 & ASH11	Fresh Poultry Litter	3357	651	451	294	298	291	39
ASH10	Bulk Ash	43100	9457	13267	3607	3520	1333	302
ASH11	Fly Ash	39700	7630	12700	2800	2390	2960	301
ASH12 & ASH13	Fresh Poultry Litter	3867	333	467	359	567	337	49
ASH12	Bulk Ash	13267	5680	6333	1363	1927	755	135
ASH13	Fly Ash	36767	10957	8067	3757	4880	1870	621

Table 5.4 Concentrations of nutrients from the densification of poultry litter entering the thermal conversion unit and poultry litter ash exiting the unit from three different units in the Mid-Atlantic

	N	P	K	S	Mg	Ca	Na	Fe	Al	Mn	Cu	Zn	B	CCE	Average‡
	---Times Concentrated†---														
ASH7	0.2	10.0	3.2	2.9	5.5	5.1	5.9	25.7	18.5	4.8	4.5	4.1	4.1	7.3	7.3
ASH10	0.0	12.2	12.9	4.8	13.5	11.6	12.8	14.5	29.4	12.3	11.8	4.6	7.7	21.4	12.1
ASH12	0.4	4.5	4.9	1.6	1.7	2.6	3.4	17.0	13.6	3.8	3.4	2.2	2.7	10.4	5.2

†Times Concentrated = (ash nutrient concentration % / feedstock poultry litter nutrient concentration %) on an “as-is” basis.
‡Average is mean value of all nutrients and is not weight balanced.

6. Summary and Conclusions

Several factors impact the overall nutrient concentrations of poultry litter co-products and their resulting availability. The thermal combustion system is one variable, which includes the temperature of combustion, fuel-to-oxygen ratio, residence time of the poultry litter feedstock, and whether or not the system has an exhaust scrubbing system to catch fly ash. Another major factor is the poultry litter from which the co-product is formed; the initial concentration of nutrients, bedding material, and moisture content of the poultry litter impact the co-product.

Our study found that nutrient densification varied between systems: phosphorus was concentrated between 4-12 times its original density, potassium was concentrated between 3-13 times its original density, and sulfur was concentrated between 2-5 times its original density. Our comparisons between total nutrient digestions and water-soluble extractions found that the ash co-products were significantly less plant available than the standard inorganic fertilizers (TSP and KCl). A greater amount of the co-products will have to be applied to meet the same nutrient availability of the standards. Overall, if all ideal combustion criteria are met, poultry litter co-products are feasible fertilizers; however, they will need to be individually analyzed for nutrient content before making application recommendations. More research into balance comparisons are needed to be able to identify stronger relationships within the nutrients.

TSP and fresh poultry litter had the greatest initial availability for phosphorus and potassium. Over time, some of the ash co-products reached similar availabilities comparable to the standards but differed due to the variability in their systems of formation. The system that produced ASH4 generated the co-product that was most similar to the standards and provided an ideal fertilizer that was both nutrient dense and plant available. The ASH2 system converted the feedstock at higher temperatures and had longer residence times, creating a nutrient-dense product that was not readily water soluble. The biochar co-products were among the least available of the fertilizers in the study; this was expected because biochars are formed with a slow-release product in mind to strongly hold and remove nutrients and carbon from the soil system for many years. Further ash research will be needed for each thermal conversion system and feedstock, as the burning process significantly alters the overall nutrient water solubility over time.

Appendix G

Nutrient Balance: Fate of Nitrogen and Phosphorus

A summary of preliminary findings funded by the
Farm Manure-to-Energy Initiative

December 2015

Contents

1. Introduction

A critical design objective for the thermal technologies demonstrated by the Farm Manure-to-Energy Initiative was to reduce nitrogen and phosphorus transported to surface waters relative to local land application of poultry litter for use as a fertilizer.

Poultry litter contains nitrogen, phosphorus, potassium, organic matter, and trace minerals and is a valued form of fertilizer. The project focused on high-density animal production areas of the Chesapeake Bay region because these are areas where long-term use of poultry litter as a fertilizer has resulted in especially high rates of phosphorus loading (on a per acre basis) (Figure 1).

The addition of phytase to poultry feed (which reduces phosphorus concentrations in poultry litter) and improved feed conversion efficiency has increased the nitrogen-to-phosphorus ratio in poultry litter so that it more closely matches crop nutrient requirements. However, in general, application of poultry litter to meet crop nitrogen requirements results in over-application of phosphorus. Use of poultry litter as the crop's primary nitrogen source results in soils saturated with phosphorus and increased risk of phosphorus transport to surface waters, either via surface runoff or subsurface drainage. Subsurface transport of phosphorus can occur in fields with high water tables and drainage systems (e.g., tile drains or field ditches). However, nitrogen-based poultry litter applications are largely no longer allowed in the Chesapeake Bay watershed as states have moved to a phosphorus-based nutrient management plan, thus limiting use of poultry litter as a fertilizer in high-density production areas. To support compliance with regulations, stakeholders in the Chesapeake Bay region are working with poultry growers to identify opportunities for recycling this valuable fertilizer.

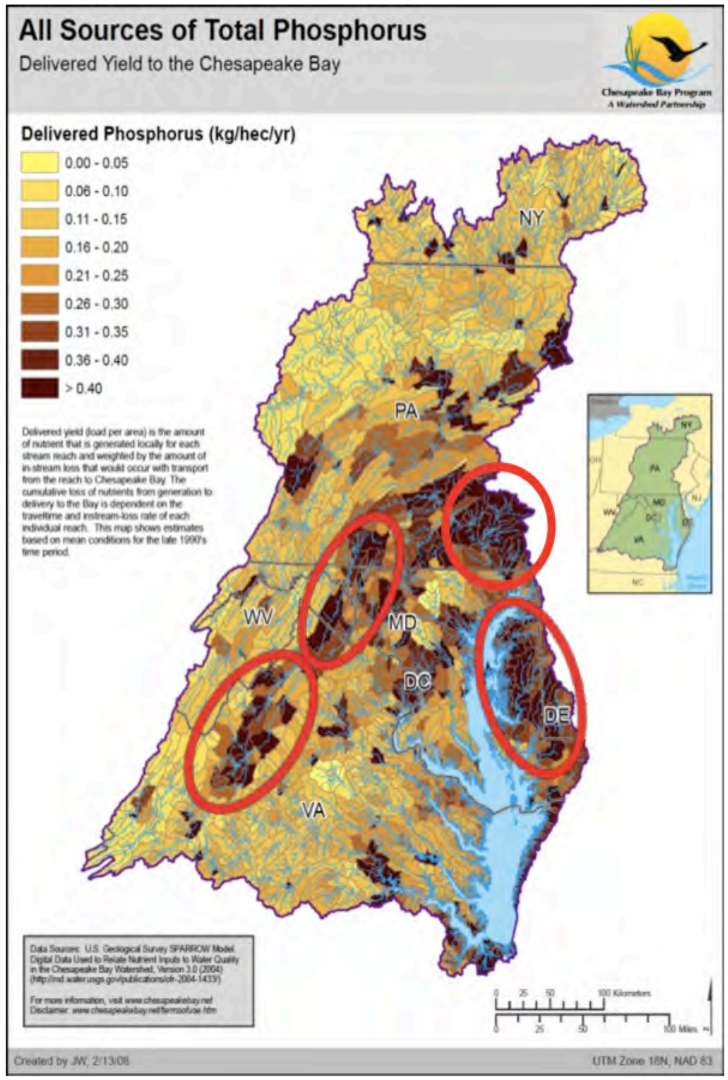

Figure 1. U.S. Geological Survey SPARROW map of the Chesapeake Bay regions contributing the most phosphorus to the Chesapeake Bay. Red circles indicate areas of high density animal production.

One potential benefit of the technologies selected for demonstration in the Farm Manure-to-Energy Initiative is that these technologies concentrate poultry litter phosphorus in an ash or biochar co-product. Field trials on row crops as well as laboratory analysis indicated that the concentrated ash has value as a fertilizer (Appendix F) and that this material could be cost-effectively transported out of high-density animal production areas for use in regions that are phosphorus-deficient. The ash co-product could also be used locally on crops where untreated poultry litter is typically not used, like fresh market vegetables, for which untreated poultry litter increases risks for pathogen transport. Thermal treatment of poultry litter eliminates pathogens that pose a risk to public health.

2. Nutrient Balance Performance Objectives

For nutrient balance, the project team set the following criteria for appropriate technologies:

- The technology must facilitate the transport and re-use of excess phosphorus from areas of high-density animal production regions to areas with phosphorus deficiency and/or facilitate local use on crops that cannot currently use untreated poultry litter as a fertilizer.
- Reactive nitrogen emissions to the atmosphere should be reduced and, at the minimum, should not exceed reactive nitrogen emissions from local land application as a fertilizer.

3. Methods

A nutrient mass balance was developed for three poultry litter-fueled technologies: the Ecoremedy ® gasifier, Blue Flame boiler, and Bio-Burner 500.

Nitrogen and phosphorus concentrations in untreated poultry litter were compared to nitrogen and phosphorus in the ash (including the bottom ash from the thermal conversion chamber and the fly ash collected by the emissions control systems). Methods for determination of fertilizer value of the poultry litter and ash are detailed in Appendix F. Fresh poultry litter and ash samples (0.5 g) were digested in nitric acid and hydrogen peroxide using method 3050B (U.S. EPA, 1996) and then analyzed using ICP-OES (Spectro Analytical Instruments, Kleve, Germany) at the Virginia Tech Soil Testing Laboratory (Maguire and Henkendorn, 2011).

- Nitrogen (NOx and ammonia) and phosphorus concentrations in air emissions were measured using methods detailed in Appendix E.
- Poultry litter feed rate and ash production rates were also measured. Methods for poultry litter feed rate are detailed in Appendix E.
- Ash production rates were measured by the volume of ash produced over time intervals concurrent with air emissions testing. The bulk density of the ash was used to convert the volume rate to a mass rate for the Blue Flame boiler (Reiter and Daniel, 2013). For the Bio-Burner 500, ash production was measured by

weighing all ash produced over selected time intervals during the emissions testing period.

Analysis of fuel feed rate, ash production, poultry litter, and ash nutrient concentrations, as well as nitrogen and phosphorus in air emissions, were conducted simultaneously. On the same day that data on air emissions was being collected by the certified air emissions testing company, data on poultry litter and ash nutrients, fuel feed rates, and ash production rates were also collected.

Annual poultry litter use, ash production rate, and nitrogen and phosphorus in air emissions assume the unit is operating 24 hours a day for 365 days a year. In reality, the thermal manure-to-energy systems do not operate during periods of high ambient air temperature. One vendor (Bhsl), however, does recommends that their clients use dry heat from the thermal poultry litter-fueled technology to reduce moisture in the poultry houses during all times of the year except when the house is ventilated with tunnel fans (e.g., the hottest periods of the year).

Reactive nitrogen in air emissions (including NOx and ammonia species) were compared with published estimates of ammonia emissions associated with the use of poultry litter as a fertilizer in conservation tillage systems (Pote and Meisinger, 2014). Because the method used to apply fertilizer impacts the potential ammonia emissions, estimates are provided for poultry litter that is immediately incorporated (tilled in with shallow disking) as well as poultry litter that is left on the surface of the field. Pote and Meisinger (2014) documented total ammonia (as ammonium-nitrogen [NH_4-N] from poultry litter applied over a two-year period and found that injected poultry litter had the lowest total ammonia loss (Mean = 12.1 and 7.9% for 2008 and 2009, respectively), followed by shallow disc injection (Mean 21.5 and 32.4% for 2008 and 2009). Surface application had the highest rate of ammonia loss ranging from a mean of 73.9% of poultry litter ammonia in 2008 to a mean of 95.2% in 2009.

4. Results

Calculation of fuel feed rate and ash production rates are presented in Table 1. Fly ash from the Ecoremedy gasifier was not feasible to collect according to proposed methods. Two cyclones for ash collection were on this unit and ash varied from being dry to wet during collection periods. Also, ash volume was not consistent over the runs as the material was sticking within the cyclone collection system. For instance, some collection periods had a few inches of ash in a 5-gallon bucket and sometimes hardly enough to cover the bottom of the bucket.

Table 1. Calculation of fuel feed rate and ash production

	Bio-Burner 500	Ecoremedy Gasifier	Blue Flame Boiler
	lbs/hr		
Poultry Litter	73	260	333
Bottom Ash	14	42	20
Fly Ash	2.5	n/a	3.9
Total Ash	16.8	42.5	24.35
PL:Ash Production Ratio	4.35	6.12	13.68

Results from system input and output analysis are presented in Tables 2 and 3. System outputs for poultry litter are based on poultry litter feed rates; system outputs for ash are based on ash production rates; and system outputs for air emissions are based on reported values (lbs/hr). For the Ecoremedy gasifier, nutrients in fly ash were not taken into consideration in the nutrient balance since we could not quantify the mass being produced on an hourly rate.

Table 2. Nutrient balance comparing nitrogren (N) and phosphorus (P) in poultry litter with N and P in ash and air emissions

	Bio-Burner 500	Ecoremedy Gasifier	Blue Flame Boiler
	Input / Output rate		
System Inputs	lbs/hr		
Poultry Litter Fuel			
NH4-N	0.55	1.85	1.53
NO3-N	7.91E-03	9.98E-02	1.57E-02
TOTAL N	2.08	7.25	7.97
TOTAL P	0.82	2.05	2.60
System Outputs			
Air Emissions			
NO x (lbs/hr)	0.16	0.13	1.36
NO x derived - Elemental N (lbs/hr)	4.87E-02	3.96E-02	0.41
NH3 (lbs/hr)	1.00E-04	3.90E-03	1.00E-04
NH3 derived - Elemental N (lbs/hr)	8.22E-05	3.21E-03	1.20E-03
TOTAL N (sum of NH4-N and NO3-N)	4.88E-02	4.28E-02	0.42
Total P	4.33E-03	1.65E-03	1.99E-02
Ash			
Bottom Ash (Total Elemental N)	0.16	0.25	0.80
Fly Ash (Total Elemental N)	4.93E-04	n/a	1.80
TOTAL N (Bottom + Fly Ash)	0.16	0.25	2.60
Bottom Ash (Total Elemental P)	0.72	3.38	1.94
Fly Ash (Total Elemental P)	0.27	0.00	0.26
TOTAL P (Bottom + Fly Ash)	0.99	3.38	2.20

Table 3 summarizes unaccounted-for nitrogen and phosphorus based on analysis of inputs and outputs. The percent of unaccounted-for nitrogen ranges from 90.1 to 95.9% of the total poultry litter nitrogen content. Unaccounted-for phosphorus is more variable, ranging from -64.9 to 14.5% of the total poultry litter phosphorus. A negative number means that calculations suggest there is more phosphorus in the outputs than in the inputs. Concentrations of nitrogen and phosphorus in untreated poultry litter, ash, and air emissions for each of the technologies are presented graphically in Figures 1-3.

