GOT MANURE?
ENHANCING ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY CONFERENCE

MARCH 28-29, 2012
HOLIDAY INN
LIVERPOOL, NEW YORK

CO-HOSTED BY:
AgSTAR
PRO-DAIRY PROGRAM AT CORNELL UNIVERSITY
NEW YORK STATE ENERGY RESEARCH AND DEVELOPMENT AUTHORITY
U.S. DEPARTMENT OF AGRICULTURE - NATURAL RESOURCES CONSERVATION SERVICE
TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agenda</td>
<td>1</td>
</tr>
<tr>
<td>Core Conference Committee Members</td>
<td>5</td>
</tr>
<tr>
<td>Conference Sponsors</td>
<td>5</td>
</tr>
<tr>
<td>Speaker Biographies</td>
<td>6</td>
</tr>
<tr>
<td>Danish Experience with AD Plants and Future Direction</td>
<td>19</td>
</tr>
<tr>
<td>K. Hjort-Gregersen</td>
<td></td>
</tr>
<tr>
<td>Standard for Manure Management Systems</td>
<td>28</td>
</tr>
<tr>
<td>P. Wright</td>
<td></td>
</tr>
<tr>
<td>The Impact of Dairy Housing and Manure Management on Anaerobic Digestion</td>
<td>34</td>
</tr>
<tr>
<td>D. Kirk and L. Faivor</td>
<td></td>
</tr>
<tr>
<td>Manure Collections and Transfer Systems in Livestock Operations with Digesters</td>
<td>43</td>
</tr>
<tr>
<td>A.C. Lenkaitis</td>
<td></td>
</tr>
<tr>
<td>Sand Laden Manure Storage and Transfer</td>
<td>51</td>
</tr>
<tr>
<td>J. Skinner</td>
<td></td>
</tr>
<tr>
<td>Sand-Manure Separation for Anaerobic Digestion Pretreatment</td>
<td>62</td>
</tr>
<tr>
<td>A.W. Wedel</td>
<td></td>
</tr>
<tr>
<td>Source Separated Food Waste Flow to Farm Digesters</td>
<td>74</td>
</tr>
<tr>
<td>N. Goldstein</td>
<td></td>
</tr>
<tr>
<td>Anaerobic Digestion of Biobased Plastics</td>
<td>81</td>
</tr>
<tr>
<td>T. Zauche and D. Hitchins</td>
<td></td>
</tr>
<tr>
<td>Dairy Cattle Mortality Management via Anaerobic Digestion</td>
<td>86</td>
</tr>
<tr>
<td>J.H. Martin, Jr., J. Coombe, and K. Henn</td>
<td></td>
</tr>
<tr>
<td>Experience with Three On-Farm Digester Systems Using Additional Off Farm Organic Substrates</td>
<td>93</td>
</tr>
<tr>
<td>S. Weeks</td>
<td></td>
</tr>
<tr>
<td>Feasibility Studies: Why and What Should They Entail?</td>
<td>99</td>
</tr>
<tr>
<td>P. Ries</td>
<td></td>
</tr>
<tr>
<td>Economic Analysis for Digester Development</td>
<td>112</td>
</tr>
<tr>
<td>R. Joblin</td>
<td></td>
</tr>
<tr>
<td>Development and Application of an Economic Anaerobic Digester Optimization (ADOPT) Model</td>
<td>118</td>
</tr>
<tr>
<td>J.S. Neibergs, J. Harrison, E. Whitefield, and M. DeHart</td>
<td></td>
</tr>
<tr>
<td>Title</td>
<td>Authors</td>
</tr>
<tr>
<td>----------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Biogas Composition and Cleanup Options</td>
<td>N.S. McDonald</td>
</tr>
<tr>
<td>Biomethane as an Option for On-Farm Energy Production (Powerpoint presentation)</td>
<td>N.S. McDonald</td>
</tr>
<tr>
<td>Digester Gas Combustion</td>
<td>J. Hower and D.S. Chianese</td>
</tr>
<tr>
<td>Overview of Nitrogen Removal Technologies and Application/Use of Associated End Products</td>
<td>M. Orentlicher</td>
</tr>
<tr>
<td>Commercial Demonstration of Nutrient Recovery of Ammonium Sulfate and Phosphorus Rich Fines From AD Effluent</td>
<td>S. Dvorak and C. Frear</td>
</tr>
<tr>
<td>Small-Scale Anaerobic Digestion in the United States: Design Options and Financial Viability</td>
<td>S. Lansing and K. Klavon</td>
</tr>
<tr>
<td>Estimating Farm Size Required to Economically Justify Anaerobic Digestion on Small Dairy Farms</td>
<td>T. Shelford</td>
</tr>
<tr>
<td>Reducing Risk of Entry Into Confined Space Manure Storages</td>
<td>D.J. Murphy, H.B. Manbeck, J.S. Steel</td>
</tr>
<tr>
<td>Monitoring of Anaerobic Digestion Process to Optimize Performance and Prevent System Failure</td>
<td>R.A. Labatut and C.A. Gooch</td>
</tr>
<tr>
<td>On-Farm Anaerobic Digestion: Messages and Methods to Educate a Lay Audience</td>
<td>J. Pronto and B. Meyer</td>
</tr>
<tr>
<td>The Business Case for Carbon Management: New Opportunities for Offset Revenues From Manure Digesters</td>
<td>S. Hernandez</td>
</tr>
<tr>
<td>How Carbon Dioxide Offsets and Other Policies Impact the Financial Feasibility of Anaerobic Digestion Systems on U.S. Dairy Farms</td>
<td>B.A. Gloy</td>
</tr>
<tr>
<td>APPENDIX: POSTER PRESENTATION PAPERS</td>
<td></td>
</tr>
<tr>
<td>Financial Feasibility of Biodigester Development in Washington State</td>
<td>N. Lake-Brown</td>
</tr>
<tr>
<td>On-Farm Co-Digestion of Food Waste with Dairy Manure</td>
<td>M.S. Lisboa, S. Lansing and C. Jackson</td>
</tr>
<tr>
<td>Additional Proceedings Order Form</td>
<td></td>
</tr>
</tbody>
</table>


Got Manure? Enhancing Environmental and Economic Sustainability Conference Agenda

Tuesday, March 27, 2012 (optional activities)

Anaerobic Digester Site Tours
7:30 AM  Full Day Tour
- Cayuga County Soil and Water Conservation District Community Digester
- Patterson Dairy Farm
- Synergy Farm

12:00 PM  Half Day Tour
- Cayuga County Soil and Water Conservation District Community Digester
- Patterson Dairy Farm

5:30 PM  Tours Return to Holiday Inn

Climate Action Reserve Workshop
2:00 PM  Carbon Management Workshop: the Business Case for Manure Digesters

Wednesday, March 28, 2012

9:00 AM  Welcome
- George Allen, Northeast Dairy Producers Association & Owner of Allen Waite Farms, Inc.

9:15 AM  Opening Remarks
- Pat Hooker, NYS Senior Director of Industry Development; Agribusiness

9:35 AM  Cows, Manure, People, Money, and the Environment
Moderator: Joe Kramer, Energy Center of Wisconsin
- Anaerobic Digestion: The Cornerstone of an Integrated Dairy Manure Handling and Treatment System
  Curt Gooch, Cornell University PRO-DAIRY
- Anaerobic Digestion: Reintegrating Dairy Farms and Communities
  Dean Doornink, Jon-De Farm
- Danish Experience with AD Plants and Future Direction
  Kurt Hjort-Gregersen, AgroTech
- Questions

10:50 AM  Break and Poster Session  Sponsored by:  

Mclanahan
11:20 AM  **Integrated Manure Treatment System Operator Panel**  
*Moderator: Curt Gooch, Cornell PRO-DAIRY*  
- Dean Doornink, Jon-De Farm (WI)  
- John Jacobs, Green Valley Dairy (WI)  
- Steve Reinford, Reinford Farms Inc. (PA)  
- Greg Rejman, Sunny Side Dairy (NY)  
- Bill Rowell, Green Mountain Dairy (VT)  
- and others

12:35 PM  **Lunch**

1:50 PM  **Integrated Manure Management System Planning**  
*Moderator: Peter Wright, NRCS*  
- Update on Natural Resource Conservation Service (NRCS) Standards  
  *Peter Wright, NRCS*  
- The Impact of Dairy Housing and Manure Management on Anaerobic Digestion  
  *Dana Kirk, Michigan State University*  
- Manure Collection and Transfer Systems in Livestock Operations with Digesters  
  *Andy Lenkaitis, GEA Houle, Inc.*  
- Sand Laden Manure Storage and Transfer  
  *Jessica Skinner, JESS Engineering*  
- Sand-Manure Separation for Anaerobic Digestion Pretreatment  
  *Andrew Wedel, McLanahan Corporation*  
- Questions

3:30 PM  **Break**  
*Sponsored by: [CAT Financial](#)*

4:10 PM  **Co-Digestion: Role and Impacts**  
*Moderator: Bruce Bailey, quasar energy group*  
- Overview of Permitting Requirements for Co-Digestion  
  *Allison Costa, AgSTAR*  
- Source Separated Food Waste Flow to Farm Digesters  
  *Nora Goldstein, BioCycle*  
- Anaerobic Digestion of Biobased Plastics  
  *Tim Zauche, University of Wisconsin - Platteville*  
- Dairy Cattle Mortality Management via Anaerobic Digestion  
  *John H. Martin, Jr., Tetra Tech, Inc.*  
- Experience with Three On-farm Anaerobic Digester Systems Using Additional Off-farm Organic Substrates  
  *Stan Weeks, Stanley A. Weeks, LLC*  
- Questions

5:45 PM  **Reception**
8:00 PM  Discussion of NYS Anaerobic Digestion Challenges and Opportunities (optional)
-  Tom Fiesinger, NYSERDA

Thursday, March 29, 2012

8:30 AM  Economics of Manure Handling/Treatment/Utilization Systems
Moderator: Garth Boyd, Camco
-  Feasibility Studies: Why and What Should They Entail?
  Patrick Ries, Asset Resource Management LLC
-  Economic Analysis for Digester Development
  Bob Joblin, AgPower Group
-  Development and Application of an Economic Anaerobic Digester Optimization (ADOPT) Model
  J. Shannon Neibergs, Washington State University
-  Questions

9:40 AM  Break

10:20 AM  Biogas Utilization
Moderator: Michael Mitariten, Guild Associates, Inc.
-  Biogas Composition and Cleanup Options
  Norma McDonald, Organic Waste Systems, Inc.
-  Digester Gas Combustion
  Joe Hower, Environcorp
-  Questions

11:15 AM  Track 1: Advanced Manure Treatment
Moderator: Jeff Porter, NRCS
-  Overview of Nitrogen Removal Technologies and Application/Use of Associated End Products
  Morton Orentlicher, ThermoEnergy Corp.
-  Commercial Demonstration of Nutrient Recovery of Ammonium Sulfate and Phosphorus Rich Fines from AD Effluent
  Steve Dvorak, DVO Inc. & Craig Frear, Washington State University
-  Questions

11:15 AM  Track 2: Small Scale Anaerobic Digestion
Moderator: Dave Dunn, Central Vermont Public Service
-  Small-Scale Anaerobic Digestion in the United States: Design Options and Financial Viability
  Stephanie Lansing, University of Maryland
-  Estimating Farm Size Required to Economically Justify Anaerobic Digestion on Small Dairy Farms
  Tim Shelford, Cornell University
-  Questions
12:05 PM  Lunch

1:05 PM  Making the News Rather than Being in the News  
Moderator: Grant Grinstead, Northern Biogas LLC  
- Reducing Risk of Entry into Confined Space Manure Storages  
  Dennis Murphy, Pennsylvania State University  
- Monitoring of Anaerobic Digester Process to Optimize Performance and  
  Prevent System Failure  
  Rodrigo Labatut, Cornell University  
- On-Farm Anaerobic Digestion: Messages and Methods to Educate a Lay  
  Audience  
  Jenny Pronto, Cornell University & Beth Meyer, American Dairy  
  Association & Dairy Council, Inc.  
- Questions

2:15 PM  Break

2:55 PM  Impacts of Greenhouse Gas Policy on Anaerobic Digestion  
Moderator: Rick Stowell, University of Nebraska, Lincoln  
- The Business Case for Carbon Management: New Opportunities for  
  Offset Revenues from Manure Digesters  
  Scott Hernandez, Climate Action Reserve  
- How Carbon Dioxide Offsets and Other Policies Impact the Financial  
  Feasibility of Anaerobic Digestion Systems on U.S. Dairy Farms  
  Brent Gloy, Purdue University  
- Questions

3:45 PM  Conference Wrap-Up  
Moderator: Jerry Bingold, Innovation Center for US Dairy  
- Challenges and Opportunities: Advancements towards Widespread  
  Adoption of On-Farm Digestion  
  Mike McCloskey, Fair Oaks Dairy Farms and Innovation Center for U.S.  
  Dairy  
- Discussion and Questions  
- Closing Remarks  
  AgSTAR, Cornell PRO-DAIRY, NRCS, & NYSERDA

4:55 PM  Adjourn
Core Conference Committee Members

Allison Costa  
Program Manager  
AgSTAR  
U.S. Environmental Protection Agency

Tom Fiesinger  
Project Manager  
Environmental Research & Development  
New York State Energy Research and Development Authority

Curt Gooch P.E.  
Senior Extension Associate  
Cornell PRO-DAIRY  
Cornell University

Tim Shelford (Conference Coordinator)  
Post Doctoral Associate  
Cornell PRO-DAIRY  
Cornell University

Peter Wright P.E.  
State Conservation Engineer  
Natural Resources Conservation Service

Conference Sponsors

As of March 1, 2012

Wednesday Morning Break sponsored by:  

Wednesday Afternoon Break sponsored by:  

In addition to our event sponsors, we would like to thank the following general sponsors:
Speaker Biographies

**Dean Doornink, Co-owner**  
Jon-De Farm  
Baldwin, Wisconsin

Dean Doornink is co-owner of Jon-De Farm located in St Croix County of Wisconsin. His partner is son Todd Doornink who is Dairy and Replacement Heifer Manager. The dairy at Jon-De Farm consists of 1700 cows milked in two herringbone parlors and housed in 2 naturally ventilated barns and 2 cross ventilated barns. All barns are bedded with sand and manure is scraped to sand separator. The sand is reused for bedding. The manure from all barns is separated via a screw press separator into solids and liquid portion. The separated solids are stored on NRCS approved stacking pad and land spread when conditions allow. The liquid portion is stored in NRCS approved clay lined lagoons until injected into cropland via a drag hose system.

About 2100 acres of land are cropped to provide the corn silage and haylage for Jon-De Farm. All other feed ingredients are purchased. The manure from the dairy and the 1500 replacement young-stock provides almost all of the crop nutrients to grow these crops. A comprehensive nutrient management plan is followed to grow these crops and manage these facilities.

Dean Doornink obtained a BS in Agricultural Engineering and a BS in Mechanical Engineering from the University of Wisconsin-Madison in 1965. He received his MS & PhD from the University of Illinois in Mechanical Engineering in 1970. He was an Assistant Professor of Mechanical Engineering at South Dakota School of Mines and Technology. He has been operating Jon-De Farm since 1972. During that period Jon-De Farm has grown from a 75 cow dairy housed in a tie stall barn to its present size.

**Stephen Dvorak, President**  
DVO, Inc.  
Chilton, Wisconsin

Stephen Dvorak, P.E., obtained a degree in Industrial/Mechanical Engineering from the University of Wisconsin-Madison. He earned his Professional Engineer designation in 1977.

In 1989, Stephen founded an environmental engineering firm, known today as DVO, Inc. (formerly GHD, Inc.). Since 2001, DVO has designed its market-leading, patented mixed plug-flow digester systems for dairy and poultry farms, beef feedlots, and slaughterhouse waste across the nation, as well as internationally. DVO is the largest on-farm anaerobic digester developer in the United States, with 66 sites currently operating a DVO digester and another 19 sites under construction.
Craig Frear, Assistant Professor
Center for Sustaining Agriculture and Natural Resources
Department of Biological Systems Engineering
Washington State University
Pullman, Washington

Craig is currently an Assistant Research Professor at Washington State University housed both within the Center for Sustaining Agriculture and Natural Resources (CSANR) and the Department of Biological Systems Engineering. Craig’s research focus is on development of anaerobic digestion and nutrient recovery systems associated with the treatment of organic wastes, particularly animal manures and municipal solid wastes. Other research interests involve the development of biological and chemical technologies for production of high value products from organic wastes, including isolation of organic acids, lipids and polyphenolic nutraceuticals. In his role at CSANR, Craig also provides a large fraction of his time towards biofuels and bioenergy extension, working closely with government agencies and industries to help further development of renewable energy projects and implementation of a bio-economy. Prior to attaining this position and his PhD in Engineering Science, Craig was a high school science educator, administrator and coach for over 15 years.

Brent Gloy, Associate Professor
Purdue University
West Lafayette, Indiana

Brent is an associate professor in the Department of Agricultural Economics at Purdue University. He teaches and conducts research and Extension programs in the areas of agricultural finance and agribusiness management. The majority of his research has focused on issues related to the supply and demand for credit. Brent currently serves as the director of the Center for Commercial Agriculture and as the associate director of research for the Center for Food and Agricultural Business. He also teaches an undergraduate course in agricultural and food business strategy.

Prior to arriving at Purdue, Brent was an associate professor in the Department of Applied Economics and Management at Cornell University. He taught undergraduate courses in agribusiness strategy and agricultural finance and a graduate course in agricultural finance. In addition to his traditional classroom teaching, Brent participated in and led classes on a number of international and domestic farm and agribusiness field studies. These included trips to Hungary, Slovakia, Poland, Holland, and Australia. Domestic farm management field study destinations included California, Texas, Florida, and Georgia.

Brent received his master’s degree and doctorate in agricultural economics from Purdue University. In addition to his activities in West Lafayette, he remains involved in the family farm business located in Southwestern Nebraska.
Nora Goldstein is Editor of BioCycle: Composting, Renewable Energy, Sustainability, published by The JG Press, Inc. in Emmaus, PA (www.biocycle.net). BioCycle celebrated its 50th Anniversary in 2009. Nora has authored numerous articles on all facets of composting and anaerobic digestion. She has edited a number of books and other publications, and has served on numerous solid waste and biosolids recycling advisory committees. BioCycle is a Founding Member of the American Biogas Council; Nora serves on the ABC Board. She also services on the Technical Core Committee for the Sustainable Sites Initiative. Additional responsibilities at BioCycle include BioCycle National Surveys, including the State of Garbage in America and the Food Composting Infrastructure in the U.S., and BioCycle’s FindAComposter.com, a free online directory service. Nora has a B.A. in history and political science from Union College in Schenectady, New York.

Curt Gooch, Senior Extension Associate
Cornell PRO-DAIRY
Ithaca, New York

Curt Gooch, P.E. is a Senior Extension Associate in the Department of Biological and Environmental Engineering at Cornell University. Mr. Gooch developed from inception and directs the dairy facilities and waste management component of Cornell’s PRO-DAIRY program, a joint-venture applied research/outreach program by the New York State Department of Agriculture and Markets and Cornell University’s College of Agriculture and Life Sciences.

In this capacity, Gooch conducts applied research with the goal of furthering the understanding of dairy housing and waste management systems and their effects on dairy animals, the environment, farm profitability, and dairy industry sustainability. Results of this work are used to develop and deliver extension/outreach materials to dairy farmers and other stakeholders. He has authored/co-authored over 190 papers, popular press articles, and web site publications since coming to Cornell in 1998. Professionally, Curt enjoys and receives the most satisfaction from working closely with dairy producers and their advisors.

Previously, Curt worked for 9 years as a Project Engineer for the Maryland Agricultural Experiment Station where he was responsible for design and construction management of large animal agricultural research and research support facilities. He has several years of farm experience, including 4 years working on a commercial dairy farm, and previously owning his own truck farming business.
Curt has undergraduate and graduate degrees from the James Clark School of Engineering at the University of Maryland at College Park and has held a professional engineer’s license since 1995. Curt, his wife, and three daughters live in Lansing, New York.

Scott Hernandez, Business Development Manager
Climate Action Reserve
Los Angeles, California

Scott Hernandez, Business Development Manager at the Climate Action Reserve, leads the development and implementation of strategies to promote the Reserve and its protocols to a wide range of audiences, including project developers, regulated businesses and voluntary offset buyers. In particular, Scott focuses on promoting the Livestock Project Protocol to farmers throughout North America. Prior to joining the Reserve, Scott was an Energy and Climate Change Specialist at the Association of California Water Agencies (ACWA), in Sacramento. In addition to tirelessly advocating the California’s state regulatory agencies on behalf of public water agencies, Scott lead initiatives to facilitate the adoption and implementation of onsite renewable energy and water -and-energy efficiency technologies at water agencies throughout California. Prior to ACWA, Scott worked as a market research analyst for a boutique telecommunications consultancy based in Carmel, California, as well as a marketing analyst for a retail solar energy provider in Monterey. Scott has master degrees in International Management (M.B.A.) and International Environmental Policy (M.A.) from the Monterey Institute of International Studies (MIIS), in California, as well as a bachelor’s degree in Spanish and International Business (B.A.) from the University of Tennessee, in Knoxville. Scott lives with his two dogs in Los Angeles, CA.

Kurt Hjort-Gregersen, Senior consultant
Centre for Bio-resources, AgroTech Ltd.
Aarhus, Denmark

Kurt holds more than 20 years’ experience in anaerobic digestion technology development. Affiliated with the Danish Research Institute of Food Economics, University of Copenhagen, his main role from 1987 to 2002 was monitoring and analyzing the economic development and performance of centralized biogas plants. The work was part of the Danish Biogas Development Programs that were accomplished over the period. The purpose of this work was to collect, analyze and communicate the gained experience in order to improve performance of existing and new plants. In recent years he participated in national and European projects on anaerobic digestion, of which some were R&D projects and some were technology promotion activities. In 2010 he was appointed as a senior consultant at AgroTech Ltd. Main line of work in AgroTech is technology development within anaerobic digestion and bioenergy. In addition he is the secretary of Danish Biogas Plant Association. Kurt holds an MSc in agricultural economics.
Joe Hower, Managing Principal and Air Quality Management Practice Leader
ENVIRON
Los Angeles, CA

Joseph Hower is the Managing Principal and Air Quality Management practice leader of ENVIRON’s Southwest operations. He has over 30 years of experience in air quality management, including greenhouse gas (GHG) management, regulatory compliance, permitting, litigation support, expert witness work, risk management and pollution control engineering. Specific projects have ranged from conducting Title V permit evaluations to managing the installation and startup of multimillion-dollar air pollution control systems. Joseph also leads ENVIRON’s work in the area of emissions trading. His service on the South Coast Air Quality Management District (SCAQMD) Advisory Council for nearly five years, and current membership in the SCAQMD’s New Source Review Working Group, provide an excellent understanding of regulatory processes. He uses this information to negotiate complex technical agreements and permits with agencies, assist facilities with compliance programs and provide technical expertise to litigation teams. Joseph teaches air quality permitting and air pollution control courses at the University of California-Los Angeles (UCLA). He also serves on the University of Southern California (USC) Civil and Environmental Engineering program’s Industrial Advisory Council. Joseph is the immediate past chair of the West Coast Section of the Air & Waste Management Association.

Bob Joblin, President
Cenergy USA
Little Rock, Arkansas

Bob Joblin is the President of Cenergy USA, which has investments in AgPower Partners and AgPower Group. Through AgPower Partners, the Big Sky West dairy digester facility was built and has been operating for three years. It is the first successful third-party build-own-operate model, and earlier this month was named recipient of the U.S. Dairy Outstanding Achievement in Energy national award sponsored by the Center for Advanced Energy Studies and the Idaho National Laboratory. Also this month, AgPower Group completed construction of the largest dairy digester facility in the nation at the 15,000-cow Double A dairy. AgPower Group is also the designated developer for the 22-dairy Pecos Valley Biomass Cooperative regional dairy digester.

Bob has been active in commercial development and finance for more than 30 years and has concentrated on energy efficiency and renewable energy projects for the past ten years. He is a graduate of the University of Arkansas at Little Rock and the U.S. Army Combat Engineering Officer Candidate School.
Dana M. Kirk, Manager ADREC  
Michigan State University  
East Lansing, Michigan

Dana Kirk has B.S. degrees in animal science and biosystems engineering, an M.S. in biosystems engineering and a Ph.D. in biosystems engineering, all from Michigan State University (MSU). He has ten years of experience as an environmental engineering working on livestock waste related issues. Consulting projects have ranged from CAFO permitting, environmental compliance and reporting, waste storage facility design, livestock facility design, construction oversight, waste treatment technology evaluation and anaerobic digestion optimization.

Dana is currently employed by MSU as manager of the Anaerobic Digester Research and Education Center (ADREC). The ADREC is collaborative effort between the University and a private foundation to provide a continuum of research, professional development and outreach support for waste-to-energy systems. Mr. Kirk’s research at the ADREC includes bench top, pilot scale and commercial anaerobic digestion systems used to evaluate feedstocks, optimize performance and integrate technologies.

Rodrigo Labatut, Research Associate  
Cornell PRO-DAIRY  
Ithaca, NY

Rodrigo received a B.S. and an Eng. Degree in Aquacultural Engineering from Universidad Católica del Norte, Chile, where his work was primarily focused on wastewater treatment technologies and recirculating aquaculture systems (RAS) using biological filtration and advance oxidation processes (AOP). Rodrigo moved to the U.S. to begin graduate studies in the Department of Biological and Environmental Engineering at Cornell University. Under the guidance of Mike Timmons, he pursued a M.S. which he directed on the study of the hydrodynamics of aquaculture tanks using experimental and computational fluid dynamics (CFD) methods. Motivated by his interest in bioenergy, he helped to write a proposal which provided funding to pursue a Ph.D. in the same department. Under the direction of Norm Scott, Rodrigo’s work was mainly focused on the co-digestion of dairy manure with high-strength substrates; specifically, to develop an understanding of how different chemical components in the influent material affect biodegradability and biogas production under mesophilic and thermophilic conditions. Currently, Rodrigo holds a position as a Research Associate at Cornell University where his work is focused on the monitoring and evaluation of commercial-scale on-farm anaerobic digestion systems in New York State, and the training of anaerobic digester operators in management and process control.
Stephanie Lansing, Assistant Professor  
Dept of Environmental Science & Technology  
University of Maryland  
College Park, Maryland

Dr. Stephanie Lansing has 15 years of research and teaching experience in agricultural and municipal waste treatment, ecological engineering, anaerobic digestion design, and wetland treatment systems. She has a B.S. in environmental science from the University of Oklahoma and an M.S. and Ph.D. in agricultural engineering from the Ohio State University. Dr. Lansing current research projects include small-scale digester design for a variety of applications, including small-scale dairy farmers in temperate regions, co-digesting dairy manure and food wastes and radish cover crops, human wastewater treatment in Haiti, combining microbial fuel cells and anaerobic digestion for human wastewaters, palm-oil wastewater digestion in West Africa, and digestion of algae from algal turf scrubbers. In addition, Dr. Lansing develops dynamic models of waste treatment systems and incorporates life cycle analyses and “emergy” into her research projects. She currently teaches classes at the University of Maryland in Renewable Energy, Ecological Design, and Sustainable Technologies for Developing Countries. She lives in Hyattsville, MD with her husband and two children.

Andy Lenkaitis, E.I.T., Environmental Systems Engineer  
GEA Farm Technologies  
Naperville, Illinois

Environments that maximize both comfort and production for livestock is the ultimate goal Andy Lenkaitis is working towards. Andy works alongside manure equipment dealers and producers to design and manure handling and transfer systems. Additionally, he works with the research and development department at GEA Houle to develop new products and coordinate field test sites.

Andy completed a dual B.S and M.S. degrees in Agricultural Engineering at the University of Illinois. Within the BioEnvironmental Engineering group, his studies and research focused on data collection in the environment around the livestock animal. In 2010, Andy was named one of the “Top New Faces in ASABE”, selected for Class 7 of the Young Dairy Leaders Institute and was chosen for the GEA First Professional Program. Andy was raised on his family’s 40-cow Registered Holstein farm in St. Charles, IL. He now resides close to the home farm with his wife, Sarah.

John H. Martin, Jr., Senior Environmental and Alternative Energy Engineer  
Tetra Tech, Inc.  
Pittsburgh, Pennsylvania

Jack Martin has over 40 years of research and consulting experience specializing in livestock and food processing waste management including utilization of anaerobic
processes for the stabilization with the capture and utilization of the biogas produced. He previously has worked as a Research Associate and Senior Extension Associate at Cornell University, a Research Scientist and Watershed Agricultural Program Coordinator for the New York City Department of Environmental Protection, an Associate Professor at the University of Delaware, and as a consultant.

Jack has authored or co-authored over 70 peer reviewed journal articles and major technical reports. He has a B.S. in Agricultural Sciences from Rutgers University, an M.S. in Agricultural Engineering also from Rutgers University, and a Ph.D. in Agricultural and Biological Engineering from Cornell University. Jack is a member of the American Society of Agricultural and Biological Engineers, the Water Environment Federation, the Soil Science Society of America, and Sigma Xi, the Scientific Research Society. Jack has a wife and two-step daughters and lives in southern Delaware.

Norma McDonald, North American Sales Manager
ORGANIC WASTE SYSTEMS, INC.
Cincinnati, Ohio

Ms. McDonald has over twenty five years of international experience in a variety of positions relating to anaerobic digestion, fermentation and biochemicals. Her responsibilities have included: Sales and marketing of laboratory services for compostability and biodegradability testing; sales and marketing of anaerobic digestion systems for organic waste; establishing and managing a company focused on anaerobic digestion of organic residuals; purchasing enzymes and specialty chemicals; managing research, development and commercialization of new chemicals and bioplastics.

Norma is a member of the following professional associations: American Biogas Council (Board Member, Vice Chair, Co-Chair of Legislative and Regulatory Affairs); US Composting Council; American Council on Renewable Energy (ACORE); Great Lakes Renewable Energy Association; and 25 X 25 (25% renewable energy by 2025).

Beth Meyer, Director of Communications
American Dairy Association & Dairy Council Inc
North Syracuse, New York

Beth Meyer is the Director of Communications for American Dairy Association and Dairy Council, the checkoff organization representing farmers in New York, northern NJ and Northeastern PA. As spokesperson for ADADC, she has completed dozens of media interviews with local and national print and broadcast media outlets on topics ranging from farm energy efficiencies and sustainability efforts, consumer milk pricing, the nutritional benefits of dairy products, and of course, the annual butter sculpture at the New York State Fair. She has also prepared a variety of diverse audiences, including dairy farmers, CAFO planners, Soil and Water staff, veterinarians and registered
dietitians for both positive and potentially controversial media interviews. Beth heads up the Crisis Management team for ADADC and serves as point person in developing strategies, talking points, and response plans for issues affecting the dairy industry.

**Dennis J. Murphy**, Extension Safety Specialist  
Department of Agricultural and Biological Engineering  
Pennsylvania State University  
University Park, Pennsylvania

Dennis is the Extension Safety Specialist and has been leading funded research and educational projects related to confined space manure storages for the past 10 years. He is part of a national committee currently looking at all aspects of safety and health relating to agricultural confined spaces. Other current projects include applied research and education for: tractor and machinery safety issues; youth safety; classification of agricultural deaths and injuries; methods of modifying farm worker safety behavior; evaluating safety interventions; and responding to farm injury emergencies. He is a registered Certified Safety Professional (CSP). Dennis is a native of Illinois and prior to coming to Penn State in 1976, was employed as a Safety Services Representative by Crum and Forster Insurance Co., St. Louis, MO, and as a Fire and Safety Engineer by Argonne National Laboratory, Argonne, IL.

**J. Shannon Neibergs**, Extension Economist  
Washington State University  
Pullman, Washington

Shannon currently works as a livestock Extension Economist and is the Director of the Western Center for Risk Management Education. He works with livestock producers to develop improved methods of production efficiency and risk management. In the dairy sector, Shannon has evaluated the economic impact of the state's dairy sector and evaluating the economic return of improved herd health management. Concerning dairy nutrient management, while previously at Iowa State University Shannon worked on the EPA funded Livestock and the Environment which examined surface water contamination from dairies at a watershed scale in Erath county Texas. Presently in Washington, Shannon is involved with two projects evaluating the environmental sustainability and net economic efficiency of anaerobic digestion. Shannon has also done work evaluating the potential economic benefit of carbon trading to dairy producers. Shannon has degrees in Agricultural Economics from Washington State University and Texas A&M.
Morton Orentlicher, Consultant  
Resources from Waste: Management & Engineering  
New York, New York

Dr. Orentlicher is currently an independent consultant. He was previously Director of Special Projects for the ThermoEnergy Corporation, where his primary responsibilities are in the development and commercialization of waste water technologies. Dr. Orentlicher’s experience includes over 30 years’ in infrastructure and environmental projects. Following service as head of an environmental review unit of the New York City Department of Environmental Protection (NYCDEP) and Assistant to the Mayor of New York for engineering and quantitative issues, he occupied a number of positions as an engineering consultant before joining ThermoEnergy Corporation. Prior to government service, he had a 10-year affiliation with Columbia University’s College of Physicians and Surgeons, Department of Neurology. Dr. Orentlicher holds a Ph.D. in Chemical Engineering from the University of California at Berkeley, and M.B.A. in Operations Management from Columbia University and a B.S. in Chemical Engineering from Cooper Union.

Jennifer Pronto, Research Support Specialist  
Cornell PRO-DAIRY  
Ithaca, New York

Jenny currently works with the Dairy and Environmental Systems group at Cornell University. She has worked on anaerobic digester-related projects including: digester performance monitoring, greenhouse gas emission reductions and carbon credits, technology transfer, outreach and education and feasibility studies, among others. Current efforts include developing anaerobic digester workforce training programs. Jenny received B.S. degrees in Environmental Engineering and Science of Natural and Environmental Systems (focus: Sustainable Development) from Cornell University in 2007. She has worked as a Research Assistant in the Department of Biological and Environmental Engineering at Cornell since 2007.

Patrick Ries, P.E.  
Asset Resource Management LLC  
Mount Calvary, Wisconsin

Patrick currently provides business management services to various industries and service providers. These services range from analyzing investment opportunities, providing consulting services for various family owned businesses, and providing project management services on various legal issues. In the past, he worked in the environmental engineering field, specializing in solid and hazardous waste management. His combination of technical training, regulatory knowledge, management skills, and business judgment allowed him to assess environmental situations, perform feasibility studies on available alternatives, explain the alternatives to the owner, and
implement the selected alternative. He has a Bachelor of Science degree in Civil Engineering from the University of Wisconsin – Madison, and a Master of Science degree in Civil Engineering from Marquette University, Milwaukee, Wisconsin. He is a registered professional engineer in six states. Patrick lives on a farm in Mount Calvary, Wisconsin, with his wife Rebecca, where they raise bison.