Table 3. Unaccounted-for nitrogen (N) and phosphorus (P) presented in lb/hr and percent of total

	Bio-Burner 500	Ecoremedy Gasifier	Blue Flame Boiler
N (lb/hr)	1.87	6.96	7.53
P (lb/hr)	-0.18	-1.33	0.38
N (% total)	90.1	95.9	94.5
P (% total)	-21.6	-64.9	14.5

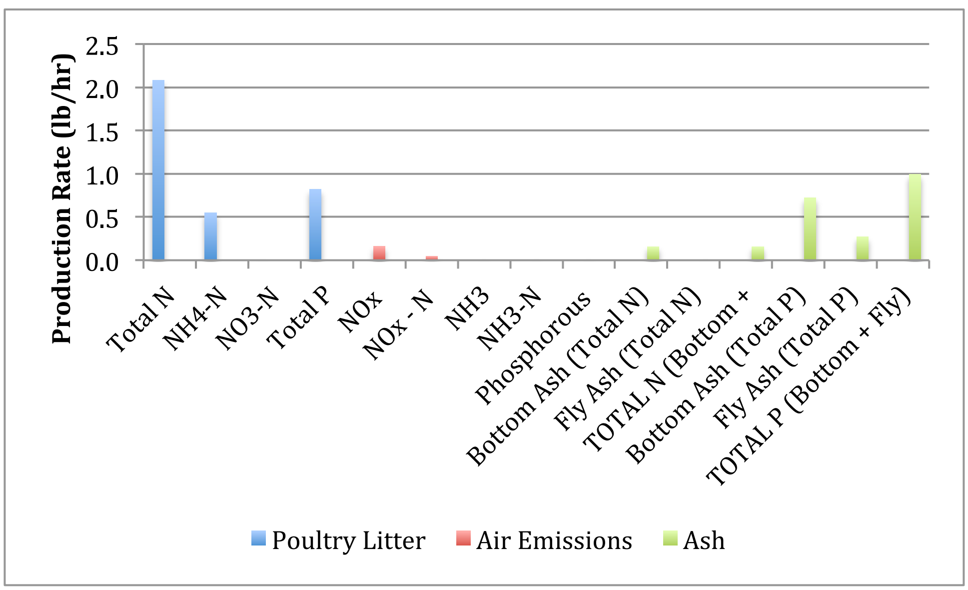

Figure 1. Nutrient balance (poultry litter inputs and ash and air emissions outputs) for the Bio-Burner 500

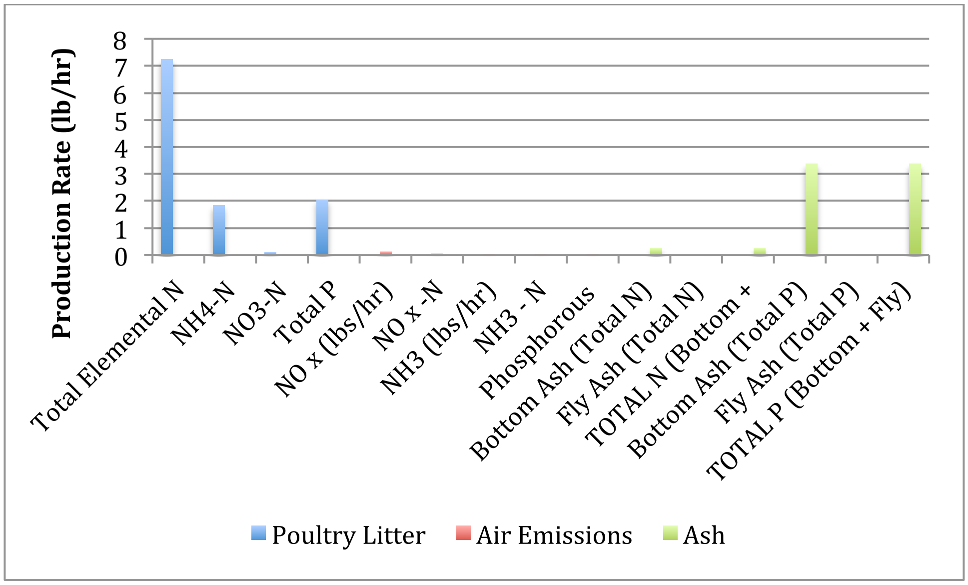

Figure 2. Nutrient balance (poultry litter inputs and ash and air emissions outputs) for the Ecoremedy gasifier

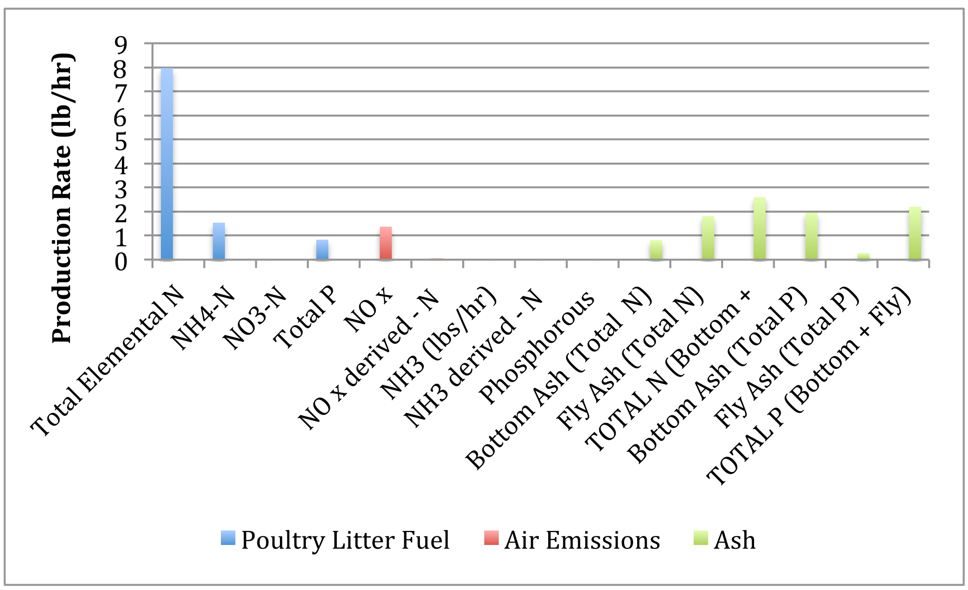

Figure 3. Nutrient balance (poultry litter inputs and ash and air emissions outputs) for the Blue Flame boiler

Reactive nitrogen emissions in feedstock poultry litter compared to estimated reactive nitrogen emissions from land application are presented in Table 4 and Figure 4.

Table 4. Reactive nitrogen (N) loss from three thermal manure-to-energy systems using poultry litter as a fuel over 1 hour compared to Pote and Meisinger (2014) reactive nitrogen (as ammonium-nitrogen) loss from the same amount of poultry litter land applied to conservation tillage systems

	Poultry Litter Used as Fuel in Manure-to-Energy Scenario			Poultry Litter Land Application Scenario (lbs NH-4-N Emissions Associated with Poultry Litter Used to Fuel 1-hr of Operation)		
	Total Reactive N in Air Emissions (lb/hr)	Feed rate for Manure-to-Energy Systems	NH4-N Content in Untreated Poultry Litter	NH4-N in Air Emissions (Injected - 9.6% NH4-N Loss)	NH4-N in Air Emissions (Disked-in, Assume 27% NH4-N Loss)	NH4-N in Air Emissions (Surface Applied, Assume 85% NH4-N Loss)
	lb/hr		lb NH4-N Associated with Poultry Litter Required to Fuel 1-Hr of manure-to-energy operation			
Bio-Burner 500	0.05	73	0.55	0.05	0.15	0.47
Ecoremedy Gasifier	0.04	260	1.85	0.18	0.50	1.57
Blue Flame Boiler	0.42	333	1.53	0.15	0.41	1.30

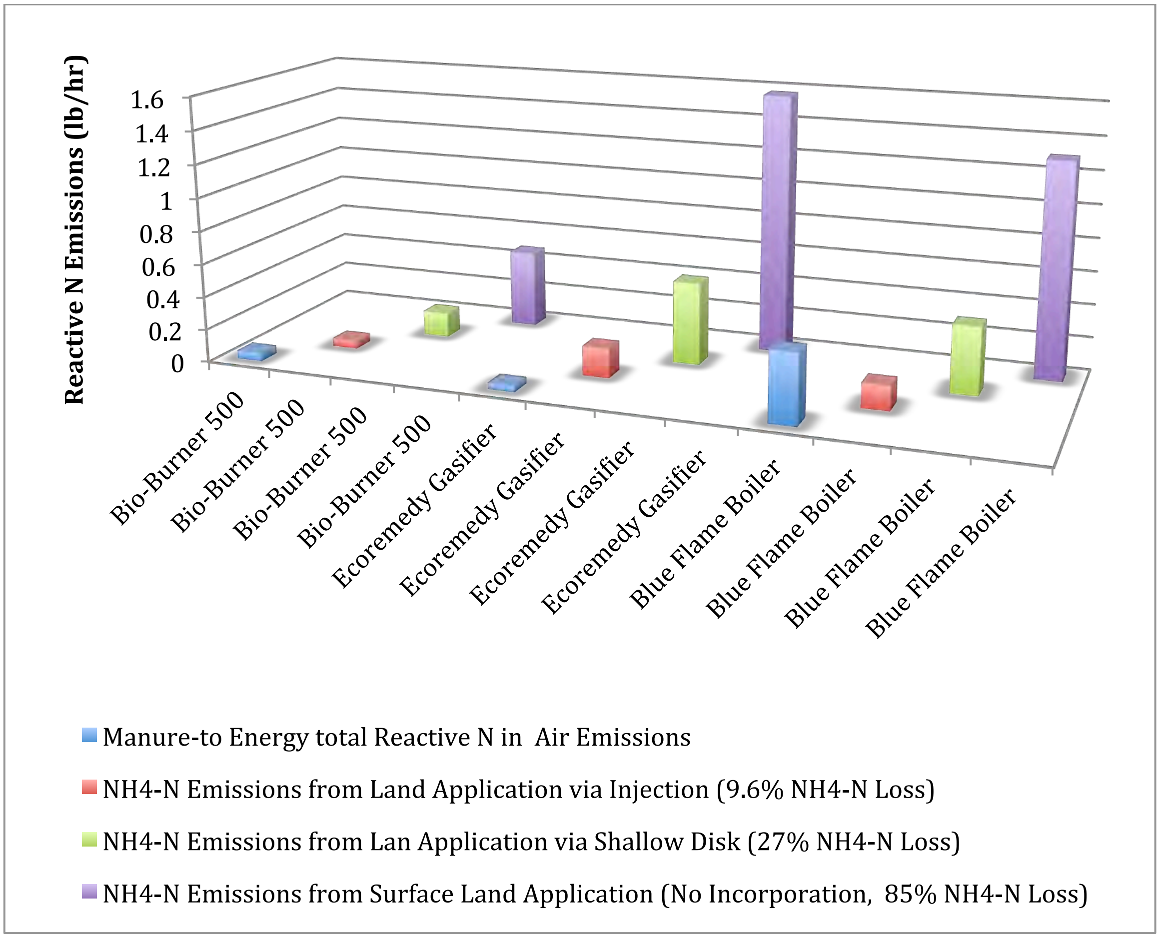

Figure 4. Reactive nitrogen emission from poultry litter used to fuel manure-to-energy technologies for 1 hour compared to land application of the same amount of poultry litter using three different methods: injection, light disking following application, and surface application only (no incorporation). Emissions of NH4-N are from Pote and Meisinger (2014).

5. Discussion

Calculating nutrient balance in poultry litter using a poultry litter "in" and ash and air emissions "out" approach was not as straightforward as anticipated. Initial analysis of elemental nitrogen and phosphorus in the poultry litter fuel did not correlate directly with the sum of elemental nitrogen and phosphorus measured in the ash and nitrogen (as NH3-N and NOx) and phosphorus measured in air emissions. For example, results from mass balance for the Bio-Burner 500 and Ecoremedy gasifier indicated that there is more phosphorus in the system outputs (ash and air emissions) than was present in the poultry litter fuel; this is likely due to the mass balance methodology, among similar discrepancies.

Table 4 also indicated a significant amount of unaccounted-for nitrogen, ranging from 90 to 96%. Loss of reactive nitrogen (NH_4 and NOx) as non-reactive nitrogen (N_2) is anticipated in the thermal conversion process. However, nitrogen in air can contribute to nitrogen emissions. At temperatures above 950°C, thermal NOx formation from nitrogen contained in combustion air can occur (Quaak, P. et. al. 1999). Stubenberger (2008) discussed nitrogen species release from different solid biomass fuels and suggested that thermal NOx production occurs at temperatures above 1300°C, which are not likely to occur in most biomass combustion systems. Rather, they observed that the fuel's nitrogen content was the dominant source of NOx.

Koger et. al, 2005 and Koger et. al. 2004 also observed discrepancies in nutrient balance determination for a batch-fed gasifier fueled with pig manure. Their mass balance (using fuel feed rate, ash production rate, and air emissions) accounted for 85 to 100% of the fuel's nitrogen, phosphorus, potassium, and calcium. Magnesium measured in the system outputs accounted for 75% of magnesium in the fuel. Output for several minerals (copper and zinc) suggested outputs contained more than inputs. For this reason, Kroger et. al. 2005 concluded that "further analytical work is needed to clarify this issue."

The discrepancy between nitrogen and phosphorus in fuel versus nitrogen and phosphorus in system outputs (air emissions and ash) could be the result of a number of issues. For example, the use of composite samples to estimate mean nitrogen and phosphorus values in poultry litter and ash could have introduced error. Poultry litter is not a homogenous material. Characteristics vary from farm-to-farm (see Table 5 in Appendix E, as well as within a house or houses on the same farm. Poultry litter contains large wood particles and rocks. Nutrient concentration, moisture, and air emissions from poultry litter vary spatially throughout the poultry house (Miles et. al., 2008). While poultry litter sampling protocols were selected to generate composite samples for analysis reflective of all poultry litter and were replicated, increasing the number of poultry litter and ash samples over time along with more runs of air emissions data (i.e., different times of year, ambient air temperature, etc.) will improve accuracy of mass balance calculations.

The method by which bulk density was calculated (e.g., field measurements versus laboratory measurements) also demonstrated variability that impacts the nutrient balance. Increased sample size could help to refine bulk density calculations and improve the accuracy of ash nutrient production estimates. While field bulk density measurements were used for this nutrient balance, it warrants further investigation to determine which approach is the most appropriate for use future analysis.

Also, for one technology (the Ecoremedy gasifier), the fly ash generation rate was difficult to quantify and therefore not reported. Thus, Table 4 likely underestimates unaccounted for nitrogen and phosphorus.

Given limitations of this data, it appears that a considerable amount of reactive nitrogen is reduced when poultry litter is used as a fuel in thermal manure-to-energy systems. Compared to land application, all the technologies have reactive nitrogen emissions similar to or lower than best practices for land application of poultry litter (shallow disk incorporation). Even the system with the highest reactive nitrogen emissions demonstrates reduced nitrogen loss to the atmosphere when compared with surface application of poultry litter, a common practice in the region.

The Blue Flame boiler and Bio-Burner 500 had the highest rates of reactive nitrogen emissions, but this may have been due to a lack of tuning. Stubenberger (2008) found that in addition to the fuel nitrogen content, the stoichiometric air ratio has a major influence on NOx emissions in biomass systems. Stoichiometric air ratio can be adjusted by tuning the system to optimize performance and reduce NOx emissions.

It also appears that a small amount of phosphorus is released in air emissions. This phosphorus is likely associated with particulate matter, and thus efforts to further reduce particulate matter should also reduce phosphorus loss to the atmosphere. However, phosphorus loss via emissions was minor and most of the phosphorus was concentrated in the ash. This conclusion is consistent with findings presented in Appendix F.

6. References

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Appendix H

Financial Assessment of the Farm Manure-to-Energy Initiative

Prepared by the Environmental Finance Center, University of Maryland

Provided to Sustainable Chesapeake and partners of the Farm Manure-to-Energy Initiative with funds provided by the National Fish and Wildlife Foundation

December 2015

Contents

UNIVERSITY OF MARYLAND
ENVIRONMENTAL FINANCE CENTER

1. Introduction

The Environmental Finance Center at the University of Maryland (EFC) was part of a collaborative project to investigate the use of innovative technologies that produce energy from the conversion of poultry litter. These technologies are of particular interest for protecting water quality in the Chesapeake Bay region, in that they provide alternative uses and markets for excess poultry litter that, if applied to farmland in excess of crop needs, can reach local waterways through stormwater runoff.