Tim Shelford, Post-Doctoral Associate
Cornell PRO-DAIRY
Ithaca, New York

Tim Shelford is a Post-Doctoral Associate in the Department of Biological and Environmental Engineering at Cornell University. Tim’s duties within Cornell PRO-DAIRY have included developing a white paper outlining the challenges facing small farm anaerobic digestion, assisting with the organization of a national Manure Management conference, monitoring existing AD projects, and various other AD projects. Tim graduated from Cornell University with a Ph.D. in 2010 in Biological and Environmental Engineering with a focus in Controlled Environment Agriculture where he gained experience in modeling agricultural production systems and instrumentation and control. Previously, Tim received a bachelors (1997) and masters (2000) of applied science from the University of British Columbia, in Bio-resource Engineering. Before that Tim grew up in Vancouver, BC where he was exposed to production agriculture through his uncle’s 200 cow dairy and the research labs of his father (a former professor of Dairy Nutrition at the University of British Columbia.)

Jessica Skinner, PE
JESS Engineering, PLLC
Alpine, New York

Jessica currently works mainly in New York State with livestock farms on manure management and CAFO related engineering projects. Jessica works with farms in the design and implementation of projects, utilizing field experience and ensuring that the projects meet all applicable standards. While working on manure storage and transport for the past fourteen years Jessica has held positions with both governmental agencies and the private sector. Seven years ago she formed JESS Engineering and has continued to serve agricultural clients throughout New York. With extensive field experience regarding the evolution of the transportation and storage of sand laden manure systems in New York, Jessica works to find her clients the system that will best meld with their management style. Jessica has a husband and two children and lives in Alpine, NY.
Andrew W. Wedel, P.E., Agricultural Engineer
McLanahan Corporation Agricultural Systems Division
Hollidaysburg, PA

Andrew Wedel is the General Manager of McLanahan Corporation’s Agricultural Systems Division where he is part of a team that develops, designs, and sells mining-duty systems for handling, processing, and storing sand-laden dairy manure. Specific designs include: anaerobic digester pre-treatment systems; conveyance and separation systems; earthen, concrete, and HDPE lined manure storage structures; runoff control structures; and pump and gravity conveyance systems.

Andrew holds a B.S. degree in Agricultural Engineering from the University of Delaware and a M.S. degree in Agricultural Engineering from Michigan State University. He is a registered professional engineer in: Delaware, Maryland, Michigan, New York, Pennsylvania, Virginia, and Wisconsin. In 2010, Andrew received the Young Agricultural Engineer of the Year award by the Northeast Agricultural and Biological Engineering Conference.

Prior to joining McLanahan Corporation in 1996, Andrew was an Agricultural Engineering Specialist at Michigan State University where he, along with a group of ag engineers and dairy producers, researched and developed systems for handling sand-laden dairy manure.

Stanley A. Weeks, Materials Handling Consultant
Stanley A. Weeks, LLC
Middle Grove, New York

Dr. Weeks is a private consultant to the dairy industry. He has extensive experience with agricultural systems and equipment, and consults in the Northeast on issues related to buildings and equipment layout for dairy facilities. Stan has designed, supervised construction of, and modified a number of anaerobic digester systems for converting animal manure to energy. Evaluation of liquid/solid separators and composting systems are two other major efforts. Dr. Weeks has engineering degrees from the University of Maine, University of Massachusetts, and University of Nebraska. Work experience includes teaching, research and extension at the University of Maine, University of Massachusetts, University of Nebraska, and Cornell University. He also spent two years with H.P. Hood, a dairy processor in New England. From 1977 to 1997, Stan was with Agway Inc., an agricultural supply and marketing cooperative in the Northeast, in several positions with their Research & Development Department. His last position with Agway was as Director, Research Farm Operations at the Agway Farm Research Center in Tully, NY. Stan has served as a Director for the American Society of Agricultural and Biological Engineers. He completed a five year term on the Finance Committee of ASABE, and served a six year term as Director of the Farm Building and Equipment Task Force for The Dairy Practices Council.
Tim Zauche, Professor
Department of Chemistry & Renewable Energy
University of Wisconsin – Platteville
Platteville, Wisconsin

Zauche has worked with anaerobic digesters for the last ten years. He first developed and patented a potting mix using digested solids as a complete replacement for peat moss. He has carried out feasibility studies for dairy farm digester installations as well.

He is currently working to develop protocols to verify if biobased plastics will anaerobically digest at mesophilic conditions. He has worked with a variety of digester companies and the university is currently offering biomethane potential services for the industry. By the time of the conference, the university will hopefully have implemented a new major called Sustainable & Renewable Energy Systems. Zauche is leading the team of faculty who are developing this new program. Zauche grew up on a beef farm in Iowa, earned his Bachelor’s in chemistry at Northern Iowa and PhD at Iowa State where he met his wife. They have four kids and currently reside in Platteville, WI.
DANISH EXPERIENCE WITH AD PLANTS AND FUTURE DIRECTION

K. Hjort-Gregersen
Agrotech Ltd.
Aarhus Denmark

INTRODUCTION

Since 1988 the centralized co-digestion plant concept was developed and implemented in Denmark. It turned out to be a considerable success, and since 1995 the technology held a prominent position in Danish energy policy and green-house gas mitigation strategy. This is because the technology addresses not only energy production, but also a number of environmental issues such as fertilizer utilization and odor control.

The development was initiated by implementation of an ambitious government technology development effort, and was also a result of the fact that the technology emerged at a time and a place, which generally provided a favorable environment for the development. Over time, several set-backs have also occurred, however, the ambitions are still remarkably high. The government Green-Growth-Plan from 2009 targets 50% of the manure production should be utilized for biogas production by 2020.

WHAT WAS SUCCESSFUL IN ENCOURAGING AD ADOPTION IN DENMARK, AND WHAT WERE THE RESULTS?

From 1988 to 1998 twenty (20) centralized biogas plants were established in Denmark and remain in operation today. More than 500 farmers are involved, 1 million metric tons of manure and 0.3 million tons of organic waste are treated on a yearly basis. Energy production from the centralized plants amount to approx. 2 PJ and 60 on farm plants account for another 1 PJ, which means it still covers just a minor share of national energy consumption, which amounts to 900 PJ. The development was stimulated by an ambitious government initiated technology development effort, and also by a range of “push & pulls” not always introduced to support this specific development, but on the other hand turned out to favor it.

The development is linked closely to the implementation of the first so-called “fresh-water-action-plan” in 1987. It all started with a basket of dead lobsters from the Baltic Sea. These pictures were shown in the evening news on national TV on October 8, 1986. As it turned out later, it was carefully coordinated with a massive campaign initiated by the nature conservation society. Nevertheless it created a tremendous debate, political action was demanded, which ended up in the mentioned fresh-water-action-plan, which actually later had two successors. But nutrient leaches from industry, households and agriculture were held responsible for the poor quality of the Baltic Sea waters in general and the destiny of the lobsters in specific. So, wastewater treatment should now be widely implemented, and livestock farmers faced restrictions in their handling and application of livestock manure.
First, they required 6-9 months storage capacity for manure, in order to secure that manure was only spread in times where nutrients could be obtained by crops. Secondly, the amounts of manure applied per hectare was restricted. For dairy farmers it was set in the range between 1.7 – 2.3 so-called animal units (Examples; 1 unit was for one Holstein dairy cow, for pig producers it was 1.7 animal units, and 1 one unit was three sows and their piglets). This regulation, which is normally referred to as the “harmony rules” secures a certain balance (harmony) between livestock production and the amount of land controlled by each individual farm. Third, minimum nitrate utilization ratios on manure were introduced and nitrate quotas were assigned to each crop, which basically restricts the amount of chemical fertilizer used in crop production.

No wonder farmers strongly opposed these regulations at the time, as they were consequently subject to significantly increased production costs. So when the Danish Biogas Action Program was launched in 1988, many farmers recognized the centralized biogas plant concept as a multifunctional technology which might help or ease farmers’ compliance with the new restrictions. This is due to the fact that biogas companies might make the investments in the necessary storage tanks, which enable farmers to rent the required capacity. If carefully planned, the tanks were placed in positions optimal for the end-use of the manure as a fertilizer. This would in fact, from the farmer’s point of view save money from manure storage, transport, and spreading. Another important aspect is the fact that surplus manure is easily distributed from one farm with a surplus to another farm with a deficit, as it is transported in trucks owned by the biogas company. The redistribution reduces the land required for manure spreading for the livestock producer. Thus, the restrictions on manure handling and utilization formed a kind of regulatory push that initiated farmer’s interest in centralized biogas plants.

The Danish Biogas Action Program was a government initiative from 1988. The aim of the program was to investigate, whether centralized biogas plants could be economically viable if all agricultural, energy, and environmental aspects were taken into account. The program provided investment grants for a number of plants, a monitoring program and funding for identified research and development tasks. Undoubtedly farmer’s interest concentrated on the 40% investment grants obtainable for the first plants from 1988 to 1992. Later the grant ratio was reduced to 20%.

During the Danish Biogas Action Program the understanding of the centralized plant concept as an integrated energy production, waste treatment and green-house gas reduction facility emerged. And there is no doubt that the Program was crucial to the Danish development for a number of reasons (Raven and Hjort-Gregersen, 2005). First, because a bottom-up strategy was applied and interaction between farmers, operators and researchers was stimulated in order to integrate gained experience. Second, the first program was succeeded by new programs for more than a decade, which secured the continuity of the activities maintaining the documentation of experience and keeping it available for new players in the field. Third, the technology developed in a time and a country, in which many regulations, initiatives, and other preconditions actually favored the development and implementation of the centralized biogas plant concept.
Legislative vs. economic incentives

There is no doubt that the first Fresh Water Action Plan turned on farmers’ interest in the AD Technology, and it was the main incentive. The optional investment grants were recognized as a kind of co-responsibility from society, which helped convincing farmers that their plants might be economically successful. In addition, the market for produced biogas was provided by purchase obligations for electricity. When produced from biogas or other renewables, energy prices were (and are) subsidized. In the beginning they were just exempted from energy tax. Heat from biogas still is, but electricity from biogas production has since 1992 been sold at fixed, subsidized price. For several years it was about 11 cents/kWh, but since 2008 the price has been 14 cents/kWh. Whether this level is sufficient or not mainly depends on what biomass sources are available for biogas production and this is where the waste enters the scene. Since the early 1990’s landfilling of organic waste was prohibited. Instead it should be either recycled or incinerated (for heat and power production). Incineration is more costly than recycling due to taxation, which made application to biogas plants both an economic and convenient way for food processing industries to dispose their organic waste.

In Denmark biogas has so far only been utilized for combined heat and power production. District heating systems are very widespread in towns and cities. Many of these were fuelled by natural gas and the transition into biogas was easy, though, sometimes mandatory through central energy planning by the Danish Energy Authority. So more or less voluntarily the district heating companies buy the biogas or the heat from the biogas plants, and the power companies buy the electricity production. Thermal heat is sold in a price range from 50 – 100 US$ per MWH. Electricity is sold at a fixed price, which for the time being is 14 cents per KWH. Traditionally energy production and supply in Denmark has been based on a non-profit principle. For some years now that has been changing, but not for district heating companies and companies supplying fuels to district heating companies. The principle is maintained to protect heat consumers in towns or cities from uncontrollable heating costs, but for the biogas plants the system implies that basically they may only produce modest profits. If they do, they will have to agree on reduced biogas or heat prices next year. Now that does not make sense from a business point of view. Not unless you remember, that farmers’ main interest was to apply the technology in order to ease their compliance with new environmental restrictions and reduce their costs to do so. So, from the beginning, they accepted not to be able to withdraw profits from the biogas plant company.

However, this is about to change. Now farmers tend to insist on considering biogas production as a new branch of business, and they look enviously to the German border, where some farmers actually make a living on biogas production. But in the historical perspective, the economic incentives were not the most important drivers for farmers’ adoption of AD technology in Denmark. On the other hand, the provision of a market and economic preconditions that enabled viable biogas production was indeed important.
Lessons learned from 20 years of community digestion

One major lesson was that the monitoring program during the Biogas development program from 1988 - 2002 provided an eminent learning system especially for plant operators and owners. Gained experience was effectively communicated, and the activities proved crucial to the gradually improved technical performance of the plants, which was, not surprisingly, accompanied by improved economic performance as well. In addition, if special problems needed further attention, they were identified as special research tasks and addressed.

Another lesson is that the above mentioned incentives for food processing industry to direct their waste streams to biogas plants turned out to be the major key to both technical and economic success of AD technology in Denmark. It is much easier to achieve process stability and high biogas production when waste supplies are in ample quantities. And if that is the case, the risk of economic failure is limited. But in year 2000 – 2001 round 50 new on-farm plants were established and put into operation. At first, the constructors supplied the necessary waste, but after a while they left, which made demand and competition about most attractive waste resources increase dramatically, and treatment fees turned into costs from a plant perspective. Lack of good waste has been a problem for some time now, and plants and developers are searching for other types of concentrated input. Thus, a high level of certainty for sufficient biomass supplies from the start is recommended. In fact, lack of waste is an important reason why only very few new plants were established during the last decade.

Furthermore, it turned out that the farmers’ involvement seems to be crucial for the success of the plant. In Denmark very often farmers own their service companies like dairies, slaughter-houses and feed-stuff supply companies as co-operative companies. Thus, it seemed natural to organize many of the centralized biogas plants as co-operative companies, which gave farmers full control, as well as responsibility. In theory this provides the incentives for farmers to supply good quality manure to the plant, which becomes increasingly important as waste resources become more and more scarce.

Application of biogas for combined heat and power production in local district heating systems left many biogas plants with only one customer, which is not always an optimal situation. The situation lead to a number of disagreements, and many plants look forward to the optional distribution of biogas via the natural gas grid in near future.

On the technical front, the continuously stirred reactor is the prevailing digester type in Denmark, at least at the centralized plants. It is made of steel and in most cases with a slowly rotating top-mounted stirrer. Several tanks of this kind have been built at sizes of 5000 m$^3$ and an 8000 m$^3$ tank is in planning. However, in these cases they need several stirrers, and more experience to be gained from that. Also concepts were developed in which advanced manure separation technology was integrated after the digester, but so far without much success.

Most of the larger plants operate at thermophilic temperature, 53-55$^\circ$C.

One major technical breakthrough was the upcoming of a bio-scrubber for biogas cleaning. In a separate tank biogas is desulfurized in a bacteriological process using
atmospheric air. Earlier, the quality of biogas was a major challenge for CHP engines, which led to significant maintenance costs. Biogas quality is no longer considered as a problem.

Optimization of influent dry matter

In Denmark dry matter content in manure is relatively low as shown in Table 1. That in fact, represents a substantial challenge for biogas production as biogas is not produced from water but from organic matter.

Table 1. Dry matter content in different slurry types. Average figures from 3 centralized biogas plants.

<table>
<thead>
<tr>
<th>Slurry from</th>
<th>Sows</th>
<th>Fattening pigs</th>
<th>Dairy cows</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter content, %</td>
<td>2.5</td>
<td>4.5</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Source: Information from Linkogas, Ribe Biogas and Lemvig Biogas

The reasons for this situation are numerous, but the consequences for plant economy are significant. The methane production per ton of as fed material is shown in Table 2. In some cases even the energy content cannot cover the transport costs.

Table 2. Methane production potential in pig slurry at different levels of dry matter content.

<table>
<thead>
<tr>
<th>Dry matter content, %</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH4 potential, m3/ton</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>19</td>
<td>24</td>
</tr>
</tbody>
</table>

Source: Own calculations

The figures show dramatically increasing methane production potential by increasing dry matter content in pig slurry, which of course will directly affect the economic potential by digesting it. As a matter of fact, there are very good reasons for attempting to optimize or increase the dry matter content. But how can that be done?

First of all, no builders of animal houses ever made any considerations about the fact that manure could finally be utilized for energy production. So in production systems water consumption is designed for the needs of the livestock production, sanitation and inexpensive disposal, which means that optional optimizations are relatively easily identified.

In Dairy production, for example, it is known that some milking robots consume 6 m³ of fresh water per cow annually just for cleaning. If led to the slurry system, it increases the amount of slurry by approximately 25%.

In pig production large amounts of water is used for cleaning. If directed into the slurry system the dry matter content may be compromised. But certain system designs allow slurry to be taken out before cleaning, and water to be led to separate storage facilities after cleaning, but before pigs re-occupy the house.
In many cases, rain water from roofs and outside areas is led to the slurry system, because it was considered an inexpensive way to dispose it. This water may be led to separate storage tanks or in the future into small nearby willow groves.

Manure separation has been subject to considerable interest among farmers in recent years, because if slurry is separated and the fiber fraction is exported from the farm, the land requirements of the previously mentioned harmony rules are eased. Consequently, farmers who wish to expand their livestock production need to control less land if their slurry is separated, and the fiber fraction for example is exported to a biogas plant. Thus, the system represents a mutual win-win situation for farmers and biogas plants. However, different separation technologies have different characteristics.

Table 3. Separation efficiency. Efficiency defined as the relative share of the component found in the fiber fraction.

<table>
<thead>
<tr>
<th>Separation efficiency %</th>
<th>Screw-press</th>
<th>Decanting centrifuge</th>
<th>Band-pass filter with polymers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td>3-5</td>
<td>5-21</td>
<td>15</td>
</tr>
<tr>
<td>Total solids</td>
<td>17-32</td>
<td>45-63</td>
<td>89</td>
</tr>
<tr>
<td>Organic solids</td>
<td>7-15</td>
<td>50-80</td>
<td>86</td>
</tr>
<tr>
<td>Total N</td>
<td>5-9</td>
<td>11-28</td>
<td>40</td>
</tr>
<tr>
<td>Phosphorous</td>
<td>7-15</td>
<td>52-80</td>
<td>89</td>
</tr>
<tr>
<td>Biogas production potential, m3 CH4/ton</td>
<td>36-64</td>
<td>40-90</td>
<td>56-80</td>
</tr>
</tbody>
</table>

Also in-house separation systems may become more widespread in the future. So-called source-separation systems, which separate urine and feces fractions have been developed, but are not yet widespread as they are typically more costly.

In European countries and especially in Germany a considerable enlargement with plants using energy crops has taken place. This kind of development requires a high subsidy level to cover production costs of the energy crops, which so far is not the case in Denmark, and the use of energy crops is limited. It is not that farmers are not interested in producing and selling energy crops to biogas plants, but this activity is not encouraged by the subsidy system. It is a government opinion that energy crops should not substitute food production in agriculture. Instead they encourage digestion of concentrated manure fractions like deep litter, poultry manure and manure fibers. The government also other favors digestion of surplus biomass materials like straw, tops from carrots and potatoes, waste from vegetable or fruit production, and even grass from uncultivated grass-lands. Methane yields for some of these biomass sources are provided in Table 3. Currently special attention is paid to these biomass types, as these are seen as an option to collect and recycle nitrogen from extensive grass-lands on to cultivated agricultural areas.
Table 4. Methane production potential from concentrated manure types, crops and residues from agriculture, Nm$^3$ CH$_4$ per ton as fed

<table>
<thead>
<tr>
<th>Crop/Residue Type</th>
<th>DM (%)</th>
<th>OM (%)</th>
<th>CH$_4$ Potential (m$^3$/ton)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep litter from dairy</td>
<td>30</td>
<td>24</td>
<td>48</td>
</tr>
<tr>
<td>Fiber fraction from pig manure</td>
<td>28</td>
<td>22</td>
<td>54</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>48</td>
<td>38</td>
<td>108</td>
</tr>
<tr>
<td>Sugar beets</td>
<td>20</td>
<td>18</td>
<td>65</td>
</tr>
<tr>
<td>Corn silage</td>
<td>30</td>
<td>28</td>
<td>100</td>
</tr>
<tr>
<td>Green grass silage</td>
<td>30</td>
<td>27</td>
<td>59</td>
</tr>
<tr>
<td>Grass/hay from extensive lands</td>
<td>80</td>
<td>64</td>
<td>160</td>
</tr>
</tbody>
</table>

Source: Own calculations

A comparison between Table 2 and Table 3 reveals significant differences in the per ton methane production potential. That means that the biomass types in Table 3 may be supplied to slurry based biogas plants in order to increase average dry matter content, and thereby to increase biogas production. But it has to be taken into consideration that it takes costs at different levels either to grow or procure them, and some existing plants may need additional equipment to handle the higher DM content. Furthermore some of the most lignified biomass types like straw may require pre-treatment to achieve higher digestibility.

Danish “Green-Growth” Plan

In 2009 the Danish Government launched the so-called “Green-Growth” Plan. It can be seen as recognition of the importance of agriculture for Danish society in a time where agriculture in general is not that popular. And also a recognition that in the future agriculture still has a role to play as a new-job facilitator and a food producer in growth, as long as the development is green.

The Green-Growth Plan has two headlines:

1. An Environment and Nature Plan for Denmark

2. A Strategy for a Green Agriculture and Food Industry in Growth

The Environment and Nature Plan picks up the line from the previous initiatives and introduces new regulations to improve quality of water systems to: reduce impacts from pesticides on humans and animals, reduce green-house gas emissions, improve biodiversity, increase access to nature for the public, and to improve monitoring of nature. In case of restrictions certain compensation can be obtained.

The Strategy for a Green Agriculture and Food Industry contains a removal of some and a simplification of other regulations that previously restricted individual farms to grow larger in size. These initiatives should help improving the competitiveness in livestock production. The plan also encourages farmers to become suppliers of green
energy. It contains the ambition that 50% of livestock manure should be utilized for biogas production by 2020. In order to accomplish this target a new investment grant scheme was established. In addition, negotiations on restructuring the subsidy scheme have been going on for a long time. (They are not yet concluded, but in November the government signaled an increase in electricity prices form 14 – 18 cents per KWH). Also, the strategy tends to encourage perennial energy crops like willow groves.

Future direction for Danish centralized biogas plants

The existing plants were designed mainly for digesting liquid manure and certain amounts of organic waste. In recent years this strategy has become far more problematic due to the competition of the waste. In fact they face significant challenges, technically as well as mentally, in the transition towards application of more concentrated biomass types. New plants, of course, are from the beginning equipped with necessary facilities for mixing and feeding of concentrated biomass types. Also in the future, biogas plants may demand higher quality of manure supplies from farmers, especially with focus on dry matter contents in pig slurry. Some farmers may have to introduce separation technology if they want to supply manure to a biogas plant.

For more than 20 years Denmark was a producer of natural gas from the North Sea. At an early stage a widely branched natural gas grid was established and most major cities are connected. The natural gas is used for local combined heat and power production. In the first place, it formed a brilliant opportunity for biogas plants as they could simply substitute the natural gas at the local CHP facilities. However, as mentioned, having only one customer was not always an ideal situation. But now the natural gas resources are diminishing and production already declining. Natural gas distribution companies turned out to be more than interested in purchasing biogas, upgrading and distributing it via the natural gas grid. From there it can be used for CHP production, heating purposes, industrial use, and especially as vehicle fuel. Recent rising in oil prices have made fuel prices so high that we are close to a situation, where biogas is competitive. Thus, with little or no subsidies, biogas is likely to be distributed via the natural gas grid and substitute gasoline or diesel as a vehicle fuel. Biogas will be produced in the western, rural areas, where the livestock production takes place, and applied into cars and busses in major cities.

Finally, we see a development where large slaughterhouses and dairy companies involve in large biogas projects for marketing reasons, as they can then brand themselves with a greener profile.
REFERENCES/FURTHER READING

Danish Government, 2009, Agreement on Green Growth
http://www.mim.dk/NR/rdonlyres/54887891-D450-4CD7-B823-CD5B12C6867A/0/DanishAgreementonGreenGrowth_300909.pdf


HEALTH AND SAFETY

Manure management systems have the potential to expose owners, employees, and the public with safety hazards that include: drowning, asphyxiation, mechanical hazards, electric shock, explosions, etc. A properly designed system following standards from a number of different organizations can reduce the potential for harm. At times safety issues are ignored because the operator has successfully practiced unsafe acts in the past with no repercussions. The cause of many accidents is from ignoring known safety practices. The result of an accident is often tragic for the victims and their families. The safety and health protection of following standards should motivate us all.

COMPATIBILITY

Manure Management can be an extremely complex combination of systems. These systems need to not only be compatible but also to meet the expectations of the design, that is they need to function to the satisfaction of the owner operator as well as protect the health and safety of the public (including the employees). Standards are needed to make this happen so that systems can communicate their output characteristics as well as their expectations of the inputs from other components and ultimately function as a whole with each other. Standards are needed so that compatibility can be determined prior to purchase and installation.

LAW

Legally many standards have to be followed as a matter of law. Governments have set up a range of laws to protect the health and Safety of the public. These include Building Codes, Fire Codes, Electric Codes, Zoning Codes, Professional Engineering requirements, OSHA Codes, even Traffic Codes. Any sustainable operation will need to comply with CAFO regulations. The owner and designer have an legal obligation to conform to regulations.

FINANCIAL ASSISTANCE

Most sources of financial assistance including loans and grants require that the appropriate standards are followed to protect not only the operators and the public but also the funders. Cost estimates for manure management systems should include following the needed standards.
STANDARDS

Natural Resources Conservation Service (NRCS) standards can be found for each state at: http://efotg.sc.egov.usda.gov//efotg_locator.aspx. The website explains that:

The conservation practice standard contains information on why and where the practice is applied, and it sets forth the minimum quality criteria that must be met during the application of that practice in order for it to achieve its intended purpose(s).

National Conservation Practice standards should not be used to plan, design or install a conservation practice. You must have the conservation practice standard developed by the state in which you are working to insure that you meet all state and local criteria, which may be more restrictive than national criteria. State conservation practice standards are available through the Field Office Technical Guide (FOTG). If no state conservation practice standard is available in the FOTG, you should contact the appropriate State Office or your local USDA Service Center.

In FOTG Section IV — Practice Standards and Specifications you will find the NRCS Conservation Practices. Practice Standards define the practice and where it applies. Practice specifications are detailed requirements for installing the practice in the state. The following standards are useful in designing manure management systems:

- Above Ground, Multi-Outlet Pipeline Standard (FT) (431)
- Air Filtration and Scrubbing Standard (NO) (371)
- Amendments for the Treatment of Agricultural Waste Standard (AU) (591)
- Anaerobic Digester Controlled Temperature Standard (366)
- Animal Mortality Facility Standard (316)
- Atmospheric Resource Quality Management Standard (370)
- Composting Facility Standard (NO) (317)
- Constructed Wetland Standard (AC) (656)
- Critical Area Planting Standard (AC) (342)
- Fence Standard (FT) (382)
- Field Border Standard (FT) (386)
- Heavy Use Area Protection Standard (AC) (561)
- Irrigation Pipeline Standard (FT) (430)
- Irrigation System, Sprinkler Standard (NO AND AC) (442)
- Monitoring Well Standard (353)
- Nutrient Management Standard (590)
- Pathogen Management Standard (NO) (783)
- Pipeline Standard (FT) (516)
- Pumping Plant Standard (NO) (533)
- Roof Runoff Structure Standard (NO) (558)
- Roofs and Covers Standard (367)
- Solid/Liquid Waste Separation Facility Standard (NO) (632)
- Vegetated Treatment Area Standard (AC) (635)
The American Society for Agricultural and Biological Engineering (ASABE) Standards Program states that it “is the recognized standards developer for engineering in agricultural, food, and biological systems. The Program is accredited by the American National Standards Institute (ANSI) and is the U.S. Technical Advisory Group (US TAG) Administrator for several ISO technical committees and subcommittees, and one IEC committee”.

"Standards are essential for all human activity, but most people take them for granted. Only when products fail to work, or mishaps occur, does the average person think about standards. Even in business, where money is at stake, standards are often given a low priority. There is a clear need in the United States for greater attention to standards."

"Global Standards: Building Blocks for the Future" Congress of the United States, Office of Technology Assessment (March 1992) Standards, Engineering Practices, and Data (hereafter referred to collectively as standards) are normally generated for one or more of the following reasons:

- To provide interchangeability between similarly functional products and systems manufactured by two or more organizations, thus improving compatibility, safety and performance for users;
- To reduce the variety of components required to serve an industry, thus improving availability and economy;
- To improve personal safety during operation of equipment and application of products and materials;
- To establish performance criteria for products, materials, or systems;
- To provide a common basis for testing, analyzing, describing, or informing regarding the performance and characteristics of products, methods, materials, or systems;
- To provide design data in readily available form;
- To develop a sound basis for codes, education, and legislation; and to promote uniformity of practice;
- To provide a technical basis for international standardization;
- To increase efficiency of engineering effort in design, development, and production.
“Standards are engineering requirements (specifications) prepared to define materials, products, processes, tests, testing procedures and performance criteria in an effort to achieve certain specified purposes. They are developed and adopted because of a need for action on a common problem. Their effectiveness is dependent upon voluntary compliance with the standards adopted. Standards must accurately and specifically define the properties required without unnecessary, restrictive specifications that thwart originality or progress”.

Some ASABE Standards that are used in manure management systems include:

- Nomenclature/Terminology for Livestock Manure Handling Equipment ASAE S466.1 December 1998
- Management of Manure Odors ASAE EP379.4 January 2007
- Volumetric Capacity of Box Type Manure Spreaders--Dual Rating Method ASAE S324.1 April 1986
- Manure Storage Safety ASAE EP470.1 October 2011
- Uniform Terminology for Rural Waste Management ASAE S292.5 October 1994
- Volumetric Capacity of Closed Tank Type Manure Spreaders ASAE S326.1 January 1989
- Volumetric Capacity of Open Tank Type Manure Spreaders ASAE S325.1 January 1989
- Manure Production and Characteristics ASAE D384.2 March 2005
- Manure Storages ASAE EP393.3 December 1998

A one-stop resource for online education and distance-learning resources provided by American National Standards Institute (ANSI) who are accredited standards developers, includes a partial listing of the organizations that have standards that might impact a manure management system (including Anaerobic Digestion):

- A2LA (American Association for Laboratory Accreditation)
- ACI International (American Concrete Institute)
- Air Movement and Control Association International
- American Institute of Steel Construction
- American National Standards Institute
- American Society of Agricultural and Biological Engineers (ASABE)
- American Society of Civil Engineers
- American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
- American Society of Mechanical Engineers (ASME)
- American Society of Safety Engineers
- American Society of Sanitary Engineering
- American Water Works Association
American Welding Society
ASTM International
Building Owners and Manufacturers Association
Compressed Gas Association
Electrical Apparatus Service Association
Electrical Generating Systems Association
Environmental Industry Associations
Fertilizer Institute
Hydraulic Institute
ICC International Code Council
Independent Electrical Contractors
Institute of Electrical and Electronics Engineers
Institute of Environmental Science & Technology
International Association of Electrical Inspectors (IAEI)
International Association of Plumbing and Mechanical Officials
IPC Association Connecting Electronics Industries
ISA - The Instrumentation, Systems, and Automation Society
National Board of Boiler and Pressure Vessel Inspectors
National Concrete Masonry Association
National Electrical Contractors Association
National Electrical Manufacturers Association
National Fire Protection Association
National Pork Producers Council
National Propane Gas Association
National Safety Council
NIST - US Department of Commerce
North American Energy Standards Board
SAE International (Society of Automotive Engineers)
Sheet Metal and Air Conditioning Contractors National Association
Society for Biomolecular Sciences
Standards Engineering Society
Underwriters Laboratories
Uniform Code Council
US Department of Energy
US Fuel Cell Council
Water Quality Association

Most states and many funding organizations require the use a professional engineer registered in the state to complete designs that impact the health and safety of the public. Manure management systems often fall into this category. Professional Engineers are familiar with standards and specifications that make manure management systems safe. They are also more aware of the characteristics of individual pieces of equipment or components of systems that need to fit together in order to make a manure management system work. Although not exclusive professional engineers that are familiar with manure management systems in each state
can be found on the NRCS technical Registration site: http://techreg.usda.gov/CustLocateTSP.aspx. This site is a useful beginning point for a search for qualified professional engineers working in your location.

REFERENCES


ASABE Standards: http://www.asabe.org/standards.aspx


THE IMPACT OF DAIRY HOUSING AND MANURE MANAGEMENT ON ANAEROBIC DIGESTION

D.Kirk¹ and L. Faivor
¹Anaerobic Digester Research and Education Center
Department of Biosystems & Agricultural Engineering
Michigan State University, East Lansing, MI

- Differences in manure characteristics and biogas potential from different housing systems
- How these characteristics affect digester technology selection

The Impact of Dairy Housing and Manure Management on Anaerobic Digestion

ABSTRACT

When considering the development of an anaerobic digester system, it is important to understand how differences in dairy housing and manure management impact manure characteristics and biogas potential. Two common dairy housing practices suitable for anaerobic digestion are freestall barns and open or dry lot. Manure collection and conveyance practices with these housing systems range from daily to weekly collection using scrape, scrape-flush or flush. Bedding type and usage as well as climactic conditions are factors that should also be taken into account during planning. Differences in these systems influence the availability and digestibility of the dairy manure as well as the appropriateness of various digester technologies.

Utilizing a pool of data from dairy manure samples submitted to the Michigan State University Anaerobic Digestion Research and Education Center (ADREC) over the past several years, manure solids characteristics from the various systems will be presented. Measured biogas and methane production data from biogas assays conducted at the ADREC will also be evaluated. Based on the characterization and biogas potential information, the discussion will focus on the challenges of digesting manure from various dairy housing systems and the appropriateness of different digester technologies.

Keywords: anaerobic digestion; dairy housing; biogas potential, manure characteristics
INTRODUCTION

The solids content of dairy manure varies from farm to farm based on the type of housing, manure collection practice, bedding usage and environmental conditions. The American Society of Agricultural and Biological Engineers (ASABE) and Midwest Plan Service (MWPS) have published “as excreted” or fresh manure characteristic data which provides a starting point for conceptual design and business plan development for an anaerobic digester project. Table 1 summarizes the basic manure solids data from ASABE in terms of total solids (TS), volatile solids (VS), fixed solids (FS) for a lactating dairy cow.

Table 1. ASABE manure characteristics

<table>
<thead>
<tr>
<th>Description</th>
<th>TS (%)</th>
<th>VS (%)</th>
<th>FS (%)</th>
<th>VS : TS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy - lactating cow</td>
<td>13.3</td>
<td>11.3</td>
<td>2.0</td>
<td>85.0</td>
</tr>
</tbody>
</table>

Manure is a mix of water, undigested solids, gut microflora and their metabolic byproducts. The characteristics of “as excreted” manure are useful for initial planning, however it does not describe the site-specific nature of the manure needed for full design of an anaerobic digestion system. During the collection, manure from barn floor or lot is mixed with other material including urine, bedding, feed and water from drinkers or precipitation, resulting in a feedstock with different solids characteristics compared to “as excreted” manure. The composition of the manure as collected is critical in determining the appropriate handling options and digester technology as shown in Figure 1.

Figure 1: Manure Handling Practices Affect the Feasibility and Choice of Biogas Digester Systems

---

Figure 1 provides general guidance for a few digester technologies based on the TS concentration of the feedstock. The TS concentration of manure is a key selection factor for appropriate digester technology because it impacts both the material handling and ability to mix the manure. In Table 2, the acceptable ranges for organic loading rate (OLR), hydraulic retention time (HRT) and TS are shown for several common digester systems used with dairy manure feedstock. Organic loading rate is a design feeding range for organic matter, measured as VS or chemical oxygen demand (COD), intended to maintain biological health and maximize biogas production. Hydraulic retention time is the theoretical time which the fluid or slurry remains in the anaerobic digester.

Table 2: Design Parameters for Common Anaerobic Digestion Technologies

<table>
<thead>
<tr>
<th>AD System</th>
<th>OLR</th>
<th>HRT</th>
<th>TS range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Covered lagoon</td>
<td>&lt; 0.20</td>
<td>&gt; 40</td>
<td>0.5 - 3</td>
</tr>
<tr>
<td>Plug-flow</td>
<td>1 - 6</td>
<td>&gt; 15</td>
<td>11 - 13</td>
</tr>
<tr>
<td>Complete mix</td>
<td>1 - 10</td>
<td>&gt; 15</td>
<td>3 - 10</td>
</tr>
<tr>
<td>Fixed-film</td>
<td>5 - 10</td>
<td>&lt; 5</td>
<td>1 - 5</td>
</tr>
<tr>
<td>Induced blanket reactor</td>
<td>5 - 10</td>
<td>&lt; 5</td>
<td>6 - 12</td>
</tr>
<tr>
<td>Up-flow sludge blanket</td>
<td>5 - 10</td>
<td>&lt; 5</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>Sequencing batch reactors</td>
<td>&lt; 5</td>
<td></td>
<td>2.5 - 8</td>
</tr>
</tbody>
</table>

Manure moisture content and bedding usage are two critical factors affected by dairy housing, which influence the design parameters in Table 2 as well as the system volume, heating requirements, flow characteristics and material handling. In addition, the type and quantity of bedding may also contribute to a loss of usable volume and biogas production due to sludge accumulation or the formation of a floating blanket. Obtaining site-specific manure characteristics is critical during the design of an on-farm anaerobic digester to ensure a long term, successful system.

DAIRY HOUSING AND BEDDING

Dairy Housing Systems

The most common dairy housing systems in the United States are the freestall barn and the open or dry lots. Freestall housing, which combines the resting and feed areas under roof can be found throughout the country but are most common in the cooler regions or areas with high precipitation. By maintaining the herd under roof, manure is not exposed to direct sunlight and precipitation is excluded. During the collection of

---


6 EPA AgSTAR. 2011. Recovering Value from Waste Anaerobic Digester System Basics

7 EPA AgSTAR. 2011. Recovering Value from Waste Anaerobic Digester System Basics.
manure, the solids characteristics will change when the “as excreted” manure is mixed with urine, bedding, feed and additional water from drinkers, sprinklers or precipitation. Generally, 100% of the manure is collected from freestall barns daily and available as feedstock.

Open and dry lot housing uses separate areas for cattle feeding, rest and exercise. The open lot typically consists of a large, uncovered dirt or concrete corral, a shaded loafing area and a feed area. Providing a shaded area gives cattle relief from precipitation and heat. While open lot housing is found throughout the country, it is the predominate system used in the dry, southwest. Manure is typically collected and removed from the feed alley and shaded resting area of the lot daily. Similar to freestall housing, manure collected from these areas will be mixed with bedding, feed, urine and water. Collection of manure from the open area will vary from daily to annually depending on environmental conditions and management preferences. Availability of manure for anaerobic digestion will depend on the amount of manure deposited on the concrete alley and the site-specific collection practices. In addition, manure collected from the open lot area may contain large amounts of grit depending on what material is used to construct the lot. Environmental conditions will have a significant impact on the moisture and solids content of the manure from open lot dairies.

While less common, tie-stall and manure pack systems are used on many smaller or older dairy farms. Similar to the freestall barn, the cattle are housed under roof and the manure is not exposed to precipitation or direct sunlight. Less frequent cleaning and greater usage of bedding may result in manure from these systems having a higher TS concentration compared to “as excreted” manure. The higher solids concentration could easily exceed the TS ranges for conventional technologies shown in Table 2 and will require special consideration during planning. Another consideration with manure packs is the potential loss of biogas production potential due to biological activity while the material is stored in place. This natural loss of biogas potential should not be overlooked when planning digestion systems. Similar to freestall housing, 100% of the manure from tie-stall or manure packs should be available for anaerobic digestion once the material is removed from the barn.

Bedding

Bedding is used in most dairy housing systems to provide a clean, dry and comfortable resting area. Materials used for bedding are divided into two categories; inorganic and organic.

Sand is the most common inorganic bedding material used for dairy bedding. While sand is an ideal bedding for cow comfort, it does contribute a significant mass of FS to the manure stream and does not improve biogas production. Mechanical issues associated with inorganic bedding include premature equipment wear, clogging pipes and loss of digester capacity due to grit or sludge accumulation. Sand manure

---

separation systems can remove adequate quantities of sand and reduce the mean particle size to residual sand to allow for successful anaerobic digestion. Drawbacks to sand separation include the addition of dilution water which increase volume and the potential loss VS during the sand removal. Generally, the minimum dilution needed to achieve meaningful separation is one part dilution water to one part sand-laden dairy manure (SLDM)\(^9\). Based on research conducted at a Michigan dairy farm, the VS loss due to sand separation ranged from 10% to 40% depending on the system complexity and management\(^10\).

Organic bedding options vary depending on regional availability. Common organic bedding materials include wood shavings, sawdust, newspaper, straw or composted/digested/dried manure solids. For digestion, organic bedding poses fewer mechanical challenges and may contribute to biogas production. While there are significantly less FS compared to sand, grit accumulation can be an issue with organic bedding as it does contain some FS.

**MANURE COLLECTION AND CONVEYANCE**

Collection & Conveyance

Traditionally, manure collection and conveyance systems have been classified as scrape (mechanical), flush or a scrape-flush combination. Manure collection is the process of removing manure from the alley, gutter or lot. Conveyance is the movement of manure from the point of collection to the treatment system or storage. Housing practices and environmental conditions are two factors which drive the selection of manure collection and conveyance practices. Scrape collection is common in northern and eastern regions, where cold temperatures and wet conditions are prevalent. Conveyance of scrape manure can be scrape or flush. Flush, or hydraulic, manure collection is common in the warm, dry climates of the south and west, where irrigation is common. With flush systems, typically collection and conveyance are combined into a single process. Both scrape and flush system can be used in either freestall or open lot housing and with both inorganic and organic bedding.

Scrape or mechanical collection involves the physical removal of the manure from the freestall alley using either a blade or tire mounted to a tractor, an automatic scrape driven by a pulley system or a vacuum tank. Scraping manure from alleys results in well-mixed slurry containing anything deposited in the alley (manure, urine, bedding, feed, water from drinkers and other debris). Incorporating the other material deposited on the alley or surface with manure will result in minor changes in the solids make up. A drawback to scrape systems is manure conveyance. Unless the manure storage or treatment system is located adjacent to the manure source, a secondary system will be needed to convey the manure to its final destination. Many variations of conveyance systems exist including tractor scrape, mechanical conveyors (gutter cleaners, augers,

---

cable scrapers) or flush flume. Traditional scrape collection and conveyance generally do not result in a loss of VS or a large increase in water content, with the exception of scrape-flush which relies on water to convey manure from the barn.

Flush systems utilize water, recycled or fresh, to scour and collect manure from the freestall alley and convey it to the point of treatment or storage\(^\text{11}\). Similar to scrape systems, any material deposited in the alley or on the barn floor will be incorporated into the manure stream with flush collection. For anaerobic digestion, the addition of water during flush collection is drawback. Flush manure collection systems can use as little as 3,500 gpm for organic bedding to over 10,000 gpm for sand bedded farms to adequately clean the floor\(^\text{12,13}\). The addition of water due to flush collection conveyance can be as high as 220 to 620 gallons per cow per day\(^\text{9}\). This large addition of water may require additional digester volume and heating capacity for successful digestion.

Manure Characteristics and Biogas Potential

Manure characteristics will vary depending on the type of dairy housing facility, the use of bedding and the manure collection system. Table 3 summarizes manure characteristics data from several different combinations of dairy housing and manure collection. The data provide was collected from raw samples evaluated at the Michigan State University Anaerobic Digestion Research and Education Center (MSU ADREC) between 2006 and 2011.

As shown in Table 3, the “as excreted” manure from both the dry lot and freestall facilities had a slightly higher TS compared to the ASABE values in Table 1. This is due to the fact that sample collection from the freestall barn and dry lot excluded urine (only feces was collected).

Dry lot manure samples in Table 3 were collected from several New Mexico facilities during the late summer and early fall. The increase in TS from the “as excreted” sample to the daily scrape to the weekly scrape is largely due to the addition of bedding and the evaporation of moisture. Daily scrape manure samples were collected from the feed alleys. At the time of collection the dry lot daily scrape samples were mixed with urine, feed, additional water and bedding which was tracked in the alley. Daily scrape samples were collected approximately 6 to 24 hours after the manure was collected from the freestall alley.

---


Table 3. Average dairy manure solids characteristics for different housing systems

<table>
<thead>
<tr>
<th>Dairy Housing System</th>
<th>Bedding</th>
<th>Manure Collection/Type</th>
<th>TS (%)</th>
<th>VS (%)</th>
<th>FS (%)</th>
<th>VS : TS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry lot</td>
<td>Dried manure solids</td>
<td>As excreted</td>
<td>14.3</td>
<td>11.5</td>
<td>2.8</td>
<td>80.7</td>
</tr>
<tr>
<td>Dry lot</td>
<td>Dried manure solids</td>
<td>Daily scrape</td>
<td>21.9</td>
<td>15.1</td>
<td>6.7</td>
<td>69.3</td>
</tr>
<tr>
<td>Dry lot</td>
<td>Dried manure solids</td>
<td>Weekly scrape</td>
<td>58.8</td>
<td>22.6</td>
<td>36.2</td>
<td>39.1</td>
</tr>
<tr>
<td>Freestall</td>
<td>Sand</td>
<td>As excreted</td>
<td>15.0</td>
<td>12.8</td>
<td>2.6</td>
<td>85.3</td>
</tr>
<tr>
<td>Freestall</td>
<td>Sand</td>
<td>Sand laden</td>
<td>23.7</td>
<td>7.3</td>
<td>16.4</td>
<td>30.8</td>
</tr>
<tr>
<td>Freestall</td>
<td>Sand</td>
<td>Sand separator effluent</td>
<td>5.4</td>
<td>3.2</td>
<td>4.5</td>
<td>59.4</td>
</tr>
<tr>
<td>Tiestall</td>
<td>Wood shavings</td>
<td>Daily scrape</td>
<td>16.3</td>
<td>14.3</td>
<td>2.1</td>
<td>87.3</td>
</tr>
</tbody>
</table>

1Data from testing completed at the MSU Anaerobic Digestion Research & Education Center

Weekly scrape manure from the dry lot dairies were collected from manure piles that were scraped from the shaded loafing area into the open to facilitate drying. This material was typically allowed to dry for a period of days to weeks before being returned to the shaded area for bedding, resulting in the large increase in TS. During the collection process, the weekly scrape manure was mixed with gravel and other inorganic debris used to create the base of the dry lot increasing the concentration of FS. Aerobic decomposition may also contribute to a loss of VS in the weekly scrape samples, resulting in an increase in the FS concentration.

Numerous samples were collected from sand bedded freestall dairies in the upper Midwest and Northwest. Sand for bedding has a density over 1.5 times greater than manure. The density coupled with the quantity of sand used for bedding, 35 lb of sand for every 1,000 lb of body weight, explain the large increase in TS and FS in the SLDM samples. Due to the mechanical and settling issues associated with SLDM, to date all digesters on sand bedded dairy farms separate sand prior to entering the anaerobic digester. The sand separator effluent samples were collected from mechanical sand separation systems which used recycled liquid manure for dilution.

The tie-stall manure sample was collected from the MSU Dairy Teaching and Research Center. Tie-stall manure at the dairy was mixed with urine, wood shavings bedding and water spilled from drinkers.

In all instances presented in Table 3, the TS increased compared to the baseline "as excreted" manure due to a loss of moisture or the inclusion of bedding. In addition to the consideration of the specific TS, VS and FS concentrations during the planning of a digester it is also important to consider the VS to TS ratio (VS:TS). The VS:TS ratio is an indicator of site specific changes in the manure solids characteristics which will impact the system design and performance. For example, if a systems is designed for a specific OLR, a declining VS:TS ratio suggests that additional feedstock will be needed.

---

to maintain the design OLR. A VS:TS ratio significantly different that what was used in the design process will impact the OLR, biogas production, hydraulic retention time and many other physical and biological processes.

Biogas potential of manure is based largely on the organic matter (VS) which can be degraded anaerobically. Table 4 contains biogas potential data from the dairy manure of three different dairy housing systems. The biogas potential data based on the initial or feedstock VS, was generated under ideal laboratory conditions using Biochemical Methane Potential (BMP) assay procedures\textsuperscript{16}. While “as excreted” and daily scrape manure had similar biogas potentials, the weekly scrape and sand separator effluent generated significantly less biogas per pound of VS.

<table>
<thead>
<tr>
<th>Dairy Housing System</th>
<th>Bedding</th>
<th>Manure Type</th>
<th>VS Ave. (ft$^3$ of biogas/ lb of VS)</th>
<th>VS St. Dev. (ft$^3$ of biogas/ lb of VS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry lot</td>
<td>Dried manure solids</td>
<td>As excreted</td>
<td>8.8</td>
<td>2.5</td>
</tr>
<tr>
<td>Dry lot</td>
<td>Dried manure solids</td>
<td>Daily scrape\textsuperscript{2}</td>
<td>8.2</td>
<td>1.8</td>
</tr>
<tr>
<td>Dry lot</td>
<td>Dried manure solids</td>
<td>Weekly scrape</td>
<td>5.4</td>
<td>1.2</td>
</tr>
<tr>
<td>Freestall</td>
<td>Sand</td>
<td>Sand separator effluent</td>
<td>6.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Tiestall</td>
<td>Wood shavings</td>
<td>Daily scrape</td>
<td>8.5</td>
<td></td>
</tr>
</tbody>
</table>

\textsuperscript{1} Data from testing completed at the MSU Anaerobic Digestion Research & Education Center
\textsuperscript{2} For the biogas assay, daily scrape manure was blended with green water

This is an indication that the mixtures of VS contained in those samples are not as readily digestible as fresh manure with minimal handling. It is important to remember that VS are a mixture of organic compounds ranging from simple organic compounds (acids, sugars, cell matter) to large particles of undigested feedstuffs. Several factors could contribute to the differences in biogas potential for sand separator effluent or weekly scrape manure. Losses of smaller, more readily degradable VS during sand separation or due to aerobic decomposition resulting from the weekly scrape could contribute to the differences in biogas potential.

CONCLUSIONS

Dairy manure from most housing system can be an ideal feedstock for anaerobic digestion. Key to developing a successful project is understanding during the planning phase, how site-specific conditions influence the solids characteristics and the biogas potential of the manure. The moisture content of manure is influenced by the housing system, environmental conditions and type of bedding. Reductions in the TS concentration and increases in the volume of manure are attributed to the addition of water from cattle drinkers, cooling systems and hydraulic manure collection and conveyance. Bedding generally increases the TS concentration. However, the addition of VS or FS will depend on the type and quantity of the bedding. Sand bedding will add significantly to the TS and FS in the manure and will require removal prior to introduction into the digester. Organic bedding will add to the TS, FS, and VS in the manure and will require planning to avoid sludge accumulation or the development of a floating layer.

To avoid technological problems during the operation of a digester, it is important to consider how the housing and manure collection practices influence the manure characteristics. Reviewing the manure collection and conveyance practices as well as the annual application records will provide site-specific data on the manure volume. In addition, testing the manure intended for anaerobic digestion and reviewing historical manure analysis records will provide important information regarding the solids characteristics. If there are significant changes in the volume or solids concentrations compared to published data, it may warrant further investigation to determine the cause and impact on anaerobic digestion. While success is never guaranteed, a little extra effort during planning will significantly increase the likelihood of creating a long term, robust project.

ACKNOWLEDGMENTS

Dry and open lot data presented in this paper was generated thanks to support from the United States Department of Energy and the Pecos Valley Biomass Cooperative.
MANURE COLLECTION AND TRANSFER SYSTEMS IN LIVESTOCK OPERATIONS WITH DIGESTERS

A. C. Lenkaitis
GEA Farm Technologies Inc. (Houle USA), Naperville, IL

INTRODUCTION

Manure collection systems are influenced by many factors on livestock operations. Management style, bedding type, topography and manure application methods dictate the design and ultimate success of a manure collection system. Traditional collection systems have evolved based primarily on animal comfort and increased labor efficiency, with long term storage and land application being the only ultimate use of collected manure.

Adaptation of advanced manure processing requires integration of the manure collection systems to provide a consistent, reliable product. Flush, scrape and cross gutter systems all collect and transfer manure, but provide significantly different end products to a manure treatment system. Each system has their advantages and challenges and costs from an operational and processing standpoint.

SYSTEM DESCRIPTIONS

Flush Systems

A flush system will substantially dilute the solids content of the material available for processing, dilution rates can vary from 10:1 to 2:1 parts of water to manure. The final solids concentration will typically be below 2%. The costs to operate and maintain a flush system are dominated by the cost to transfer liquid for flushing. Depending on topography, several high horsepower pumps are often required.

Scrape Systems

Scraping does not use any additional liquid for manure collection. Manure is collected as close to as excreted solids concentrations as possible, typically above 10 % total solids, depending on the amount of bedding and the amount of water used in cow cooling. Collection is accomplished by mechanical means using an automatic alley scraper, skid loader bucket scraper or a vacuum scrape and haul combination.

Cross Gutter Collection Systems

Most collection system will require an additional transfer system to move manure from each alley across the barn to a central reception pit outside of the animal housing system. Manure is scraped along the alleys, parallel to the feed lane and dropped into a cross gutter channel which carries manure to a reception pit. Cross gutter systems use a square channel or round tube underneath the barn floor.
Figure 1. Typical dairy barn layout with a conventional scrape system into a cross gutter collection system to transfer manure to a reception pit.

A flush flume system utilizes fast flowing liquid to transfer manure across the width of a barn or across several barns in a round tube. A high volume pumps creates an adequate flow rate to prevent settling of manure solids and bedding material. Water addition, and separation or dewatering is needed before evacuating to further processing to have enough liquid to keep the flush flume operating. Solids content of a flush flume will typically vary between 4 to 9% total solids.

A mechanical cross gutter uses a cable or chain pulled scraper or a horizontal auger in a square concrete channel to mechanically convey manure. Flush and some vacuum scrape and haul systems will not require a cross gutter scraper to bring manure to a central reception pit. Complete scraped systems with a mechanical cross gutter or a vacuum system can have collected material contents between 8 and 18% total solids. This number will change throughout the year based on weather conditions, cow cooling methods such as sprinklers and parlor water addition.

Table 1. Expected total solids content of common manure collection systems on US dairies

<table>
<thead>
<tr>
<th>System</th>
<th>Volume Per Cow Per Day (US gallons)</th>
<th>Expected % Total Solids in Reception Pit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flush System</td>
<td>60 -200</td>
<td>1-3</td>
</tr>
<tr>
<td>Scrape w/Flush Flume</td>
<td>30-50</td>
<td>4-9</td>
</tr>
<tr>
<td>Scrape w/Mechanical Cross Gutter</td>
<td>20</td>
<td>8-18 &quot;As excreted&quot;</td>
</tr>
<tr>
<td>Vacuum Scrape or Scrape to Reception Pit</td>
<td>20</td>
<td>8-18 &quot;As excreted&quot;</td>
</tr>
</tbody>
</table>
Vacuum scrape and scrape systems with a mechanical cross gutter offer the lowest volumes per cow per day, but can also have the highest variability throughout the year. Additionally, milking center water and the small portion of manure excreted in the milking center will have to be handled separately.

Figure 2. Closed loop system: Scrape with flush flume system on a dairy facility.

Dairy manure scrape systems with flush flumes offer an extremely attractive balance between volume per cow per day and consistency of the product available for processing throughout the year. The closed loop concept of a flush flume with separation or dewaterering offers control by the dairyman with minimal fresh water addition over and above normal liquid for the milking center. An additional bedding removal or recovery process can be added to provide the farm with bedding independent of the type of further processing.
Flush flumes systems require liquid to be pumped at high rates to create velocity for manure conveyance through a round tube or circular channel. Constant manure addition without adequate dewatering or water addition will lead to reduced pumping volumes, lower fluid velocities and increased solids settling in the flume line.

System Management: Unwanted Material

Inevitably there will be bedding and other unwanted material in the manure system. Wooden hoof blocks, breeding gloves, plastic pieces, rocks and neck straps will clog pumps and create problems in different points in the systems. Easily accessible bar racks or removable catch baskets should be incorporated into a manure system to limit system downtime.

Other unwanted material may include the bedding used for the animal in the production system. Sand bedding in particular is wonderful for dairy cows, useless in most further processing systems and very hard on manure handling equipment. Additionally, even when sand is not used for bedding, cows will excrete several pounds per day of grit passed through from the feed they receive. A properly managed sand separation system, settling pit or grit chamber will remove heavy sediment from the system before further processing.

COST TO COLLECT MANURE

All manure systems have costs associated with initial construction, operation, maintenance and labor expenses. In order to estimate operational expenses, a theoretical 1,200 cow dairy was used to evaluate different systems. The dairy consists of two 600 ft long barns with center manure drops. Each building holds 4 pens of 150 cows each. Assumptions based on equipment sizing, energy usage and maintenance expenses were calculated based upon manufacturer’s specifications for each situation. The site was assumed to be feasible within reason for topography and climate for each collection system, initial construction costs are not included. Fuel consumption data was calculated from ASABE standards for Machinery Data based on horsepower required for the desired task. Calculated numbers were compared against actual producer responses with similar collection systems.

For manure collection systems, flush, vacuum scrape and skid loader scrape systems tend to have higher energy usage based upon the higher horsepower required to move large volumes of water or large pieces of machinery. Additionally, the labor cost on vacuum scrape and skid loader scrape are higher since an operator is required to be in the machine at all times. Flush systems and automatic alley scraper systems are generally timed or push button operation. Automatic alley scraper systems require less energy but require more maintenance time and expense per day. For a cross gutter system, scraping is dominated by the daily maintenance costs, whereas auger and flush flumes are energy dominated.
Table 2. Daily energy, labor and maintenance costs for different manure collection and cross gutter systems on a calculated 1,200 cow dairy

<table>
<thead>
<tr>
<th></th>
<th>Manure Collection Systems</th>
<th>Cross Gutter Systems</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alley Scraper</td>
<td>Flush System</td>
</tr>
<tr>
<td>Daily energy usage</td>
<td>6.48</td>
<td>18.51</td>
</tr>
<tr>
<td>Labor cost per day</td>
<td>17.14</td>
<td>4.29</td>
</tr>
<tr>
<td>Daily maintenance Cost</td>
<td>16.44</td>
<td>8.22</td>
</tr>
<tr>
<td>Cost per day to operate</td>
<td>40.06</td>
<td>31.02</td>
</tr>
<tr>
<td>Cost per cow per day</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

As with any system, there are other factors that will contribute to long term success. Vacuum scrapers and skid-loaders can be driven to a shop for maintenance in an area with readily accessible tools and lifts. Flush systems are limited in certain regions due to freezing and the need to handle and store large volumes of liquid. Alley scraper systems require daily maintenance in the barn, as well as some forward thinking when spreading fresh bedding and using stall grooming equipment.

LONG DISTANCE MANURE TRANSFER

As further manure processing gains acceptance on livestock facilities, a centralized processing location often appears as the most attractive solution for multiple site locations. Advantages are numerous for both the producer of manure as well as the operator of the manure processing location. A major cost obstruction to a centralized plant is the expense of transferring manure or feed stock from individual locations, and returning effluent to utilize existing waste storage facilities.

There are three common methods to transfer manure long distances:
- Trucks and tanks over the road
- High volume, intermediate pipeline transfer
- Low volume, continuous pipeline transfer

Using semi trucks or tractors and manure tanks is the most common way today to transfer manure from one location to another. Tanks are readily available, may already part of a farms equipment package, and would not require any additional infrastructure.
Pumping manure has often been limited by distance and energy usage. High volume, high horsepower pumps are commonly used during times of manure application. Temporary pipelines are laid across the ground and manure is pumped directly to the field where it is applied. A similar, permanent system can be installed using a high horsepower pump to transfer manure in short bursts throughout the day. An alternative pumping method is to use a low horsepower, low flow rate, positive displacement pump to transfer manure slowly throughout the day. A permanent pipeline is still required.

With either high or low volume pumping, sedimentation of material in the pipeline is a concern during idle and pumping times.

Energy Usage to Transfer Manure

In order to compare different manure transfer systems a representative example was selected. Equipment packages and motor sizes were selected on manufacturer’s recommendations to transfer 72,000 gallons of manure over a distance of 5,000 ft. The manure tank transfer assumed time for loading/unloading and road transport. The two pumping schemes assumed level ground with a permanent PVC pipeline and electric motors with a 78% efficiency.
Table 3. Comparison of different manure transfer systems

<table>
<thead>
<tr>
<th></th>
<th>Manure Tank Transfer</th>
<th>High Volume, High Horsepower</th>
<th>Low Volume, Low Horsepower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Size</td>
<td>7,300 gal. manure tank</td>
<td>6&quot; PVC</td>
<td>4&quot; PVC</td>
</tr>
<tr>
<td>Engine/Motor HP</td>
<td>200 hp (149 kW)</td>
<td>150 hp (112 kW)</td>
<td>7.5 hp (5.6 kW)</td>
</tr>
<tr>
<td>Transfer Rate (US Gal. per hour)</td>
<td>28,800 (4, 7,200 gal. loads per hr)</td>
<td>48,000 (800 gal. per min)</td>
<td>6,000 (100 gal. per min)</td>
</tr>
<tr>
<td>Total Time for Transfer</td>
<td>2.5 hrs</td>
<td>1.5 hrs</td>
<td>12 hrs</td>
</tr>
<tr>
<td>Energy Usage per Day</td>
<td>40.7 gal. diesel</td>
<td>215 kWh</td>
<td>86 kWh</td>
</tr>
<tr>
<td>Cost @ $3.50 per gallon diesel and $0.08 per kWh</td>
<td>$142.45</td>
<td>$17.20</td>
<td>$6.88</td>
</tr>
</tbody>
</table>

Overall, a low volume, low horsepower pumping system uses the least amount of energy to transfer the required volume, even though the total operating time is significantly longer. The energy savings are achieved by the enormous reduction in friction due to the low flow rates along the length of the pipeline. Other factors need to be considered such as: back-up plans for line plugging, time commitments for employees and maintenance costs.

CONCLUSIONS

Manure collection systems are unique to each type of livestock production system. Each system will deliver a different available product to a reception pit available for further processing. Manure collection systems designs should be dominated by animal performance and management style prior to considering further processing. A system’s success is determined by the ability to maintain animal comfort in the production system while delivering a consistent product for the further processing. Minimizing labor inputs, allowing for redundancies and establishing emergency plans must be established in the design phase of a project.

REFERENCES

ASABE. D497.7 MAR2011, Agricultural Machinery Management Data. American Society of Agricultural and Biological Engineers, St. Joseph, MI 49085.


1111819. Louisville, Kentucky, American Society of Agricultural and Biological Engineers

Lenkaitis, A. C., J. J. Sanford (2011) Manure Data Collection Results. GEA Houle, Inc. Available via e-mail. Andy.lenkaitis@geagroup.com
SAND LADEN MANURE STORAGE AND TRANSFER

J. Skinner
JESS Engineering, PLLC, Alpine, NY

INTRODUCTION

As sand bedding has gained popularity in New York State, farms have continued to struggle with how to convey and store the mixture of manure and sand. Sand Laden Manure poses challenges throughout the transfer and storage chain. Sand settles in inconvenient locations while at the same time staying suspended in locations designed to promote settling. The unique characteristics of Sand Laden Manure have posed many problems and learning opportunities for producers throughout New York State. Over the past fifteen years sand laden manure handling systems in New York have developed through a combination of trial and error and incorporation and adaptation of ideas and concepts obtained by researching designs found on farms in other states.

BACKGROUND

Throughout the mid 1980’s there were many manure transfer systems in New York installed that utilized gravity to transfer material from inside of the barn to an earthen structure immediately adjacent to the barn. These gravity transfer structures were usually installed utilizing a 30” HDPE transfer pipe with an approximately 3% slope and outlet to the bottom of a manure storage located close to the barn. The slopes on the pipes were designed based upon the angle of repose of manure and relied on head pressure to force material into the storage. The systems worked reasonably well with organic bedding as long as excessive amounts of bedding material were not used or were kept out of the transfer system.

As sand began to gain popularity as a bedding product in New York through the early and mid 1990’s it quickly became apparent that these previously installed transfer systems were not designed to handle the new mixture of sand and manure. As the farms converted to sand bedding and continued to utilize their existing conveyance and storage system, the transfer systems quickly plugged with sand, some in as little as two to three weeks. With below the ground conveyance systems plugged, many farms converted to a system where they directly scraped into their earthen manure storage(s). These earthen structures were not designed to have manure pushed down their slopes leading to excessive cases of erosion. In addition, before sand was utilized as bedding material in New York, farms rarely needed the ability to get into their structures to excavate and haul built up material out of their storage. With the conveyance issue solved by a direct push system sand and manure build up in long term storage(s) quickly became the next problem. Depending upon the particle size of the sand utilized, sand and manure settled together, gradually reducing the available capacity of the structures unless removed on a regular basis. Farms then had to skim manure from the top of the structure and excavate the sand and manure from the structure and attempt
to land apply the mixture. The excavated material frequently had dirt and rocks from the storage floor mixed in, making it impossible to use traditional spreading equipment.

I have been involved in working with clients who are implementing Sand Laden Manure handling systems since the late 1990’s. By this time most farms utilizing sand bedding had gone away from conveyance with underground pipes and were direct scraping into storages. Some farms had improved the pushoff areas as well as the bottom of their storages for removal of solids by adding concrete. Farms were beginning to experiment with multiple celled manure storages in hopes of promoting settling and segregate the sand from the liquid portion of the manure. These systems were marginal at best, often constructed with earthen cells that were difficult to clean and settled sand was not removed frequently enough, reducing the effectiveness of the settling cells. Between the limited capacity of these cells when clean out was not performed frequently and the mucus in manure that bonds the sand to organic material, farms struggled to remove 40% of the sand in the first cell.

In order to promote increased sand settling and ease conveyance struggles, farms began to experiment with below barn concrete structures that were installed with ramps to enter and clean the structures. Due to financial and space constraints, these structures only held a small volume of waste which still has to be transferred to a long term (higher capacity) storage. These systems allowed farms to push the manure straight into the storage without having to turn manure or deal with an outside push off; however these systems pose great danger to the person that is operating the skid steer or loader utilized to remove material from the structure, with the potential for hazardous gas build up internal to the structure. These below barn structures can trap noxious gases that can cause illness or even death. Many farms have emptied these storages multiple times with no incident, creating a false sense of security. It is important that consultants continue to stress to clients how dangerous these facilities are and supply alternatives that meet their needs.

SAND LADEN MANURE CONVEYANCE

Direct scrape systems seem to have worked relatively well on dairies with 400 cows or less, the farm is generally able to scrape manure directly to a long-term, central manure storage. If these storages are designed appropriately, allowing for frequent clean out with large equipment, farms of this size seem to be able to rather easily manage pumping liquids off of the structure and then loading and hauling built up sand. As the farm size increases, so does the required frequency of sand removal from the system, making the handling system more arduous and forcing farms to continue to look for alternatives.

With the topography in New York we are constantly looking for ways to utilize and take advantage of gravity to transfer manure. With sand laden manure this is always a challenge; traditional gravity transfer lines with sand laden manure have proven to be ineffective. Over the past ten years farms in New York have begun to adopt flush barns and flush flumes to transfer manure. The mixing of manure with large volumes of
flowing water allows for the movement of sand laden manure reliably to a treatment/storage area. The addition of flowing water degrades the mucus attachment of the manure to the sand and creates the potential to incorporate a gravity separation system.

Flush barns have been used in a limited capacity due to the cold winter weather. Whether real or perceived, there is a concern that these barns will be slippery for a significant period during the winter months. In the past four years I have been involved with the installation of three different flush facilities, all of which have functioned well, with only a few days each year where the farm has to find an alternative way to remove manure from the barn. This is not an uncommon issue to face in our climate and we attempt to design all facilities with an alternate cleaning plan when cold weather prevents utilization of the primary gravity system. Because all of these facilities are bedded with sand, the alleys are very forgiving; even with a 5% slope on one of the farm’s walkways we have seen little issue with slipperiness due to cold weather. The largest challenge with flush systems seems to be that the flush barn alleys must be designed as conveyance structures; the flow rate and distribution systems are vital to ensuring that the alleys work to transfer material out of the barn and to the storage system. Some of the initial flush barns were installed with flow rates in the 1500-2000 gallon per minute range, while research has shown that flush flow rates along the scrape alley should be between 6500 and 8000 gallons per minute for a typical alley width of 10-12 feet. This flow rate helps maintain a minimum cross sectional velocity of 8 feet per second, which is necessary to suspend and transfer the sand laden manure. We have utilized both pre-manufactured flush valves and custom made manifolds to accomplish this. The custom made manifolds distribute flow better at the start of the alleys; however in general both do a satisfactory job of cleaning if appropriate velocities are achieved. All farms report having to scrape built up sand from behind the stall bed curb a minimum of once per week. Collection of the flush water at the end of the alleys also has proven to be challenging. Collecting 7500 gallons per minute of flush water from a 10’ to 14’ wide cow alley and funneling it into an 18 to 30” HDPE transfer pipe has certainly been a learning experience. Some of the first systems collected the material in a concrete hopper and outlet to a gravity transfer pipe. This led to settling of sand in the concrete hoppers and reduction of flow rates, leading to plugging of the transfer lines. Newer systems were constructed utilizing smooth bore HDPE lines with slots cut in the top, many of these lines were installed with little fall from the alley floor. With little fall, flush water backed into the alley causing settling, or in some cases overflowed the collection pipes and exited the barns. After several installations it has become apparent that there should be approximately four feet of fall from the alley floor to the invert of the collection pipe to allow for head losses generated in the transition. Continuous smooth bore HDPE pipe with slots cut in the top seem to currently be the most reliable systems, if the pipes are well supported at the top to prevent collapse. The current flush systems work reliably and also help cut down on building maintenance due to damage caused by scrape equipment and overzealous employees.