The coalition conducted the Farm Manure-to-Energy Initiative between 2012-2015, working with five farms in the Chesapeake region to implement and evaluate the use of thermal technologies to produce energy from poultry litter. The coalition, under the organizational umbrella of the National Fish and Wildlife Foundation, included the following partners: Sustainable Chesapeake; Farm Pilot Project Coordination, Inc.; Virginia Cooperative Extension; Virginia Polytechnic University (VA Tech); Lancaster County Conservation District; University of Maryland Center for Environmental Science; Eastern Shore Resource Conservation & Development Council; and the International Biochar Initiative. Funders included the National Fish and Wildlife Foundation, Chesapeake Bay Funders Network, USDA Conservation Innovation Grant Program, and U.S. EPA's Innovative Nutrient and Sediment Reduction Program.

The purpose of the Farm Manure-to-Energy Initiative was to evaluate the effectiveness and performance of thermal manure-to-energy technologies that use excess animal manure or poultry litter (comprised of manure, bedding, and feathers) to produce electricity or heat for animal housing on farms in high-density animal production areas of the Chesapeake Bay watershed. The evaluation included technical, environmental, and financial performance of the systems. The role of the EFC was to provide a financial assessment of the investment at each host farm.

It is important to note that the even when technical problems resulted in failure of the thermal technologies to deliver heat or electricity throughout an entire flock cycle, there were periods of successful energy production that reduced the use of propane for heating the poultry houses. While the data did not quantify the generated heat in a way that statistically correlates the technology with reduced propane use, farmers repeatedly observed and reported the trend toward reduced propane use while the systems were running. This saved energy and money for the growers and reduced their carbon footprint.

Farmers also observed improved bird health (weight gain, decreased foot disease, and lower ammonia levels). Although this project did not seek to correlate bird health performance with the technology, farmer testimonials indicate that bird health benefits are worth future investigation.

While the cost balance provides an overview of the costs associated per farm, it does not fully characterize all farm labor and costs. The propane reduction estimates in this assessment were calculated using the data available to demonstrate the type of energy offset analyses that will be needed in future assessments, when the technology runs for a sufficient duration of multiple flock cycles at a farm.

The experience at these five host farms offers various pieces of a puzzle that help define the benefits of thermal manure-to-energy systems at the farm level. While no one farm currently offers this information, the five farms collectively allow for a preliminary characterization of costs associated with installing and operating such systems. All farmers have exhibited willingness to communicate with the EFC and its partners to conduct this assessment; however, privacy issues and farm administration duties affected some data availability, compounded with relatively short durations of continuous run-time of the technology during flock cycles. Host farmers also demonstrated a high degree of commitment to the assist the technology vendor in seeking system success.

The host farms included:

- **Windview Farms**, Port Treverton, PA, owned by Morrell "Mac" Curtis. Windview Farm has historical data for the use of manure-to-energy technology for consecutive years prior to a fire in May 2014. This data demonstrates long-term operation and maintenance of this technology once the learning curve has leveled out. Windview Farm experienced success with its previous technology, but the system was undersized and design of the heat delivery system was not optimized. Hence, the system did not demonstrate as large a savings in propane offsets as would be expected. The newly installed technology is sized appropriately for the amount of poultry litter generated and the poultry house needs; the new system should demonstrate increased savings and offer important information during upcoming cold weather seasons.
- **Farm B**, Lititz, PA. Farm B offers detailed electricity and propane savings for short-term running of the thermal technology during part of two flock cycles. The energy-efficient poultry houses and high-performance boiler and heat delivery system offer a glimpse of cost performance for high-end monitoring, heat delivery, and vendor technology capacities.
- **Mark Rohrer Farm**, Strasburg, Lancaster County, PA. Mr. Rohrer demonstrates side-by-side in-situ energy comparisons with two poultry houses adjacent to a manure-to-energy system, run by his brother. The geographic proximity allows for a comparison of houses with and without manure-to-energy technologies, including the energy offsets in similar climatic conditions. Mr. Rohrer's transition from conventional to organic chickens, as well as his transition from conventional to solar energy, make the data comparison challenging for pre-technology to post-technology energy offsets. However, this is also ameliorated by using his brother's adjacent farm for comparison.
- **Mike Weaver Farm**, Fort Seybert, WV. Mr. Weaver's farm demonstrates technology similar to that at the Mark Rohrer Farm. While the technology did not operate continuously during the flock cycles, there is some flock data and propane offset information available to further characterize the potential for energy offsets at an energy efficient farm. Mr. Weaver provided decommissioning costs.

- **Riverhill Farm**, Port Republic, VA. Owned by Glenn Rodes, this farm provided an example of expended time and energy on air permitting for the manure-to-energy technology. The permitting experience is transferable to future generations of host farmers if they are in a non-attainment air quality area, or in Virginia, where permit compliance requires farmer time and fees. Mr. Rodes grows turkeys, and the moisture content of turkey litter challenged the original construction of the technology. The boiler was replaced with a new system by a different manufacturer. This farm offers more information on air quality data and capital costs; however, data on energy offsets was not available at this time for inclusion in this assessment.

The experiences of these farms show that implementing manure-to-energy technologies is still a challenge. Learning curves in design, installation, and operation are often substantial, pointing to the importance of services and subsidies provided by the public sector in the wider adoption of this technology.

Additionally, the unique circumstances and varied experiences of each of these farms raise questions about the ability to construct meaningful general cost ranges (capital and operational) that determine financial impacts of the technology on a farm's bottom line. At the same time, these experiences illustrate the willingness of farmers to test new technologies with the potential to generate positive environmental and economic impacts.

An additional component of this financial assessment is the financial value of the ash co-product that is generated by the manure-to-energy system. The ash has potential value as a crop fertilizer. Mark S. Reiter, Ph.D., a crop and soil specialist with the Eastern Shore Agricultural Research and Extension Center of Virginia Tech compared poultry litter and poultry litter ash in terms of market prices. Based on a series of field trials, his research suggests that poultry ash may have some promise as a fertilizer even when taking into account variability in fertilizer prices and nutrient values over time. Based on the five-year average retail fertilizer value for nitrogen, phosphorus, and potash, Dr. Reiter identified a wide range in the potential sale value of poultry fly ash ($0 to $463 per ton). As a point of comparison, poultry litter is either being given away or sold at prices typically in the range of $8 to $20 per ton. In the event future market assessments indicate a lack of targeted users, disposal costs should be included under the $0 per ton value scenario. Dr. Reiter also asserts that ash is microbially benign and offers high value market potential.

It is important to note that an extensive amount of market development and infrastructure is needed to support the emergence of poultry litter ash as a revenue source for farmers. These efforts should include: a thorough market analysis; education and outreach on the use of this new value-added product; a transportation analysis on the logistics of bringing this product to market; and a more comprehensive database to develop a basis for the cost of the ash. For example, the basis for the nutrient value should include additional field trials and laboratory analysis on a larger composition of ash samples from multiple poultry litter farms, with ash produced under consistent litter combustion rates. Future market analysis needs to consider the potential end-market value as well as the cost of marketing, packaging, and transportation, all of which impact the potential net revenue received by the farmer but does not necessarily reflect the net revenue available to farmer (or quantify if there is a net revenue to farmer).

2. Assessment Purpose

The purpose of the financial assessment is to measure the cost balance for each host farm. The EFC focused on estimating the costs for the life cycle of the technology at the farm sites. These costs are based on performance assessments of technologies obtained through farmer interviews and data collection on-site. However, because of the timing of installation and, in some cases, technical or vendor issues with performance, data was limited. Because of the limited timeframe for operational data collection, the cost balance does not capture the full value of life cycle costs and equipment aging.

This financial assessment does not include the revenue-generating opportunities of the nutrient-dense ash or biochar, which can be cost-effectively transported long distances or used to replace imported commercial phosphorus for fresh-market vegetable production. The laboratory analysis and field trials of the co-products were conducted side-by-side with this financial assessment. However, as previously discussed, Dr. Reiter's work suggests that ash or biochar from thermal manure-to-energy technologies has the potential to generate revenue and should be considered if markets are developed for this nutrient-dense material. Development of end-user markets will also facilitate phosphorus and potash recycling and should address transport of excess nutrients to regions of the country reliant on commercial fertilizer.

3. Farm Costs

This section summarizes farm costs for each host farm, including:

- A description of the farm
- Capital costs (infrastructure, installation costs, and permitting)
- Routine operations and maintenance costs (including regular maintenance)
- Fate of the poultry litter pre- and post- installation of manure-to-energy technology as available
- Energy costs:
  - Electricity and propane offsets listed during technology run-times
  - Weather conditions and integrator allowances
- Overall farm revenue, including the footprint of poultry production within the context of the overall farm revenue

3.1 Blue Flame Boiler Heating System at Windview Farm

3.1.1 Farm Description

Windview Farm is located in Port Treverton, Snyder County, PA. The farm includes two broiler houses that produce approximately 440,000 anti-biotic free broiler chickens per year for Sullivan's Natural. Each building consists of a 10,000 ft^2 section and a 20,000 ft^2 section, for 30,000ft^2 per building, or 60,000 ft^2 total. The farm hosts six to seven flocks per year with an average flock cycle of 40 days. Broilers are grown to varying weights depending on market demand.

3.1.2 Infrastructure costs, Installation Costs, and Permitting Costs

Note: Famer time was calculated at $34.89 per Bureau of Labor and Statistics, modified rates March 2015 (http://www.bls.gov/oes/current/oes119013.htm).

Windview Farm previously had a Blue Flame boiler, first fed with turkey litter and then broiler litter, provided through farmer funding and a grant from the National Fish and Wildlife Foundation. The system operated for five years, but an electrical fire in May 2014 damaged the system beyond repair.

With support from the Farm Manure-to-Energy Initiative, a new Blue Flame boiler and heating system was designed and installed by Total Energy during the spring and summer of 2015. Funding from the Farm Manure-to-Energy Initiative helped make system improvements, based on lessons learned. Given the timing of installation, no flocks were heated using the new technology during the performance assessment period. However, historic data was available on propane savings from the previous system. Mr. Curtis, the farm owner, also offered the lessons learned from past experience: how upfront costs and the learning curve shape a farmer's perspective, as well as the typical operation and maintenance costs incurred while the system was running.

The previous boiler that was destroyed by fire cost approximately $140,000. Infrastructure costs are still being incurred from that system, including payments of $1,100 per month on a mortgage for the equipment. The Farm Manure-to-Energy Initiative provided capital costs for the new technology installation totaling $41,500. The technology vendor and an insurance settlement for the system damaged in the electrical fire provided the remainder of the boiler costs.

Construction of a concrete pad includes 12x26 or 312 square feet for the pad under the hopper shed and 20x30 or 600 square feet under the burner building. The total concrete pad covers 912 square feet. Materials and construction costs were estimated to be $4,350 from the farmer.

Farmer labor is a significant portion of the upfront construction and installation costs as well as troubleshooting. For example, Mr. Curtis estimates that to install the boiler and lay 2,600 feet of pipe, dig ditch, and tear out tubing, he contributed 12 hours per day for 6 days a week for 2.5 months. This totals 72 hours per week for 10.86 weeks or 781.92 hours. Using a rate of $34.89 for a farmer, the initial labor is valued around $27,280. Troubleshooting time plus hardware for fittings, etc., not covered by budget was estimated between $17,000 to $18,000, or an average upfront cost of $17,500.

Obtaining permits for air emissions involved minimal farmer time. The new installation of air equipment costs were estimated by Farm Pilot Project Coordination Inc. (FPPC) as $14,500 (including support from Dr. Mike Buser of Oklahoma State University for emissions control design support). Mr. Curtis estimated he spent 2-4 hours (used 4 hours times $34.89 = $104.67 or $105) in support of obtaining air permit approval. There was unaccounted time spent by Denise Bechtel of the Small Business Development Center (Bucknell office in Lewisburg). Without help from the Small Business Development Center, the farmer's time on air permitting would have increased costs. The Small Business Development Center spent an estimated 80 hours to write the grant proposal that funded the first boiler and investigated air permitting (per conversation with Mac Curtis, September 2015). If Mr. Curtis was the sole source of permitting advocacy and grant writing, his time for 80 hours would be valued at $2,773.60 at the BLS rate of $34.89/hour.

Laboratory analysis of air sampling and ash contents were performed during the fall of 2015. Based on availability of data, the following is estimated as laboratory costs. Poultry litter ash and air sampling laboratory analysis were estimated by FPPC as $16,364 for three farms (Curtis, Rodes, and Farmer B), therefore an estimated one third or $5,454 was considered expended in analysis from Virginia Tech, Clemson, and Brookside.

Costs for poultry litter analysis were $419 per sample (Clemson and Brookside). This does not include data collection, which farmers typically would not be expected to do. In other words, data collection costs incurred by the project team supported information gathering beyond what an individual farmer would be required to do on his or her own. It is important to note that one sample is sufficient for federal permitting and does not constitute routine laboratory costs anticipated in the future.

A summary of the costs is provided below.

Windview Farm Cost-Share Contributions			
	Miles	Hours	Cost
Labor*			
Mac Curtis: 12 hours per day, 6 days per week, for 2.5 months		720	$16,294
Infrastructure			
Original system investment, re-invested in this project			$140,000
Over-budget, out-of-pocket expenses			$17,500
Cost to re-build hopper			$400
Mileage**			
Travel to Lancaster County Conservation District for manure-to-energy meeting (Jan. 2015)	160		$92
Travel for purchase of supplies and equipment (spring/summer 2015)	120		$69
Total			$174,194

* Volunteer Cost Calculation Notes: Farmer volunteer time valued at Independent Sector PA volunteer time estimate at $22.63 (http://www.independentsector.org/volunteer_time).
**Mileage calculated at federal rate for 2015 at $57.50.

3.1.3 Routine Operations and Maintenance Costs

Regular maintenance, when the system was running smoothly, averaged 45 minutes per day ($26.17) or $183 per week hauling four bucket loads of litter to the hopper to burn. In colder weather, average maintenance was about one hour per day or $244.23 per week ($34.89/hour/day). Occasional additional maintenance was required due to a stone in the auger; however, preventive removal of stones from litter minimized stone remediation. The initial learning curve for running the manure-to-energy burner the appropriate way involved modulating the dial from low to high demand. That depended on the litter and the weather; after a few months, Mr. Curtis said that it was fairly low maintenance. This initial learning time is not accounted for with Mr. Curtis. A steep learning curve and higher farmer input is mostly what we see with the other host farms, due to the duration of experience with the technology.

Mr. Curtis cleans out the poultry houses between flocks, which is required by his integrator and by the thermal manure-to-energy technology vendor, Total Energy. As such, this effort is presumed the same with and without manure-to-energy technology; therefore, no additional costs are anticipated from litter clean-outs. The University of Georgia Extension provides detailed cost savings on litter bedding and costs for machine clean-outs; however, these were not applied since the activities remained the same with and without the manure-to-energy technology (http://extension.uga.edu/publications/detail.cfm?number=B1267).

It is important to note that, due to the high cost of replacement litter, most growers remove only the top portion of the litter between flocks (called “cake-out” or “crust-out”). Whole-house litter removal is typically done once every 2 to 5 years. So for most poultry growers, a whole-house clean-out between every flock would be considered an additional cost.