In an attempt to utilize the benefits of water to convey sand laden manure while allowing the farm the flexibility of a manual scrape system, farms in New York have
begun to adopt flush flumes. Flush flumes utilize an HDPE transfer pipe with flowing water to collect sand laden manure and convey it to the storage/treatment area. Flush flumes work well in a retrofit situation allowing the farm to continue using their current cleaning system. On one of the farms that we worked with to install a flush flume, the farm had an existing 800 cow barn with a center collection auger and did not want to disrupt cattle traffic to install a collection channel. We designed a manhole (see photo 1) at the end of the auger to carry manure down to the flush flume. With the slow rate of material exiting the auger and the 2500 gallon per minute flow rate maintained within the flume, the system has worked flawlessly for three years.

Photo 1. Auger depositing to a flush flume.

The flush flume systems that we have installed to date have been very forgiving and posed few growing pains. All of the systems have been installed at slopes between 1 and 1.75%, with flow rates ranging from 1500 to 2500 gallons per minute. Just as with the flush barn alleys, the design flow rate within the collection pipe must generate velocities of around 8 feet per second.
GRAVITY SEPARATION

Just as with conveyance issues, gravity separation in New York has evolved over the past ten to fifteen years. Many farms visited facilities across the nation and appreciated the simplicity of their gravity separation systems. The first gravity separation systems that I was involved with were a variation on the hog slat systems that are popular on flush dairies in the midwest and southwest. These systems accept manure into a three sided structure with a fourth wall constructed of hog slats. Solids build up against the hog slates and the system filters out sands and solids while allowing the liquid portion of the manure to continue to a long term storage. These facilities are generally constructed of concrete for ease of cleaning and have proven to be very effective. A variation of this system was developed by Southern Minnesota Agricultural Engineering Services. The structure was designed to have a manure depth of only 5 feet and utilized screen towers located near the center of an earthen structure with a concrete floor. Manure could be scraped directly into the structure and the towers would allow the liquids to drain to a long term storage.

Photo 2. Screen Towers
The mixture of sand and solids that accumulated still had to be loaded out of the structure and land applied. Two of these systems were installed in New York on 400 cow dairies. The facilities worked marginally when the farms had 400 cows. As the facilities expanded they quickly became difficult to manage and both systems have since been replaced.

As farms continued to travel and search for systems that they felt would work well with limited mechanical components they began to come across sand lanes in the upper midwest and southern Pennsylvania. These were appealing because they required little mechanical equipment and provided the opportunity to reuse the sand that was settled out. The sand lanes that farms had seen were utilized on both flush and flush flume systems, and there was a consensus that these climates were close enough to New York that we could make sand lanes work here. Unlike many of the sand lane facilities that were visited, the ones in New York would all be retrofits to existing facilities. This poses some unique challenges for these systems. The area required for gravity separation is large and many of these facilities had limited space. In addition, the systems that the farms were visiting had large amounts of secondary settling and storage ponds, with supply water for the flumes and flush alleys pulled from the last stage of the storage structures. Most of the dairies in New York that were considering these systems only had long term storage for about six months with their traditional scrape systems. The additional water that is required to be kept within the systems for flush supply created challenges with storage capacity and CAFO regulations. In an attempt to reduce the size and number of cells needed to produce acceptable flush water many farms opted to incorporate mechanical solid separation as a part of their overall system.

In order to ensure that sand lanes function to settle out sand and keep manure solids entrained, the flow rates in these systems need to be around 1 foot per second. This can be adjusted by slope and width of the sand lane. To allow for ease of cleaning, it is advisable to keep the minimum width of the sand lane at a minimum of 12 feet and adjust the slope to achieve the desired flow depth and velocity. Most commonly the sand lanes that were visited had a narrow access point on the side for cleaning. After working with the farms and consulting Jake Martin, a layout specialist from Florida, all of our New York farms decided that access throughout the entire length of the sand lane was their preference.

CASE STUDIES

Case 1 – 400 Cow Scrape Dairy With Flush Barn Addition – Wyoming County NY

Design

In 2006 we began design work on the first of several sand lanes that we have been involved with. This system was planned for one of the facilities that had an original tower separation system and was building a new 1000 stall barn that would be bedded with sand and flushed. The project involved the installation of an 18” flush flume line
that would double as a flush collection line for the new barn. Due to site constraints the new barn was designed to slope to the end of each pen which necessitated the installation of two separate collection points. The new building was designed with commercially available 15" flush valves to supply the flush water and flush towers up in elevation approximately 15’ from the barn. This layout required that the collection line turn several times on the way to the space that was available and designated for the sand lane. All lines were installed at a minimum 1.25% slope and all turns were completed utilizing manholes with vertical drops of at least 1’. The collection line at the end of the new barn presented the greatest elevation challenge. This line was installed only 2’ in elevation below the alley in the barn.

The sand lane was installed adjacent to the abandoned tower structure. The concrete floor of the tower structure could then be utilized to pile sand after removal from the sand lane, saving the farm approximately $125,000 by avoiding the installation of a sand stacking area. This stacking area allowed the sand to continue to drain and discharged this runoff to the farm’s long term storage through the piping already installed at the screen towers. The sand lane design was difficult in that we had to account for several different flow rates entering the lane, ranging from 7500 gallons per minute for the wider cow alley flushes to as little as 2500 gallons per minute for the flume outlet. The decision was made to design the sand lane for the largest flow rate and see how the lower flow rates reacted; this approach dictated a 20' wide sand lane. In addition, the farm installed a settling basin directly off the end of their sand lane, allowing for some sand to settle. The basin is also the source of flume water for this facility. The location of the farms long term storages are several hundred feet from the barns and down in elevation approximately 15 feet. Installation of the flume pump within this structure allowed for the use of a reasonably priced pump as well as reducing the amount of 12” supply line by fifty percent.

This farm has a very limited footprint at their facility and did not have room to install the number of cells and settling basins necessary to remove solids passively; instead they chose to install a mechanical solid separator in an attempt to preserve their flush water quality. Manure is taken from the settling basin at the end of the sand lane, run through an inclined screen separator and discharged to the long term storage system, including additional long term settling basins. Understanding that water quality was the key to the successful operation of any sand separation system, the farm installed an additional 2 million gallon storage to act as an supplemental settling basin to use in conjunction with a converted 1.5 million gallon storage. From these two basins water is pumped off of the top to the farms 7 million gallon storage structure where water is drawn for use in refilling the flush towers.

Operational Evaluation

This system has functioned adequately for the farm. As operations began there were five main areas of concern where we paid particular attention to the results obtained. The first concern was the flush supply system; we were concerned about the performance of the manufactured pop up valves in providing a high enough flow rate
and adequate distribution for cleaning. With the increased head available from the elevated flush tanks the largest problem that was faced at startup was blowing the tops off of the flush valves. Some simple field welded steel plates and a decrease in water level in the flush tanks solved this issue. The valves do an adequate job of spreading out the flow and the farm pulls accumulated sand and manure away from the stall curb on a schedule similar to that of other dairies.

Photo 3. Completed Sand Lane

The next area of concern was the collection of flush water. This was the first installation where we realized that the depth of the collection pipe needed to be greater. With only two feet between the floor alley and the bottom of the pipe the farm frequently overflowed the collection channel. With assistance from their local steel fabrication shop they have since installed a hood system that ensures the flow is directed to the pipe (photo 4 and 5). This system does slow the water slightly as it approaches the collection trench; however there has been no issue with sand settling in the alley.

The third area of concern for this installation was the functionality of the manholes as turning structures with as little as 1’ of drop. This quickly became a non-issue on this installation. With the slopes into and out of the manholes adequate and the angle between the inlet and outlet pipes no more than 45 degrees the flows are not restricted enough to cause settling or backup.

The fourth area of concern was the width of the sand lane and how it would handle the varied flows that it was to receive. The lane seems to work fine with these varied flow rates, even though the 2500 gallon per minute flow rate results in flows much less
than 1 foot per second the farm has not experienced excessive amounts of organic matter in their settled sand.

The final area of concern was the availability of space for settling basins and the attempt to utilize a solids separator to provide clean enough water. As with all sand removal systems this is an issue that causes problems from time to time. In addition, the water cycle necessitates additional storage to achieve a six month capacity. To meet these needs the farm installed a large satellite storage structure in 2009. The farm has made a significant modification to the structure. As indicated the farm is located in Wyoming County, and particularly in the southwest corner of the county, which receives a large amount of lake effect snow. After working with the system through one winter the farm decided that to continue operation it was important for them to install a roof over the sand lane (see photo 6). The large volume of snow and ice buildup impeded the day to day cleaning and maintenance of the sand lane and took a large area to dispose of the “dirty” snow within the sand stacking area.

Photos 4. and 5. Two different views of the hood system installed

Photo 6. Roofed sand lane
Case 2 – 600 Cow Scrape Dairy With Flush Flume Barn Addition – Genesee County NY

Design

In 2008 a farm that we had worked with on the design of a new 600 cow facility several years earlier contacted us to work on a new flush flume and sand lane for the original facility as well as a new 600 cow barn. The farm bedded with sand and pumped to an earthen storage. The manure transfer system had worked well for them; however they had significant issues with sand build up in their manure storage as well as having issues with equipment failures during spreading operations. The farm’s main objective was to continue to bed with sand and achieve a level of sand removal that reduced the amount of material in their manure storage system while also improving equipment operation and reducing wear during spreading operations. The farm wanted to install the sand lane, but was not interested in solid separation at the time, feeling that their existing two celled manure storage would allow for clean enough flush flume water to remove sand. At inception, the goal of the system was not to reuse sand bedding. The farm had a limited budget and wanted to install only the sand lane and then remove sand from the area. No provisions were made for a concrete sand stacking area.

A 24” flush flume was designed and installed at a minimum 1.25% slope from the existing milking facility through the new barn to the sand lane. The system was designed to allow for the farm to pump manure from their existing barn into the end of the flume. Similar to case 1, the lane was installed with a “beach” configuration to the side, allowing access throughout (Photo 8). Also similar to case 1, this system was designed with the flume supply pump placed in the sand lane reception pit (Photo 7). In this situation the sand lane was located downslope from all of the farm’s manure storage structures. By placing the flume supply pump in the sand lane reception pit, it is virtually impossible to overflow the system.

Photo 7. and 8. Sand lane and adjacent “beach”
Operational Evaluation

This system came on line in the winter of 2008-2009. During the installation of the system the farm decided that they would attempt to recover sand for bedding purposes. Temporary stacking areas were designated and the farm continues to work to receive funding to install permanent sand stacking areas.

As time has progressed at this facility water quality has become a significant challenge. With no mechanical solids separation the quality of the flume water has made separation of quality sand difficult. A significant amount of sand is settled in the sand lane; however for this material to be utilized for bedding the farm must stack and rotate it for a significant amount of time in order for the organic material to break down and decompose.

The amount of sand reaching the farm's long term storage has been significantly reduced with the addition of this sand lane; however to make a more consistent bedding product additional solids separation would be beneficial. The farm has considered this enhancement, but after reviewing several other sand lanes in the area, the farm feels that the increase in sand quality would not offset the equipment investment required and the additional operational costs of a solids separation system.

CONCLUSION

Over the last ten years New York State farmers have learned a significant amount about the transfer and storage of sand laden manure. As with all manure systems on farms there is no one size fits all solutions. Pre-manufactured flush supply valves have continued to improve and we have also continued to improve the collection systems.

One of the biggest lessons learned in New York is the importance of the passive settling that occurs in the multistage storage systems of the midwest sand settling systems. We have had difficulty replicating these systems in New York, with many dairies having limited footprints or soils that are not suitable for earthen storages. The limited long term storage capacities have made consistent water quality a challenge. Overall the systems work to remove sand and reduce loads in the farms long term storage.
SAND-MANURE SEPARATION FOR ANAEROBIC DIGESTION PRETREATMENT

A. W. Wedel, P.E.
Agricultural Systems Division
McLanahan Corporation, Hollidaysburg, PA

BACKGROUND

Cow comfort is a key ingredient to high milk production and ultimately producer profitability. Sand remains the freestall bedding of choice among dairy producers and veterinarians. Mastitis causing organisms require food (carbon source), water, and heat to thrive and survive. Properly selected and/or separated bedding sand contains minimal organic matter. Less organic matter translates to less moisture as organic matter absorbs moisture. Alternative organic beddings such as manure and wood products, although perhaps low in bacteria content at first, experience substantial increases in bacteria counts as soon as a bed is seeded with bacteria. In addition to the biological advantage offered by sand, there are positive physical attributes as well. A cow in the process of lying undergoes what resembles a controlled fall. The cushiony surface offered by sand reduces stresses on knees and joints due to impact with the stall surface. Sand also offers sure footing when rising and moving about freestall alley. Ultimately, the goal being to increase the number of lactations a cow spends in the milking herd by reducing cull rate due to stress, injury, and disease.

Traditionally, sand bedding has caused substantial manure handling challenges even with relatively straightforward systems such as daily haul and short- or long-term storage. These challenges come to fruition when manure handling equipment and systems are used to process sand-laden manure. Anaerobic digestion (AD) systems are particularly susceptible to sand settling and equipment wear. The implementation of mining equipment and associated system design methodologies to separate sand from manure prior to AD has proven successful over the long-term on dairies. Pretreatment systems to separate sand from manure could potentially increase AD adoption since some producers will elect not to bed with manure—the norm with traditional AD systems.

The specific objectives of this paper are to describe:
1. Physical characteristics of sand-laden manure related to handling, storage, and separation.
2. Sand-Manure Separation (SMS) pre-treatment system operation.
3. Operating characteristics of SMS systems serving as pre-treatment to AD including SMS performance data for use by system designers.

SAND-LADEN MANURE PHYSICAL CHARACTERISTICS

An understanding of the physical characteristics of sand-laden manure (SLM) is essential when designing handling and separation systems pre-AD and advanced treatment. Certain considerations need to be made for SLM as compared to “normal”
manure. These considerations must address sand settling and scour. Abrasiveness of sand is another obvious consideration where pumps and other process equipment are concerned. Abrasiveness can be addressed by using materials of construction harder than sand grains and/or materials capable of returning to their “normal” shapes after contact with sand. Low operational speeds also reduce abrasive wear as wear is directly proportional to the speed squared—that is to say, if speed is doubled, wear is increased by a factor of four.

Factors Affecting Settling and Scour

The size, shape, and density (in relation to a bulk medium) of a particle affects the velocity at which it settles and settling velocity is the primary consideration in the design of sand-manure separation systems pre-AD and/or advanced treatment systems. A sand gradation is a description of the particle sizes as well as the quantity of said sizes in a sand sample. Bedding sand can be naturally occurring or manufactured. Manufacturing of sand involves washing processes that remove fine material and organic matter. Sand, free from silts and clay, and organic matter, is an ingredient in concrete. To qualify as concrete sand, sand must meet a size specification prepared by the ASTM (formerly American Society for Testing and Materials), otherwise known as ASTM C-33 (ASTM, 2003). This is a washed sand product. Being washed, C-33 contains a minimal amount of fine material—fine material being described as smaller than 100 mesh or 149 microns. The particle size distribution (gradation) for specification concrete sand is found in Figure 1 and shows the acceptable particle size range.

Figure 1: Concrete sand particle size gradation
Density of sand particles is typically assumed to be 165 lb/ft³ (SG = 2.65) for analysis of settling (Merritt, 1968). This is not to be confused with the bulk density of stock piled sand, which depending on moisture content and particle size distribution, can range from between 110 to 130 lb/ft³ (SG = 1.76 to 2.08). The fact sand is approximately more than 2 times more dense than manure (density equal to 62 lb/ft³, for SG approximately equal to 1.00) (ASABE, 2011) makes settling an ideal mechanism for separating sand from manure.

Settling

Sand-laden manure (SLM) is a mucosal gel where sand grains, along with water, are enveloped between the folds of long chain carbohydrates. Sand is not necessarily in suspension in undiluted SLM mass, but instead held intact due to the viscous nature of the manure. Some sand grains settle from undiluted SLM—those that possess the physical characteristics enabling them to overcome slurry viscosity. These tend to be the largest sand grains. Sand settles primarily in the presence of dilution. Laboratory research has shown, as verified in the field, diluting SLM one to one (one mass part water to one mass part SLM) is enough to disrupt the manure structure (e.g. reduce viscosity) to a point where the sand grains are released and readily able to settle (Wedel and Bickert, 1996). Factors affecting sand settling can be described using Stokes’ Law, which states, settling velocity is directly related to: the difference in density between the particle (sand) and the medium (manure); the square of particle diameter (d); and inversely related to viscosity (Merritt, 1968). This is essentially a ratio of inertial forces and viscous forces acting on a particle. In short, large, dense particles in clean water settle fastest compared to small, less dense particles in dirty water. It is conceivable to encounter sand grains and organic matter that settle together at the same velocity when similar Stokes conditions are satisfied, that is to say, a small, dense particle will settle at the same velocity as a large, less-dense particle. This explains why in passive sand settling systems, finer sand grains are laden with organic manure solids.

Scour

Scour is the process by which particles are kept in suspension or suspension is initiated by flowing with water. As it relates to dilute SLM, Shields’ equation models (validated in practice) scour velocity in pipes and/or channels designed to convey dilute sand and manure for specific particle sizes. Since scour velocity is directly related to particle size (amongst other factors), to maintain scour (in flume pipes), the largest particle in the gradation should be considered. For settling of fines (sand-manure separation), the finest particle to be captured is modeled. Whereas the goal of conveyance is to maintain particles in suspension, the goals of separation are to allow sand grains to settle, yet maintain adequate velocity to scour organic matter. Scour velocities for conveyance and separation typically range between 5 to 8 ft/sec (Wedel, 2000) and 0.75 to 1 ft/sec (Merritt, 1968), respectively. A detailed description of Shields’ equation can be found in Camp (1946) and Merritt (1968).
The principles of settling and scour will be shown below to support design considerations related to handling and separation systems. In summary, to properly design handling and/or separation systems pre-AD, knowing the gradation of the bedding sand is essential. Controlling scour and settling is important to successful design and operation of any SLM handling system. Improperly considering settling and scour leads to pipes, channels and tanks full of sand as well as dirty separated sand (e.g. high organic and moisture loading).

Figure 2 pictorially describes, in relative terms, the relationships of settling and scour velocities for sand and organic matter. The shaded region is where similar particle sizes exhibit similar settling and scour characteristics.

Figure 2: Relative Settling and Scour Velocities for Varying Particle Size (not to scale)

SAND-LADEN MANURE HANDLING

Systems designed for manure rather than sand tend to not consider the fact sand settles from diluted manure, which translates to a need to maintain high pipeline velocities and adequate safe access to locations where sand may settle. Furthermore, traditional manure handling equipment relies on materials of construction, component selection, and speeds that are not conducive to long service life in the presence of sand. Mining duty equipment and systems are used to process sand gravel and crushed stone for construction purposes. Sand and gravel plant operators require high recovery of fines so as not to fill ponds and to produce a maximum amount of usable sand product. These goals are in complete alignment with those of a dairy operation.

Challenges with sand bedding extend to anaerobic digestion (AD) systems and other manure treatment systems. With complex networks of influent piping and sealed tanks lacking loader access, ADs are exceptionally sensitive to sand (and debris) settling. Even small amounts of bypass sand, overtime, can be exceptionally problematic.
Consider a 1,000 cow dairy using sand at a rate of 50 lb/cow/day. Assuming, 5% bypass, 2,500 lb sand/day—almost one cubic yard or 200 gal/day would be introduced to the digester daily. In addition to bedding sand, manure contains grit from other sources, such as blow sand, degrading concrete, soil from harvesting, etc. Grit from these sources, often overlooked by designers, alone causes AD failures even on dairies not bedding with sand. It is also reasonable to assume some bypass sand, by virtue of the viscous nature of the AD tank contents, will stay in suspension and discharge from the AD tank. Nevertheless, the goal should be complete sand removal as to relieve all doubt as to the fate of bypass sand. Although, 100% sand recovery pre-AD is not practically achievable without also removing a substantial portion of organic solids where settling processes are concerned, digesters are operating successfully over the long-term where ASTM C-33 concrete sand is used as bedding and 95% sand recovery or greater is achieved.

Conveyance

Conveyance to Sand-Manure Separation (SMS) systems with ADs usually involves some form of scraping without the addition of water. Manure may be augered, alley scraped, vacuum tanked, or scraped directly into a SMS reception pit. Each option has been proven reliable provided, as mentioned previously, steps are taken to mitigate abrasive wear and the tendency for sand to settle in unintended locations. Under no circumstances should gravity be used to convey undiluted SLM. The settling of large sand grains, over time, will lead to clogging. Pipes as short as 12 feet and 2 feet in diameter are susceptible to clogging. Conveying diluted SLM in flush flumes—that is, using water to dilute and provide energy necessary to move manure and sand, can successfully be achieved by selecting the proper combination of pipe slope, diameter, and flow rate to match the required minimum scour velocity (Wedel, 2000). Flume pipes then must be installed by reputable contractors willing to and capable of strictly adhering to design drawings. Flume systems are not particularly common when teamed with ADs as they require substantial quantities of water, thereby, diluting the influent and increasing reactor size and parasitic heat demand (e.g. heating water). Recently, however, ADs have successfully operated in flume systems where pre-AD the manure influent it thickened using conventional liquid-solid separation equipment.

The SMS systems presented here as AD pretreatment rely on scrape systems or any system that does not rely on dilution to convey SLM. These systems include: scraping directly to a reception pit, scraping (manual or automatic) to an auger, or vacuum tanking.

Sand-Manure Separation pre-AD

All sand-manure separation (SMS) systems rely on gravity settling, which is largely due to the favorable conditions leading to differential settling. As previously noted, mining-duty sand washing equipment and system design methodologies are used to separate sand from manure. To achieve maximum sand recovery, three Stages of SMS are necessary and shown as Stages 1 through 3, below. Each Stage is designated as
either controlled (sand recycle) or non-controlled (sand disposal) separation. The complete SMS process, pictorially, is shown in Figure 3 and material process flow diagram in Figure 4.

**Stage 1: Primary SMS**

The Stage 1 SMS is a mining duty sand washing system modified for washing manure solids from sand. In mining duty operations, the same class of equipment is used to wash organic contaminants from sand deposits. Using an auger or piston pump, SLM is conveyed into the Stage 1 SMS unit where it is diluted approximately 1:1 (one part water to one part of SLM) using parlor wash water at an approximate rate of 80 gal/min. This is not extra fresh water being added to the system for the purpose of SMS, per se, but instead water that is normally necessary for milking and parlor/holding pen hygiene. Quality of the recycled water is critical and should contain less than 2% TS. Once diluted, settled sand is conveyed out of the SMS using a mining duty auger. Prior to discharging from the SMS, the sand is rinsed with fresh water at an approximate rate of 5 gal/min (1 to 2 gal/cow/day = 0.25 ft³/cow/day). Even though this is indeed fresh water being introduced into the system for the purpose of reclaiming sand, the amount of sand removed (0.4 ft³/cow/day) from manure exceeds the amount of fresh water added. Manure, fine sand, along with water flows over a series of overflow weirs.

![Figure 3: Sand-Manure Separation System](image)

1. INCLINED MANURE AUGER
2. SAND-MANURE SEPARATOR
3. PUMP TO HYDROCYCLONE
4. HYDROCYCLONE
This primary phase of SMS achieves recovery of approximately 85 to 90%. The total solids content of the Stage 1 SMS effluent is approximately 5 to 7% TS. This corresponds to a dilution ratio of 1:1, or, one mass part of water to one mass part of SLM added to the system.

The level of sand recovery and conversely sand bypass achieved in Stage 1 is acceptable for many dairy operations, however, unacceptable for AD systems. The reason for fine sand bypass is fine sand grains cannot overcome the viscosity of the bulk slurry even at a 1:1 dilution.

**Stage 2: Hydrocyclone**

Recalling Stokes’ Law, for particles to settle, inertial forces causing settling must be greater than the viscous forces keeping particles in suspension. Hydrocyclones are mining-duty devices used to separate fine sand from slurry (Figure 5). A hydrocyclone consists simply of a hollow, conical “body”. SMS effluent from Stage 1 flows into an above ground steel sump and pumped using a rubber lined pump into a hydrocyclone. In the hydrocyclone particles flow at a high velocity in a circular motion. This imposes centrifugal force on solid particles greater than that which is experienced at 1 “g”. The heaviest particles such as sand are forced to the wall of the hydrocyclone and essentially flow and/or settle to the discharge opening at the bottom of the cone (underflow). The underflow material is discharged back to the Stage 1 SMS and combined with the settled sand recovered in Stage 1. The hydrocyclone captures an additional 5 to 15% of the sand entering the system depending on the original sand
gradation. Liquids, lighter materials like manure solids, and fine sand grains are forced out through the top of the cone (overflow).

**Stage 3: Gravity Settling**

Gravity settling by means of a sand lane follows the hydrocyclone. Sand lanes capture a majority of the fine sand discharged from the hydrocyclone. Sand bypass from the hydrocyclone can occur due to multiple reasons. There are physical limits as to how fine of sand grains a hydrocyclone capture. Fine sand grains may also be embedded or otherwise attached to manure solids. After the turbulence induced by the pumping, the sand grains are physically removed from the organic matter. Finally, the water velocity down the sand lane can be such that fine grains of sand may settle, however, in doing

Figure 5: Hydrocyclone installed above a SMS (l) and hydrocyclone schematic (r)

so a portion of manure solids settle as well (as illustrated in Figure 2). In the interest of preventing sand from filling digesters, this loss of organic matter is considered acceptable in comparison to the alternative, that being, decommissioning and removing solids from AD vessels.

Sand lane dimensions and characteristics (slope, length, width, and surface roughness) are designed based on Mannings’ equation (see Merritt, 1968) using hydrocyclone underflow flowrate to optimize horizontal flow velocity at 0.75 to 1 ft/sec. The goal is to have a sand grain enter the lane, settle (particle flow trajectory intersect the basin floor), and not become re-entrained (scoured) into the flow. Proper management of the sand lane is critical to system success. As soon as sand begins to settle on the lane, performance changes. As the “front” of settled sand migrates down the lane, it is imperative to clean the lane before sand discharges from the lane. A sand
lane full of sand will discharge sand particles that do not have an opportunity to settle (Figure 6b).

Figure 6: Sand settling lane schematic

Two lanes facilitate cleaning since flow can be diverted to the lane not being cleaned. This results in a drier recovered product. Sand lanes are a means of non-controlled settling—that is, once constructed, nothing can be done physically to enhance performance (e.g. capture more sand and/or capture fewer manure solids). The only means of control available to the operator is cleaning frequency. Stage 3 sand contains high organic solids loading (VS approximately 5%) compared to Stages 1 and 2 and, therefore, not suitable for recycling. This sand is typically land applied.

Overall System Performance

SMS system performance data was collected from an AD system processing SLM manure at a 3,500 cow dairy after three years of operation. Concrete sand is used for bedding. It is assumed the bedding sand particle size gradation and recovery has reached equilibrium—that is, it is assumed a system recovery is lower initially as fines are washed from a large quantity of newly purchased sand. It is further assumed recovery increases and stabilizes once the fines are removed and some sand is purchased to account for the losses. The analysis considers the need to separate all fixed solids (FS) from a manure stream. Some of the fixed solids are attributable to bedding sand and some to grit in manure (not sand bedding)—the result of harvesting, blow sand, concrete degradation, and inorganic minerals in a dairy ration. All sand and grit, regardless of the source, has the potential to settle in tanks. Furthermore, gravimetric analyses of sand-laden manure samples for FS do not differentiate between sand FS and FS found in excreted manure.

Sand reclaimed from the SMS system was discharged at an average dry basis organic matter content (VS) of 1.6%. Sand is recycled to bed milk cows within one
month. By comparing the gradation of the: 1) recycled sand to the, 2) bypassed fines, and 3) input sand using an analysis method described by Svarovsky (1990), average overall recovery of useable sand (SMS Stages 1 and 2) was found to be 95%. This is a sum of the Stage 1 SMS and Stage 2 hydrocyclone recoveries of 87.0 and 8.1%, respectively (see Figure 7). Figure 8 is a complete mass flow analysis for a SMS pretreatment system. Additionally, 3.2% of sand is captured on the sand lane (Stage 3) and land applied. Settled sand recovered from the sand lane had an organic matter content of 5.0% and is judged too dirty for reuse. Overall sand recovery for the three Stages of separation is 98.3%. The remainder of the sand (1.7%) bypasses the SMS process and is discharged to the digester. For 3,500 cows, 1.7% bypass represents 3,027 pounds of sand per day or approximately one cubic yard. Although some of this sand could eventually settle in an AD vessel, the majority of it is extremely fine (less than 100 mesh) and will remain in suspension due to the viscosity of the manure. Using concrete sand is advantageous since a majority of sand fines are washed out during the manufacturing process. AD designers should have a contingency plan in place to address potential sand accumulation in tanks. Due to the dilute nature of the SMS system discharge (5.7%), any AD receiving this influent will include some kind of mixing. Influent at these low TS concentrations are best suited for mixed plug flow or complete mix systems.

Figure 7: Separated sand outcomes

As previously described, due to the dilution necessary to facilitate sand settling, SLM is typically introduced to a SMS system at approximately 30% TS. Sand lane (Stage 3) liquid discharge ranges between 5 and 7% TS. AD designers should be aware of the composition of AD effluent post SMS, particularly TS and VS. Gooch et al. (2006) describes considerations with regard to AD heating requirements when digesting diluted versus undiluted SLM. Lower TS creates a higher parasitic heat load and potentially a system with lower energy output when compared to undiluted AD influents. Some AD operators have observed digesting influent at lower TS concentrations, despite gas output being lower, methane concentration is higher when compared to biogas produced from less dilute manure since contaminants such as carbon dioxide remain in solution. This is a topic for further study. Generally speaking, biogas production is decreased since volatile organic solids (VS) are captured in sand throughout the SMS
settling processes. These VS are otherwise fuel for the AD. Approximately, 4.6% of the VS introduced to the SMS system are lost to the recycled sand (Stages 1 and 2) and discard sand (Stage 3).

Figure 8: Sand-manure separation (SMS) system mass balance

<table>
<thead>
<tr>
<th>Sand-Laden Manure In</th>
<th>Stage 1: SMS Sand</th>
<th>Stage 2: Hydrocyclone sand</th>
<th>Stage 3: Sand Lane Liquids</th>
<th>Stage 3: Sand Lane Solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass 700000 lb</td>
<td>Dry FS (sand) 154914 lb</td>
<td>Dry FS (sand) 14423 lb</td>
<td>Dry FS (sand) 3027 lb</td>
<td>Dry FS (sand) 5698 lb</td>
</tr>
<tr>
<td>Dry FS (sand) 178063 lb</td>
<td>Recovery 87%</td>
<td>Recovery 8.1%</td>
<td>Recovery of total 1.7%</td>
<td>Recovery of total 3.2%</td>
</tr>
<tr>
<td>TS 35.0%</td>
<td>TS 80.0%</td>
<td>TS 60.0%</td>
<td>TS 5.7%</td>
<td>TS 60.0%</td>
</tr>
<tr>
<td>VS db 1.5%</td>
<td>VS db 1.5%</td>
<td>VS (db) 3.0%</td>
<td>VS 5.5%</td>
<td>VS (db) 5.0%</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Sand remains the freestall bedding of choice amongst dairy producers due to benefits related to cow comfort, udder health, and milk quality and quantity. Sand-manure separation (SMS) systems operating as anaerobic digester (AD) pretreatment
are proven on large dairies over the long-term. Accommodating sand users interested in AD could potentially increase AD adoption since some producers will elect not to bed with manure—the norm with traditional AD systems.

1. Understanding the relationships involving the settling characteristics of sand and manure solids are key to designing successful SMS systems and sand-laden manure handling systems in general.

2. Mining duty design methodologies and equipment are used to separate sand from manure pre-AD. Properly designed SMS systems are capable of 98% sand recovery. This level of sand recovery is achieved via three Stages of SMS: 1) primary SMS, 2) hydrocyclone, and 3) gravity settling.

3. Of the 98% sand recovery, 95% is recycled in Stages 1 and 2 and used to bed milk cows. The remainder captured in Step 3 is land applied. Bypassed sand must be accounted for whether by agitation (preferred) and/or by providing means for tank clean-out. Some organic solids are captured along with the separated sand due to similar settling characteristics for some sand and manure solids. The result is a 4% loss of organic matter (4% not delivered to the AD). The loss of organic matter must be accounted for when estimating biogas production. SMS effluent (AD influent) discharges at approximately 6% TS. AD systems should be selected accordingly with regard to mixing and heating requirements.

REFERENCES

American Society of Agricultural and Biological Engineers. 2011. ASABE Standards. ASABE. St. Joseph, MI.
Wedel, A.W. 2000. Hydraulic conveyance of sand-laden dairy manure in collection channels (paper # 20004106). Annual International Meeting of ASABE, Milwaukee, WI.
SOURCE SEPARATED FOOD WASTE FLOW TO FARM DIGESTERS

N. Goldstein
BioCycle/The JG Press, Inc.
Emmaus, PA

INTRODUCTION


\(^1\) a total of 34.76 million tons of food waste was generated by the residential, commercial and institutional sectors in 2010. Of that 34.76 million tons, only 2.8 percent — or 0.97 million tons — were recovered and utilized as animal feed, or composted or anaerobically digested. The USEPA’s definition of municipal solid waste (MSW) does not include industrial or agricultural waste streams. Therefore the 34.76 million tons do not include residuals from food processors and manufacturers, beverage industries or agricultural operations.

In its food waste management hierarchy, USEPA lists the highest and best end uses for food waste in the MSW stream. At the top of the hierarchy is source reduction, i.e., not generating food waste in the first place, e.g., through better food purchasing practices and inventory management. Next on the list is donation of edible food, e.g., food that is close to its sell date that can be donated to food banks. After donation on the hierarchy is animal feed, followed by “industrial uses,” which includes anaerobic digestion, then composting and finally, disposal.