3.1.4 Fate of Manure (pre- and post-manure-to-energy technology)

The farm produced 400 tons per year of manure when growing turkeys; now, with broilers, they produce approximately 375 tons per year. Prior to installing manure-to-energy technology, poultry litter was land applied on the home farm (40 acres) and rented land (100 acres) and sold off the farm. It was applied at varying rates, depending on the farm’s nutrient management plan and whether corn or beans were planted, which occurred in alternate years. The volume was approximately 2 tons of manure applied per acre when growing corn or 280 tons of manure in total. The remaining manure was sold at a rate of $8 per ton (current rates are now $10/ton). Since manure is applied on alternate years, the remaining manure for sale varies from $960 to $3,200 annually, based on the $8 per ton rate. The revenue generated on selling manure during corn years is estimated as $960 per year for the remaining 120 tons sold at $8 per ton. The revenue generated for manure sold during bean planting years is estimated as $3,200 per year because no manure is applied and all goes to sale. Therefore, an average $2,080 per year is generated from sale of manure (based on a corn plus bean year). This estimated average revenue is not presumed to be available for farmers who burn litter for energy; it needs to be accounted for when calculating the savings from propane as a loss of revenue.

3.1.5 Energy Costs

Electricity and propane costs listed during technology run-times

Mr. Curtis described significant propane savings during his years with the manure-to-energy system. The manure-to-energy technology on Windview Farm burns approximately 320 tons per year, leaving none for sale. Any remaining litter, if available, was used on crops. Future modeling of financial performance of the manure-to-energy technology should account for loss of revenue from manure that was burned instead of sold. Additional detailed energy assessments are provided in Section 4.

While the loss of revenue for manure sold is $2,080 a year (on average), Mr. Curtis estimates that he saved more than 90 percent in his propane bill using poultry litter for energy over the recent few years.

Energy trends were based on years of propane and electric bills. In general, Mr. Curtis indicated propane prices have dropped, but were more than $3 per gallon when he began running the manure-to-energy technology. He has four 1,000-gallon tanks at the poultry houses that hold up to 3,200 gallons total (80 percent is full capacity to allow room for off-gassing). Mr. Curtis estimated that he used 3,500 gallons of propane in 2014. The savings in propane is realized when the integrator provided a stipend for propane; the stipend was not needed for propane and was therefore a source of revenue. The amount of propane offered varies per flock, based on the time of year. Mr. Curtis received a stipend for gas allowance from the integrator during 2012 through 2015, while he used the manure-to-energy system to generate heat and therefore decrease his propane use. In 2012, he received $41,100 as a propane stipend; in 2013, he received $34,650; in 2014, he received $41,700; and, as of July 2015, he received a propane stipend of $10,200. Because his propane bills were less than the stipends, he was able to earn the revenue using the litter burning technology as described below.

Integrator Gas/Electricity Allowance as Income

The integrators pay an allowance for both gas and electricity based on average grower usage in the geographic area. These allowances exceeded the propane bill and became a source of income. In 2012, the electricity allowance from the integrator was also a small income.

It is important to note that the integrator told Mr. Curtis that because he does not actually pay such high gas bills, his allowance should be reduced (personal communication between the EFC and Mr. Curtis, September 2015). Mr. Curtis contends that it would be unfair to penalize him for having technology that allows him to save on propane. Future implementation of manure-to-energy technology needs to consider whether or not integrators may lower the gas allowance and thereby null the propane savings.

Propane

In 2012, Mr. Curtis spent $5,558.99 on 3,716.6 gallons of propane, and his net income from the propane stipend was $35,541.01. In 2012, he spent $7,554.80 on electricity, and his stipend was $10,672; therefore, Mr. Curtis was able to receive the remaining $3,117.20. By burning litter, Mr. Curtis earned an additional $38,658.21 from the savings on his integrator allowance stipends. In 2013, Mr. Curtis spent $6,446.56 for 5,261.7 gallons of propane, which translated to an earned income of $28,203.44 from the allowance ($34,650.00 – $6,446.56).

In May 2014, Mr. Curtis lost his manure-to-energy boiler in a fire. Therefore, his use of propane was higher and his earned amount from the gas allowance was slightly less than the previous two years. In 2014, Mr. Curtis spent $14,348.74 for 8,987.9 gallons of propane, which translated to an earned income of $27,351.26 from the gas allowance of $41,700.00 ($41,700.00 - $14,348.74).

Electricity

Trends in electricity usage for the past few years are primarily observed by the Curtis family. No electric bills were available for 2013 or 2014. Mr. Curtis noted that electricity was usually higher when using the manure-to-energy system (2012 was an exception). The electric fee is based on pounds of birds (as a stipend by the integrator to the grower). The electric rate is the same per flock. Electricity also runs the pumps for the water wells. No other water use is a cost, per se. The grower is responsible for all washing of the fans, inlets, and stove between flocks and the building once a year. The farm labor for this was not accounted for because the farmer performs these tasks whether or not manure-to-energy technology is running.

3.1.6 Weather conditions

The on-farm use of propane for heating was reviewed in light of the weather patterns, based on the NOAA National Center for Environmental Information, with the statewide ranking of average temperature data reviewed monthly for Pennsylvania (based on historic data from 1895 to 2015). In general, the period between January and April 2012 was much warmer than normal to near normal. October through December 2012 was near normal, below normal, and much above normal (varied greatly) for Pennsylvania. In 2013, NOAA reported January through February as normal, March below normal, and April above normal. The cold weather months later in 2013 had near normal temperatures for October and December, while November 2013 was much below average. The NOAA database characterized January and February of 2014 below average temperature and March as much below average. The April and May 2014 temperatures were near average. Later in 2014, the NOAA database indicated that October and December had above average temperatures, while November 2014 was below average. In 2015, NOAA recorded below average and much below average temperatures for January through March.

3.1.7 Overall Farm Revenue

Windview Farm revenue consists of income from the birds, income from the 40 acres, and income from selling poultry litter. Corn can generate $12,000, and manure can generate $3,395, plus $257 in hay. In summary, poultry is 95 percent of the total farm revenue. The estimated total farm revenue was calculated from data on the settlement sheets for 2012, 2013, 2014, and part of 2015. During 2012, Mr. Curtis earned a $94,876.80 flat fee for growing poultry per pound. With the additional integrator stipends for gas, electricity, litter, and bonuses, his total income in 2012 was $180,158.71. Based on Mr. Curtis' assertion that poultry represents 95 percent of the total farm revenue, his proportioned total farm revenue for 2012 was estimated as $189,166.64. During 2013, he earned a $97,566.80 flat fee for growing poultry per pound. With the additional integrator stipends for gas, electricity, litter, and bonuses, his total income in 2013 was $177,786.87. The total farm revenue was calculated using the 95 percent proportion of revenue from birds and was calculated as $186,676.21. During 2014, he earned a $103,012.28 flat fee for growing poultry per pound. With the additional integrator stipends for gas, electricity, litter, and bonuses, his total income in 2014 was $190,894.02. The total estimated farm revenue for 2014, using the proportion of 95:100 for poultry-revenue to total farm revenue, was estimated as $200,438.72. From January through July 2015, Mr. Curtis earned a $44,359.80 flat fee for growing poultry per pound. With the additional integrator stipends for gas, electricity, litter, and bonuses, his total income in 2015 as of July was $66,416.01.

3.2 Ecoremedy Gasfier Demonstration at Farm B

(Name of farmer and farm redacted, per farmer request.)

3.2.1 Farm Description

Farm B is located in Lititz, PA. It has four poultry houses producing organic poultry broilers using a manure-to-energy system to provide heat.

3.2.2 Infrastructure costs, Installation Costs, and Permitting Costs

The following funding totaled $957,987 for the infrastructure of a manure-to-energy boiler and heat delivery system. Of the $957,987, $441,487 was from the farmer and vendor, as partner match ($247,969 from Enginuity Energy LLC, $183,518 from Ecoremedy Energy Technologies, and $10,000 from Flintrock Farm). The farmer also obtained funding from the Pennsylvania Natural Resource Conservation Service Environmental Quality Incentives Program totaling $150,000. The balance was funded via private funds from the National Fish and Wildlife Foundation in collaboration with the Chesapeake Bay Funders Network, which provided $366,500 through the Farm Manure-to-Energy Initiative.

Heating exists for four poultry houses fueled by manure-to-energy technology. The poultry houses in place are not included into the capital costs; however, $53,000 in upgrades for energy efficiency are included in the capital costs. The poultry houses that are heated by the technology fuel include 243,000 cubic feet for Houses 11 and 12 and 170,500 cubic feet for houses 9 and 10.

Farm B had an existing concrete pad under the storage shed so no additional costs were incurred. The concrete pad under the hopper shed is located under the building. Farmer B said he put $200 into the concrete pad for capital costs. Estimated labor and materials to install an estimated 400 square feet for a concrete pad under the boiler shed concrete pad is $1,900 from the farmer plus his estimated $200, or $2,100 for labor and materials to construct the concrete pad under the hopper and boiler sheds, covering 400 square feet.

Obtaining permits for air emissions involved no farmer time. No water or stormwater permitting costs were associated with the project. Laboratory analysis of air sampling and ash contents are being performed during the fall of 2015. Based on availability of data, the following is estimated as laboratory costs. Poultry litter ash and air sampling laboratory analysis were estimated by FPPC as $16,364 for three farms (Windview Farm, Riverhill Farm, and Farm B); therefore an estimated one third or $5,454 was considered expended in analysis from Virginia Tech, Clemson, and Brookside. Costs for poultry litter analysis were $419 per sample (Clemson and Brookside). This does not include data collection, which no other farmer had to do since one sample is sufficient for federal permitting.

3.2.3 Installation Costs

Farmer B estimates he spent a total of 830 hours between 2012 through 2014 to help get the manure-to-energy system running. This was broken down at 10 hours per month from January 2012 through January 2013, 20 hours per month from February 2013 through December 2013, and 40 hours per month from January through December 2014. At the farmer labor rate of $34.89 per hour, total farmer time for installation is estimated as $28,960. Farmer time for up-front preparation included two trips to Lancaster Conservation District and two trips to the vendor in Mechanicsburg, PA. Famer time was calculated at $34.89 per Bureau of Labor and Statistics, modified rates March 2015 (http://www.bls.gov/oes/current/oes119013.htm). The farmer labor included above is a significant portion of the up-front construction and installation costs as well as troubleshooting. The time estimates from Farmer B include installing the boiler and laying pipe, digging ditch and tearing out tubing, troubleshooting time plus hardware for fittings.

The travel to the Conservation District is estimated as 0.5 hours travel plus a two hour meeting, which totals 2.5 hours for one meeting or five hours for both meetings. Travel gasoline at the IRS reimbursement rate for 2014 was 0.56 per mile, totaling $11.20 per trip or $22.40.

Distance to the vendor was 90 miles round trip, or two hours travel plus two hours per meeting for a total of four hours per meeting of farmer time. For two meetings, total farmer time was estimated at eight hours and gasoline for travelling 180 miles at the same rate is $110.80.

Total costs for four trips to prepare for the technology include $453.57 for 15 hours of farmer time and $133.20 for gasoline, or a total of $587.

3.2.4 Routine Operations and Maintenance Costs

(Includes regular maintenance when running smoothly.)

Farmer B estimates regular maintenance to be $5 per ton for the daily labor of moving litter to the boiler, or $8,000 (per his pro forma). Farmer B estimates daily labor of filling and checking the system to be 1.5 hours when it gets up and smoothly running, which would be $10,950 for 1,600 tons (per his pro forma). These were best-guest farmer estimates because the actual labor was heavy and the manure-to-energy technology did not run smoothly during the performance assessment period.

Farmer B cleans out the poultry houses between flocks to remove the top crust of the bedding. He changes the entire bedding and replaces litter on whole-house cleans-outs, which are conducted once every 12 to 18 months. Whole-house clean-outs cost $1,700 per house. For four houses to be cleaned out every 12 to 18 months, the cost is $5,100 annually. Farmer B used to be allowed to use spent horse stall bedding for litter; however, his current integrator does not permit that so it is an additional cost for him to do the whole-house clean-out and replace bedding. (Note: the additional four houses not using manure-to-energy technology likewise cost $5,100 annually.)

3.2.5 Fate of Manure (before and after manure-to-energy technology)

Farm B produces about 800 to 900 tons a year of manure with organic broilers (personal communication, Farmer B, September 3, 2015). Farmer B has 40 acres of cropland and uses about 2-3 tons of litter per acre per year to fertilize it, or 100 tons of litter (2.5 acres over 40 acres). The remaining 700 to 800 tons of litter, prior to implementing manure-to-energy technology, was sold to brokers at a rate of $9 to $10 per ton (current rate is $9 per ton). Prior to burning litter, this generated approximately $6,750 per year in income using an average of 750 tons of litter. The buyer would pick up the manure, so Farmer B incurred no disposal or hauling costs in the transaction. When the manure-to-energy technology is fully functional and running continuously, the loss of $6,750 per year should be reflected in the cost balance sheet.

It is important to note that this farmer sold his poultry litter ash to growers in Missouri.

This sale is a milestone, as it represents the first in interstate market sales and reflects the potential marketability of the fly ash. As presented in Section 1 of this report, market values for ash should be refined in future market assessments.

3.2.6 Energy Costs

(Electricity and propane costs listed during technology run-times.)

Propane

The boiler did not run for a sufficient duration to affirm long-term propane savings. However, Farmer B noted that he had decreased propane consumption while using the manure-to-energy system to heat one flock (for a portion of the flock cycle) from December 2014 through January 2015. The houses on the north hilltop use the heat from the manure-to-energy system, whereas the southern houses are heated by propane only. Based on propane bills from 2014 and 2015, the houses that were using manure-to-energy technology during a flock placed from December 5, 2014 through January 1, 2015 realized a savings of propane; however, without more data, it is a qualitative trend rather than a statistically significant savings. Farmer B indicated that during one week when the manure-to-energy system was running, he used $2.20 propane per pound of bird, versus $4.76 for propane per pound of bird for an average grower that same week. It is important to note that the manure-to-energy run time during that flock placement was about three weeks and did not run during the high heat time of initial placement for pre-heat or the first few days, when chick heating needs are most intense.

Electricity

The electricity is solar-generated. Under net metering, Farmer B has a refunded amount credited to his account for the solar production, or he gets a deduction if they use less than they generate. They are capturing most of the manure-to-energy heat offsets with the independent meter.

Additional electric not covered by this meter includes: three ¾ HP motors per house running all the time, or 12 motors running total for his four houses. Also, if Farmer B was running the system per the guidance of bird health advocates, he would be making more use of in-house fans, so the electricity meter on the manure-to-energy boiler alone does not quite cover the price difference.

Note: Farmer B estimates that his electricity use will be in the range of $7,000 per year because of the manure-to-energy system for four houses. The electricity data is not as specific as propane. Farmer B runs an inventory of propane used per flock but does not do the same inventory of electricity as he does for propane.

Integrator Gas / Electricity Allowance as Income

The integrators pay an allowance for both gas and electricity based on average grower uses in the geographic area.

3.2.7 Weather conditions

The on-farm use of propane for heating was reviewed in light of the weather patterns, based on the NOAA National Center for Environmental Information, with the statewide ranking of average temperature data reviewed monthly for Pennsylvania (based on historic data from 1895 to 2015). In general, the period from January through April 2012 was much warmer than normal to near normal. October through December 2012 was near normal, below normal, and much above normal (varied greatly) for Pennsylvania. In 2013, NOAA reported January through February as normal, March below normal, and April above normal. The cold weather months later in 2013 had near normal temperatures for October and December, while November 2013 was much below average. The NOAA database characterized January and February of 2014 below average temperature and March as much below average. The April and May 2014 temperatures were near average. Later in 2014, the NOAA database indicated that October and December had above average temperatures, while November 2014 was below average. In 2015, NOAA recorded below average and much below average temperatures for January through March.

3.2.8 Overall Farm Revenue

Farm B's overall revenue is generated by selling some manure that is not used on the fields and by running an averate of seven poultry flocks per year in eight houses. Annual poultry income was not disclosed.