Several factors contribute to the reality that less than 3 percent of the food waste generated in the United States is recovered. First is the lack of processing infrastructure for food waste, either via composting or anaerobic digestion. Second is relatively low landfill tipping fees that make it challenging for food waste recycling facilities to compete. Third is the potential for contamination in the food waste, primarily plastic— even when food waste is separated from packaging and there is signage on “organics only” collection containers explaining what is allowed. Contaminants are a deterrent to processing facilities (both composting and digesters).

On the other hand, a number of factors have been facilitating more diversion of source separated food waste from disposal. Many state and local government agencies have established programs to encourage source separation of food waste in the commercial and residential sectors. This includes training programs for businesses and institutions on how to separate and collect food waste from kitchens, cafeterias, restaurants and other food service establishments, as well as grocery stores and

produce terminals. As more programs have been established, haulers have responded with collection services, and processors have taken steps to be permitted to receive the feedstocks.

Also driving diversion of food waste are corporate and institutional commitments to sustainability, which include reducing waste generation and disposal, and increasing food donations and diversion to composting and anaerobic digestion. This commitment includes recognition that even though the costs to start a diversion program may be higher than what companies and institutions currently pay for disposal (and more labor may be involved for separation and collection), they are willing to take that step. Furthermore, as companies and institutions begin diversion programs, they quickly find that the decrease in frequency of trash disposal service offsets the higher costs of diversion. They also become aware of how much food is being disposed, which leads to better purchasing practices.

On the food processing side of the source separated food waste stream, industries are facing more restrictions on direct land application, or else are having to haul materials longer distances to farmland. Discharge directly to the wastewater treatment plant may be restricted, or the sewer surcharges may be costly. These trends are leading more industrial generators of source separated food waste to consider diversion to anaerobic digestion.

Finally, states are recognizing the benefits of food waste diversion, and are revising and/or creating regulations that make it easier to receive and process food waste. Increasingly, states also are establishing guidelines and permitting procedures for diversion of food waste to anaerobic digesters.

SOURCE SEPARATED MATERIALS AVAILABLE FOR AD

Source separated food waste, as distinguished from mixed waste, is material that has been separated at the point of generation, removing nonorganic items such as plastic, metal and glass. In the municipal solid waste stream (commercial, institutional, residential), source separated food waste generally falls into two categories — preconsumer and postconsumer. Preconsumer food waste is any food that has not yet been served. This includes kitchen prep waste, food that is past its sell date and prepared foods that cannot be donated. Preconsumer food waste, primarily from a regulatory perspective, is further divided into vegetative and nonvegetative (e.g., meat, dairy, fish) categories. This distinction revolves around potential pathogen and vectors in the nonvegetative stream.

Postconsumer food waste is comprised of food that has been served but not consumed, e.g., plate scrapings, salad bar contents. It typically is regulated as nonvegetative. Finally, many source separated food waste diversion programs include soiled paper and wet and/or waxed corrugated cardboard.
While the USEPA distinguishes between food waste from the residential, commercial and institutional sectors and food waste from the industrial and agricultural sectors, most state regulatory agencies have not designed their permits in the same way. Typically, vegetative food processing residuals fall into a similar category as vegetative preconsumer food waste from the MSW stream. For example, a composting facility permitted to receive source separated, preconsumer vegetative materials can receive produce waste from grocery stores and potato peels from a food processor. In fact, many composters prefer the “industrial” materials because they have little to no contamination and can be immediately incorporated into composting operations.

Anaerobic digestion facilities are tapping into many of these same source separated food waste streams. They are able to benefit from many years of outreach, education and training on source separation procedures as well as establishment of collection and hauling services — primarily developed for diversion to composting. The challenge, however, is that the much of this material requires preprocessing before it can be added to anaerobic digesters (unless a higher solids AD technology is utilized).

Quantification of Source Separated Food Waste Streams

Quantifying how much source separate food waste is available for diversion by various sectors is not an exact science. The data available is typically based on waste characterization studies, such as sorting and weighing food waste from a cross section of generators. In terms of the commercial sector, a June 2006 waste characterization study by Cascadia Consulting Group, prepared for the California Integrated Waste Management Board (now CalRecycle) focused on waste disposal and diversion for selected industry groups, including food service and grocery stores. The following is a summary:

- Full service restaurants generate 4,400 lbs waste/yr/employee (after recycling) of which 66% are food scraps.
- Fast food restaurants generate 4,250 lbs waste/yr/employee (after recycling) of which 52% are food scraps.
- Grocery stores generate 4,750 lbs waste/yr/employee (after recycling) of which 65% are food scraps.
- Large hotels generate 3,900 lbs waste/yr/employee (after recycling) of which 44% are food scraps.

Biomethane Potential of Food Waste

Scientific literature typically reports yield of biomethane in terms of methane yield per dry weight of volatile solids. It is commonly recognized that food waste has about double the methane yield per pound of volatile solids than dairy manure (15.0 ft³/lb VS

---

vs 7.0 ft$^3$/lb VS). In a study on pretreatment of municipal solid waste prior to anaerobic digestion, Zhang et al reported that food waste has 511 ml/g volatile solids, or a methane content of 9,630 ft$^3$/dry ton. This is equivalent to 64% methane content.

A fact sheet prepared by Washington State University Extension, “Anaerobic Co-Digestion On Dairies in Washington State,” cites an economic analysis of an anaerobic digester facility installed on a 700-cow dairy in northwest Washington. “…co-digestion with 16% organic wastes more than doubled biogas production and almost quadrupled annual digester revenues compared to a manure-only baseline, with 72% of all receipts directly attributable to the addition of organic wastes.”

A 2011 report by David Paul Rosen & Associates, Anaerobic Biodigester Financial Feasibility Assessment, conducted for the Washington State Housing Finance Commission, calculated that the average electricity output from manure alone is 0.25 kW/cow. Adding 10% food waste by volume is estimated to increase electrical production by 25%. Adding 20% food waste by volume is estimated to increase electrical production by 50%.

Costs To Accommodate Source Separated Food Waste

Unlike some industrial or agricultural food processing residuals that are in a slurry form when delivered to a farm digester, source separated organic wastes arrive in a solid or semi-solid state. In order to be loaded into the digester, these materials must be preprocessed to reduce the solids content. This can entail capital expenditures on the part of the farm, however these costs can be offset by anticipated revenue from tipping fees as well as increased biogas production.

Ideally, digester developers and owners would like to secure multiyear contracts to receive source separated food waste, but generators and/or the haulers may be reluctant to commit to a certain price (per ton or per gallon) as the solid waste disposal market is highly competitive. Another consideration for the farms is having some storage capacity for these food wastes if the digester is down for maintenance or repairs.

Reinford Farm in Mifflintown, Pennsylvania, receives 60 to 70 tons/week of commercial food waste primarily from Walmart and Sam’s Club stores in the region.

---


4 Anaerobic Co-Digestion on Dairies in Washington State. Washington State University Extension Fact Sheet (FS040E)

which it processes with manure from about 500 cows. Walmart associates are trained to separate packaging from the food waste, which consists primarily of nonedible produce and bakery waste, and a small amount of dairy. The food waste is stored in 3- and 4-cubic yard locked receptacles, and hauled about once a week to Reinford Farm.

The food waste is emptied into a holding pit and then loaded into a grinder designed and built by Reinford. (It is a forage chopper that was revamped to grind food waste.) The food waste is ground for 30 to 45 minutes and then added to a concrete influent tank where it is mixed with manure. The mixed materials, at about 14 percent solids, are gravity-fed through a six-inch pipe into the digester every four hours for 15 minutes.

Haulers who deliver source separated food waste to dairy farms for co-digestion note that it is optimum to have the ability to observe the loads prior to preprocessing in order to remove any contaminants. Having a visual inspection pit enables the driver to pull out contaminants. Locating the unloading area and/or pit where the truck has adequate room to raise the trailer is also critical, as is having easy in and out access to the unloading area. To eliminate the need to preprocess on the farm, some haulers are evaluating the feasibility of either having a grinder installed on the truck, or else having a centralized transfer station where source separated food waste can be processed prior to delivery to the farm.

Brubaker Farms near Mount Joy, Pennsylvania receives preprocessed food waste from the dining hall at nearby Elizabethtown College, which it adds to its digester. At the college’s main Marketplace Dining Facility, a revolving carousel delivers students’ trays to the kitchen, where staff scrapes the food waste into a grinder — basically an industrial-sized garbage disposal. Processing is helped along by a recirculating stream of water. The pulped food waste slurry from approximately 2,400 meals served daily travels through 2-inch copper piping to an extractor, where it is pressed to 80 percent solids. These are placed into 32-gallon toters for a twice-weekly haul to Brubaker Farms. The recirculating grey water from the pulping process is changed with fresh water daily at an appointed shutdown time and gets pumped to an outside holding tank where it is mixed with the fats, oils and grease (FOG) also generated by the cafeteria. That mixture is pumped twice weekly through a 1.5-inch pipe (insulated and encased in a 6-inch pipe) into a mobile 1,200-gallon tank mounted to the front cargo area of a box truck. That leaves room for the six to eight toters — weighing about 200 pounds each — of pulped and separated solids.

The farm receives about $400/month in tipping fees. A 25,000-gallon reception pit holds food waste from Elizabethtown College as well as what Brubaker refers to as “spot loads” of rejected milk from other area dairies and food processing waste from local manufacturers including candy rinse water and chocolate. About 725 of 800 total milking cows along with 500 heifers of varying ages supply the digester with approximately 22,000 gallons of manure daily. The manure gets delivered to a twin 25,000-gallon reception pit and then goes into the digester four times daily via a Vaughn chopper pump. The food waste gets added to the manure right before the Vaughn unit
pumps it into the digester. The reception tanks are rarely full, and therefore can accommodate several truckloads of food waste at one time if needed.

Increasingly, farm digesters are being designed with capacity to receive source separated food waste streams, as well as other high strength organics such as ethanol thin stillage, glycerin, and food processing residuals. For example, a community digester constructed near Waunakee, Wisconsin in Dane County installed a stand-alone substrate tank to receive fats, oils, grease and other high strength organic wastes that are blended with the raw manure and added to the digester tanks. The facility is designed to receive about 8,000 gallons/day of food waste and other substrates, which are expected to increase biogas production by 50%.

PERMITTING CONSIDERATIONS

Farm digesters processing only manure often are regulated under CAFO rules, and/or within a state’s Department of Agriculture. Source separated food waste from the municipal solid waste stream is typically regulated under a state’s solid waste management rules. Agricultural and industrial food processing residuals can fall within agricultural, solid waste and/or wastewater rules.

Recently, the USEPA AgSTAR website added a page on State Permitting Requirements for anaerobic digesters.\(^6\) The table is divided into air, solid waste and water permits. In Washington State, for example, AD systems that contain at least 50 percent manure and no more than 30 percent other organic waste may operate under an exemption from solid waste handling permits. Systems not subject to the exemptions must obtain a permit.

In Michigan, if a material other than manure is added to the AD system, authorization may be required before composting or land applying the solids; each operation is encouraged to work with the Michigan Department of Environmental Quality to determine what might be required. Some materials are exempted from permitting including food processing residuals, syrup from ethanol production and grease trap wastes that do not contain septage and fish wastes. To be exempt, the anaerobic digester must accept less than 20% other organics.

In Ohio, AD systems accepting manure only and less than 25% by volume of organic wastes can be permitted through the Ohio Department of Agriculture, as long as the facility complies with its nutrient management plan. Approved organic materials include preconsumer food wastes, grease trap wastes and similar organics. For AD systems processing more than 25% of other organic wastes, the Ohio EPA becomes involved in the permitting process and a separate permit may be required.

Massachusetts has a draft rule out for public comment that will create regulations for anaerobic digesters processing source separated food waste. A draft circulated in the summer of 2011 establishes a new exemption from site assignment for anaerobic digesters receiving source separated organics. (Normally, a solid waste facility is required to obtain site assignment from the local board of health, and a solid waste permit from the Massachusetts Department of Environmental Protection.) Three categories of digester facilities were proposed:

- Farm AD Unit: exempt from solid waste regulations as long as complies with Department of Agricultural Resources regulations.
- Non-Farm Unit: obtains Permit By Rule if <60 tons/day and complies with performance standards.
- Non-Farm Unit > 60 tons/day taking source separated organics must apply for recycling, composting or conversion permit that would exempt unit from site assignment and solid waste permitting. Would need to obtain permit to manage SSO.

CONCLUSIONS

The high energy content of source separated food waste from the municipal, industrial and agricultural sectors makes these organic wastes good feedstocks for anaerobic digestion. Public and private sector interest in diverting source separated food waste from disposal in landfills is contributing to establishment of collection programs. The potential for contamination of source separated food waste — primarily from the commercial (e.g., foodservice), institutional and residential sectors — is a deterrent to accepting these feedstocks at anaerobic digesters, as contaminants can cause mechanical breakdowns and add labor to pick contaminants out of incoming feedstocks. Furthermore, source separated food waste typically requires particle size reduction prior to addition to the digester.

At the same time, anaerobic digesters that receive source separated food waste typically receive a tipping fee, and benefit from increased biogas production. It is becoming more common for digesters being built today to include receiving and or storage capacity for source separated food waste and other substrates.

Recognition of the "biogas boost" from food waste — as well as the tipping fee revenues — is attracting other digester facilities to build capacity to receive these feedstocks. This includes existing municipal wastewater treatment plants and new commercial, non-farm digesters. This has the potential to increase competition for source separated food waste.
UW-Platteville and Underwriter Laboratories-Environmental along with the Wisconsin State Energy Office entered into an agreement over the summer of 2010 to carry out an analysis of biobased plastics at the benchtop and pilot scale level. Telles also served in an advisory role during this study. The goal was to determine if biobased plastics that have been shown under ASTM procedures (ATSM 6400) to be compostable could also be anaerobically digested. If the plastic can be shown to be digestible, it could lead to a large shift in food waste being diverted from landfills in the near future. This study carried the analysis one step further than by not only doing benchtop analysis, but also performing the analysis at the pilot scale level.

EXPERIMENTAL

The benchtop studies were carried out using a Bioprocess Control AMPTS unit. The procedure was altered from the standard ASTM 5511 test to better reflect actual dairy farm anaerobic digester conditions. The procedure mixed 300 ml of seed stock (digested manure) with 30 ml of a micronutrient buffer similar to the ASTM 5511 buffer solution providing 10% of the micronutrients in the ASTM procedure. Then 2 – 9 grams of the plastic to be tested was added to the bottle. Each test was done in triplicate along with a blank, negative (polyethylene), and positive (paper/cellulose) control. The analysis was then performed for 28 days to determine the total methane potential of each sample.

The pilot scale analysis was carried out using a trailer manufactured by Duane Hanusa of Baraboo, WI. This digester consisted of four 70 gallon tanks with individual temperature controls, a time controlled injection pump and a chopper pump. The tanks were filled to the 50 gallon level with about 20 gallons of gas space at the top. Each tank was heated individually. The procedure was to take 5 gallons of manure, add 5 gallons of water, run it through the chopper pump for 3-5 mins, and then place these 10 gallons in the tub with the injection pump. The injection pump was set up to inject for 6 seconds every 160 mins, so that within 24 hours, all of the manure mix would be added. The next day, a gas reading would be taken and then 10 gallons would be drained out and the process repeated. The gas monitoring unit consisted of a weighted flow meter that measured between 0.0 and 5.0 ft³/hr of total gas flow. The digester was run at mesophilic conditions of 35 °C, as 95% of dairy digesters are run at the temperature of ~100 F.

Initially the pilot scale digester was started in the middle of September with 5 gallons of seed stock from a DVO (was GHD) digester and 195 gallons of manure from the
dairy barn flush pit. To replicate the barns flush pit, 5 gallons of manure was collected from an aisle that was low in sawdust bedding, but far from the foot bath area and then mixed with 5 gallons of water.

RESULTS

Benchtop Analysis

In Figure 1, you can see a typical graph of the Biomethane potential experiments carried out at 38 °C with the average of methane production for the three trials displayed. These were performed using the Bioprocess Control AMPTS II unit.

![Figure 1. AD of Telles PHA Plastic](image)

It should be noted that the blank and negative control are almost identical and can hardly be seen on the graph. As displayed in Figure 1, the Telles plastic acts very similarly to the positive control of cellullosic paper with a short induction period. The main difference between the three plastics was the total amount added, two to eight grams. The total vaules for these experiments follow in Table 1 showing very good % of biodegradation of all Telles plastics. The P 5001 plastic was a film that could be used in food wrapping. The P 1008 was thermoformed into plastic utensils and the F 3002 was ground factory beads. It was found that the factory beads need to have their outer shell broken; otherwise the bacteria cannot access the polymer chains effectively to break it down in a timely manner.

Not shown in Figure 1 are Natureworks PLA type plastics. PLA did not show gas production above the blank except for PLA coated paper cups. This gas production however, was from the digestion of the paper since the thin plastic coating could still be found in the container after the 28 day trial. It was later determined that the PLA plastic does not compost below temperatures of 160 °F, or 60 °C which is when the ester bonds of the PLA backbone start to hydrolyze.
Table 1. Benchtop Digestion of Telles Plastics

<table>
<thead>
<tr>
<th></th>
<th>grams added</th>
<th>Methane Produced (Liters)</th>
<th>% CH₄</th>
<th>% Biodegradation</th>
<th>Methane per gram (L/gram)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank</td>
<td>0.000</td>
<td>0.535</td>
<td>64.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Positive</td>
<td>8.006</td>
<td>0.572</td>
<td>49.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Negative</td>
<td>8.007</td>
<td>3.83</td>
<td>60.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>P 5001</td>
<td>2.012</td>
<td>1.5</td>
<td>51.8</td>
<td>94.5</td>
<td>0.480</td>
</tr>
<tr>
<td>F 3002</td>
<td>2.021</td>
<td>1.48</td>
<td>59.4</td>
<td>91.9</td>
<td>0.468</td>
</tr>
<tr>
<td>P 1008</td>
<td>8.022</td>
<td>3.72</td>
<td>57.3</td>
<td>78.5</td>
<td>0.397</td>
</tr>
</tbody>
</table>

PILOT SCALE ANALYSIS

Figure 2, displays the gas production over the time of the experiments at the pilot scale level. Since most of the plastics were digested at the benchtop scale within 14 days, all trials were carried out by adding substrate for 14 days and then followed with 14 days of manure mix only. It was not until looking back at the results that it was determined that this should have been closer to 20 days which is the average retention time of this digester design. The plastics were added with incremental amounts; 2 lbs the first day, 3 lbs the second day, and then 4 lbs every day after until the supply ran out.

The final analysis carried out was adding copier paper that was shredded with a cross cut shredder. For this analysis only 2 lbs of paper was added each day due to the clogging of paper wads. With 10 gallons of manure mix, at about 8 lbs per gallon, this is only an addition of 2.5% by mass, but closer to 40% based on volatile solids. The plastics tested at the pilot scale were the Telles F1005, Telles F3002, BPSM, and Corn Products RD704.

Looking at Figure 2, it becomes quickly apparent that using a gas monitoring device that is only good to 0.2 ft³ volume/hour lead to very sporadic readings. These readings were only taken once a day and were observed while tank 2 was mixing. This was chosen to try to be consistent from day to day realizing that each tank produced different amounts of gas as well as differences in release when stirring and not stirring.
Many of the plastics in the 200 gallon digester behaved as predicted by the benchtop. The amount of gas production for comparison was determined by taking the last 5 days of gas readings before making changes. This would mean that the baseline used to calculate the increase in gas production for a given plastic was calculated by taking the average of the gas readings for the 5 days before adding the plastic to the manure mix. The plastic gas production was then calculated by averaging the last 5 days of gas production when adding the plastic, for instance, days 9-14. With standard deviations, the gas production for any of the plastics was about the same. What can be said however is that the plastics did not hinder the digestion of the manure.

All of the Telles plastic was digested in the pilot scale digester with no plastic observed in the effluent until the BPSM plastic was added. The BPSM plastic was noticed in the effluent after 9 days of addition. The BPSM plastic factory beads were not ground and were tested in the pilot scale digester in the hopes that the chopper pump or internal pumps of the four tanks would crack the beads.

The Corn Products, #RD704, plastic showed potential according to the benchtop results where it produced 0.20 L of methane per gram of plastic with about 75% of the plastic disappearing. This plastic is not certified to undergo composting as it does contain some non-biodegradable plastic mixed with corn starch. When it was tested in the pilot scale however, the corn starch portion of the plastic turned tank #1 into “gravy”.

Figure 2. Pilot Digester with Various Feed Stock

![Graph showing gas production with various feed stocks over time. The graph includes data points for Manure, F1005, F3002, BPSM, RD704, and Paper, with Manure showing the highest gas production.](image-url)
That is, the solution became very viscous and plugged the system. Therefore, this test
did not last more than 4 days before tank 1 had to be partially drained.

CONCLUSION

The plastics behaved very similarly at the pilot scale when compared to the
benchtop in relation to digestion. For instance, all of the Mirel products (F1005 and
F3002) broke down with none of the plastic coming out the effluent.

This cracking was only needed for the factory beads as some Mirel thermoformed
plastics were tested at the benchtop and the results were the same if not better than the
ground factory beads. These beads are how the plastic is typically shipped to the
factories where it is processed into a final product, so very few of these should be in a
waste stream.

With the limited quantitative ability of the gas monitoring device, it can be determined
with only a small amount of confidence if the gas production increased or decreased
when substrates were added. In all cases, an increase in gas production was observed.
Therefore, the data does support that the benchtop studies are good predictors of
digestion at the pilot scale. This study also supports the concept of testing plastics at
the pilot scale level before placing large quantities in a full scale digester where any
negative consequences could be disastrous.
DAIRY CATTLE MORTALITY MANAGEMENT VIA ANAEROBIC DIGESTION

J. H. Martin, Jr., J. Coombe, and K. Henn
Tetra Tech, Inc.
Pittsburgh, Pennsylvania

INTRODUCTION

With the decline in the number of rendering operations due to industry consolidation and concern about Bovine Spongiform Encephalopathy (BSE) transmission, disposal of dairy and beef cattle mortalities by rendering either is not an option or is prohibitively expensive in many areas of the United States. On-site burial remains an alternative in many states, but impact on ground water quality is of concern. Many landfill operators either refuse to accept livestock mortalities for disposal, or the cost is difficult for producers to absorb. Incineration, an option for carcass disposal, has high investment and operating costs and is complicated by regulatory compliance issues. Another disposal alternative is co-composting with a carbonaceous material such as sawdust or straw. However, both incineration and composting generally are more suitable for the disposal of small animal mortalities such as those from poultry operations.

The success, especially in Europe, of using anaerobic digestion for the stabilization of slaughterhouse wastes suggests co-digestion of large animal mortalities with manure and possibly other wastes is a viable disposal option for dairy cattle, beef cattle, and swine mortalities. To evaluate the feasibility of this approach for dairy cattle mortality disposal, we began by estimating methane production potential. Our approach was based on typical dairy cow carcass composition and a validated mathematical model that translates carcass composition into methane production potential. We also evaluated the risk of BSE and Johne’s disease transmission via digester effluent.

DAIRY CATTLE CARCASS COMPOSITION

Andrews et al. (1994) determined the composition of mature Holstein cows at three physiological stages: prepartum (dry), early lactation, and late lactation. Based on their findings, we calculated average Holstein carcass composition based on the prepartum, early lactation, and late lactation values listed in Table 1. These values include gastrointestinal tract contents and embryos. We assumed that: 1) the mass of non-protein nitrogen present is negligible, and 2) the mass of carbohydrates present can be estimated as the difference between total volatile matter and the sum of protein and fat.

METHANE PRODUCTION POTENTIAL BASED ON GROSS ENERGY

As shown in Table 2, conversion of gross energy as kcal per kg live weight to specific methane yield as ft$^3$ per lb of volatile solids (VS) produces an average specific methane yield of 2.5 ft$^3$ per lb of VS. This is an unrealistically low value considering that the generally accepted specific methane yield for dairy cattle manure is about three to four ft$^3$ per lb of VS added.
Table 1. Mature Holstein carcass composition (after Andrews et al, 1994)

<table>
<thead>
<tr>
<th></th>
<th>Prepartum</th>
<th>Early Lactation</th>
<th>Late Lactation</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live weight, kg</td>
<td>584</td>
<td>555</td>
<td>556</td>
<td>565</td>
</tr>
<tr>
<td>Moisture, kg</td>
<td>274</td>
<td>299</td>
<td>289</td>
<td>287</td>
</tr>
<tr>
<td>Dry matter, kg</td>
<td>310</td>
<td>256</td>
<td>267</td>
<td>278</td>
</tr>
<tr>
<td>Volatile solids (VS), kg</td>
<td>289</td>
<td>232</td>
<td>243</td>
<td>255</td>
</tr>
<tr>
<td>Ash, kg</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>23</td>
</tr>
</tbody>
</table>

| Protein, kg<sup>a</sup>                  | 78        | 81              | 86             | 82    |
| Protein, % of VS                  | 42.2      | 48.2            | 49.3           | 46.6  |
| Fat, kg                              | 90        | 48              | 81             | 73    |
| Fat, % of VS                        | 38.1      | 25.4            | 37.4           | 33.6  |
| Carbohydrates, kg<sup>b</sup>        | 121       | 104             | 77             | 100   |
| Carbohydrates, % of VS              | 19.6      | 26.4            | 13.3           | 19.8  |
| Gross energy, kcal/kg LW            | 2120      | 1620            | 2170           | 1970  |

<sup>a</sup> Calculated from total nitrogen by multiplying by 6.25
<sup>b</sup> Calculated as the difference between total volatile matter and the sum of protein and fat

Table 2. Estimate of carcass methane production potential based on gross energy

<table>
<thead>
<tr>
<th></th>
<th>Prepartum</th>
<th>Early Lactation</th>
<th>Late Lactation</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross energy, kcal/kg LW</td>
<td>2120</td>
<td>1620</td>
<td>2170</td>
<td>1970</td>
</tr>
<tr>
<td>Gross energy, Btu/kg LW</td>
<td>534</td>
<td>408</td>
<td>547</td>
<td>496</td>
</tr>
<tr>
<td>Methane, ft³/kg VS</td>
<td>0.56</td>
<td>0.43</td>
<td>0.57</td>
<td>0.52</td>
</tr>
<tr>
<td>Methane, ft³/lb VS</td>
<td>2.50</td>
<td>2.23</td>
<td>2.85</td>
<td>2.53</td>
</tr>
</tbody>
</table>
METHANE PRODUCTION POTENTIAL BASED ON THEORETICAL CONSIDERATIONS

Buswell and Neave (1930) proposed that the theoretical methane production potential of specific organic compounds could be calculated as follows:

\[ C_nH_{2b}O_b + \left( n - \frac{a}{4} - \frac{b}{2} \right) xH_2O \rightarrow \left( \frac{n + a}{2} - \frac{b}{4} \right) xCH_4 + \left( \frac{n + a}{2} - \frac{a}{8} - \frac{b}{4} \right) xCO_2 \]  

(1)

On this basis, Angelidaki and Sanders (2004) calculated the theoretical methane production potential of representative proteins, carbohydrates, and lipids per g of VS and the methane content of the biogas produced (Table 3). They noted that practical methane yield always would be lower because of the following factors:

- substrate utilized to synthesize microbial mass
- substrate lost in the effluent
- resistance of lignin to anaerobic microbial degradation
- binding in particulate matter
- nutrient limitations

Although some lignin will be present in the gastro-intestinal tract of dairy cow mortalities, it will be minimal and not significantly reduce carbohydrate biodegradability.

Table 3. Theoretical methane production potential of carbohydrates, proteins, and lipids (Angelidaki and Sanders (2004)).

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Composition</th>
<th>CH4 yield, L/g VS</th>
<th>Biogas CH4 content, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbohydrates</td>
<td>(C6H10O5)n</td>
<td>0.415</td>
<td>50</td>
</tr>
<tr>
<td>Proteins(^a)</td>
<td>C5H7NO2</td>
<td>0.496</td>
<td>50</td>
</tr>
<tr>
<td>Lipids</td>
<td>C57H104O8</td>
<td>1.014</td>
<td>70</td>
</tr>
</tbody>
</table>

\(^a\)Nitrogen is converted to NH3.

Based on the work of Angelidaki and Sanders (2008), Hejnfelt and Angelidaki (2009) proposed that theoretical methane yield from slaughterhouse wastes could be calculated based on the relative fractions of proteins, lipids, and carbohydrates as follows:

\[ \text{CH}_4, \ \text{m}^3/\text{kg VS} = (0.496X)+(1.014Y)+(0.415Z) \]  

(2)

where:  
X = protein fraction of VS, decimal  
Y = lipid fraction of VS, decimal  
Z = carbohydrate fraction of VS, decimal
As shown in Table 1, Andrews et al. (1994) data suggest that the VS in an average mature Holstein carcass are 46.6 percent protein, 33.6 percent fat, and 19.8 percent carbohydrates. Substituting these values into Equation 2 yields a theoretical methane yield of 0.654 m$^3$ per kg of VS (10.5 ft$^3$ per lb of VS) for dairy cow mortalities. This translates into approximately 3,000 ft$^3$ of methane per 1,400 lb cow.

**EXPERIMENTAL RESULTS**

In their study of the anaerobic digestion of swine slaughterhouse wastes, Hejnfelt and Angelidaki (2009) reported that a mixture of solid wastes with blood produced a maximum rate of 0.620 m$^3$ of methane per kg of VS added (9.9 ft$^3$ per lb of VS added) in a series of 40-day, mesophilic batch studies. This maximum rate occurred at a waste-loading rate of five percent by volume. Waste loading rates of 20, 50, and 80 percent decreased methane yield. The theoretical methane yield for this waste was calculated using Equation 2 to be 0.600 m$^3$ per kg of VS added (9.6 ft$^3$ per lb of VS added). Neither thermal pretreatment nor pretreatment by the addition of sodium hydroxide had a significant effect on the biodegradability or methane yield of the mixed pork waste.

In a continuously stirred tank reactor experiment at 37 °C in which mixed pork wastes were co-digested with swine manure, the mixed pork loading rate of five percent by volume produced the highest specific methane yield from the pork waste of 0.900 m$^3$ per kg of VS added (14.4 ft$^3$ per lb VS added). Given that the specific methane yield for the pork waste was higher than the theoretical methane yield and the yield observed in the batch studies, Hejnfelt and Angelidaki suggested the possibility of a synergetic effect increasing the methane yield from the swine manure.

Hejnfelt and Angelidaki suggest that a high dilution rate, such as five percent, is preferable, and animal by-products may contain compounds that can inhibit methanogenesis. Specifically, they cite the work of Angelidaki et al. (1990), Angelidaki and Ahring (1992), and Broughton et al. (1998), which indicates that lipids could cause problems during anaerobic digestion because of the possible accumulation of intermediates, such as long-chain fatty acids inhibiting microbial activity. They also suggest that process stability is problematic with thermophilic digestion and probably is due to the inhibition of methane-forming bacteria by ammonia.

Massé et al. (2008) investigated the feasibility of co-digesting swine mortalities with swine manure in sequencing batch reactors at 20 and 25 °C as a method for on-farm carcass disposal. Sequencing batch reactor performance at loading rates of 20 and 40 kg of ground whole 130 kg carcasses per L of manure was determined for two and four week treatment cycles. At 25 °C, there were no statistically significant differences in methane production between the control reactors (only manure) and reactors that received a mixture of manure and 20 or 40 kg per L of ground carcasses per kg of chemical oxygen demand (COD) added. Methane production ranged from 0.274 to 0.334 m$^3$ of methane per kg of COD (approximately 0.702 to 0.856 m$^3$ of methane per kg of VS or 11.24 to 13.7 ft$^3$ per lb of VS) fed. Based on the composition of the
carcasses used in this study, Equation 2 predicts a specific methane yield of 0.727 m$^3$ of methane per kg of VS added (11.6 ft$^3$ per lb of VS added).

Massé et al. (2008) also mentioned the inhibitory effect of long-chain fatty acid accumulation and cited the work of Chen and Shyu (1998) exploring the feasibility of anaerobically digesting poultry mortalities. Chen and Shyu found methane formation was inhibited even at the low loading rate of 2 g COD per L of reactor volume per day. Massé et al. also cited the work of Abraham et al. (2006), which indicated that total fatty acids accumulated and pH decreased when the ratio of lipids to proteins exceeded 0.1.

**BIOSECURITY ISSUES**

Acceptance of anaerobic digestion as a method of dairy cattle mortality disposal will depend on the perception of the risk for transmission of BSE and Johne's disease in digester effluent. BSE is a progressive, fatal, neurologic disease of adult domestic cattle that is similar to scapie in sheep and goats (Merck and Company, Inc., 1998). Johne's disease, also known as paratuberculosis, is chronic, contagious enteritis characterized by persistent and progressive diarrhea, weight loss, debilitation, and eventually death (Merck and Company, Inc., 1998).

Incidence of BSE has been linked to the inclusion of bovine derived meat and bone meal in cattle rations. In response to this finding, the feeding of rendering products that contain or may contain protein derived from mammalian tissues to cattle or other ruminants has been prohibited in the United States since May 1997 (Federal Register, 1997). Canada, the European Union, and the United Kingdom have similar regulations in effect.

Through February 2011, surveillance has identified 22 cases of BSE in North America of which three were in the United States and 19 in Canada (CDC, 2011). Of the three cases in the United States, one animal was born in Canada. The first known case of BSE in the United States was identified in 2003. These data suggest that the probability is extremely low that a dairy cattle mortality received for disposal by anaerobic digestion with manure contains the prion responsible for BSE. In addition, the Peer Review of the Estimation of BSE Prevalence in the United States (Patil, 2006) supported the U.S. Department of Agriculture Animal and Plant Health Inspection Service’s estimated prevalence of BSE of only 1 in 1,000,000 live cattle in the United States.

This information suggests that the risk of the presence of the prion responsible for BSE in dairy cattle mortalities received for disposal by anaerobic digestion is highly unlikely. In addition, transmission to man or other animals only can occur by ingestion of infected tissue. However, removal of brain and spinal column tissue before mortality maceration prior to anaerobic digestion would be an option, although removal would be a manual process.
The causative agent of Johne’s disease is *Mycobacterium avium paratuberculosis*, which is present in the feces of infected animals and is transmitted by ingestion of fecal material. Given the prevalence of Johne’s disease in U.S. dairy cattle, it is unlikely that co-digesting dairy cattle mortalities with manure will exacerbate this problem. Conversely, some mitigation in the risk of transmission may be realized. Martin *et al.* (2003) reported an average of a two log₁₀ (99 percent) reduction in the density of *M. avium paratuberculosis* during the anaerobic digestion of dairy cattle manure in a plug-flow digester at 35 °C.

**INFRASTRUCTURE REQUIREMENTS**

Prior to anaerobic digestion, dairy cattle mortalities will have to be macerated to maximize decomposition and avoid clogging of pumps, etc. Two sources of apparently suitable equipment are Supreme International Limited of Wetaskiwin, Alberta, Canada and Karl Schnell, Inc., New London, WI, the U.S. distributor for Karl Schnell GmbH and Company of Winterbach, Germany. Supreme International manufactures feed processing equipment as well as equipment for cutting and blending a variety of organic wastes including cattle mortalities. Karl Schnell GmbH primarily is a manufacturer of equipment for the food processing industry.

Mortality processing should be performed in an enclosed facility with a receiving and a processing area and the appropriate equipment for the transfer of the carcasses from the receiving area into the macerating unit. The addition of manure to the maceration unit will be necessary manure to facilitate the production of slurry that can be transferred by gravity or pumping. Ideally, the mortality processing facility should be located near the digester influent storage tank that will receive the macerated mortalities. This will facilitate transfer by gravity.

**ECONOMIC FEASIBILITY**

Because of the substantial cost of the required maceration equipment and the other infrastructure requirements, we believe that on-site disposal of dairy cattle mortalities by anaerobic digestion is suitable only for very large operations. Our research suggests that the cost of a suitable maceration unit will be at least $50,000 and could be as much as $250,000, depending on the manufacturer. For smaller operations, delivery of mortalities to a centralized anaerobic digestion operation, or use of a portable maceration unit owned cooperatively or by a third party could be options.

**SUMMARY**

Both theoretical considerations and experimental results suggest that anaerobic digestion with a suitable co-substrate such as manure is a technically feasible option for the disposal of dairy as well as other large animal mortalities. However, economic feasibility will depend on site-specific variables such as the monetary value of the additional methane produced and the cost of available alternatives for mortality disposal.
REFERENCES


Federal Register. 1997. Substances Prohibited from Use in Animal Food or Feed; Animal Proteins Prohibited in Ruminant Feed; Final Rule. 21 CFR 589, Food and Drug Administration, Department of Health and Human Services, Washington, DC. pp. 30935-30978.


EXPERIENCE WITH THREE ON-FARM DIGESTER SYSTEMS USING ADDITIONAL OFF FARM ORGANIC SUBSTRATES

S. Weeks
Stanley A. Weeks, LLC
Middle Grove, NY

INTRODUCTION

One strategy to improve economics of on-farm anaerobic digester systems is to add off-farm organic substrates in order to increase Biogas production. This co-digestion strategy also has the potential advantage of receiving a tipping fee at the farm. This paper will discuss use of this strategy on three farms, while also examining issues such as; expected Biogas production per dairy cow, engine-generator set efficiency at several digester systems, methods of measuring methane content of Biogas, and hydrogen sulfide levels in Biogas at eight operating digester systems in New York State.

SUBSTRATES POTENTIAL

A study by Labatut et al. (2011) determined the specific biomethane potential and biodegradability of an array of substrates, including mono and co-digestion samples using a biochemical methane potential (BMP) assay, a bench-scale anaerobic digestion test. This test is designed to determine methane yield and biodegradability of organic materials. The results of about 175 individual BMP assays indicated that substrates rich in lipids and easily degradable carbohydrates possess the highest methane potential, while more recalcitrant substrates, with a high fraction of lignocellulosic components have the lowest. Results also showed that co-digestion of dairy manure with easily degradable substrates increases the specific methane yield when compared with manure-only digestion methods.

EXPERIENCES WITH SUBSTRATES

The University of Maine experimented by adding organic substrates to their 250 cow anaerobic digester in the 1980’s. First experience was with cheese whey and no specific results were reported; only the general report that Biogas production did increase. Their second experience with added organics was much more interesting to the University, as food service waste from dining halls was collected and run through a grinder prior to being added to the raw manure pit. The food service waste added to Biogas production, but more importantly eliminated tipping fees to the local landfill. The University dairy herd was downsized in 1991, and digester operation ceased.

Recent experience has been with two farms in central Pennsylvania (330 cows & 420 cows) and one farm (560 cows) in central New York. Both Pennsylvania systems were designed with added substrates in mind, with consideration to both added revenue and future expansion. The complete mixed digesters were designed for 17 days retention time for substrates plus the current cow numbers, and the engine-generator set was specified to produce double the electricity expected from the current herd. Both farms
wanted to design for possible expansion, and this design concept anticipates that added substrates will be reduced as cow numbers increase, keeping Biogas production essentially constant and the engine operating at high efficiency.

As an example calculation, from prior experience anaerobic digestion of dairy manure is expected to yield 80 cubic feet of Biogas per cow per day, with methane content of 60%, and heat value of 550 BTU per cubic foot. For a 330 cow operation, expect about 25 gallons of 11% dry matter liquid manure per day, or 8,250 gallons per day. Organic substrates added at 25% of total volume would thus equal 2,750 gallons per day, and total input volume would be 11,000 gallons per day. It was expected that high yield organic substrates added at 25% of total volume could as much as double electricity production compared to dairy manure alone.

A total system designed to handle off-farm substrates should have separate containment for substrates, with mixing system and feed pump to allow for periodic addition of completely mixed substrates to the main manure reception pit. The main manure reception pit should also have a mixer and feed pump to periodically feed completely mixed manure and substrates to the digester. Consistent feeding is essential to good digester performance, so substrates need to be as consistent as possible, both in terms of quality and quantity. This need for consistency of feeding leads to the desirability of a separate holding tank and subsequent dosing system. Both Pennsylvania farm systems were designed with separate holding tanks for substrates, while the New York farm was not initially designed for substrates. On a trial basis, substrates were added to the manure reception pit at the barn on the New York farm.

In all cases when substrates are added an effective digester mixing system will be required within a digester. Mixing will keep solids from settling, but most important function is to eliminate upper crust formation. When too much liquid is added to as-produced dairy manure the fibers are washed and subsequently float to the top of a digester or manure storage. Without mixing, this crust will continue to form within a digester, causing outflow plugging and requiring eventual shut-down of the digester for cleaning, a difficult and costly operation. Crusts as much as 4 feet in depth have been experienced in digesters, and mechanical removal is extremely difficult.

Waste material from a local poultry processing plant was delivered to the 330 cow dairy farm, while wash water from a molasses plant was added to the 420 cow operation. Whey from a yogurt plant was added to the 560 cow digester system. In all three cases substrates came from a single, local source, an important factor related to the desire for consistent quantity/quality substrates. Poultry processing plant waste increased Biogas production from 26.4 CFM to 39.0 CFM and doubled resulting electricity production at the 330 cow dairy, from 50 KW to 100 KW. Conversion from Biogas energy to electrical energy efficiency increased from 19.6% (at 50 KW) to 26.5% (at 100 KW) as a result of the engine operating near full capacity. Farm was paid a tipping fee, and agreement also involved land spreading a portion of the digester effluent.

Molasses plant wash water (sugar water) was added to the 420 cow digester at an approximate rate of 7% of digester infeed for a period of several months, resulting in an increase of electricity production from 90 KW to 120 KW. Frequency of mixing was also
increased to eliminate the possibility of crust formation. Biogas meter was not functioning properly during this period, so Biogas production figures are not available. Subsequent tests with Biogas meter in place indicate that conversion from Biogas energy to electrical energy efficiency was 24.6% when operating at 90 KW (maximum rated load is 120 KW). Use of this sugar water ceased when the molasses plant would no longer pay a tipping fee.

Whey from a yogurt plant at approximately 25% of total volume added to the 560 cow digester increased Biogas production from 40.3 CFM to 41.7CFM, with little change in electrical output as the engine-generator set had been at near capacity with manure alone. Small increase in gas production may have been due to retention time being decreased from 17 to 13 days due to increased input volume. Separation prior to the digester took place at this farm to guarantee adequate quantity and quality separated/composted manure solids would be produced for bedding of cow stalls. Conversion from Biogas energy to electrical energy efficiency was 28.4% when operating at 96 KW (maximum rated load is 108 KW). Use of cheese whey ceased when yogurt plant would no longer pay a tipping fee.

Manure separation subsequent to anaerobic digestion is very common for on-farm systems, as separated solids are a source of bedding and/or a potential cash crop. The addition of organic substrates to manure does not appear to be detrimental to operation of manure separators. Expect approximately 1.0 cubic feet of separated manure solids per cow per day when separation takes place after digestion. If separation takes place prior to digestion, as in the case of the 560 cow farm, expect 1.5 cubic feet of separated solids per cow per day. Separated solids will shrink about 50% during complete composting, so consider that factor when considering cash crop value. Depending on location, value of separated manure solids for either bedding or cash sale may well exceed value of electricity produced by the engine-generator set. Economics thus depends upon electricity prices, cost of other types of bedding, and market for fresh or completely composted separated manure solids.

When adding substrates, consideration must be given to long-term manure storage capacity. Added nutrients brought in with substrates must be land applied in accordance with the Nutrient Management Plan for the farm.

HYDROGEN SULFIDE AND BIOGAS

Ludington, et al. (2011) studied the flow of elemental sulfur (S) in the manure treatment system at eight dairy farms with anaerobic digesters in New York State from January 2007 to March 2008. The dairies ranged in size from 430 to 948 milking cows. Digesters on five farms were traditional plug flow, two were horizontal and mixed, and one was vertical with a mixer. Food waste was imported at two farms, and there was pre-digester separation of solids at two farms. The sources of sulfur in the manure treatment system included the total mixed ration (TMR), drinking water, bedding, foot bath and food waste.

The major source of sulfur in the digester influent originated with the total mixed ration (TMR) as shown in the table below, 11.3 lb S/100 cow-days. The low standard deviation
shows the uniformity between farms. This was not true for water and bedding. Two farms had high sulfur drinking water (2.9 lb S/100 cow-days) while the other 6 were in the normal range (0.26 lb S/100 cow-days).

<table>
<thead>
<tr>
<th>Summary of Mass Flow Inputs*</th>
<th>Farms</th>
<th>lb S/100 cow-days</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMR (8 farms)</td>
<td>8</td>
<td>11.3 ± 1.7</td>
</tr>
<tr>
<td>Water, “normal sulfate”</td>
<td>6</td>
<td>0.26 ± .22</td>
</tr>
<tr>
<td>Water, “high sulfate”</td>
<td>2</td>
<td>2.9 ± 1.2</td>
</tr>
<tr>
<td>Bedding, wood shavings</td>
<td>3</td>
<td>2.1 ± 0.5</td>
</tr>
<tr>
<td>Bedding, separated solids</td>
<td>5</td>
<td>5.3 ± 1.3</td>
</tr>
<tr>
<td>Food Waste</td>
<td>2</td>
<td>1.5</td>
</tr>
</tbody>
</table>
* Sulfur in milk was subtracted from these inputs to determine output from barn.

Five farms used separated solids (SS) which contains more than twice the sulfur as wood shaving (0.01 vs. 0.28 % S dry weight). At the same time farmers using SS used more bedding. As shown in the table, three farms using wood shavings for bedding averaged 2.1 lb S/100 cow-days while the 5 farms using SS averaged 5.3 lb S.

The sources of sulfur on the 5 farms not importing food waste are shown in the pie chart, Figure 1 with 88% from TMR. For the 2 farms importing food waste, the food waste contributed only 10 % of the sulfur.
The farm with the highest concentration of sulfur in the drinking water [420 mg SO$_4$\(2^-\)] also imported food waste. This is the reason for the higher average contribution of S in the water (13\%) on the two farms that import food waste.

The pre-digester separation reduced the sulfur content of the digester influent by about 40\%.

Two farms used copper sulfate in the foot bath. At one 900 cow dairy the foot bath contributed 5 lbs S/day (5 lbs out of total of 104 lb S/day). At the second farm, only 1 lb S/day for 1,060 cows was contributed (1 lb out of a total of 140 lb S/day). Both farms used cupric sulfate· pentahydrate, where sulfur (S) amounts to only 12.8 percent of the molecular weight. The exact amount of sulfur that entered the digester from the foot bath is not known. Because of the copper, the foot bath was not emptied into the digester.

For the six farms not importing food waste the digesters produced an average of 79 ft$^3$ (wet biogas at 60 F) per equivalent milking cow-day. An “equivalent milking cow” is based on the total solids from all animals and bedding. Considering the destruction of volatile solids, the average production of biogas was 15.5 $\pm$ 0.5 ft$^3$ per lb of VS destroyed.

The concentration of hydrogen sulfide in the biogas averaged 3,860 $\pm$ 1,880 ppm for all 8 farms with a range of 1,020 to 6,730 ppm. (90 tests were made at each farm over a one month period) Approximately 28 \% of the sulfur in the digester influent was released in the biogas, with a range from 17.5\% to 46.1\%. The mass flow of sulfur in the biogas averaged 2.57 $\pm$ 0.37 lb S per 100 cow-days. With roughly 80 \% of the sulfur originating in the TMR, efforts to reduce sulfur would likely focus on TMR.

Three methods for determining the concentration of CO2 and CH4, 1) GEM 2000 unit, 2) Gastec gas tubes, and 3) Bacharach unit were compared. The GEM 2000 measures the gases in terms of dry biogas, while the Gastec and Bacharach units refer to wet biogas. The GEM 2000 measures CO2 and CH4 directly, while the Gastec and Bacharach units measure CO2 only, with CH4 assumed to be 100 minus the CO2 reading. This subtraction method ignores water vapor present in the biogas. Comparing these three methods yielded average CH4 readings of 59.8\% for the GEM 2000, 63.9\% for the Bacharach, and 63.0\% for the Gastec unit. The Bacharach and Gastec units will always indicate elevated values for percent methane.

ENGINE-GENERATOR SET PERFORMANCE

As noted above, engine-generator set performance and conversion efficiency will depend on Biogas quality and quantity. Engine efficiency drops rapidly when loaded below 75\% of full load, so engine-generator set selection is very important. The Bacharach CO2 tester is a cost effective method for measuring CO2, but an adjustment of 4\% (add 4\% to the CO2 reading) needs to be made to account for water vapor in the Biogas. The two best measures of digester performance are CO2 level and gas production. A gas meter is an essential instrument for all digester systems. Consistent
feeding and good temperature control are essential for digester operation, as taking care of a digester is similar to care for any other living creature.

Continuous operation is probably the main criteria for good engine performance, as Biogas contains both water vapor and hydrogen sulfide which can form sulfuric acid when engines are shut down and water vapor condenses. Hydrogen sulfide scrubbing continues to be an issue, with engine oil selection, oil change interval, and oil analysis all important factors to consider.

A good example of nearly continuous operation is the 330 cow farm digester discussed above, with 13,106 operating hours and 187 hours down, a run time of 98.6% of available hours. The 420 cow farm digester has 11,681 operating hours with 171 hours down time, a run time of 98.6% of available hours. The 560 cow farm digester is in its fifth year of operation and last year it had 8,554 operating hours with 206 hours down time, a run time of 97.6% of available hours. Hydrogen sulfide content in the Biogas on these farms ranged from 1,200 to 2,400 ppm. All three systems are a testament to good design, maintenance, and oversight. A good on-site operator is always the most critical contributor to success.

REFERENCES


FEASIBILITY STUDIES: WHY AND WHAT SHOULD THEY ENTAIL?

P. Ries
Asset Resource Management LLC

I have been asked to present a paper addressing feasibility studies, as they relate to consideration of a digester project for large dairies.

I am hoping to answer the following questions, so that you, as a dairy producer, can properly address whether or not a digester project fits within your overall business model, that is, successfully managing and operating a large scale dairy operation. As I said, the questions I hope to answer for you are as follows:

1. What is a feasibility study?
2. Why is a feasibility study important?
3. What should be included?
4. Who should do a feasibility study?
5. How much should they cost?

1. What is a feasibility study?

A feasibility study is an analysis and evaluation of a proposed project to determine if it is
a. technically feasible;
b. is feasible within the estimated cost; and
c. will be profitable.

I am focusing my presentation on feasibility studies of digester projects, because that is why I’ve been asked to make this presentation. However, one should be able to use these same concepts when considering any opportunity your farm might consider, especially where large sums of money are at stake.

With respect to digester projects, the technical concepts of collecting the cow manure, pumping it into a digester, producing methane gas, and using this methane gas to power turbines, which in turn produce electricity, is a proven technology, and no further evaluation of the technical feasibility of this concept is necessary. However, there are always some twists that a producer might want to consider, especially if the amount of electricity a project can generate cannot all be used on the farm, or if there is no capacity in the local electric grid to accept the power being generated from the project.

Another alternative one might want to consider is to convert the methane to a usable fuel for truck fleets, or for powering the equipment on the farm. This too requires an understanding of the power unit conversion costs, storage, distribution, and other local considerations.
Other issues that are addressed include will the farm own and operate the “digester project”; or will it be owned and operated by a developer? This may seem like a pretty simple question to answer, but you will find that as vendors propose their systems to you, the promise of making a 15% return on your investment is pretty hard to turn down.

That is why you, as the individual farmer, should conduct a feasibility study.

Do you have the capital to devote to a digester project?
Do you have the time to develop a digester project?
Do you have the manpower resources to own and operate a digester project?
And probably many other questions requiring answers before you pursue this type of project.

2. Why is a feasibility study important?

It is my understanding that these types of projects typically involve a milking herd size of 1,000 cows, or more. Frequently, the farmer will indicate that they intend to grow their dairy herd over the lifetime of a digester project. Let’s assume that they say they will increase the number of cows they are milking, from 1,000 head, to 1,300 head over the next five years. That is a 30% increase in your business over a 5 year period. Even if you break this down to an annual growth rate, a 6% increase in your business would be considered pretty aggressive in any business environment. If you are going to use your capital reserves to develop the digester project, where will the money come from to increase the capacity of your milking parlor, free stall barns, calf care, raising out replacement heifers, additional land required for feed and manure application, labor, and additional or bigger equipment? What impact will these capital requirements have on your profit/loss and balance sheets? Do you have a lending institution that is willing to partner with you on a project of this scale?

The questions asked in the previous paragraph show why a feasibility study is important. It forces you to look at the “big picture”. While addressing the issues above should not scare you away from considering an energy project, it will have you consider where your farm business has been and where it will be 5, 10 or 15 years from now. By answering the questions posed, you might find that you have to adjust your accounting methods of your farm operation, to make them conform to normal business practices and what banks or investors are looking for when considering financing a business expansion.

3. What should be included?

I find that developing a narrative about the farm and its’ operation is very useful. By actually writing this down, this allows the farmer to see how the farm operation has developed over the past 5, 10, or even 25 years. This narrative should include how the farm started. Usually this is a family operation. It is important to document the origins of the farm, who started it, how long ago, original size, both in acreage and numbers of livestock.
Getting into the current operations, the qualifications of the family members and/or key employees should be discussed. Backgrounds in farming, education, and other attributes of the “key” members should be presented.

Another element of what should be included is a presentation of past financial performance. This will include three to five years of profit/loss statements and balance sheets. Not only will this be some of the first questions asked by the bank/investor, it should also help you in deciding if you are ready to take the next step into the growth of your business.

While you think that this might not be necessary, you will find that when you approach your lending institution and/or an investment group, these will be some of the first questions they will ask. By having this done beforehand, you will accelerate the financial borrowing/investment process and you will impress the bank/investors on your organization skills. This will be one aspect in demonstrating that you are ready to take on more growth in your business.

The next part of your business plan (like it or not, this is actually what you are doing) you will describe the expansion you are considering. For purposes of this presentation, we are talking about a digester project, producing energy from manure. Before you identify the requirements of your energy project, you need to address the items I have previously identified. Besides the energy project, what components of your existing operation are going to have to change to accommodate this project? Will you need to increase:

i. The capacity of your milking parlor?
ii. The capacity of your free stall barns?
iii. Calf care?
iv. The capacity to raise out replacement heifers?
v. Additional land required for feed and manure application?
vi. Labor? and
vii. Additional or bigger equipment?

The capital requirements to address these items will probably not come from your cash flow. If it can, you probably don’t need to consider an energy project. Once you make it past these considerations, and decide that you have the financial ability to address this growth, you are now ready to study the feasibility of your energy project.

Are you going to own and operate the energy project or will you have a vendor own and operate the energy project? Your background is raising and milking cows, planting and harvesting crops, and probably some minor maintenance on your power units. Operating large capacity pumps, managing the proper environment for your biologic microorganisms, measuring feedstocks, methane production, operating turbines to produce electricity, and making sure this biologic reactor produces energy 24/7 is probably not something you thought you would be doing next year. Of course, there are
individuals who can perform these functions, and are ready to move their family to your remote location to work for you.

Vendors will come and begin to study your dairy operation. They will evaluate all of the components that will be the waste stream to be considered for the energy project. They will know how much wash water is used, what your bedding is comprised of, and how the manure is moved from the barns to a point where it can be directed into a digester.

The first thing they will tell you that your project will have an internal rate of return of over 20% and that you will have a project payback of 4 to 6 years. Who wouldn’t jump at this opportunity?

Then you start reviewing their spreadsheets. You know that you have 1,000 milking cows, and you plan on expanding to 1,300 within the next 5 years. You see that in the pro formas presented by the vendors, they have assumed 1,500 milking cows and 1,000 heifers contributing to the energy project, from day one. If this isn’t your operation, you cannot count on the rate of return or the projected payback.

You will be approached by many vendors who want to develop your energy project. Typically, they will want to perform a feasibility study on your operation to determine if the proposed energy project will successful. I was retained by a local dairy to assist them in the evaluation of the feasibility studies provided by the vendors, perform detailed evaluations of the pro forma’s from the vendors, evaluate the impact to cash flow to the dairy, and assist in evaluating financing options.

Due to confidentiality claims made by the vendors for my project, I cannot provide copies of their feasibility studies on which I made comments. However, I will provide excerpts from their feasibility studies on which some of my comments were based.

For example, the vendor provided an estimated cost to construct the energy project. Table 1 presents their construction estimate. This is the exact table the vendor provided for their cost estimate. My comments are shown in red. You will see this same presentation in Table 2 and 3 as well.

You can see that I felt more detail was needed in evaluating this vendor’s proposal.

The vendor then showed the inputs they used in developing the financial model for their proposal. Table 2 presents those inputs and my comments.
Table 1. Construction Estimate

<table>
<thead>
<tr>
<th>Item</th>
<th>Capital Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Conditions</td>
<td>64,000</td>
</tr>
<tr>
<td>Digester</td>
<td>898,350</td>
</tr>
<tr>
<td>Site Piping</td>
<td>455,500</td>
</tr>
<tr>
<td>Mechanical Building</td>
<td>219,100</td>
</tr>
<tr>
<td>Generator</td>
<td>330,000</td>
</tr>
<tr>
<td>Solids</td>
<td>82,500</td>
</tr>
<tr>
<td>Handling</td>
<td>30,000</td>
</tr>
<tr>
<td>Flare</td>
<td>410,000</td>
</tr>
<tr>
<td>Freight and Installation</td>
<td>149,367</td>
</tr>
<tr>
<td>Engineering and Construction Management</td>
<td></td>
</tr>
<tr>
<td>GC</td>
<td>248,945</td>
</tr>
<tr>
<td>Fee</td>
<td>124,473</td>
</tr>
<tr>
<td>Contingency</td>
<td></td>
</tr>
<tr>
<td><strong>Total Construction Estimate</strong></td>
<td><strong>3,012,235</strong></td>
</tr>
</tbody>
</table>
Table 2. Inputs

The economic evaluation is based on the following inputs. The kWh are based on the existing dairy loads and the expected additional load of the digestion plant. Sale to the grid is limited to 200 kW and the sale amount is based on 200 kW sold over 8500 hours per year.

The vendor then presented a financial analysis, which showed the project would generate sufficient revenues to cover operating costs, pay the debt service on the loan and generate profits for the operation. Table 3 presents the financial analysis.
Table 3. Financial Analysis

Table 4 presents my comments on one of the feasibility studies I reviewed for the local dairy. Some of my comments may seem rather insignificant, and I’m sure I didn’t capture all of the issues that others may raise if it were to reviewed by others.

Table 4. Comments on Review of XXXX Feasibility Study, dated XXX, XX, 2010

1. Cannot read captions in the process flow diagram.
2. The “Financial Feasibility” section does not provide any details as to what is included in the various cost components. For example, new air permits will need to be prepared. There is no cost for the interconnect fee with Utility.
3. The cost analysis uses 1350 cows. This is not the starting point for the Dairy. The Dairy has 1100 cows, with a planned growth of 10% per year.
4. There is no reference on how the basis for electric generation was made. It all starts with manure production per animal, percent (%) solids in manure, conversion to total solids of the manure, percent volatile solids in manure on a dry basis, etc. Additional water flow to the system needs to be provided. Basically, a mass balance needs to be shown to support the calculations for electric generation and gas generation. In addition, assumptions for converting the methane gas to electricity needs to be shown. Without this information, the Dairy cannot evaluate the pro forma.
5. There is no basis for the $500,000 State Grant. Is this a flat grant amount, or is there a specific method in determining the amount of the grant?
6. This pro forma assumes the Dairy will provide $251,223 in capital for this project.
7. Financing period is shown over a 15 year period, while the depreciation is over a 10 year period.
8. Pro forma shows sales of electricity to the dairy operation as income. This will still be an expense to the Dairy.
9. Pro forma shows sales of electricity increasing at rate of 2% per year. Based on our meeting with the Utility, it was my understanding that the rate is fixed every two years. According to the Utility, the Utility has excess capacity, and the likelihood of these rates increasing for the next time interval are very slim.
10. Income from Greenhouse Gas credits should not be included. There is no basis for this income.
11. Thermal savings. I believe this is a "cost avoidance" on the dairy side of the operations. Again, there is no calculation provided demonstrating that there is excess thermal energy to be used by the dairy.
12. Bedding savings. I believe this is a "cost avoidance" on the dairy side of the operations. I’m assuming this is the cost of trucking only to bring bedding into the dairy at it’s current rate. This also is increasing at a rate of 2% per year. No justification is provided for these numbers.
13. Fiber sales. I am assuming this includes fiber sales to the dairy operation. No support for the amount of fiber produced, fiber used by the dairy, and therefore excess fiber available for off-farm sale is provided.

Comments on Electric Generation: Using Vendor’s pro forma, I was able to construct a spreadsheet that addressed assumptions necessary to determine the amount of energy produced from the digester project. Based on the 1100 head herd currently in use, and based on the current electric needs of the dairy, there is not enough electricity produced to sell 200 kWh to the Utility. I arrive at approximately 130 kWh that is available to the Utility. All of the assumptions that are included in calculating manure generation to methane production to electric generation need to be understood before moving forward.

Comments on Fiber Generation: Using Vendor’s pro forma, I was able to construct a spreadsheet that addressed assumptions necessary to determine the amount of fiber produced from the digester project. I calculated a similar number to what is provided in the feasibility study. I am concerned that fiber sales might decrease over time as more becomes available from other dairies.

As my comments in Table 4 reflect, it is necessary to know the components that are necessary to conduct a mass balance. This will provide a picture of the volumes of materials you will be dealing with. Components of the mass balance are found in Table 5.
Table 5. Components of the Mass Balance

<table>
<thead>
<tr>
<th>Description</th>
<th>Unit</th>
<th>Per Cow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Cows - Scrape</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure per animal</td>
<td>gallons</td>
<td></td>
</tr>
<tr>
<td>Manure per animal</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Milk Production per cow per day</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Manure correction factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Manure per animal</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Correction Factor for Thickened Flush Manure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Manure per animal - Flush</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Total Manure produced</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Total Manure as liquid (8.34 lbs/gal)</td>
<td>gallons</td>
<td></td>
</tr>
<tr>
<td>Parlor Water added</td>
<td>gallons</td>
<td></td>
</tr>
<tr>
<td>Total Water Volume</td>
<td>gallons</td>
<td></td>
</tr>
<tr>
<td>Total diluted manure volume</td>
<td>gallons</td>
<td></td>
</tr>
<tr>
<td>Solids as Bedding</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Percent Total Solids in Manure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids in Manure Dry Basis</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Percent Volatile Solids in Manure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile Solids Available</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Total Solids</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Total Volume to Digester</td>
<td>gallons</td>
<td></td>
</tr>
<tr>
<td>Total Volume to Digester (8.34 lbs/gal)</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Total Solids to Digester</td>
<td>lbs</td>
<td></td>
</tr>
<tr>
<td>Total Volatile Solids available to Digester</td>
<td>lbs</td>
<td></td>
</tr>
</tbody>
</table>

Many of the components of the mass balance are “book” values or “rules of thumb” values. Table 6 presents the same information as shown in Table 5, however, I have included information that can be used by the Dairy in determining the inputs. I have highlighted in yellow the values that are specific to the Dairy or values that should be properly sourced. Table 6 also shows the amount of biogas available for electrical generation and thermal generation.
### Table 6. Mass Balance

<table>
<thead>
<tr>
<th>Dairy/Vendor Analysis</th>
<th>Unit</th>
<th>Per Cow</th>
<th>Per Day</th>
<th>Per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Number of Cows - Scrape</td>
<td></td>
<td>1500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure per animal</td>
<td>gallons</td>
<td>25.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure per animal</td>
<td>lbs</td>
<td>230.176</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milk Production per cow per day</td>
<td>lbs</td>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manure correction factor</td>
<td></td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Manure per animal</td>
<td>lbs</td>
<td>187.549</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Corrected Manure per animal - Flush</td>
<td>lbs</td>
<td>187.549</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Manure produced</td>
<td>lbs</td>
<td>224,579.52</td>
<td>9,971,324.80</td>
<td></td>
</tr>
<tr>
<td>Total Manure as liquid (8.34 lbs/gal)</td>
<td>gallons</td>
<td>26,928.00</td>
<td>9,928,720.00</td>
<td></td>
</tr>
<tr>
<td>Parlor Water added</td>
<td>gallons</td>
<td>12,000.00</td>
<td>4,380,000.00</td>
<td></td>
</tr>
<tr>
<td>Total Water Volume</td>
<td>gallons</td>
<td>12,000.00</td>
<td>4,380,000.00</td>
<td></td>
</tr>
<tr>
<td>Total Diluted manure volume</td>
<td>gallons</td>
<td>38,928.00</td>
<td>14,308,720.00</td>
<td></td>
</tr>
<tr>
<td>Solids as bedding</td>
<td>lbs</td>
<td>6,000.00</td>
<td>2,190,000.00</td>
<td></td>
</tr>
<tr>
<td>Percent Total Solids in Manure</td>
<td></td>
<td>2.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Solids in Manure Dry Basis</td>
<td>lbs</td>
<td>22,457.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Percent Volatile Solids in Manure</td>
<td>lbs</td>
<td>90.00%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volatile Solids Available</td>
<td>lbs</td>
<td>17,963.68</td>
<td>21,559.63</td>
<td>7,869,266.18</td>
</tr>
<tr>
<td>Total Solids</td>
<td>lbs</td>
<td>27,457.95</td>
<td>33,049.54</td>
<td>13,026,582.98</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy Generation</th>
<th>Energy Potential - Biogas</th>
<th>BTU</th>
<th>68,990,828.54</th>
</tr>
</thead>
<tbody>
<tr>
<td>Organic Solids (dry basis) (Volatile Solids Available)</td>
<td>lbs</td>
<td>21,559.63</td>
<td>7,869,266.18</td>
</tr>
<tr>
<td>Organic Solids Recovered</td>
<td>lbs</td>
<td>8,623.85</td>
<td>3,147,706.55</td>
</tr>
<tr>
<td>Organic solids (10% moisture)</td>
<td>lbs</td>
<td>18,746.18</td>
<td>30,493,355.17</td>
</tr>
<tr>
<td>Manure Volume Reduction</td>
<td>lbs</td>
<td>21,559.63</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy Generation</th>
<th>Per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Potential - Biogas</td>
<td>BTU</td>
</tr>
<tr>
<td>Electrical Energy Efficiency</td>
<td></td>
</tr>
<tr>
<td>Thermal Energy Efficiency</td>
<td></td>
</tr>
<tr>
<td>System Energy Efficiency (Electrical + Thermal)</td>
<td></td>
</tr>
<tr>
<td>Energy Lost</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biogas Available for Electrical Generation</th>
<th>MMBTU/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Biogas Energy Converted to Electrical Energy</td>
<td>24,976,799.3</td>
</tr>
<tr>
<td>Total Biogas Energy Converted to Hot Water</td>
<td>27,589,313.42</td>
</tr>
<tr>
<td>Total Biogas Energy Lost</td>
<td>16,418,171.9</td>
</tr>
<tr>
<td>Total Biogas Available</td>
<td>68,990,828.54</td>
</tr>
<tr>
<td>Thermal Energy Equivalent to 1 kWh</td>
<td>BTU/kWh</td>
</tr>
<tr>
<td>Total Electrical Energy Generated (GROSS)</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Host Rate to Generate 1 kWh of electrical energy</td>
<td>BTU/kWh</td>
</tr>
<tr>
<td>Host Rate to Generate 1 kWh of electrical energy</td>
<td>BTU/kWh</td>
</tr>
<tr>
<td>Hourly/Day</td>
<td>h/day</td>
</tr>
<tr>
<td>Electrical Power Generation with zero % downtime</td>
<td>kW</td>
</tr>
<tr>
<td>Uptime Percentage for Engine/Generator Set</td>
<td>%</td>
</tr>
<tr>
<td>Power Generation w/Availability Factor</td>
<td>kW</td>
</tr>
<tr>
<td>Average Electrical Energy Available to utility</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Electrical Load Usage by Digestor System</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Electrical Energy Consumed by Digestor System</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Electrical Load Usage by Dryer</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Electrical Energy Used by Dryer</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Net Electrical Energy Available to Utility</td>
<td>kWh/day</td>
</tr>
<tr>
<td>Total Biogas Energy Converted to Hot Water</td>
<td>MMBTU/day</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biogas Available for Thermal Generation</th>
<th>MMBTU/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assumed Influent Temperature</td>
<td>degree F</td>
</tr>
<tr>
<td>Required Digestor Temperature</td>
<td>degree F</td>
</tr>
<tr>
<td>Available Hot Water that is used to Heat Anaerobic Digester</td>
<td>%</td>
</tr>
<tr>
<td>Thermal Energy Needed to Heat the Anaerobic Digester @ 80% efficiency</td>
<td>MMBTU/day</td>
</tr>
<tr>
<td>Thermal Energy Needed to Heat the Dairy @ 80% efficiency</td>
<td>MMBTU/day</td>
</tr>
</tbody>
</table>
After you develop the information found in Table 6, you can then begin projecting what your cash flow might look like. Table 7 presents a pro forma, using information presented in the tables above to estimate the net income to the dairy. I have presented the first year in this pro forma, which includes the current cow population. The fourth year is result of growing 10% per year, until 1500 cows are realized (in this case, 1597). The fifteenth year is presented because that is the last year of the loan. In year 15, the “Net Income after Dairy Electric Savings” is over ($48,012). The story doesn’t end here however.