3.3 The Mark Rohrer Farm

3.3.1 Farm Description

The Mark Rohrer Farm is located in Strasburg, Lancaster County, PA. Organic chickens are raised in two poultry houses, heated with manure-to-energy technology. Mr. Rohrer's brother, Todd Rohrer, has two poultry houses situated next door that do not use manure-to-energy technology.

3.3.2 Infrastructure costs, Installation Costs, and Permitting Costs

The Rohrer farm used the two existing poultry houses and a manure shed during the time hosting this technology. The hard infrastructure in support of the manure-to-energy system included the boiler, the shed for the boiler, the heat delivery system, air quality abatement equipment, and a concrete pad under the boiler shed.

The infrastructure for the manure-to-energy boiler and heat delivery system totaled $303,012. A subtotal of $181,512 was provided as partner match; this was based on $26,365 from the farmer and $155,147 from the vendor. The remaining was funded through a grant Farm Manure-to-Energy Initiative providing $121,500 in funding.

The vendor paid for materials and construction of concrete padding in the amount of $5,000. While no concrete pad dimensions or time estimates were available regarding farmer contribution, it is estimated there were no out-of-pocket costs borne by the farmer for the concrete pad. This estimate is based on the $4,350 paid by Mr. Curtis for materials and time to install a concrete pad under his boiler and hopper. For the purposes of this assessment, we assume that Mr. Rohrer's cost was a similar amount, covered by the vendor's contribution of $5,000. The vendor provided $17,500 for the shelter for the system.

Farmer labor is a significant portion of the up-front construction and installation costs as well as troubleshooting. For example, Mr. Rohrer indicated he paid $5,363 in out-of-pocket expenses and time for the initial installation. The fan ventilation system cost $50,000, paid for through a cost-share arrangement that also covered installation and equipment training.

Cost-share funding and the FPPC's contribution of $15,000 were used to fund the air pollution remediation equipment and installation.

There were no air emission permits, so no farmer time or permit fees were incurred. A contractor and FPPC performed initial and subsequent air pollution sampling, with no costs available at this time, as sampling was performed in September 2015. Future financial assessments should include air source sampling, laboratory analysis, and time for regulatory agencies, as required based on local and state regulations.

3.3.3 Routine Operations and Maintenance Costs

Note: Famer time was calculated at $34.89 per Bureau of Labor and Statistics, modified rates March 2015 (http://www.bls.gov/oes/current/oes119013.htm).

Regular maintenance was not experienced for a significant duration. The maintenance time incurred by the farmer to support the system was documented on farmer log sheets. Mr. Rohrer logged a total of 44 hours for maintenance and troubleshooting between September 28 and November 30, 2014. Mr. Rohrer's time during this period was estimated to be valued at $34.89 per hour or $1,535. This reflects the steep learning curve and higher farmer input exhibited during the duration of the technology run times.

Mr. Rohrer cleans out the surface litter of the poultry houses (a "crust out") between flocks. This effort is presumed the same with and without manure-to-energy technology; therefore, no additional costs are anticipated from litter clean-outs. The University of Georgia Extension provides detailed cost savings on litter bedding and costs for machine clean-outs; however, these were not applied since the activities remained the same with and without the manure-to-energy technology (http://extension.uga.edu/publications/detail.cfm?number=B1267).

3.3.4 Fate of Manure (before and after manure-to-energy technology)

The Rohrer farm did not provide data on the fate of manure before the manure-to-energy system was using litter to generate heat. It is assumed that the manure was used on their crops and not sold.

3.3.5 Energy Costs

(Electricity and propane costs listed during technology run-times. Detailed energy assessments are provided in Section 4 and in Appendix A.)

Propane

The average daily propane consumed by the Rohrer farm for the two months that the farm hosted flocks and the system was delivering heat was 55 gallons per day, compared to the estimated pre-technology use of propane of about 98 gallons of propane per day. This estimate was calculated by comparing his propane use to propane on an adjacent farm. For two flocks in a side-by-side comparison, Mark Rohrer's propane bill was $5,901.37 plus $136.02 in propane costs for running the system, for a total propane cost for two flocks of $6,037.39. This can be directly compared to the adjacent farm's propane bill of $8,009.76 for the same time period with two flocks. In theory, the data from the adjacent farm can emulate pre-technology conditions for Mark Rohrer. While the poultry houses are not identical, they are similar for the purposes of demonstrating trends in energy savings. This side-by-side comparison indicates a 25 percent reduction in propane use by Mark Rohrer for the time he was using the heat delivered by the manure-to-energy system.

Integrator Gas / Electricity Allowance as Income

No integrator for gas or electricity allowance from flock settlement was confirmed and was therefore not included in this assessment.

Electricity

Mark Rohrer's electricity cost for running the system was $404 for the duration of two flocks from September 28 through November 30, 2014. Other electricity data is extrapolated from the two flocks and presented in Section 4.

3.3.6 Weather conditions

Due to the geographic proximity, the weather conditions are similar to those of Farm B, described above.

3.3.7 Overall Farm Revenue

Mr. Rohrer has an estimated six flock cycles a year. No data was available on the income generated annually from the poultry, or what percent that constitutes of his overall farm revenue. Income presented on the flock settlement sheets from June through November 2014 indicated a net grower pay of $38,575.97. If doubled, the estimated annual net grower pay from poultry could be estimated as $77,151.94.

Data on total farm revenue plus the percentage of revenue generated from poultry compared to the total farm, while useful in future analyses, is sensitive in nature and was not easily secured from the farmers.

3.4 The Mike Weaver Farm

3.4.1 Farm Description

The Mike Weaver Farm is located in Fort Seybert, Pendleton County, WV. Mr. Weaver produces broilers conventionally in two poultry houses.

3.4.2 Infrastructure costs, Installation Costs, Permitting Costs

The infrastructure for the manure-to-energy boiler and heat delivery system totaled $297,647. A subtotal of $176,147 was provided as a partner match; this was based on $21,000 from the farmer and $155,147 from the vendor. The remaining was funded by leveraged grants through the National Fish and Wildlife Foundation's Conservation Innovation Grant number 33043 and partners.

Mr. Weaver had an existing concrete pad under the storage shed so no additional costs were incurred. The cost for the concrete pad under the hopper shed was not available, but estimated at $5,000 (based on the Curtis farm).

No environmental permitting costs, fees, or farmer time were expended in this project. Obtaining permits for air emissions involved partner support but no farmer time.

No water or stormwater permitting costs were associated with the project. The state issues a research permit for the project and did not have a cost.

3.4.3 Installation Costs

A ditch was dug for the pipe ductwork to delivery hot air to the two poultry houses. Farmer labor was not available.

There was no travel for permitting, vendor consultation, or to the regional Conservation District (no information was available for inclusion of these parameters, if applicable). No laboratory analyses costs were provided for ash or air sampling material.

3.4.4 Decommissioning Costs

Based on a cooperative agreement, dated December 17, 2013, between FPPC and Mr. Weaver, FPPC paid the farmer $12,000 for decommissioning of the equipment and hard infrastructure. This farm is the only host site with decommissioning data available.

3.4.5 Routine Operation and Maintenance Costs

(Includes regular maintenance when running smoothly.)

Regular maintenance data was not gathered to a large degree, given that the boiler, when running fairly routinely, was turned off during Flock 1, due to warmer weather and the size of birds (shut off after October 11, 2014). During Flock 1, the boiler ran 304 hours according to the FPPC data logger (farmer-logged hours indicated that the boiler ran 354 hours). Mr. Weaver's time was 32 hours and included tasks such as hopper feeding and boiler repair. The farmer hours were approximately 10 percent of the run-time hours.

Mr. Weaver cleans out the poultry houses between flocks. These activities do not change with burning litter in the manure-to-energy system. Per the farmer questionnaire, Mr. Weaver pays approximately $4,000 per house a year in ammonia treatment.

Mr. Weaver raises approximately seven flocks a year, with 14-day increments between flocks. Flock cycles typically run 38 days for 46,000 birds per house. Weaver removes cake litter between flocks. He does not totally clean out his houses. Each house has approximately 150 tons of litter. The remaining litter is stored in a shed beside the houses. Annual cost to replace bedding of wood shavings is about $4,000 a year.

Another operation and routine maintenance cost is to move litter into the shed for burning, using his front end loader. Mr. Weaver included that activity in his hours for 32 hours of Flock 1 and 22 hours during Flock 2, while the boiler was burning litter. There was no further breakdown of costs for this activity. The estimated farmer labor time from September 11 through December 1, 2014, was valued at $1,884 for 54 hours of farmer time at $34.89 per hour.

3.4.6 Run-times of Technology

The boiler ran for a portion of three flock cycles, as noted below.

- Flock 1, September 26 - October 11, 2014

  - During Flock 1, the system ran for a total of 304 out of 360 hours due to mechanical failures.
  - Farmer time to deal with the mechanical issues and routine hopper loader totaled 32 hours during flock 1, or roughly 10 percent of the run-time.
- Flock 2, November 16 - December 1, 2014.
  - During Flock 2, the boiler ran a total of 120 hours (per farmer log sheets) out of the 360 hours it was partially up, before being permanently turned off.
  - During Flock 2, farmer time was 22 hours or 18 percent of the run-time.
- Flock 3, January 11 - February 20, 2015.
  - During Flock 3, the boiler ran a total of 224.2 hours for House 1 and 228.2 hours for House 2, or an average of 226.2 hours during 960.

3.4.7 Fate of Manure (before and after manure-to energy technology)

Prior to burning litter as fuel for the boiler, some of the litter was applied to the land and some was sold. The amounts were not specified on the farm survey. No additional litter data was available.

3.4.8 Energy Costs

(Electricity and propane offsets listed during technology run-times.)

Mr. Weaver receives a stipend from the integrator for fuel. The amount received depends upon flock performance. Weaver uses liquid propane to fuel two houses, in addition to the heat generated from the manure-to-energy boiler. His current rate is $1.30/gallon. Mr. Weaver's annual fuel costs run $2,000 for the poultry houses. His poultry house has insulated walls and an insulated drop ceiling to maximize energy efficiency. His poultry house dimensions are 31,200 square feet each (624 feet by 50 feet). The brooding space is 312 feet by 50 feet or 15,600 square feet.

The manure-to-energy boiler did not run for a sufficient duration to affirm long-term propane savings. The boiler run-time was intermittent for three flock cycles. Also, most the heat was delivered during the early growth time for the flocks, when a curtain keeps the birds and heat at half-house conditions. Mr. Weaver noted that the half-house temperature difference is 3 degrees, while the full-house temperature difference is 5 degrees (email communication, August 24, 2015).

Air flow in the houses is managed by actuator controlled vents and exhaust fans set to run with average house temperature curves of Day 1: 86 degrees, Day 3: 84 degrees, Day 7: 82 degrees, Day 10: 79 degrees, and Day 14: 75 degrees, etc. The heated air from the boiler is pumped through underground ducts and enters the two houses.

Integrator Gas / Electricity Allowance as Income

The integrators pay an allowance for both gas and electricity based on average grower usage in the geographic area.

3.4.9 Weather Conditions

The on-farm use of propane for heating was reviewed in light of the weather patterns, based on the NOAA National Center for Environmental Information, with the statewide ranking of average temperature data reviewed monthly for West Virginia based on period of record (http://www.ncdc.noaa.gov/temp-and-precip/climatological-rankings/index.php?parameter=tavg&state=46&div=0&periods[]=1&month=2&year=2015#ranks-form). In general, in 2014, NOAA reported warmer than normal temperatures for October, much cooler than average temperatures during November, and temperatures near average during December of 2014. The NOAA database indicated average temperatures in January 2015, below average temperatures in February 2015, and much below average temperatures in March 2015. April and May 2015 were cooler than average.

3.4.10 Overall Farm Revenue

Mr. Weaver earns revenue from two flocks of 46,000 birds each, approximately seven times a year. He sells a small amount of manure. No other revenue was reported.

Mr. Weaver used approximately 554 gallons of propane to fire the furnace for both flocks (beginning in September and November 2014), with approximately 327 gallons of propane used on multiple re-fire start-ups during the week of November 16-23. He pays $1.36 per gallon of propane, so this amounts to $510 in propane for Flock 2 (November 11-23) and a total of more than $864 in two flocks.

3.5 Riverhill Farm

3.5.1 Farm Description

Riverhill Farm is located in Port Republic, Virginia. The owner, Glenn Rodes, grows about 280,000 turkeys per year in one turkey brooder and four grow-out houses. His costs include capital costs and air permitting. Due to a change in technology, no additional costs were tracked for this farm.

3.5.2 Infrastructure costs, Installation Costs, Permitting Costs

The equipment costs for Riverhill Farm represent capital costs for the manure-to-energy system originally in place, which are no longer at this farm. Therefore, the capital costs were not included for the heat delivery system. An LEI Bioburner eventually replaced the original system, in order to better combust the higher moisture content of turkey litter at Riverhill Farm, compared to broilers at the other host farms.

Riverhill Farm offers insight into air pollution permitting requirements. The host farm sites in PA and WV are free from air pollution permitting costs, to date. There was time provided by FPPC but no farmer time was estimated. Virginia offers a biomass test permit for air pollution compliance. No technology system to date has exceeded the test permit timeframe; therefore the permitting process is still unexplored for the long-term in Virginia. There was an air pollution research permit in WV, which did not have a cost.

4. Energy Assessments and Recommendations

4.1 Impacts on Energy Consumption and Costs from Manure-to-Energy Technology

The future success of manure-to-energy systems on individual farms primarily depends on a system's ability to compete economically with conventional forms of thermal and electrical energy. There are other potential benefits associated with manure-to-energy technology, including displaced manure transportation and management costs, and the sale of ash as nutrients; however, avoided energy costs are the factor that will determine whether or not on-farm manure-to-energy technology is feasible. Referencing the experience and energy records from farms participating in the manure-to-energy Farm Pilot Project, this section seeks to quantify the changes in energy use and costs resulting from the installation and operation of manure-to-energy systems on four of the five farms that participated in this project.

4.2 Overview of Poultry Farm Energy Use

In general, farms with the greatest energy use and greatest associated cost will have the most to gain by installing manure-to-energy systems and realizing avoided costs. It is critical to understand the baseline, pre-technology thermal and electrical energy load at a given farm in order to properly assess the feasibility of a manure-to-energy system in a specific setting. In the case of the Farm Manure-to-Energy Initiative, the installed systems delivered heat, not electricity. In turn, the focus of this financial analysis is on displaced costs for heat; however, there are also some notable changes to electricity consumption resulting from the switch to manure-based heat and its delivery and ventilation systems.

For these farms, the default heating fuel was propane. Its consumption was dependent on a number of factors. Table 1 characterizes each of these factors and the approximate relationship to the heat load, or the amount of heat and fuel needed to maintain poultry health.

Table 1. Factors influencing heat load and fuel consumption in poultry houses

Determining Factor	Description of Impact
Poultry type (chickens vs. turkeys)	Chickens (including broilers and layers) and turkeys have variable growth rates and heating needs. The longer the life cycle and the smaller the bird, the greater the heating loads.
Market type (conventional vs. organic)	Feed is used as a substitute for warmer temperatures when raising conventional chickens. Due to the high cost of organic feed, this relationship breaks down for organic birds, which requires higher temperatures and more fuel use. Warmer poultry results in higher weight. Organic birds are correlated with increased water consumption. These effects were not assessed.
Number and age of birds	Larger, densely packed birds put off their own heat. As birds age, the indoor temperature requirements will decrease.
Building size and conditions	Larger buildings require more fuel to heat the available space. Poorly insulated buildings will lose heat faster through leakage. Also, houses frequently operate at a fraction of their size (e.g., half-houses, ¾-houses) through the use of barriers that concentrate the heated bird area and reduce the heat load.
Outdoor Temperature, Delta Temperate	The difference between the outside temperature and indoor temperature, which varies based on the factors listed above, is the biggest driver of heat load. Fuel use peaks during the winter months.
Humidity and ventilation	Humidity, and its relationship to the creation of ammonia, is critical to poultry health and profitability. Ventilation is necessary despite the fact that it expedites heat loss and increases energy usage.
Heating system, fuel, and efficiency	The heating system (including the design, fuel, and efficiency of the system) meets the heat load as it cycles through seasons and flocks. More efficient systems use less fuel to meet that heating load. Fuel type has an indirect impact; for example, "wet fuel" requires more ventilation.