There should be savings to the dairy because of the bedding the digester process creates. In this case, the Dairy was trucking into the operation bedding. This trucking expense will disappear when the digester is up and running. There also is projected to be excess bedding material produced, that will be able to be marketed. I did not participate in this portion of the pro forma, but was told that the net income to the Dairy for bedding was estimated to be $20,000 per year.

The other component not discussed here is the concrete lined manure pit this Dairy was required to install. This pit cost over $400,000.00. This pit was also necessary for holding effluent from the digester.

The dairy also did not calculate what the savings would be in land application of the effluent from the digester. Because they were currently limited by the phosphorus in their manure, the amount of acres required for disposal of manure was assumed to be greater than the acreage needed for manure application using the effluent from the digester.

Bottom line is that this paper presents the cost feasibility of a digester project up to a certain point. As mentioned earlier, the entire farming process needs to considered when evaluating an energy project.

In this dairy’s case, the project was put off for about 18 months. This allowed the dairy to get some of the it’s finances in order. This dairy ultimately chose a vendor who would own and operate the digester, and the manure pit. In order to make this a more feasible project, the vendor will size the project to produce more energy than what this dairy could produce on its’ own and will import additional substrate to the digester. The additional substrate will probably have more volatile solids, thereby having the potential of creating more methane.
Table 7. Projected Cash Flow

<table>
<thead>
<tr>
<th>Dairy Projected Cash Flow</th>
<th>Year</th>
<th>1</th>
<th>4</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>kW/hr Produced</td>
<td></td>
<td>304.99</td>
<td>405.89</td>
<td>405.89</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td>90%</td>
<td>90%</td>
<td>90%</td>
</tr>
<tr>
<td>Annual kW Production</td>
<td></td>
<td>2,404,541</td>
<td>3,200,037</td>
<td>3,200,037</td>
</tr>
<tr>
<td>Daily kW Production</td>
<td></td>
<td>6587.78</td>
<td>8767.22</td>
<td>8767.22</td>
</tr>
<tr>
<td>Hourly kW Production</td>
<td></td>
<td>274.49</td>
<td>365.30</td>
<td>365.30</td>
</tr>
<tr>
<td>Number of Cows</td>
<td></td>
<td>1,200</td>
<td>1,597</td>
<td>1,597</td>
</tr>
<tr>
<td>Number of Heifers</td>
<td></td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total Number of Animals</td>
<td></td>
<td>1200</td>
<td>1597.2</td>
<td>1597.2</td>
</tr>
<tr>
<td>Annual Manure Produced (gallons/year)</td>
<td>9,828,720</td>
<td>13,080,388</td>
<td>13,080,388</td>
<td></td>
</tr>
<tr>
<td>Gallons/KW</td>
<td></td>
<td>4.09</td>
<td>4.09</td>
<td>4.09</td>
</tr>
<tr>
<td>Current Dairy Animal Population</td>
<td>1,200</td>
<td>1,597</td>
<td>1,597</td>
<td></td>
</tr>
<tr>
<td>Projected 10% Growth Per Year until 1500 cows</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual Manure Produced (gallons/year)</td>
<td>9,828,720</td>
<td>13,080,388</td>
<td>13,080,388</td>
<td></td>
</tr>
<tr>
<td>Gallons/KW</td>
<td></td>
<td>4.09</td>
<td>4.09</td>
<td>4.09</td>
</tr>
<tr>
<td>Actual Annual kW Production</td>
<td>2,404,541</td>
<td>3,200,037</td>
<td>3,200,037</td>
<td></td>
</tr>
<tr>
<td>Daily kW Production</td>
<td></td>
<td>6587.78</td>
<td>8767.22</td>
<td>8767.22</td>
</tr>
<tr>
<td>Hourly kW Production</td>
<td></td>
<td>274</td>
<td>365</td>
<td>365</td>
</tr>
<tr>
<td>Electrical Load Usage by Digester System</td>
<td>20%</td>
<td>14%</td>
<td>14%</td>
<td></td>
</tr>
<tr>
<td>Electrical Energy Consumed by Digester System (kW/day)</td>
<td>1318</td>
<td>1227</td>
<td>1227</td>
<td></td>
</tr>
<tr>
<td>Electrical Load Usage by Dairy</td>
<td>32%</td>
<td>26%</td>
<td>26%</td>
<td></td>
</tr>
<tr>
<td>Electrical Energy Used by Dairy (kW/day)</td>
<td>2108</td>
<td>2279</td>
<td>2279</td>
<td></td>
</tr>
<tr>
<td>Net Electrical Energy Available to Utility (kW/day)</td>
<td>3162</td>
<td>5260</td>
<td>5260</td>
<td></td>
</tr>
<tr>
<td>Net Electrical Energy Available to Utility (kW/hr)</td>
<td>131.76</td>
<td>219.18</td>
<td>219.18</td>
<td></td>
</tr>
<tr>
<td>Average Utility Rate ($/Kwh)</td>
<td>0.1082</td>
<td>0.1082</td>
<td>0.1082</td>
<td></td>
</tr>
<tr>
<td>Yearly Revenue from Utility</td>
<td>$124,882.25</td>
<td>$207,746.39</td>
<td>$207,746.39</td>
<td></td>
</tr>
</tbody>
</table>

Expenses (increase 2% per year)

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>4</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Generet</td>
<td>$46,319</td>
<td>$49,164</td>
<td>$61,117</td>
</tr>
<tr>
<td>Digester</td>
<td>$4,632</td>
<td>$4,916</td>
<td>$6,112</td>
</tr>
<tr>
<td>Misc</td>
<td>$14,600</td>
<td>$15,494</td>
<td>$19,204</td>
</tr>
<tr>
<td>Labor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Expenses</td>
<td>$65,551</td>
<td>$69,563</td>
<td>$86,493</td>
</tr>
</tbody>
</table>

P&I On Loan

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$259,289</td>
</tr>
<tr>
<td>4</td>
<td>$259,289</td>
</tr>
<tr>
<td>15</td>
<td>$259,289</td>
</tr>
</tbody>
</table>

Total Annual Expenses

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$324,840</td>
</tr>
<tr>
<td>4</td>
<td>$328,852</td>
</tr>
<tr>
<td>15</td>
<td>$345,782</td>
</tr>
</tbody>
</table>

Net Income

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(5199,958)</td>
</tr>
<tr>
<td>4</td>
<td>$(121,106)</td>
</tr>
<tr>
<td>15</td>
<td>$(133,086)</td>
</tr>
</tbody>
</table>

Farm Electric

<table>
<thead>
<tr>
<th>Item</th>
<th>1</th>
<th>4</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Energy Used by Dairy (kW/day)</td>
<td>$2108</td>
<td>$2279</td>
<td>$2279</td>
</tr>
<tr>
<td>Value of Electricity Used by Dairy</td>
<td>$83,255</td>
<td>$90,023</td>
<td>$90,023</td>
</tr>
</tbody>
</table>

Net Income after Dairy Electric Savings

<table>
<thead>
<tr>
<th>Year</th>
<th>Amount</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(516,703)</td>
</tr>
<tr>
<td>4</td>
<td>$(31,082)</td>
</tr>
<tr>
<td>15</td>
<td>$(48,012)</td>
</tr>
</tbody>
</table>
4. Who Should Do A Feasibility Study?

The dairy farmer could certainly do many of the components of the feasibility study, assuming they have the time and knowledge to collect, analyze, and perform the analysis required. I am a civil engineer by training. Many local civil engineering firms perform feasibility analyses on a routine basis. Most engineering projects require a feasibility analysis to be performed for the same reason we are discussing a feasibility study for an energy project. Typically, the owners who the engineer works for want to make sure their project will make money for them. Your accountant may also have a role in developing the total cost savings (or losses) by considering other aspects of the dairy operation.

Performing a feasibility study for an energy project may require some knowledge of the dairy operations and what components are necessary to address in the digester project. Obviously, the best team to perform the feasibility study would include the farmer, your engineer or business consultant, your accountant, and the vendors who would build the energy project. Once a project can be defined, other decisions have to made, that is does the dairy own and operate the energy project or will the vendor own and operate the energy project? The dairy then would be an energy customer to the vendor.

5. How Much Should They Cost?

Typically, the vendors who might compete for your energy project will provide much of the information on costs for their process, what their land requirements will be, operating costs, and any costs related to connections to the grid. They will provide proposals to you, which in turn you have to evaluate, perhaps using some of the tools I’ve provided in this paper.

I would propose that my role in evaluating the feasibility of the digester project would be under $10,000.00. However, you can see that the complete feasibility of the project went beyond my role, in that the farmer took it upon himself to determine the other costs/benefits when considering this project.

If a vendor is proposing to own/operate the energy themselves, there might not be a need to conduct a feasibility study. However, even if the vendor will be the owner/operator, they will be contracting with your dairy for certain volumes of manure (substrate). You will still need to make sure that what they are requiring from you, you will be able to provide. In this case, your other partner might be your attorney.
ECONOMIC ANALYSIS FOR DIGESTER DEVELOPMENT

R. Joblin
AgPower Group
Little Rock, AR

According to AgStar, there are about 150 digesters operating in the U.S. today, and most of them were financed the old fashioned way. The owner used an existing line of credit for the main business with the local banker. The banker was no as interested in the digester’s viability as he was in the continuing viability of the farm. Digesters were considered just another farm implement.

Not any more.

In 2006, there was a paradigm shift in the way farmers and lenders started to look at a multi-million dollar investment for a digester. The digester needed to ‘pay for itself;’ that is, generate revenues to pay for the investment. Quantify its value. There were two reasons for the shift: digesters were becoming more technologically advanced and therefore more expensive, and concurrently, dairy margins were declining. The farmers needed all of their lines of credit and cash available for their core business.

That is also the year we were hired by Dean Foods to do what I believe was the first independent comparison of and economic analysis for digesters as a stand alone business. I think it was the first because I could not find any other studies to plagiarize, and that that made our task daunting. We definitely undercharged for the amount of work we had to do.

I won’t bore you with all of the brilliant observations and conclusions we came up with — and of course, they were — but I do think it would be worth mentioning the hurdles we faced.

First, we could not find enough empirical data to provide any trends which would allow us to build actuarial tables from which we could construct economic models. We looked at a dozen different digester projects, and sure enough, they were operated a dozen different ways with a dozen different results. So, in plain English, we only had manure to go on.

To get financing — especially for what was considered experimental technology way back then — empirical data was mandatory. So, we had to literally create a business model for a commercially proven digester system, one that would lead a lender to the conclusion that we wanted: that a digester was a safe bet.

I am supposed to talk about the appropriate economic analysis methods (plural) “for evaluating handling/treatment/utilization systems and pros/cons of each.” To be honest, I only know of one appropriate economic analysis model, because all of the others we
tried did not work. It starts with creating a business model that works and then minimizing the risks for all involved.

So, what data is important to build the model?

Obviously, you start with the dairy. Is it well run? This is important for two reasons:

1. Will the dairy provide a **consistent** supply of feed stock as was projected in the original analysis? Dry matter intake. Amount of water used in the dairy operation. Bedding. Holstein or Jersey. All of these are factors that affect a digester’s operation and production. What goes in determines what comes out.

2. Will the dairy provide a **constant** supply of feedstock over the term of the financing? That is a nice way of asking if the dairy will stay in business that long. A lender must be comfortable with underwriting the dairy in addition to underwriting the digester project.

With all of that information, we established a base line of what should be a reasonable expectation of a consistent and constant supply of feedstock.

Second, we had to take our generic base line and apply it to each type of digester. What all did we want to know?
- Biogas production on a per cow per day basis. Obviously, the more the better.
- Parasitic load as a percentage of power production. Less is better.
- Operating costs and down times.
- Efficiency of gensets.
- Energy production from other substrates.
- Functional life of the system and major repair and replacement costs.
- Any environmental credits - carbon and RECs.
- Any co-products, especially relating to the quality of fiber and any cost of further processing. Way back then, we were concerned only with fiber as the marketable byproduct. Now we consider all other potential – present and future – co-products.
- Value of every possible revenue source.

Then, we fed this data into an economic model that we created, and voila, we had all of the answers. **Not**. But it did get us closer to having empirical data we could rely upon. Over time and with the help of a grad student much smarter than us, we built an economic model with all of the variables. An unbelievable amount of minutia went into it. I think there are about a dozen interrelated worksheets on the program. From that model, we created a simple summary spreadsheet, the one most of you have seen. We gave it to DMI for everyone’s use in doing the initial modeling for a generic digester project. Hopefully, it will help folks to compare hose apples to horse apples.
Third, to prove that we were ‘getting close’ with our analysis, we needed a controlled test of our hypothesis. We needed a guinea pig.

Let me back up for a moment. Our hypothesis was very specific: that a digester project could be a successful stand-alone business that would attract third-party investment and independent lenders, not relying on the farmer’s financial backing in any way. And, that is the way Dean Foods looked at the crazy proposal we made to the company in 2007. After Dean’s own internal analysis, we were told: “The damned thing seems to work.”

It should be noted, to Dean’s credit, the initial idea was to develop a project to prove the hypothesis, not to start a new division of a Fortune 500 Company. It was Dean’s commitment to the dairy industry and to its own sustainability effort that motivated the company.

So, we had our guinea pig. Then the hard part started.

We had to lock in all of our revenue sources:
- Energy;
- Fiber;
- Renewable energy certificates; and,
- Carbon credits.

I don’t mean the wink-wink-trust-me-we-will-get-to-it type of commitments. We had to have contracts with credit-worthy companies that would be signed at closing. Dean approached the deal as any good lender would approach any financing.

We also had to have our costs nailed down:
- A construction contract with a guaranteed cost and completion;
- An operation and maintenance cost, also with guarantees built in; and,
- A long-term land lease and feedstock supply agreement with the dairy.

Finally, we had to have an Internal Rate of Return on Dean’s money that was acceptable to company’s management and board. It had to be a prudent investment for a publicly traded company. It barely was.

Dean had bought into the project before all of the economics fell together. So, I cannot represent that the same economic return would be acceptable today. That’s why the parameters of a conventional lender would be a more prudent yardstick in this economic client.

Based upon all of the conversations we have had with all of the lenders we know, I can now report to you that it is still hard as hell to finance a digester project. About 90 – 95% of the lenders we have talked to are still unwilling to even discuss financing a digester projects.
Why? I know all of their excuses, but I am not sure I know their reasons. So, let’s remove those lenders from prospect list and concentrate on the forward-thinking, the friendly, the few lenders available to us.

A lender wants and will probably demand:

- An experienced developer;
- A proven, commercially available technology;
- Qualified operator with performance guarantees;
- Long-term off-take agreements with credit-worthy companies;
- A debt service coverage ratio of (probably) 1.5 times or higher;
- A disproportionately high percentage of equity investment; and,
- An interest rate high enough to give me a nose bleed.

To be fair, lenders do not have carve-outs for digester projects. This is not charity, nor are there government mandates to force them to lend to us. Our projects must complete with other borrowers for the same limited pool of funds, be they wind, solar or shopping center projects. Potential lenders – all black-hearted capitalists – are looking for the highest return balanced by the lowest risks they can find for their money. That is the playing field, and they have all the balls. Well, if they don’t have when you apply for a loan, they surely will before you get their money.

It is worth remembering that all federally regulated lenders are between a rock and a hard place since the collapse of the financial institutions in 2008. The rock is the Federal Reserve which is throwing almost free money at the lenders and begging them to make loans. The hard place is the Federal Deposit Insurance Corporation which is warning lenders to not take risks. Well, making a loan is taking a risk. And, making a loan on a digester is risky. What’s a lender to do? Try to minimize its risk. That usually starts with demanding more and more equity.

The most expensive money with the highest risk for loosing it that goes a project is not the debt – not the lender’s money – but the equity. The money that pays for all of the work that goes into putting together a project to take to a lender. Design engineering. Permitting, Legal. Environmental. Land acquisition. Utility bills. Food. Home mortgages. Somebody has to pay for all of that before even knowing if a lender will finance the project. That can easily be several hundreds of thousands of dollars. Then, the lender will require that a portion of the project is paid for with more equity. 25% of more. We have talked to lenders that required 50% equity. Some lenders want the equity to be first in and last out. I do not know of an equity investor who will agree to that.

Let’s try to quantify the worth of equity, at least to some degree. Using round numbers, what if it takes three hundred thousand dollars to put together a project, to get it ready to take to a lender? What is that risk worth? Is the money from your own pocket, saved for college tuition? What is it worth to you? What would you have to give up to get that money from an investor? What about when the lender wants another two million dollars of cash equity invested in the project before any of the lender’s funds are
released? What would you give up to get that money? What if you can’t get this money back out of the project until it shows a profit, a 1.5 debt service coverage? What is a fair return on that money? 10%, 20%, 25%? What is an acceptable return of that money? 2, 3, 4, 5 years? What is the premium demanded for high risk money?

The correct answer to all of these questions is: It depends. It will be different for every potential investor, from the dairy making the investment to the venture capitalist sitting in an office high above the bustling crowds in a city far, far away. However, the value of that risk capital must be factored into your economics, because it will have to be paid back someday.

Then, there are the risk factors that you cannot put on a spreadsheet:
- Will the dairy be in business in ten or fifteen years?
- What changes in regulations will there be in five or ten years?
- What will be the changes in technologies?
- What additional revenue potential might there be?

How good is your crystal ball? Probably no better than the lender’s. And, therein lies the problem. After analyzing all of the data, doing all of the due diligence and crunching all of the numbers, it is still a judgment call.

First, it is your judgment call. Can you step back and objectively look at your own project from the lender’s perspective? Have you put together all of the pieces, covered all the bases, minimized all the risks? If not, stop. Either go back and fill in the blanks and correct the mistakes or walk away. The last thing we need in this industry is another failure.

Second, it is the lender’s judgment call. Even if the developer has put together all of the pieces, covered all the bases and minimized the risks, is the digester project the best place to make a loan?

The quick answer from some folks would be: It is with a loan guarantee. No necessarily. To apply for a loan guarantee, there must first be a ready, willing and able lender offering terms and conditions acceptable to the borrower. We have walked away from a guaranteed loan because the lender’s terms did not agree with our conditions.

Let’s get specific. I am talking about USDA loan guarantees, the only viable long-term loan guarantee I know of for a digester project on a national basis. There is no question the loan guarantee can make a marginal project financable. But should it?

Here’s where things get sticky.
- A lender wants the term of the loan as short as possible. The USDA loan guarantee is designed to extend the term, allowing for an easier payback. The shorter payback that the bank wants will extend the repayment of equity and lessen an investor’s interest in the project.
A loan guarantee should make the interest rate on the loan lower, but when the annual loan guarantee fees to the cost of the loan, the effective cost of money could actually be higher than a commercial loan.

The government’s loan guarantee usually requires that each owner with 20% or more sign personally for 100% of the loan. If my share of the project is worth one million dollars, why should I guarantee five million dollars?

If my part of a five million dollar project is worth one million dollars and if I have a net worth of two million dollars, what assets I am going to guarantee the next project with? After one project, I could be out of business.

It does not seem that the loan guarantee structure was developed with any input from potential borrowers or lenders, just regulators. These regs do not reflect current economic realities, and the USDA knows it.

This administration is working hard to adapt the loan guarantee program to current economic realities, and is working with developers and lenders to review and hopefully streamline the loan guarantee program. It just takes time.

How do we take all of these pieces and make a financing plan for digesters out of it? I’m not sure, but I do know each project must have solid foundation:

- Empirical data,
- Proven, commercially available technology,
- Professional operator,
- Long-term off-take agreements with creditworthy companies,
- An experienced developer,
- Manageable risks, and
- A reasonable return on the investment for the debt as well as the equity.

Then, if all the pieces of the puzzle fit, there has to be – somewhere out there – a reasonable, receptive lender. There just has to be.
DEVELOPMENT AND APPLICATION OF AN ECONOMIC ANAEROBIC DIGESTER OPTIMIZATION (ADOPT) MODEL

J. S. Neibergs¹, J. Harrison¹, E. Whitefield¹ and M. DeHart²
¹ Washington State University and ² Veridian LLC

INTRODUCTION

Anaerobic digesters (AD) are fixed capital assets that have been constructed to improve the environmental sustainability of dairy farm nutrient management systems, and are now receiving increasing interest for their potential to generate additional revenues. Previous economic analyses of AD, have applied annual capital budgeting to evaluate economic feasibility. Annual budget estimates may oversimplify the AD management on a day to day basis when considering manure inflow rates and delivery of co-digestion feedstocks with respect to the AD design capacities and regulatory constraints. There is a need for a model that evaluates within year AD management strategies that maximizes an anaerobic digester’s economic sustainability. The Anaerobic Digester OPTimizer (ADOPT) programming model simulates daily AD management to optimize the annual net economic return of an anaerobic digester utilizing dairy manure with co-digested pre-consumer food-waste feedstocks. The feedstocks have variable value in terms of tipping fees, volumes delivered, nutrient composition and bio-gas electricity producing potential. Anaerobic digestion is receiving increased attention in the United States due to increasing interest in generating renewable energy and reducing greenhouse gas emissions. The USDA has introduced initiatives to promote agriculture based biogas energy development. The USDA signed a memorandum of understand with dairy producers through the Innovation Center for U.S. Dairy to accelerate the adoption of dairy based biogas installations with a goal of 25 percent reduction in greenhouse gas emissions from manure by the year 2020 (USDA News Release, 2011).

Technical feasibility is not the primary hurdle to successful implementation of AD at dairies provided the AD is planned, designed, constructed and operated properly. Anaerobic digestion of dairy manure technology is available for farm applications through a number of commercial vendors. Although AD technology has waste management, environmental and potential economic benefits, it has not been widely adopted in the United States. The number of new farms adopting AD has grown annually since 2000, and there are now over 100 dairy digesters in operation in the U.S., servicing approximately 150,000 cow equivalents Frear and Yorgey, (2010). Although the number of ADs is increasing, the present digesters service only small fraction of the potential farms and cows. Barriers to adoption include the intensive capital cost of the existing commercial systems, with typical systems costing as much as $1,500/cow for a 500-2,000 cow operation Frear and Yorgey, (2010).

The limited adoption of AD could be due to financial infeasibility or lack of information regarding AD profitability management. Previous economic studies of an AD apply a capital budgeting methodology using AD construction cost estimates and
annual projections of AD net revenues to determine the net present value of AD scenarios under consideration. Bishop and Shumway (2009) used a capital budget case study of a Washington AD. Leuer, Hyde and Richard (2008) used a capital budget approach and introduced stochastic parameters on AD revenue factors and life expectancy to analyze AD economics on three different sized dairy farms in Pennsylvania. In each of these and other capital budget AD feasibility studies the capital budget net economic return results are very sensitive to the modeling input parameters associated with the scenario with results ranging from large losses to large net gains. This indicates that AD design and management are critical to AD success.

ADOPT

The ADOPT model was designed to simulate the daily management of an AD. ADOPT is a linear programming model that maximizes the annual net revenue of the AD using a daily time step subject to the AD design capacity and operating constraints. The ADOPT model’s objective function is represented in the following equation.

\[
\text{Maximize } \sum_{t} \sum_{i} R_{it} P_{it} - \sum_{j} VC_{jt} - FC
\]

The equation is simply the AD profit function that the model maximizes the difference between daily revenues produced minus the daily operating variable costs and the annual fixed costs. Where t represents a day summed over the year T=365. The variable i represents each revenue source, i = 1 to n, multiplied by the price received for each revenue source, P_{it}. The daily variable cost is VC_{jt} for each variable cost factor j and FC is the annual fixed cost FC. Figure 1 shows the inflows into the AD and the n revenue sources for the ADOPT model. The following sections describe the project site, revenue sources and costs modeled in ADOPT.

Project Site

The base modeling parameters were obtained through a collaborative research project at the Qualco Energy Anaerobic Digester in Monroe, Washington. The project involves an intensive data collection on the AD inflows, bio-gas production, electricity generation, solids, and effluent. The Qualco digester was developed in 2008, and is a public-private partnership between Northwest Chinook Recovery, the Tulalip Tribe, and the Snohomish / Skykomish Agricultural Alliance. Although the digester currently receives manure from only one dairy, the digester was designed with the capacity to receive manure from several nearby dairies through a gravity fed sewer pipe system to the digester that avoids trucking transportation costs. After flowing through the AD the effluent is stored in two lagoons at the AD site. Effluent is pumped back to the dairy farm for agricultural field applications. The dairy is about 1 mile away from the digester, has about 1,100 cows, beds with sand and has a flush manure management system. Sand is separated and reused for bedding prior to leaving the dairy. The sand
separation is accomplished with a Daritech SRSsystem sand recovery system. The separated sand is recycled as bedding.

Figure 1. ADOPT Model AD Inflows and Revenue Sources

Tipping Fees

Anaerobic digestion is not limited to manure. Dairy anaerobic digesters can also accept non-manure organic wastes co-digestion feedstocks that can be digested by bacteria to produce methane. Accepting co-digestion feedstocks generates revenue through tipping fees and can also increase the amount of bio-gas produced to increase electricity sales. Bio-gas production from other organic wastes can produce more methane than from manure alone. In dairy digesters, the large feedstock of animal manure helps stabilize the digestion process by providing a high buffering capacity Murto, Bjornsson, and Mattiasson, (2004).

ADOPT simulates the daily inflow of manure and co-digestion feedstocks using daily data collected at the Qualco project site. Over the time frame modeled the following co-digestion feedstocks were added to the AD: whey, daff which is fat/grease by-product, ruminant blood from a beef packing plant, processed frozen fish byproducts, and out of date beverages which are high in sugar content. Each of these feedstocks were analyzed for nutrient composition and bio-gas production potential. The associated revenue from the feedstocks are called tipping fees to reflect a load of feedstock being tipped into the digester receiving tank. The tipping fee revenue for each feedstock is an individually negotiated contractual rate. The individual contractual tipping fee rates are
confidential and are not disclosed in this report. The cumulative tipping fee revenue is reported in the results section.

Electricity

The Qualco AD is designed to capture the bio-gas and burn the methane to produce electricity. Qualco sells all of the power generated and is not designed as a net metering system. The electricity sales are the megawatt hours generated per day sold to Puget Sound Energy transferred through Snohomish PUD. The electricity revenue is the price per megawatt sold net of the wheeling fee plus Washington’s renewable energy credit. The renewable energy credit is $5 per megawatt hour. The net revenue generated is $74 per megawatt hour in the base case analysis. Due to the availability of hydro-electric power in Washington the electricity sale rates are lower in comparison to other regions. The generator is a 450 KW Gauscor system.

Compost

Most AD use solid separators to reduce the amount of solids stored in their lagoons. The separated solids can be composted and then reused as bedding, sold off site commonly for nursery applications, or applied as a soil amendment. The compost is high in fiber and has some nutrients. The project site AD utilized an Eys brand screw press solids separator at onset of AD operation. After two years a Daritech 360 liquids-solids separator was installed. Solids are then composted using a Daritech Inc. Bedding Master composting system. The capital cost of the separator and composting system is about $600,000. Presently there are no contracts for continued sales of the compost. Some of the compost is used as bedding and the extra is used as an agriculture field soil amendment. In the base case of the ADOPT model there is no revenue from compost that reflects the current situation that there are no compost sale contracts.

Carbon Trading Credits

For digester owners, carbon trading is a potential source of revenue because methane emissions are reduced and that can be converted into a carbon credit. However due to the failure to enact federal legislation to establish a carbon cap and trade system, the carbon market has largely collapsed with the exception of regional efforts to establish carbon emission caps. Some dairies have carbon sale contracts that continue to generate revenue. The project site has a small carbon trading contract that generates revenue.

Other Potential Revenue Co-products

Adding other organic waste feedstocks to dairy digesters can increase biogas production but they can also increase nitrogen and phosphorus nutrients when compared to manure only. Under the dairies nutrient management plan, the increased
nutrients for additional feedstocks need to be quantified and incorporated into the nutrient management plan so that the field applications of effluent nutrients are balanced with crop production. There are cases where dairies receiving liquid effluent from digesters have had to obtain additional land and adjust cropping to make use of the increased nutrients. Phosphorus recovery from livestock wastewater in the form of struvite has been demonstrated in other parts of the country. A pilot-scale test at the Qualco Energy digester project site has demonstrated successful struvite recovery from dairy digester effluent, reducing total phosphorus in the effluent by 60-80% (Mena, N. 2011). Another potential revenue source is to collect and clean the bio-gas to extract methane. Clean methane can then be sold to natural gas providers. These potential revenues are not included in the base run of the ADOPT model.

Costs

Table 1 presents the annual digester operating and fixed expenses. The construction cost for the Qualco Energy digester was $3.4 million dollars with a projected economic life of twenty years. The annual straight line economic depreciation cost over this investment is $170,000. The annual interest expense on debt used to construct the digester is $15,000 on an original debt level of $2.6 million and a current debt level of about $400,000. The annual operating costs are primarily repair expenses, utilities and labor. The total annual operating expenses are $291,420 and fixed costs are $205,000. The total annual expense is $496,420.

ADOPT ANALYSIS AND DISCUSSION

The ADOPT model is programmed using GAMS mathematical programming software. The Qualco Energy digester serves to calibrate the model parameters and mimics the actual revenue and cost streams of the digester. The AD lagoon effluent is not assigned a revenue value in the modeling results, because the lagoon effluent does not generate revenue. It does have value as fertilizer nutrients in the cropping system, but it does not generate revenue. Figure 2 provides the daily revenue.

The feedstock revenue is the light grey line in Figure 2 that exhibits high daily variability. The variability is from differences in the volume of co-digestion feedstocks delivered. The contractual tipping fees differ between feedstocks, but the tipping fee of a feedstock remained fixed over the time period modeled. The electricity revenue is the relatively constant black line. The variation in the electricity revenue is when the electrical generator shut down four times for maintenance and electricity revenue went to zero. The electricity generated is fixed to the level constrained by the generator. Presently the more bio-gas is produced than the generator can use and the excess is flared. Additional analysis and data collection on the amount of bio-gas flared is ongoing to determine if a larger generator should be installed, or if adding a second generator to the system would be better economically.
Table 1. On-site digester annual operating and fixed expenses used in the base ADOPT economic analysis.

<table>
<thead>
<tr>
<th>Operating Expenses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor</td>
<td>$39,420</td>
</tr>
<tr>
<td>Professional Fees</td>
<td>5,500</td>
</tr>
<tr>
<td>Shavings</td>
<td>4,000</td>
</tr>
<tr>
<td>Supplies</td>
<td>1,000</td>
</tr>
<tr>
<td>Repairs</td>
<td></td>
</tr>
<tr>
<td>Composter</td>
<td>35,500</td>
</tr>
<tr>
<td>Digester</td>
<td>75,000</td>
</tr>
<tr>
<td>Separator</td>
<td>21,000</td>
</tr>
<tr>
<td>Site Maintenance</td>
<td>15,000</td>
</tr>
<tr>
<td>Interest</td>
<td>15,000</td>
</tr>
<tr>
<td>Utilities</td>
<td>70,000</td>
</tr>
<tr>
<td>Licensing/Testing</td>
<td>10,000</td>
</tr>
<tr>
<td>Total Operating</td>
<td>291,420</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fixed Expenses</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Insurance</td>
<td>$28,000</td>
</tr>
<tr>
<td>Taxes</td>
<td>7,000</td>
</tr>
<tr>
<td>Depreciation</td>
<td>170,000</td>
</tr>
<tr>
<td>Total Fixed Expenses</td>
<td>205,000</td>
</tr>
<tr>
<td>Total Expenses</td>
<td>$496,420</td>
</tr>
</tbody>
</table>

The total annual revenue under the base analysis is presented in Figure 3. The annual electricity revenue is $244,696, for tipping fees the annual revenue is $278,818, and the existing carbon credit contracts provide $22,000. The cumulative annual revenue is $545,514. The annual total costs previously reported in Table 1 are $496,420, which results in an annual positive net return of $49,094. On a capital investment of $3.4 million, the construction cost of the digester, the annual return on investment is less than 2 percent.
Figure 2. ADOPT model daily revenue

Figure 3. ADOPT model annual revenue from electricity, tipping fees and carbon credits.
The low annual return on investment found in this particular case and reported in other AD economic studies, is an explanatory factor to the low adoption rates of AD across the country. However in this case there is a high potential to increase revenue by improving the digesters electrical generating capacity through capturing the existing bio-gas that is currently being flared off. Also compost sales are a promising potential revenue that currently is receiving no economic value. Work on developing this market potential is ongoing.

The tipping fee revenue cannot be increased by much. Presently in this base case the volume of co-digestion feedstocks in nearly a maximum. The volume currently being received is close to the maximum allowed by state regulations and the dairy farm’s nutrient management plan for the application of the AD effluent. The only way to increase tipping fee revenue is to renegotiate the tipping fee contract. That will not be easy as additional AD are constructed and the market becomes increasingly competitive for co-digestion feedstocks. One alternative that is currently being investigated is to evaluate the co-digestion feedstocks for their ability to generate bio-gas and increase electricity revenue. This will provide AD managers information to evaluate tipping fee contractual rates. Co-digestion feedstocks with low electricity potential should require higher tipping fees. Of course this requires that the AD have sufficient electricity generating capacity to effectively convert the bio-gas potential of co-digestion feedstocks to electricity revenue.

Another factor that is often overlooked in the economic analysis of AD is the marginal comparison of a traditional nutrient management system to an AD system. The traditional lagoon – land management system is a sunk cost to the dairy farm that has no potential to generate revenue or a return on investment. The AD return may be low, but as long as it is positive it represents a better capital investment than a traditional system. Even if the AD system has a negative return it still may be a better economic investment than a traditional system when evaluated on a minimum cost basis. Also additional work is needed to evaluate the marginal value difference of the nutrient profile between traditional effluent and AD effluent. Two issues need further investigation: 1) since AD effluent has a greater content of NH4, there is a potential for greater loss of volatile nitrogen during lagoon storage, and 2) additional inputs of nutrients provided by additional feedstocks, are not not being valued by current economic models. There are several other potentially positive future developments that may improve AD economics. Increasing electricity costs in the future could have a positive effect on AD economic return. Developing a market for the AD compost should become a primary effort as this is a large volume of product. Also developing analysis on the scale economics of digesters could identify more economically sustainable AD systems.