Electricity is used for lighting, ventilation (e.g., fans), pumps, feeding systems, and as source power for heating systems (i.e., parasitic load). Electricity use varies with the efficiency of these systems and, of course, over daily and seasonal cycles. Electricity use on poultry farms is highest in the summer when tunnel fans are used to cool houses.

Manure-to-energy systems are expected to impact electricity usage by 1) generating parasitic load associated with starting and operating the heating system, which puts upward pressure on electricity use, and 2) potentially changing cold weather ventilation rates. Manure-to-energy systems avoid the need to burn propane, which is typically uses in-house heaters. Propane releases moisture, carbon dioxide, and carbon monoxide when burned, thus increasing the need for ventilation. With manure-to-energy systems, thermal conversion of manure occurs outside of the poultry house and the system delivers either hot air or hot water, thus reducing in-house generation of undesirable propane emissions byproducts.

Some farmers with manure-to-energy systems may choose to reduce ventilation in the cold weather season. However, other farmers may choose to increase cold weather ventilation for improved air quality. This approach has been recommended by poultry ventilation experts to improve bird health and growth. In cold weather, growers with propane heating systems must balance house air quality with propane use, as increasing ventilation also increases propane use. Growers with manure-to-energy systems will have more flexibility to improve air quality through ventilation in the cold weather months.

Efficiency as an Initial Investment: Prior to investing in manure-to-energy technology, farmers would be wise to focus on improving the energy efficiency of their farm operations. High-efficiency variable speed fans, insulation, LED lights, drop ceilings, and regular maintenance of heating systems can result in immediate energy and cost savings with very little cost, thereby further improving heat delivery with a new manure-to-energy system. The potential for cost savings and other financial metrics associated with an investment in manure-based energy will be inflated if a farm hasn't first invested in basic energy efficiency.[1] Further, reducing the heat demand in a poultry house through energy efficiency may reduce the size of the manure-to-energy system needed, thus reducing the installation costs. Energy audits can help identify which improvements are cost effective.

4.3 Manure-to-Energy Farm Initiative Energy Records

One of the objectives of the Farm Manure-to-Energy Initiative was to closely track participating farms across an array of metrics to accurately account for the costs and benefits accruing from manure-to-energy technology. Propane and electricity usage (pre- and post-technology), flock cycles, bird health, bird production, system run-time, temperature, and humidity are the most important metrics in terms of quantifying and understanding changes in energy use and costs. Ideally, high-resolution propane and electricity usage records would be available for an extended period of time, both before and after the installation of a manure-to-energy system. This would allow for a more accurate assessment of changes in energy use and costs and, in turn, a more accurate financial assessment.

[1] Czarick, M. 2009. *Reducing Poultry House Power Usage*. Presentation from the University of Georgia. https://www.poultryventilation.com/sites/default/files/presentations/power.pdf.

Table 2. Overview of energy records by farm

Farmer Name	Description of Available Propane Data
Mark Rohrer Farm	The Mark Rohrer Farm has metered data for the period from September 2014 through January 2015, along with detailed settlement sheets corresponding to two flocks produced during that period. The metered data corresponds to one house with manure-to-energy technology and one house without.
Windview Farm	Windview Farm has four propane tanks for two poultry houses. Available records from December 2011 though June 2015 indicate when the tanks were filled and the amount delivered.
Farm B	Farm B farm has 4 houses and a meter on each house for the period from December 2014 through May 2015.
Mike Weaver Farm	The Mike Weaver Farm has invoices for purchased propane for September 2014, December 2014, and January 2015. The rate of propane usage is unknown.

As Table 2 suggests, there are data gaps in the number of records over time, issues with data resolution, and uncertainty about how to account for changes in propane usage. For example, Windview Farm receives 5-7 deliveries of propane per year, which is pumped into tanks and used as needed to produce heat. There is no meter available to provide hourly, daily, or monthly estimates of propane use. Higher resolution propane data (i.e., propane use per day) enables tighter tracking and correlation to the factors driving propane use, including temperature, ventilation patterns, bird count, flock age, etc. By establishing the correlation between propane use and these factors driving propane use, it then becomes possible to attribute changes in propane consumption to either 1) manure-to-energy technology or 2) other factors that might be consider "noise."

There is some empirical evidence that manure-to-energy systems displace propane costs. Again, Windview Farm serves as a good example, as it has one of the few systems that ran consistently for more than two years. The farm had a manure-to-energy heating system that was installed in 2011 and ran until May 2014, when it was destroyed in an electrical fire. During its period of operation, Mr. Curtis had 3,717 gallons of propane delivered in 2012 and 5,262 gallons of propane delivered in 2013. In the fall and early winter of 2014, when the system wasn't available, 8,988 gallons of propane were delivered — a 70 percent increase compared to 2013. Also of note, Mr. Curtis received a gas allowance from his integrator totaling $41,100 in 2012, but only purchased $5,559 worth of gas. The difference between the allowance and the actual amount paid for gas, on the surface, suggests that the farm was using far less propane than would have been the case had the manure-to-energy system not been operational.

This and other anecdotes from farmers suggest the potential for manure-to-energy technology to displace propane costs. However, this is not a robust analysis of manure-based energy and its impact on costs. The remainder of this section focuses on overcoming the data gaps in energy records and using calibrated models to estimate the impact of manure-to-energy technology on energy use and costs.

4.4 Modeling Energy Use Across Manure-to-Energy Farms

A rudimentary model, based on primarily Mark Rohrer Farm data, was developed to overcome data gaps and provide a range of typical working assumptions. Data from the Rohrer Farm serves as a template for the model and contains details on the sub-modules summarized herein and is in the spreadsheet in Appendix A. It is important to note that the modeling exercise presented in this energy assessment is more detailed than commonly performed with sparse data; however, it demonstrates the level of assessment and predictions possible, given more comprehensive database for consideration in future assessments.

The purpose of the model is to create scenarios based on pre- and post- technology efficiency using variable run-times (40 and 95 percent run-times) to predict estimated energy savings. For the purposes of this report, the model is termed the On-Farm Propane and Manure-to-Energy Model. The objective of the On-Farm Propane and Manure-to-Energy Model is to estimate daily propane and electricity use as it relates to a period of past poultry production, to customize characteristics unique to specific farms, and to quantify changes in propane and electricity use resulting from the installation of a manure-to-energy system. The model enables direct comparison of energy patterns pre- and post-installation of a manure-to-energy system, and will summarize daily results across an entire year for long-term fiscal analysis. The model was developed in two phases: 1) estimate of daily energy use based on available data and testable assumptions, and 2) model calibration with actual propane and electricity data. The model, described in greater detail below, can be modified across different farms or as assumptions breakdown.

4.4.1 Temperature Differential (sub-module)

1. Collect data related to historic poultry production via settlement sheets including when flocks were placed and removed, the type of birds being raised (e.g., conventional broilers), and the number of birds placed.
2. Referencing the nearest airport weather station to each farm, pull daily minimum and average temperatures for each station.
3. Estimate the daily indoor temperature requirement based on the age and types of birds under the following assumptions:
    a. Default house temperature (no birds) = 65^0 F
    b. Organic poultry operation (weight factor) = $+12^0$ F (varies with calibration)
    c. Conventional poultry operation (weight factor) = -8^0 F (varies with calibration)

   d. Bird age < 7 days = 90^0 F, <14 days = 85^0 F, <21 days = 80^0 F, < 28 days = 75^0 F, <35 = 70^0 F, >35 = 65^0 F[2]

4. Note: The weight factor corrects for the higher fuel requirements (due to increased ventilation) of organic poultry relative to conventional. Also, the declining temperature requirements relative to bird age imply that the thermal output of birds (based on the number of birds) is correct (e.g., many birds at the end of a flock put off significant heat, and the barn doesn't need to be heated to as high a temperature).
5. Calculate the temperature differential based on the *minimum* daily temperature and the indoor temperature (see #3 above).

4.4.2 Ventilation and Heat Loss (sub-module)

1. Estimate average volume throughput of air (cubic feet per minute, CFM) based on bird age where average airflow (CFM) = 530 * flock age (days).[3]
2. Approximate hours of fan run-time per day based on assumption that peak estimated airflow of 25,440 CFM equates to approximately 24 hours of fan run-time. Hours of fan run-time are used to estimate electricity usage.
3. Insert dummy variable to correct for dryer heat produced when manure-to-energy combustion system is installed. If the system is installed, volume of air (CFM) is reduced by 15 percent (testable assumption).
4. Calculate heat loss from ventilation (BTUs/hr) = temperature differential (See temperature differential sub-module) * volume throughput * heat loss constant (1.08).

4.4.3 Total Heat Load and Loss (sub-module)

1. Estimate heat loss from floor = (square footage of floor * temperature differential) / insulation (R-value) of floor.
   a. Default R value of floor = .8
2. Estimate heat loss from ceiling = (square footage of ceiling * temperature differential) / insulation (R-value) of ceiling.
   a. Default R value of ceilings = 2
3. Estimate heat loss from walls = (square footage of walls * temperature differential) / insulation (R-value) of walls.
   a. Default R value of wall = 2
4. Calculate daily heat load (BTUs per day) = sum of items 1-3 above *plus* heat loss from ventilation (see ventilation and heat loss sub-module).

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[2] Relationship between bird age and indoor temperature and ventilation requirements derived from University of Georgia Winter Ventilation and Heating Tool.

[3] Ibid.

4.4.5 Propane Use (sub-module)

1. Daily propane use (BTUs) = daily heat load (See the heat load and loss sub-module) * 2 – efficiency of the existing heating system (e.g., boiler).
    a. Default is 80 percent efficiency boiler, meaning 10 BTU of heat load output requires 12 BTU of propane input.

4.4.6 Manure-to-Energy System Propane Impact (sub-module)

1. Estimate heat output from manure-to-energy system. Heat output = system capacity or size (BTUs/hr) * system efficiency * hours of daily operation (correcting for downtime to fill hopper).
2. Correct for annual maintenance and repair by assuming that every day of the year there is a given probability that the system is unavailable to operate.
    a. Default for a high performing system is a 5 percent probability that the system is down on any given day.
    b. Default for an intermittently operating manure-to-energy system (i.e., similar to the new Farm Pilot Project systems) is a 60-percent probability that the system is down on any given day.
3. Calculate net propane use. Propane use = heat load in poultry barn minus heat output from the manure-to-energy system. Assumes propane is used to make up shortfall in what manure-to-energy system is able to provide on a given day.

4.4.7 Electricity Use (sub-module)

1. Electricity use is estimated under the pre-technology, baseline scenario and the post-technology scenario. Only electricity used to operate the fans for ventilation and the electricity associated with parasitic load from the manure-to-energy technology is accounted for. All other end uses of electricity are assumed to remain unchanged with the introduction of a manure-to-energy system.
2. Electricity use from fans (kWh) = the number of fans * the wattage of each fan * hours of operation/ day (See # 2 under ventilation and heat loss).
    a. Default assumption is 8 fans at 150 Watts each.
3. Electricity use from parasitic load (kWh) is first derived by estimating hours of operating run time per day = heat output on a given day (see Manure-to-Energy System Propane Impact sub-module) / (system capacity * efficiency).
4. Total daily parasitic load = hours of run time * power load (Watts) of manure-to-energy system.
    a. Default assumption is 5,000-Watt power load for manure-to-energy system.

4.4.8 Model Calibration with On-Farm Energy Records

The On-Farm Propane and Manure-to-Energy Model assumptions and output can be modified on a case-by-case, farm-by-farm basis by calibrating the model results against actual on-farm energy records. The Rohrer Farm was used as the template for creating the model because it lent itself to calibration. (The Rohrer data template is provided in a spreadsheet in Appendix A.) For example, the Rohrer Farm has weekly propane meter readings and parallel bird production data. The Rohrer Farm also has the unique characteristic of having two nearly identical barns, one with a manure-to-energy system and one without. This makes a side-by-side comparison possible.

The calibration process is one of minimizing the difference between modeled results and actual energy records. The final calibrated model for the Rohrer Farm (Figure 1, Table 4) highlights the difference between the model and actual energy records.

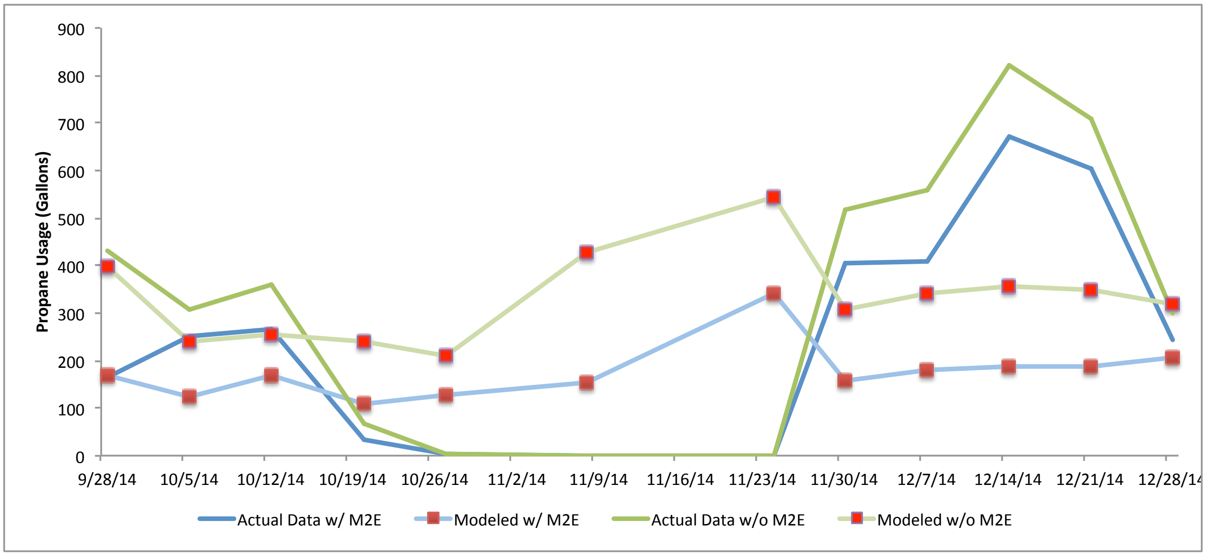

Figure 1. Modeled and actual propane use at Rohrer farm, with and without a manure-to-energy system

Table 4. Gallons of propane used, actual vs. modeled, with and without a manure-to-energy system

	Actual Data With Manure-to-Energy	Modeled With Manure-to-Energy	% Diff. With Manure-to-Energy	Actual Data Without Manure-to-Energy	Modeled Without Manure-to-Energy	% Diff. Without Manure-to-Energy
Flock 1	720.0	884.9	22.9%	1,173.2	1,775.8	51.4%
Flock 2	2,329.7	768.8	-67.0%	2,910.8	2,220.8	-23.7%
Sum	3,049.7	1,653.7	-45.8%	4,084.0	3,996.6	-2.1%

Model calibration works by adjusting the assumptions above so that the modeled energy consumption creates a better fit with actual energy records. For example, by adjusting the boiler efficiency, the R-value of insulation, the indoor temperature profile via the weighted factors for organic and conventional chickens, or any other number other factors, one can align the modeled energy use with actual energy records. In the case of the

Rohrer Farm, there is only a two-flock period of time where the settlement sheet and propane usage records align; therefore, this is the period against which the model is calibrated (Flock 1 between September 18 and November 8, 2014; Flock 2 between November 24 and January 2015). Granted, it is a relatively small sample size and there is a low degree of confidence around the model. The model can be further refined and calibrated with the aid of more high-resolution energy records, more time, and the inclusion of more variables.

4.5 Farm-Specific Assumptions and Results

The inputs, assumptions, and results of the model for all farms are presented below in Tables 5a and 5b. The first half of the table highlights the assumptions/available data that were input to each farm. These inputs drive the output in terms of propane and electricity used under different scenarios. There are three scenarios compared in the analysis below:

1) The "pre-manure-to-energy" scenario reflects the propane and electricity used prior to the installation of the manure-to-energy system. Propane use is expected to be higher than the post-manure-to-energy scenarios, but electricity use is lower in the pre-manure-to-energy scenario because there is no parasitic load from the manure-to-energy system.

- Note: Electricity totals under all scenarios include only electricity used to operate fans and the manure-to-energy system. They exclude other sources of electricity use, including lights, because these are assumed to be unchanged between the pre- and post-technology scenarios.

2) The "post-manure-to-energy intermittent" performance scenario reflects the propane and electricity used after the installation of the manure-to-energy system, but assumes that the manure-to-energy system has a 40 percent chance of being available on any given day due to frequent system repairs and troubleshooting.

- Note: The 40 percent figure comes from the Rohrer Farm during the second flock of manure-to-energy operation (November 24, 2014 through January 8, 2015), when the system ran about 40 percent of the time.

3) The "post-manure-to-energy high performance" scenario reflects the propane and electricity used after the installation of the manure-to-energy system and assumes that the system has a 95 percent chance of being available any given day.

Table 5a. Inputs and assumptions for Rohrer, Curtis, Farmer B, and Weaver Farms

	Global Re-Fuel at the Rohrer Farm (2014 Reference Year)	Blue Flame Boiler at Windview Farm* (2013 Reference Year)	Ecoremedy Gasifier at Farm B (2014 Reference Year)	Global Re-Fuel at the Weaver Farm (FY 15 Reference Year)
Poultry house size (gross square feet)	24,000	30,000	32,400	31,200 * .5 based on half-house = 15,600
Insulation (R-value)	Floor = .8; Ceiling = 2; Walls = 2	Floor = .8; Ceiling = 2; Walls = 2	Floor = 1.2; Ceiling = 4; Walls = 3	Floor = 1.2; Ceiling = 4; Walls = 3
Bird type + temperature weight	Organic (+12° F when flock in production)	Conventional (-8° F when flock in production)	Organic (+12° F when flock in production)	Conventional (-8 ° F when flock in production)
Number of flocks per year, average length	6.5 flocks, average of 47 days to maturity	6.5 flocks, average of 48.5 days to maturity	6-7 flocks per year	7 flocks, average 38 days to maturity
Sum temperature differences (indoor-outdoor), sum of daily min temperature (degrees Fahrenheit)	15,915 (15,190)	9,400 (15,007)	15,915 (15,190)	10,008 (14,082)
Propane boiler efficiency	70%	70%	88%	88%
Manure-to-energy capacity (BTUs/Hr)	500,000	135,000	132,000	500,000
Manure-to-energy system efficiency	85%	75%	85%	85%
Manure-to-energy power load (Watts)	5,450	1,000	10,000	5,450
Probability manure-to-energy is available on any given day	40% chance (intermittent scenario); 95% chance (high performance scenario)	40% chance (intermittent scenario); 95% chance (high performance scenario)	40% chance (intermittent scenario); 95% chance (high performance scenario)	40% chance (intermittent scenario); 95% chance (high performance scenario)
Number of fans, annual operating hours	8 fans, 3,061 hours	8 fans, 3,531 hours	12 fans, 3,061 hours	12 fans, 2,365 hours
Propane cost ($/Gallon)	1.6	1.2	1.2	1.06
Electricity cost ($/kWh)	0.12	0.104	0.12	0.12

*Note: There is no evidence to suggest that Windview Farm experienced technical problems that would result in intermittent performance.

Table 5b. Modeled energy usage and cost results for Rohrer, Curtis, Farmer B, and Weaver Farms

	Global Re-Fuel at the Rohrer Farm (2014 Reference Year)	Blue Flame Boiler at Windview Farm* (2013 Reference Year)	Ecoremedy Gasifier at Farm B (2014 Reference Year)	Global Re-Fuel at the Weaver Farm (FY 15 Reference Year)
Results – Propane Only				
Pre-manure-to-energy propane usage (gallons/year) @ cost ($)	12,942.6 @ $20,449.3	9,202.5 @ $11,227.1	9366.1 @ $11,239.4	3137.5 @ $3,521.9
Post-manure-to-energy propane usage (gallons/year) @ cost ($) Intermittent scenario	6,023.1 @ $9,516.5	4,904.2 @ $5,983.1	5,344.3 @ $6,413.2	1,860.7 @ $1,975.4
Post-manure-to-energy propane usage (gallons/year) @ cost ($) High performance scenario	474.9 @ $750.4	2,485.1 @ $2,982.1	1,140.2 @ $1,368.2	100.5 @ $106.7
Annual propane savings ($) % difference – intermittent scenario relative to pre-manure-to-energy	-$10,932.5 53% cost reduction	-$8,245.0 73% cost reduction	$4,826.2 43% cost reduction	$1,546.5 43% cost reduction
Results – Electricity Only				
Pre-manure-to-energy electricity usage (kWh/year) @ cost ($)	3,672 @ $440.7	4,237.5 @ $440.7	5,508.4 @ $661	4,258.3 @ $511.0
Post-manure-to-energy electricity usage (kWh/year) @ cost ($) Intermittent scenario	5,581 @ 669.7	6,140.2 @ $638.6	45,089.5 @ $5,410.7	3,696.3 @ $443.6
Post-manure-to-energy electricity usage (kWh/year) @ cost ($) High performance scenario	14,448 @ 1,733.8	7,584.8 @ $788.8	61,305.6 @ $7,356.7	4,140.6 @ $496.9
Annual electricity increase ($) % difference – intermittent scenario relative to pre-manure-to-energy	+ $229 52% cost increase	+$198 45% cost increase	+$4,749.7 700% cost increase	-$14.1 3% cost reduction
Results – All Energy (Propane + Electricity)				
Pre-manure-to-energy total energy cost ($)	$20,890.0	$11,667.8	$11,900.40	$4,032.9
Post-manure-to-energy total energy cost ($) Intermittent scenario	$10,186.2	$6,621.7	$11,823.90	$2,418.9
Post-manure-to-energy total energy cost ($) High performance scenario	$2,484.2	$3,770.9	$8,724.90	$603.5
Annual energy savings ($) % difference – intermittent scenario relative to pre-manure-to-energy	-$10,703.8 52% cost reduction	-$5,046.1 43% cost reduction	$76.50 <1% cost reduction	$1,614.0 40% cost reduction

*Note: There is no evidence to suggest that Windview Farm experienced technical problems that would result in intermittent performance.

4.6 Sensitivity Analysis

The energy modeling results suggest there are important differences across farms in terms of potential for energy and cost savings. What level of energy savings should a farmer expect given the characteristics of his or her farm? What types of farms should policymakers and vendors target as the most likely to find manure-to-energy technology cost effective? Should farm characteristics dictate how manure-to-energy technology is designed or how a particular incentive program is implemented?

To answer these questions, it is important that individual farm characteristics be isolated and examined for their ability to influence energy outcomes. This section seeks to identify those key farm characteristics most likely to indicate significant energy savings as a result of manure-to-energy technology. To be sure, evaluating only energy outcomes is imprudent because manure-to-energy technology can influence a wide range of important outcomes, including bird health, production, manure management costs, and potential new revenue streams (e.g., ash or biochar co-products).

This section relies on sensitivity analysis to quantify and rank different farm characteristics for their ability to influence energy outcomes. Sensitivity analysis adjusts the value of individual variables incrementally while holding all other variables constant. The analysis focuses on the Rohrer Farm because it provided the most detailed data and yielded what we believe to be the most accurate model of energy use and costs relative to actual data.

4.6.1 Insulation

- *Findings*: A 25 percent increase in the R-value of poultry house insulation results in 10,518 gallons of propane saved per year under the post-manure-to-energy high performance scenario. The default R-values result in 12,468 gallons of propane saved per year under the post-manure-to-energy high performance scenario. **The 25 percent increase in R-value results in an 18.5 percent decrease in the amount of propane saved from the manure-to-energy facility**.
- *Discussion*: Farmers starting with a better insulated poultry house, with all other factors being constant, will have save less propane by switching to manure-to-energy. As a rule of thumb in nearly all sectors of the economy, energy efficiency is more cost effective than switching to renewable sources of energy. Energy efficiency investments targeting fans, lighting, and insulation, provided they don't impact bird health or performance, should be prioritized before manure-to-energy investments. Farmers and policymakers should be cautious of inflated propane saving projections simply because starting conditions are a poorly insulated poultry house.

4.6.2 Propane Efficiency from Existing Heating System

- *Findings*: A 25 percent increase in the baseline conditions of the boiler efficiency (87.5%) results in 10,706 gallons of propane saved per year under the post-manure-to-energy high performance scenario. The default boiler efficiency (70%) results in 12,468 gallons of propane saved per year under the post-manure-to-energy high performance scenario. **The 25 percent increase in boiler efficiency results in a 16.5 percent decrease in the amount of propane saved from the manure-to-energy system**.
- *Discussion*: Starting conditions are critical to understanding the potential for energy savings associated with manure-to-energy technology. The efficiency of a farm's existing heating system is no exception. Farms with older, inefficient heating systems (e.g., boilers, furnaces) appear to have more to gain from installing a manure-to-energy heating system relative to a farm with a newer, high-efficiency heating system. For farms that can rely entirely on manure-to-energy systems for their heating needs, the efficiency of the existing system becomes less important because of the complete fuel switch.

  However, for farms that will require supplemental heat from propane, it is important to understand the alternative investment of purchasing a new high-efficiency boiler. Either way, by assuming existing propane heating systems will be properly maintained or replaced regularly to ensure optimal efficiency, energy savings over the life of a project will be more conservative.

4.6.3 Bird Type, Temperature, and Heat Demand

- *Findings*[4]: By switching the temperature weight on the Mark Rohrer Farm from +12^0 F, representing an organic bird environment, to -8^0 F, which represents a conventional bird environment, there is a drastic change in heat demand and energy use. The organic bird temperature setting results in 12,468 gallons of propane saved per year under the post-manure-to-energy high performance scenario. In contrast, the conventional bird temperature setting results in 7,046 gallons of propane saved per year under the post-manure-to-energy high performance scenario. **The switch from organic to conventional birds results in a 77 percent decrease in the amount of propane saved from the manure-to-energy system**.
- *Discussion*: While there is significant uncertainty around the temperature weight given to organic and conventional birds (a topic that should be further tested in future studies), the results yield an anticipated outcome. All

[4] During the model calibration process, a weight was placed on the indoor temperature requirements whereby organic birds required +12^0 F of heat. In contrast, conventional birds required -8^0 F of indoor heat. This temperature setting reflects the fact that organic birds are kept in warmer environments (because it is less expensive than feeding) and are less densely housed. The weights were calibrated to align the Rohrer Farm and Windview Farm, respectively, and actual energy usage data.

else being equal, organic poultry operations consume more propane than conventional poultry operations because of the premium cost on organic feed and the fact that food and heat are close substitutes. A related finding is that colder climates require more heating, and it would stand to reason that poultry operations in these environments have more to gain in energy savings from manure-to-energy heating systems than peer farms in warmer climates.

4.6.4 Manure-to-Energy System Capacity

- *Findings*: A 75 percent decrease in the capacity of the manure-to-energy system (125,000 BTUs per hour) (BTUs/hr) results in 10,596 gallons of propane saved per year under the post-manure-to-energy high performance scenario. The default capacity of the manure-to-energy system (500,000 BTUs/hr) results in 12,468 gallons of propane saved per year under the post-manure-to-energy high performance scenario. **The 75 percent decrease in manure-to-energy capacity yields an 18 percent decrease in the amount of propane saved from the manure-to-energy system**.
- *Discussion*: The manure-to-energy system at the Mark Rohrer Farm was sized for two poultry houses and rated for 500,000 BTUs/hr. Mike Czarick, University of Georgia's poultry ventilation expert, describes the importance of ventilation in poultry houses, which is completely different than commercial building heating models.

  For the purposes of the model, the maximum heating demand over the entire year is 5.188 million BTUs per day or about 216,208 BTUs per hour on average. The Global Re-Fuel system at the Mark Rohrer Farm is 500,000 BTUs/hr, which is acknowledged in the model. This system serves two poultry houses totaling 48,000 gross square feet of space; however, the model is designed to recognize heat demand from one house. If the only space to be heated were the size of one poultry house, 250,000 BTUs/hr of capacity would suffice, factoring in ventilation and heat loss. Therefore, it is likely one needs 500,000 BTUs/hr of capacity to heat both houses.

4.6.5 Other Factors Warranting Further Exploration

- *Parasitic load from the manure-to-energy system:* In a high-performing system, the parasitic load of manure-to-energy systems should be closely correlated to the heat output of the system. On the farms where the technology is still being vetted, the heat output varied more than would be expected by the parasitic load as a result of litter moisture, technology efficiency, heat distribution system, and other factors. For example, a wetter litter results in reduced heat output. For some farms, the parasitic load was so significant that the electricity costs nullified any propane savings. Parasitic load associated with manure-to-energy systems is critical.

- *Electricity generation from manure-to-energy systems and/or other on-site systems*: Connected to the discussion on parasitic load, it is important to consider whether the manure-to-energy system generates electricity or, as in the case of Farm B and the Mark Rohrer Farm , there is on-site capacity for renewable electricity. If a farmer has access on-site renewable electricity and little or no cost, the impact of parasitic load electricity costs is diminished. Farms with on-site capacity to generate electricity will not experience the same changes in electricity costs as their peer farms without on-site generation capacity.

7. Summary

The EFC, as part of a coalition investigating the use of innovative technologies that produce energy from the conversion of poultry litter, prepared a cost balance summary and financial assessment. The purpose of the Farm Manure-to-Energy Initiative was to evaluate the effectiveness and performance of thermal technologies that use excess poultry litter (comprised of manure, bedding, and feathers) to produce electricity or heat for poultry housing on farms located within high-density animal production areas of the Chesapeake Bay watershed. The evaluation included technical and environmental performance of the systems, their potential for future use, and market opportunities (current and future) for both the energy generated and the nutrient-rich ash and biochar co-products. The experiences of these farms show that implementing these technologies is still a challenge. Learning curves in design, installation, and operation are often substantial, pointing to the importance of services provided by the public sector in the wider adoption of this technology.

Additionally, the unique circumstances of each of these farms raise questions about the ease and potential for using their varied experiences to construct meaningful cost ranges (capital and operational) that indicate financial impacts of the technology on a farm's bottom line. At the same time, these experiences illustrate the willingness of farmers to test new technologies with the potential to generate positive environmental and economic impacts.

It is important to note that even when technical issues resulted in failure of the thermal technologies in delivering heat or electricity throughout an entire flock cycle, there were periods of successful energy production that reduced the use of propane for heating the poultry houses. While the data did not quantify the generated heat in a way that statistically correlates the technology with reduced propane use, farmers repeatedly observed and reported the trend toward reduced propane use while the systems were running. This saved energy and money for the growers and reduced their carbon footprint.

However, based on the ROI for some technologies, energy production alone will likely be insufficient to justify widespread adoption of manure-to-energy technologies from a financial standpoint. It is more likely that a combination of factors, including reduced energy costs, reduced need for nutrient pollution controls, and the added income from concentrated, lightweight ash co-product (once markets are established) will together move these technologies toward commercialization.

7.1 Return on Investment

Below are results of a return-on-investment (ROI) analysis that focused purely on infrastructure, capital costs, and energy savings.

Table 6. Return on Investment of Capital Costs by Energy Savings including comparison to present value (PV).

	Blue Flame Boiler at Windview Farm	Ecoremedy Gasfier at Farm B	Global Re-Fuel at the Rohrer Farm	Global Re-Fuel at the Weaver Farm
Cost				
Infrastructure Costs	$157,900	$957,987	$303,010	$297,647
Savings				
Electricity	-$198	-$4,749	-$229	$14
Gas	$8,245	$4,826	$10,932	$1,546
Annual Energy	$8,047	$77	$10,703	$1,560
PV (3%, 15 years)	$77,481	$741	$103,054	$15,020
PV (3%, 10 years)	$59,878	$573	$79,641	$11,608
Return on Investment				
15 years	0.49	0.00	0.34	0.05
10 years	0.38	0.00	0.26	0.04

Note: The reported capital costs in the table above may be higher than actual costs; however, no ROI shift would be anticipated unless there was a corresponding change in the energy savings.

The table above provides one way of measuring the ROI of the manure-to-energy technology. The ROI is the ratio of energy savings to capital investment and helps describe the extent to which the energy savings can offset the equipment costs over the operating life span of the technology. In the table above, the capital investment is not estimated to account for all costs of design and installation. It uses only infrastructure costs and excludes the cost of labor provided by the farmer and technical service providers. The ratio of labor costs to infrastructure costs ranged across the farms. It also assumes that the infrastructure costs were not financed but occurred as an up-front, lump-sum cost.

The return from this technology is based on the energy savings. The energy savings is the annual net of the change in electricity and gas. As demonstrated in this project, the manure-to-energy technology often significantly reduces gas costs, but tends to slightly increase the electricity costs. The savings are calculated as a net present value (NPV), which is the discounted stream of energy expenditure change aggregated over the operating life span of the technology. For illustrative purposes, the analysis conservatively assumes that the technology will operate for 10 or 15 years and uses a 3 percent discount rate. (As the discount rate rises, the NPV will fall.)

The table reports ROI over 10-year and 15-year time periods. Comparison of the ROI for 10 years versus 15 years illustrates how lengthening the operating life of the technology improves the ROI. Two of the farms have no ROI based on energy savings. However, the ROIs for Windview Farm and the Mark Rohrer Farm suggest that each dollar spent on the infrastructure generates between $0.34 and $0.49 in savings for a 15-year life of technology. With this basis for the ROI, it will improve as energy (gas) costs increase.

Another way to view the ROI is that the operational life of the technology would have to more than double in order for the energy savings alone to pay off the hard infrastructure capital costs. The results demonstrate why it is so critical that future analyses consider the multiplicity of benefits to gain a broader picture. The EFC recommends that, in the future, ROI analyses focus on flock health, whole-farm operations, and the social and environmental benefits gained from implementing manure-to-energy technology. For this reason, it is important not to focus on the value of co-products (ash and biochar) alone, and instead look at what the manure-to-energy technology does for farm operations and the greater community (which affects the role of public cost-share dollars).

It is important to note that these ROI calculations were based on short durations of the technology performing at four of the five the host farms. The assessment is based on the intermittent scenario of propane and electricity usage when the manure-to-energy technology is delivering heat 40 percent of the time on any given day. Obviously, under other scenarios where the technology is delivering heat for longer durations, the ROI will be better. Given technology performance of 40 percent of the time, Windview Farm and the Mark Rohrer Farm offer some return on the dollar invested. With the newly installed Blue Flame Boiler on Windview Farm, it is reasonable to assume that the ROI will be even more favorable in the upcoming cold months, based on the increased size (an improved match to litter generated) and improved heat delivery system.

This assessment is based on capital investment only and did not include integrator gas or electricity allowances, which are a significant source of income. For example, between 2012 and 2014, Windview Farm received a propane stipend from the integrator totaling over $117,000, far below actual propane bills. The income earned for propane and electricity will greatly impact the ROI. This calculation does not include farmer time, which can also influence the ROI. Farmer time varies for the intensive effort during the initial year and is presumed to level off after the learning curve. In summary, the ROI would change as one adds in more costs (debt if financed, labor, permitting, maintenance, and parts) and benefits (co-product value, deferred manure management costs, etc.).

7.2 Other Next Steps for Consideration

A reasonable next step is to create a tool (based on a model) that a farmer can use to plug in his or her farm data and determined if a specific manure-to-energy technology is feasible for their farm operation. This tool could analyze the amount of litter generated, insulation of poultry houses, energy bills, and policy drivers based on locations (such as net metering regulations, air quality permits, etc.) and discern anticipated farmer investments (in cost and time) and cost-share options for implementing the technology. The model could be created so that it could estimate the number of days it would need to run during cold weather for the farmer to break even, which technology vendors provide suitable systems, and other ROI influences such as market values for co-products (or if associations are available to help market the co-products).

In general, the technology appears promising and is expected to improve over time. The ROI highlights the importance of the role of public benefits. Other factors that need to be looked at more closely include: farmer time with consistent data to track and report time; quantification and influence of parasitic energy loads to run the systems; energy allowances form integrators (gas and electricity stipends as incomes and the likelihood of that continuing in the future); net metering and other offsets if electricity is generated; greenhouse gas credits such as those in the agricultural European market; and pay for performance income through which farmers are paid in accordance with science-based outcomes if that becomes a factor in the future.

Future financial assessments should also include the potential value of the ash and biochar co-products. Mark S. Reiter, Ph.D., a crop and fertility specialist with the Eastern Shore Agricultural Research and Extension Center of Virginia Tech, evaluated poultry litter and poultry litter ash in terms of market prices (see Appendix F of the final report). Based on a series of field trials, his research suggests that poultry ash may have some promise as a fertilizer even when taking into account variability in fertilizer prices and nutrient values over time. His research identified a wide range in the theoretical value of poultry fly ash ($299 to $463 per ton) based on 5-year average nitrogen, phosphorus, and potash commercial fertilizer prices. As a point of comparison, poultry litter is being given away or sold for up to $20 per ton (off the farm). In the event future market assessments indicate a lack of targeted users, the full disposal costs, including transporting and tipping fees of a landfill or monofill, should be included under the $0 per ton value scenario.

It is important to note that an extensive amount of market development and infrastructure is needed to support the emergence of poultry litter ash as a revenue-generating co-product for farmers. For example, it would be useful to explore the target amount of ash that could be produced with enough regularity to support a large, cost-effective market. Also, the basis for the nutrient value might include additional field trials and laboratory analysis on a larger composition of ash samples from multiple poultry litter farms, with ash produced under consistent litter combustion rates. Future market analysis needs to consider the potential end-market value, as well as marketing, packaging, and transportation costs to determine if sale of the ash has the potential to generate revenue compared to sale of untreated poultry litter.

Other factors for future consideration are as follows:

- Future modeling of financial performance of the manure-to-energy technology should account for loss of revenue from manure that was used as fuel instead of sold off-farm.
- Future implementation of manure-to-energy technology needs to consider whether or not integrators may lower the gas allowance and thereby null the propane savings.
- Decommissioning costs are an important factor that should be included in a full life cycle analysis of costs. Only the Mike Weaver Farm offered decommissioning data, based on a contractual agreement.

7.3 Energy Assessment Summary

Propane and electricity usage (pre- and post-technology), flock cycles, bird health, bird production, system run-time, temperature, and humidity are the most important metrics in terms of quantifying and understanding changes in energy use and costs. Ideally, high-resolution records of propane and electricity usage would be available for an extended period of time, both before and after the installation of a manure-to-energy system. This would allow for a more accurate assessment of changes in energy use and costs and, in turn, a more accurate financial assessment.

There is some empirical evidence that manure-to-energy systems displace propane costs. Again, Windview Farm serves as a good example, as it has one of the few systems that ran consistently for more than two years.

Due to data gaps in propane offsets from other farms, a model was developed using Rohrer farm data. The model offers ways to overcome the data gaps in energy records to estimate the impact of manure-to-energy technology on energy use and costs. The rudimentary model was developed to provide a range of typical working assumptions using the Rohrer farm as a template. The model contains sub-modules and is detailed in Appendix A. It is important to note that the modeling exercise presented in this energy assessment is more detailed than commonly performed with sparse data; however, it demonstrates the level of assessment and predictions possible, given more comprehensive database for consideration in future assessments.

The purpose of the model is to create scenarios based on pre- and post-technology efficiency using variable run-times (40 and 95 percent run-times) to predict estimated energy savings.

Model calibration works by adjusting the assumptions above so that the modeled energy consumption creates a better fit with actual energy records. For example, by adjusting the boiler efficiency, the R-value of insulation, the indoor temperature profile via the weighted factors for organic and conventional chickens, or any other number other factors, one can align the modeled energy use with actual energy records. In the case of the Mark Rohrer Farm, there is only a two-flock period of time where the settlement sheet and propane usage records align; therefore, this is the period against which the model is calibrated (Flock 1 between September 18 and November 8, 2014; Flock 2 between November 24 and January 2015). Granted, it is a relatively small sample size and there is a low degree of confidence around the model. The model can be further refined and calibrated with the aid of more high-resolution energy records, more time, and the inclusion of more variables.

7.4 Farm-Specific Assumptions and Results

Table 4 below displays propane use with and without the technology for actual and theoretical farms.

Table 4. Gallons of propane used, actual vs. modeled, with and without a Global Re-Fuel manure-to-energy system at actual and theoretical farms

	Actual Data with Manure-to-Energy	Modeled with Manure-to-Energy	% Diff. with Manure-to-Energy	Actual Data without Manure-to-Energy	Modeled without Manure-to-Energy	% Diff. without Manure-to-Energy
Flock 1	720.0	884.9	22.9%	1,173.2	1,775.8	51.4%
Flock 2	2,329.7	768.8	-67.0%	2,910.8	2,220.8	-23.7%
Sum	3,049.7	1,653.7	-45.8%	4,084.0	3,996.6	-2.1%

The model calibration adjusts the assumptions such that the modeled energy consumption creates a better fit with actual energy records. For example, by adjusting the boiler efficiency, the R-value of insulation, the indoor temperature profile via the weighted factors for organic and conventional chickens, or any other number other factors, one can align the modeled energy use with actual energy records. Given the small sample size, there is a low degree of confidence around the model; however, it is included as a demonstration of the potential for future with the aid of more high-resolution energy records, more time, and the inclusion of more variables.

8. Appendix A: Energy Models from the Mark Rohrer Farm

Table 8.1

Rohrer Farm: Cost Analysis per House for 2014			
		Run 40% of the time when heating is necessary	
	Base Scenario (See model)	Intermittent Run Scenario	High Performance Scenario
Gallons of Propane	12,942.6	6,023.1	475.0
Cost of Propane ($/gallon)	1.6	1.6	1.6
Sub-cost Propane Cost ($/year)	20,449.3	9,516.5	750.4
Electricity Used in kWh (Fans only)	3672.258296	3,119.4	3,119.4
Cost of Electricity ($/kWh)	0.1	0.1	0.1
Electricity Used in Thermal System (kWh) - Parasitic Load	0.0	2,461.5	11,328.7
Sub-Cost Electricity ($/year)	440.7	669.7	1,733.8
Total Energy Cost	20,890.0	10,186.2	2,484.2
Note about Propane costs: www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=W_EPLLPA_PRS_SPA_DPG&f=W			

Table 8.2

Two-Flock Sample, Side-by-Side Comparison		
	Mark Rohrer Farm	Todd Rohrer Farm
Cost of Propane for Heating	$5,901.37	$8,009.76
Cost of Electricity Used for WC System	$404.69	$0.00
Cost of Propane Used for WC System	$136.02	$0.00
Cost of Labor for WC System	$517.00	$0.00
Total Operating Cost	$6,959.09	$8,009.76

Table 8.3

Rohrer Farm: Farmer Labor to Operate/Maintain System				
Date	Bird Age (days)	% of Time House is Open	Estimated System Run-time (hrs)	Farmer Time to Run/Maintain (hrs)
Flock 1	Pre-heat	50	0	0
9/18/2014	Birds placed	50	0	
9/28/2014	10	100	144	11.5
10/5/2014	17	100	12	8
10/12/2014	24	100	0	0
10/20/2014	32	100	0	0
10/27/2014	39	100	0	0
11/8/2014	50	100	0	0
Flock Total	**50**		**156**	**19.5**
Flock 2	Pre-heat	50	0	0
11/24/2014	Birds placed	50	0	0
11/30/2014	6	50	155	5.5
12/7/2014	13	50	120	7.5
12/14/2014	20	75	96	11.5
12/21/2014	27	100	48	3
12/28/2014	34	100	0	0
1/4/2015	41	100	0	0
1/9/2015	Birds out	100		
Flock Total	**41**		**419**	**27.5**

Table 8.4

Sensitivity Results			
R-Value	Pre-Technology Propane	Post-Technology Propane High Performance	Savings (Gallons of Propane)
Default R Values (.8 Floor, 2 Ceiling, 2 Walls)	12942.61918	474.9624334	12467.6567
25% Increase in R-value (1 Floor, 2.5 Ceiling, 2.5 Walls)	10783.63575	265.2731297	10518.3626
Percent Change	-20.0%	-79.0%	-18.5%
Boiler Efficiency	Pre-Technology Propane	Post-Technology Propane High Performance	Savings (Gallons of Propane)
Default Boiler Efficiency (70% Efficiency)	12942.61918	474.9624334	12467.6567
25% Increase in Boiler Efficiency (87.5% Efficiency)	11200.34352	493.9694646	10706.3741
Percent Change	-15.6%	3.8%	-16.5%
Bird-Type and Heating Demand	Pre-Technology Propane	Post-Technology Propane High Performance	Savings (Gallons of Propane)
Default Heat Differential (15,915 Degrees F)	12942.61918	474.9624334	12467.6567
Decrease Heat Demand per Conventional Birds (8,615^{o} F)	7224.784594	177.9258165	7046.85878
Percent Change	-79.1%	-166.9%	-76.9%
Ventilation Rate	Pre-Technology Propane	Post-Technology Propane High Performance	Savings (Gallons of Propane)
Volume Throughput Rate (530 CFM * Age of Birds)	12942.61918	474.9624334	12467.6567
Reduced Volume Throughput Rate (397.5 CFM * Age of Birds)	12405.69367	515.0863815	11890.6073
Percent Change	-4.3%	7.8%	-4.9%
System Size	Pre-Technology Propane	Post-Technology Propane High Performance	Savings (Gallons of Propane)
Default Capacity (500,000 BTU/Hr)	12942.61918	474.9624334	12467.6567
75 % Decrease in Capacity (125,000 BTU/Hr)	12942.61918	2346.179622	10596.4396
Percent Change	0.0%	79.8%	-17.7%
Parasitic Load	Pre-Technology Electricity Usage	Post-Technology Electricity Usage High Performance	Increase (kWh of Electricity)
Default Parasitic Load (5,450 Watts)	0	10570.45164	10570.4516
25 % Decrease in Parasitic Load (4,087.5 Watts)	0	8042.78243	8042.78243
Percent Change	N/A	-31.43%	-31.43%