Currently the ADOPT model is in a GAMS software platform. GAMS is not a software package that is widely used outside of academia. Our intent is to create a web-based interface so that advisers and producers can enter AD system design and economic data to evaluate varying scenarios. The model will be employed to evaluate:
alternative nutrient management policies and technologies such as a fully functioning nutrient recovery system; alternative crop nutrient application constraints (N vs P based land application limits); accepting manure from additional dairies to characterize the impacts of a community AD system; and to evaluate the net economic return of various feedstocks.

REFERENCES

Frear, C. and G. Yorgey. 2010. Introduction to anaerobic digestion, CSANR Research Report 2010-001, Washington State University, Pullman, WA.
Mena, N. 2011, Washington dairies and digesters, Washington State Department of Agriculture, AGR PUB 602-343 (N/10/11).
BIOGAS COMPOSITION AND CLEANUP OPTIONS

N. S. McDonald
Organic Waste Systems, Inc.

INTRODUCTION

The decision by farms to install an anaerobic digestion system is based on many factors, the largest of which is normally the potential value to be derived from the biogas – the net value of the energy produced. While combusting biogas “as is” for electrical production has been the most common use, farms do have the option to clean up or upgrade the biogas and change the net energy value equation.

It is helpful to first establish some common definitions or nomenclature. Biogas is the raw, untreated product coming from the digester and is typically comprised of:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>55 to 65 %</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>35 to 45 %</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>0.4 to 1.2 %</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>0.0 to 0.4%</td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>250 to 3000 ppm</td>
</tr>
<tr>
<td>Water</td>
<td>Saturated</td>
</tr>
</tbody>
</table>

For electrical production, simple scrubbing or conditioning of biogas (aka scrubbed biogas) is all that is required: removal of free water droplets and hydrogen sulfide in excess of the engine manufacturer’s specifications, normally <500 ppm.

Because biogas has lower BTU content than conventional natural gas, it is normally valued at a discount to pipeline gas since equipment requires some amount of modification in order to accommodate the lower BTU content. Upgraded biogas means that the gas has been enriched for methane by removal of some or all of the non-methane components. The final composition of the resulting upgraded biogas is normally referred to as biomethane. The final purity composition of the biomethane will depend upon the specifications set by the user, the conversion equipment manufacturer, or the utility pipeline. In the chart below, the range of biomethane compositions produced is shown:

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane (CH₄)</td>
<td>99.8 % to 85%</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>0.01 to 14 %</td>
</tr>
<tr>
<td>Nitrogen (N₂)</td>
<td>0.01 to 1.0 %</td>
</tr>
<tr>
<td>Oxygen (O₂)</td>
<td>0.0 to 0.4%</td>
</tr>
<tr>
<td>Hydrogen Sulfide (H₂S)</td>
<td>0 to 3000 ppm</td>
</tr>
<tr>
<td>Water</td>
<td>2-7 lbs./million scf</td>
</tr>
</tbody>
</table>

There are a variety of technologies for upgrading biogas, including chemical absorption, high pressure water scrubbing, pressure swing adsorption, cryogenic separation, and membrane separation. Within each of these technologies, different vendors offer somewhat unique and proprietary approaches. The capital and economic
cost of each method varies by vendor and by scale (the standard cubic feet per minute – scfm - being processed) and by extent of upgrading (the final purity level required). The final effective upgrading cost including capital amortization ranges from $1.75 to $4.00 per 1000 scf (which is approximately 1 MMBTU if upgraded to 99% methane). The technologies also have different levels of methane capture efficiency, meaning that some technologies can separate and capture nearly all (98%) of the methane while others capture just 85%. This means that the total amount of biomethane which can be used to generate value will also vary by technology and must be part of the economic evaluation.

Biomethane with at least 820 BTU/scf can be used in many natural gas boilers and engines without any modification to generate heat, electricity or mechanical pressure. Biomethane with at least 900 BTU/scf is the minimum specifications for most OEM compressed natural gas vehicle engine manufacturers. Gas utility specifications will normally require at least 970 BTU/scf for pipeline insertion. This flexibility means that a farm can evaluate the economics for each of these energy values and determine which avenue provides the best rate of return.

<table>
<thead>
<tr>
<th>ENERGY</th>
<th>UNIT</th>
<th>$/UNIT</th>
<th>$/MM BTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>kWh</td>
<td>$0.10</td>
<td>$29.31</td>
</tr>
<tr>
<td>Natural gas</td>
<td>MM BTU</td>
<td>$6.00</td>
<td>$6.00</td>
</tr>
<tr>
<td>Propane</td>
<td>Gallon</td>
<td>$2.50</td>
<td>$27.47</td>
</tr>
<tr>
<td>Gasoline</td>
<td>Gallon</td>
<td>$3.50</td>
<td>$28.93</td>
</tr>
<tr>
<td>Diesel</td>
<td>Gallon</td>
<td>$3.75</td>
<td>$28.85</td>
</tr>
</tbody>
</table>
BIOMETHANE AS AN OPTION FOR ON-FARM ENERGY PRODUCTION

Norma McDonald

OWS COMPANY PROFILE

- DRANCO TECHNOLOGY DEVELOPED IN 1983
- OWS CREATED IN 1988
- SALES: $25-35 MILLION PER YEAR
- 80 PEOPLE

SUBSIDIARIES
- DRANCO NV (BELGIUM): operating and investment company (owns 52% of Nüstedt plant)
- OWS INC (Dayton, Ohio, USA since 1992; integrated Phase 3 Renewables 9/2009)
- BES GMBH (GERMANY, since 2008)

ACTIVITIES
- DESIGN & CONSTRUCTION OF ANAEROBIC DIGESTION PLANTS FOR SOLID AND SEMISOLID ORGANICS
- BIOGAS CONSULTANCY & SUPPORT
- BIODEGRADATION TESTING AND WASTE MANAGEMENT CONSULTANCY

DESIGN AND CONSTRUCTION OF AD PLANTS

27 FULL-SCALE PLANTS ON:
- FOOD/BIOWASTE: 14 DRANCO PLANTS
- RESIDUAL/MIXED WASTE: 9 DRANCO PLANTS
- ENERGY CROPS: 1 DRANCO-FARM PLANT (S/U 2006)
- ENERGY CROPS/FOOD WASTE: 3 WET AD PLANTS (S/U 2008)
- MANURE & CO-FEEDS: 3 WET AD PLANTS (S/U 2005-6)

OWS RECENTLY SELECTED FOR NEW SITES:
- YORK (UK)
- CHAGNY (FR)
- NETHERLANDS
- ST PAUL (US)
- LA AREA (US)
- BOSTON (US)
- IOWA (US)
- HONG KONG
- INDINA (US)

OPTIONS FOR USE OF BIOGAS

- Greenhouse Heat & Power
- Tie Into Gas Lines
- Wheeling power to local businesses
- ELECTRICITY FOR FARM USE & GRID
- FUEL CELLS
- CBM/LBM

WHAT VALUE CAN YOU GET FOR THE ENERGY?

TOTAL ENERGY RATE ($/MWH)

- NYMEX Natural Gas Futures
- Regular Gasoline Prices
- On-Highway Diesel Fuel Price

Input:
- Any organic waste
- Crop Residuals

www.americanbiogascouncil.org
Raw Biogas Characteristics

- **Pressure** (less than 1 psig)
  - Common: 2 – 8 inches of water column
  - Municipal applications: up to 15 inches of water column
- **Makeup by Major Constituents** (assuming manure & cofeeds):
  - Constituent | Concentration
  - Methane (CH₄) | 55 to 65 %
  - Carbon Dioxide (CO₂) | 35 to 45 %
  - Nitrogen (N₂) | 0.4 to 1.2 %
  - Oxygen (O₂) | 0.0 to 0.4%
  - Hydrogen Sulfide (H₂S) | 0.02 to 0.4%
- Saturated with water

---

THE BIOGAS UPGRADING PROCESS

Initial steps are similar to those needed when using the biogas for other purposes

BIOGAS UPGRADING REQUIRES SEPARATION OF METHANE FROM OTHER GASES

Moisture removal

- Virtually all biogas needs free moisture removal, pipeline requires maximum removal
- Systems may use more than one step in combination
- The sequence of steps are often chosen depending on what steps are used to process the biogas. It may be ideal for the gas to be hot or cold.

**Activated Carbon**

- Removes both sulfides (and siloxanes if present) by adsorption
- Process is non-selective
- Activated carbon is often used for its high surface area and catalytic properties
- Can be made from wood, coconut shells, charcoal
- Performance affected by gas temp. and moisture (better on dry, cool/warm gas)

**Sulfatreat**

- Removes sulfides
- Uses unique combination of iron oxides react with sulfides (H₂S) to produce iron pyrite.
- Can be enhanced with water spray and low air injection if some oxygen is not an issue (vehicles)
- Can be single vessel or lead/lag with 2 vessels in series, single use or regenerated
Iron Sponge
- Removes sulfides
- Iron sponge normally wood chips impregnated with iron oxide
- Upflow/Downflow of gas through packed bed of iron sponge
- Iron oxide (Fe₂O₃) reacts with sulfides (H₂S) to produce iron sulfide (Fe₂S₃) and water (H₂O)
- Must drain excess water occasionally so as not to flood the bed
- Bed can be regenerated several times before needing replacement

Biofiltration
- Removes sulfides
- Uses microbes living on a support matrix
- Microbes (and normally low level oxygen addition) consume H₂S and precipitate as elemental sulfur
- Supplied as:
  - Above grade packed towers
  - Below grade systems filled with natural media like wood chips or peat moss.
- Three major types:
  - bioscrubber
  - biofilter
  - biotrickling filter

Water Wash
- Carbon dioxide and other polar molecules have a higher solubility in water than methane. Therefore water can be used to remove contaminants from biogas.
- If the contaminants are removed or ‘scrubbed’ at high pressure (~130 psig), the water can be continuously regenerated or ‘stripped’ in a separate low pressure vessel (~3 psig).
- Produces high quality biogas (renewable natural gas)

Amine Scrubber
- Raw biogas enters and is pressurized up to 100 psig
- Biogas then flows upward through a packed column where the carbon dioxide (CO₂) and sulfides are absorbed within the counter flowing amine
- Once saturated amine leaves the scrubber and carbon dioxide is driven off to the atmosphere, the amine may be regenerated by heating it
- Produces high quality biogas (renewable natural gas)

Membrane Separation
- Membrane separates methane by retaining it ("retentate"). Undesirable molecules like carbon dioxide (CO₂), water (H₂O), sulfides (H₂S), and ammonia (NH₃) pass through the membrane ("permeate"). Produces high quality biogas (renewable natural gas).
- Polymer membranes for gas separation are typically formed into very thin, hollow fibers, clustered into modules consisting of thousands of fibers. A high pressure pump forces the gas through the fiber centers where it is collected with permeate from other fibers.
- To improve separation, multiple stages may be used. Two-stage systems are common (shown below) which increases the longevity of the membrane modules. Most installations include a desulfurization and drying step before raw biogas is sent through the membrane.

Pressure Swing Adsorption (PSA)
- An adsorbing material, either particulate (carbon molecular sieve or zeolite) or structured, preferentially adsorbs carbon dioxide and other highly adsorbed compounds at pressure (~100 psig) allowing methane to pass through
- Conventional systems have multiple tanks for separation, with only one in service at a time. Newer technology uses rotary valves, structured beds, smaller footprints, faster cycle times.
- Produces high quality biogas (renewable natural gas)
ON-FARM BIOGAS UPGRADING BACKGROUND

- Michigan Dairy
  - 2000 milking herd @ 8-12% TS, biofiber bedding
  - 1450 heifers @ 12-20% TS, straw/stover bedding
  - 350 calves @ 20-30% TS, straw bedding
- Biogas Plant
  - Original two digesters installed in 2006 with two 350kW gensets;
  - 50% expansion in 2007 to three digestion tanks
  - Increased biogas through co-feeding of ethanol and food processing waste
- Biogas Upgrading System (BUS) to Pipeline Quality – On-farm, small-scale!
  - H2S removal, chilling, moisture knockout
  - Primary Compression, moisture knockout
  - PSA gas separation
  - Revenue and energy delivery optimization approach – electric or pipeline gas

Pipeline Insertion
Cost & Feasibility Determination

- Proximity to site
- Pressure: Maximum, minimum, operational fluctuation
- Gas Specifications: BTU value, H2S, CO2, O, H2O
- Odorization
- Monitoring and Metering Requirements

WASTE HEAT USAGE?

- Digester heating
- Biofiber drying

PROCESS OVERVIEW – NATURAL GAS

- Feedstock source
- Piping & pumping
- Digestion tanks and gas storage
- Greater moisture removal requirements for compression
- Greater H2S removal requirements to meet specs

WASTE HEAT AVAILABILITY

- Biogas to boiler
- Compressor heat exchanger
- PSA exhaust gas
FIRST COMBINATION ON-FARM RENEWABLE ENERGY PRODUCTION FACILITY

SCENIC VIEW DAIRY
FENNVILLE, MI

FEED GAS: UP TO 170 CFM
PRODUCT GAS: ~75-85 CFM
INSERTION PRESSURE: 120-150 PSIG

BOTTOM LINE COMPARISON

ENERGY SALES
25,130 Total volume (1000 cft) of Natural Gas available for Pipeline / year
$175,912 Potential Natural Gas Revenue Stream / year

<table>
<thead>
<tr>
<th>Price Range - Natgas price/1000cft</th>
<th>Low</th>
<th>Modeled</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue Range / year</td>
<td>$4,000</td>
<td>$7,000</td>
<td>$10,000</td>
</tr>
</tbody>
</table>

3,057,014 Total volume (kWh) of Electricity Production / year
$115,555 Potential Electricity Revenue Stream / year

<table>
<thead>
<tr>
<th>Price Range - Elec price/kWh</th>
<th>Low</th>
<th>Modeled</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue Range / year</td>
<td>$0.030</td>
<td>$0.038</td>
<td>$0.060</td>
</tr>
</tbody>
</table>

BOTTOM LINE COMPARISON – LOW VOLUME HURTS ROR OF PIPELINE SYSTEM

<table>
<thead>
<tr>
<th>Capital Purchases</th>
<th>Farm Only</th>
<th>Farm + Elec</th>
<th>Farm + Pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas Plant</td>
<td>$502,000</td>
<td>$502,000</td>
<td>$502,000</td>
</tr>
<tr>
<td>Gen-Set(s)</td>
<td>$75,000</td>
<td>$350,000</td>
<td>$75,000</td>
</tr>
<tr>
<td>Separator &amp; Building</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Boiler</td>
<td>$10,000</td>
<td>$10,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>PSA &amp; Compressor</td>
<td>$315,000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical and Interconnections</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>Other Capital</td>
<td>$200,000</td>
<td>$200,000</td>
<td>$200,000</td>
</tr>
<tr>
<td>Total Capital Purchases</td>
<td>$987,000</td>
<td>$1,312,000</td>
<td>$1,452,000</td>
</tr>
<tr>
<td>Other Capital Cost</td>
<td>$49,350</td>
<td>$65,600</td>
<td>$72,600</td>
</tr>
<tr>
<td>Total Other Capital Costs</td>
<td>$542,375</td>
<td>$616,000</td>
<td>$694,500</td>
</tr>
<tr>
<td>Total Capital Cost</td>
<td>$1,549,375</td>
<td>$1,928,000</td>
<td>$2,146,500</td>
</tr>
</tbody>
</table>

After grant ROR
Simple payback (yrs) | 4.1 | 4.2 | 5.1
10yr MIRR | 7.0% | 6.6% | 3.2%
ROI (yrs) | 7.1 | 7.4 | 9.6

FEEDSTOCK OPTIONS TO INCREASE BIOGAS PRODUCTION

SYRUP
STILLAGE
GLYCERINE
OFFAL
WASTE
SILAGE
ALGAE
OTHER MANURES
YARD WASTE

133
**ADDITIONAL INFORMATION**

**Assumptions:**
- Manure Volume - Gallons: 10,950,000
- Assumed Total Solid %: 8%
- Co-feed - Gallons: 547,500

<table>
<thead>
<tr>
<th>Biogas Production per year - cft</th>
<th>22d</th>
<th>24d</th>
<th>28d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallons</td>
<td>186</td>
<td>186</td>
<td>177</td>
</tr>
<tr>
<td>Total gallons</td>
<td>52,980</td>
<td>56,115</td>
<td>56,115</td>
</tr>
<tr>
<td>MMBTU's per year (millions)</td>
<td>46.137</td>
<td>52.980</td>
<td>56.115</td>
</tr>
<tr>
<td>MMBTU's per hour</td>
<td>5.3</td>
<td>6.0</td>
<td>6.4</td>
</tr>
</tbody>
</table>

**CFT CH4 PER DAY**
- 7,320

**Energy generated % of farm usage**
- Farm Usage only MMBTU's factored for conversion efficiency
- Farm Usage %: 16% 14% 13%
- Energy generated % of farm usage: 63% 72% 76%

**Energy Sales**
- 44,676 Total volume (1000 cft) of Natural Gas available for Pipeline / year
- $312,732 Potential Natural Gas Revenue Stream / year

<table>
<thead>
<tr>
<th>Price Range - Natgas price/1000cft</th>
<th>Low</th>
<th>Modeled</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue Range / year</td>
<td>$4,000</td>
<td>$7,000</td>
<td>$10,000</td>
</tr>
</tbody>
</table>

**OR**

- 5,434,692 Total volume (kWh) of Electricity Production / year
- $205,431 Potential Electricity Revenue Stream / year

<table>
<thead>
<tr>
<th>Price Range - Elec price/kWh</th>
<th>Low</th>
<th>Modeled</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revenue Range / year</td>
<td>$0.030</td>
<td>$0.038</td>
<td>$0.060</td>
</tr>
</tbody>
</table>

**CAPEX INCREASES FOR HIGHER ELECTRICITY PRODUCTION – BUT PIPELINE SYSTEM STILL ADEQUATE**

<table>
<thead>
<tr>
<th>Capital Purchases</th>
<th>Biogas Plant</th>
<th>Gen-Set(s)</th>
<th>Separator &amp; Building</th>
<th>PSA &amp; Compressor</th>
<th>Electrical and Interconnections</th>
<th>Other Capital</th>
<th>Total Capital Purchases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biogas Plant</td>
<td>$502,000</td>
<td>$75,000</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$200,000</td>
<td>$987,000</td>
</tr>
<tr>
<td>Gen-Set(s)</td>
<td>$502,000</td>
<td>$75,000</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$200,000</td>
<td>$987,000</td>
</tr>
<tr>
<td>Separator &amp; Building</td>
<td>$502,000</td>
<td>$75,000</td>
<td>$100,000</td>
<td>$100,000</td>
<td>$150,000</td>
<td>$200,000</td>
<td>$987,000</td>
</tr>
<tr>
<td>PSA &amp; Compressor</td>
<td></td>
<td></td>
<td></td>
<td>$315,000</td>
<td>$260,000</td>
<td>$200,000</td>
<td>$987,000</td>
</tr>
<tr>
<td>Electrical and Interconnections</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$200,000</td>
<td>$987,000</td>
</tr>
<tr>
<td>Other Capital</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$987,000</td>
</tr>
<tr>
<td>Total Capital Purchases</td>
<td>$987,000</td>
<td>$1,662,000</td>
<td>$1,452,000</td>
<td></td>
<td></td>
<td></td>
<td>$987,000</td>
</tr>
</tbody>
</table>

**Other Capital Cost**
- Engineering & Admin: $49,350 $83,100 $72,600
- Contingencies: $74,025 $124,650 $108,900
- Total Other Capital Costs: $123,375 $207,750 $181,500
- Total Capital Cost: $1,110,375 $1,869,750 $1,633,500

**BOTTOM LINE COMPARISON**

<table>
<thead>
<tr>
<th>Farm Farm + Farm + Pipeline Only Elec</th>
<th>Revenue</th>
<th>Farm Only</th>
<th>Farm + Elec</th>
<th>Farm + Pipeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sell Energy</td>
<td>$0</td>
<td>$180,779</td>
<td>$269,523</td>
<td></td>
</tr>
<tr>
<td>Sell Excess Bedding/Compost</td>
<td>$8,326</td>
<td>$8,326</td>
<td>$8,326</td>
<td></td>
</tr>
<tr>
<td>Sell Sulfur - Fertilizer</td>
<td>$151</td>
<td>$1,090</td>
<td>$1,141</td>
<td></td>
</tr>
<tr>
<td>Sell Emission Credits</td>
<td>$83,937</td>
<td>$96,681</td>
<td>$92,937</td>
<td></td>
</tr>
<tr>
<td>Total Revenue</td>
<td>$92,414</td>
<td>$286,877</td>
<td>$371,928</td>
<td></td>
</tr>
</tbody>
</table>

**Pre-grant ROR**
- Simple payback (yrs): 4.1 4.6 3.3
- 10yr MIRR: 6.8% 5.1% 10.7%
- ROI (yrs): 7.3 8.4 5.3

**HILARIDES DAIRY**
- Lindsay, California
- 9,000 head jersey milking herd, UF to cheese plant, dried manure solids bedding
- 2000 calf hutchtes

**PRE-EXISTING SYSTEM**

**INITIAL SETTLING POND**
- Clay lined, emptied 3X/year
- Solids float, liquid gravity flows to covered lagoon

**TWO COVERED LAGOONS**
- Ambient, no agitation, clay lined
- 4 ELECTRIC GENERATORS - each 125kW, minimal controls, rebuilt, >10yrs old
RECENT EXPANSION
- Covered 3rd lagoon, adding 18 million gallons
- Ambient, no agitation, ? Retention time
- Increased biogas capture by 70%

CONNECTING TO EXISTING BIOGAS LINES
- Tied into header, creating bypass loop
- Note use of S40 PVC (no freezing)

H2S REMOVAL

- Although PSA can remove H2S, preferable to remove H2S before upgrading – otherwise H2SO4 will form somewhere!
- Initially using lead-lag Sulfatreat vessels, used tanks, with “adaptations” to increase bed life and lower cost
- Researching additional options to lower cost further

New System, New Building

Erected new 3-sided building to house BUS™, compression skid, and storage cylinders. (System could be outdoors in colder climate also with frost package added.)

Biogas Upgrading System – BUS™ A
- Switched to shop fabrication vs. field erection
- Performance check prior to shipment on entire system
- Shipped to site for faster installation

Lower cost, higher reliability

AN INTEGRATED SYSTEM APPROACH

135
HIGH SIDE COMPRESSION
3600 psig, ~775 GDE/day

30 hp three stage reciprocating compressor fills cascade storage vessels, 70,000 acf capacity, 15 hours of production time at nameplate capacity. CH4 concentration in biogas and PSA setting determine actual throughput of upgraded biomethane.

MILK TRUCKS RUNNING ON CBM
(Compressed Biomethane)

Two new Peterbilt glider kits with Cummins-Westport natural gas engines. Fill time determined by pressure differential between CBM in storage and truck fuel tank. At max differential, fill time for 120 GDE is four minutes.

PICK UP TRUCKS TOO!
- Found six used CNG pickups on e-bay and purchased for farm use

WORLD AG EXPO 2009
http://wud.telefeed.com/#latestvideo

BY THE NUMBERS
- Fuel Value: 775 GDE per day, $2,325 @ $3/gal in CA
- CA Pollution tax avoidance of $0.04/mile, $186/day
- Truck O&M: Less, but TBD
- Carbon Credits: TBD, may take as SOx or NOx
- Advanced Biofuel Production Tax Credit: TBD
- Installed cost: $1.2 million, not including new lagoon cover or trucks. Interest & depreciation of $300/day, ignoring grant contribution
- Operating cost:
  - 90hp + 30 hp compression, about 90kW. At self-generated O&M of $0.03/kWh, $64.80/day
  - H2S removal, $200-400/day at projected bed life
  - Compressor oil, belts, plugs, TBD but budgeted for $20/day.
  - Labor, 30 minutes/day, $30/day
- Net – About $1500-$1700 per day benefit
Digester Gas Combustion

J. Hower and D. S. Chianese
ENVIRON International Corporation
Los Angeles, CA

INTRODUCTION

Anaerobic digesters have become an increasingly popular method of manure handling throughout the U.S. One of the advantages of digesters is the ability to capture and beneficially use the methane generated by anaerobic digestion of manure. Once captured from a digester, biogas can be upgraded to pipeline quality and injected into a natural gas pipeline, or it can be used onsite or at a nearby facility as fuel. The many benefits associated with this practice include reduced methane emissions (a powerful greenhouse gas), potential to recoup capital costs through biogas or power sales, and ability to replace natural gas usage with biogas. However, combusting biogas can also result in issues different from those encountered when combusting natural gas, among them changes in emissions, difficulties meeting required emission standards, and capital costs required to comply with regulations. This discussion will focus on expected emissions and environmental impacts, regulations and cost of compliance, and future trends in control technologies and regulations associated with the combustion of biogas.

DIGESTER GAS GENERATION AND COMBUSTION

Anaerobic Digestion

During anaerobic digestion, microorganisms decompose organic matter in an oxygen-free environment, producing methane (CH₄) and carbon dioxide (CO₂) (Madigan et al., 2003). In fact, anaerobic manure storage vessels (e.g., digesters) are designed to maximize the production of digester gas, or biogas. By collecting the produced gas, the overall release of CH₄ from the manure storage can be reduced, depending on the end use of the gas.

There are multiple potential end uses for the gas. The first potential end use (which is more accurately a disposal method) consists of combusting the digester gas in a flare. This converts the CH₄ to CO₂; although this reduces the total global warming potential of the GHGs emitted by over 95%, it is not a beneficial use of the gas. The second potential option is the injection of processed biogas into an existing natural gas pipeline. In order for this option to be feasible, the dairy needs to be located near an existing pipeline, in an area served by a utility that accepts biogas, and purchase and operate the required gas cleanup equipment. The third potential option, which will be the focus of this paper, is the onsite production of energy. This option involves routing the digester gas to energy generation equipment such as an internal combustion engine.
(ICE), microturbines, or fuel cells.

Emissions

Digester gas is primarily CH₄. However, unlike natural gas, there are additional trace gases in digester gas. Digester gas is approximately 60% CH₄ and 35% carbon dioxide (CO₂), with the remainder consisting of other components such as oxygen, nitrogen, and hydrogen sulfide (H₂S). Similar to natural gas and other fuels, combusting digester gas results in emissions of criteria pollutants (oxides of nitrogen, NOₓ; carbon monoxide, CO; volatile organic compounds, VOC; particulate matter, PM; and oxides of sulfur, SOₓ) as well as greenhouse gases (CO₂, CH₄, and nitrous oxide, N₂O). Emissions of these pollutants from combusting digester gas vary depending on the type of combustion device, the presence of air pollution control equipment, and the composition of the gas; fewer impurities will result in emissions similar to natural gas while more impurities result in a different emissions profile as illustrated in Table 1 and Table 2.

Table 2 shows that emissions from digester gas combustion in ICEs can vary widely. These data were obtained from farms located in California. These farms used different digester configurations (i.e., plug flow, covered lagoons) and had different electric generating capacities (75 kw to 563 kW). One of the parameters that varied the most was the concentration of H₂S in the biogas. The H₂S concentrations ranged from 4 ppm to 1,586 ppm, leading to widely varying SOₓ emissions as H₂S converts to SOₓ at a very high rate in combustion devices.

Table 1. Criteria pollutant emissions from stationary turbines fired with natural gas and digester gas.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emission Factor (lb/MMscf)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NOₓ[a]</td>
</tr>
<tr>
<td>Digester gas (uncontrolled)[d]</td>
<td>96.0</td>
</tr>
<tr>
<td>Natural gas (uncontrolled)[e]</td>
<td>336.0</td>
</tr>
</tbody>
</table>

[a] Obtained from AP-42, Chapter 3.1. Stationary Gas Turbines, Table 3.1-1.
[b] Obtained from AP-42, Chapter 3.1. Stationary Gas Turbines, Table 3.1-2a (natural gas) and Table 3.1-2b(digester gas).
[c] Total particulate matter.
[d] Emission factors in AP-42 were given in lb/MMBtu. A heating value of 600 MMBtu/MMscf was used to convert to lb/MMscf.
[e] Emission factors in AP-42 were given in lb/MMBtu. A heating value of 1,050 MMBtu/MMscf was used to convert to lb/MMscf.
Table 2. Criteria pollutant emissions from engines fired with natural gas and digester gas.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Emissions (lb/MMscf) [a]</th>
<th>NO\textsubscript{x} [b]</th>
<th>CO [b]</th>
<th>SO\textsubscript{x} [b]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Digester gas [^{[c]}]</td>
<td>324</td>
<td>546</td>
<td>870</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(18 to 918)</td>
<td>(222 to 948)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural gas [^{[d],[e]}]</td>
<td>588</td>
<td>892.5</td>
<td>0.6</td>
<td></td>
</tr>
</tbody>
</table>

\[^{[a]}\] Reported average emissions are shown with the range in parentheses.
\[^{[b]}\] Emissions were obtained from CEC (2006) in units of lb/MMBtu.
\[^{[c]}\] Emissions were converted to lb/MMscf by assuming an average heating value of digester gas of 600 MMBtu/MMscf.
\[^{[d]}\] Emissions were converted to lb/MMscf by assuming an average heating value of natural gas of 1,050 MMBtu/MMscf.
\[^{[e]}\] CEC (2006) cites AP-42 as the source for natural gas emissions.

There are both human health and environmental impacts of these emissions. The US Environmental Protection Agency (US EPA) regulates the criteria pollutants because these pollutants have negative human health and welfare effects.
Table 3 describes some health effects associated with five of the six criteria pollutants (lead is not included as digesters are not a significant source of lead emissions). There is only a small population that is likely to be directly harmed by emissions from digester gas combustion (i.e., the people who live in close proximity to the farm, farm workers, etc.). However, the emissions from digester gas combustion contribute to the concentration of these pollutants in the ambient air. Because of this, the USEPA, as well as state agencies (e.g., Cal/EPA) establishes ambient air quality standards that dictate the permissible level of these pollutants in the air. These permissible levels are established to limit and prevent health effects due to cumulative concentrations of the criteria pollutants. For example, smog (ozone) is caused by a reaction of sunlight, nitrogen oxides, and VOCs. The health effects of smog have been well-documented and can include decreased lung capacity, shortness of breath, and wheezing, among others.
Table 3. Criteria pollutants, their precursors, and related health effects.\textsuperscript{[a]}

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Health Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particulate Matter\textsuperscript{[b]}</td>
<td>Respirable particulates (PM$<em>{2.5}$ and PM$</em>{10}$) pose a serious health hazard, alone or in combination with other pollutants. More than half of the smallest particles inhaled get deposited in the lungs and can cause permanent lung damage. Respirable particles have been found to increase morbidity and mortality via the following adverse health effects: decreased lung function, aggravated asthma, exacerbation of lung and heart disease symptoms, chronic bronchitis and irregular heartbeats. In addition, respirable particles can act as a carrier of absorbed toxic substance.\textsuperscript{[c]}</td>
</tr>
<tr>
<td>Ozone\textsuperscript{[d]}</td>
<td>Elevated ozone concentrations have been shown to induce airway irritation, cause airway inflammation, induce wheezing and difficulty breathing, aggravate preexisting respiratory conditions such as asthma, and can lead to permanent lung damage after repeated exposure to elevated concentrations.\textsuperscript{[e]}</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>Carbon monoxide is a colorless and odorless gas that is known to cause aggravation of various aspects of coronary heart disease, dizziness, fatigue, impairment to central nervous system functions, and possible increased risk to fetuses.</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO$_2$)</td>
<td>Sulfur dioxide is known to cause irritation in the respiratory tract, shortness of breath, and can injure lung tissue when combined with fine PM. It also reduces visibility and the level of sunlight.</td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO$_2$)</td>
<td>Long-term exposure to nitrogen dioxide has the potential to decrease lung function and worsen chronic respiratory symptoms and diseases in sensitive population. It has also been associated with cardiopulmonary mortality and emergency room asthma visits. USEPA recently adopted a 1-hour federal standard to address short-term exposure impacts (e.g., adverse respiratory effects), particularly near major roadways.</td>
</tr>
</tbody>
</table>


\textsuperscript{[b]} Particulate matter (PM$_{2.5}$ and PM$_{10}$) can be directly emitted. In addition, oxides of nitrogen (NO$_x$) and oxides of sulfur (SO$_x$) are precursors of PM$_{2.5}$ and PM$_{10}$.

\textsuperscript{[c]} USEPA National Center for Environmental Assessment, particle pollution health affects [http://www.epa.gov/air/particlepollution/health.html](http://www.epa.gov/air/particlepollution/health.html).

\textsuperscript{[d]} Ozone is not a directly emitted pollutant from emission sources. Instead, volatile organic compounds (VOCs) and NO$_x$ are precursors of ozone.

\textsuperscript{[e]} USEPA National Center for Environmental Assessment, ground level ozone health affects [http://www.epa.gov/air/ozonepollution/health.html](http://www.epa.gov/air/ozonepollution/health.html).
In addition to the human health impacts, there are environmental impacts as well. In addition to criteria pollutants, digester gas combustion also results in emissions of GHGs. In its most recent assessment report in 2007, the Intergovernmental Panel on Climate Change (IPCC, 2007b) reported that it is “extremely likely” (i.e., representing a 95% confidence level or higher) that anthropogenic emissions of GHGs are causing a change in the global climate. Although there is a scientific consensus that anthropogenic emissions of GHGs are impacting the global climate, there is still debate as to the magnitude of this impact. However, potential environmental impacts that can result from increased concentrations of GHG in the atmosphere include the following:

- Decreased crop yields – Increased temperatures can reduce the potential benefit of increased CO₂ concentrations. However, hotter temperatures create a need for additional irrigation, which may be difficult to achieve if precipitation is also impacted by the changing climate. Also, more extreme weather events are likely to occur (IPCC, 2007a).
- Human health – Evidence indicates that global climate change will change the distribution of allergenic pollen species, increase malnutrition, increase morbidity and mortality associated with ground-level ozone, and change the range of some infectious disease vectors (IPCC, 2007a).
- Freshwater resources – Climate change is expected to decrease the water resources in semi-arid and arid regions of the world, including the western US. Extreme weather events are likely to lead to increased water pollution. For example, increased precipitation intensity will cause more runoff, which will contribute more sediment, pesticides, nutrients, and other pollutants into the receiving water body (IPCC, 2007a).

REGULATORY FRAMEWORK

Criteria Pollutants

Because of the risks to the environment and human health, emissions of these pollutants are regulated. The USEPA regulates criteria pollutants by establishing permissible levels, or National Ambient Air Quality Standards (NAAQS), based on human health standards or environmental criteria. The Clean Air Act (CAA) allows states to adopt more stringent ambient air quality standards as appropriate (Table 4). State and local agencies are required under the CAA to develop a State Implementation Plans (SIP), a general plan indicating how to attain and/or maintain the NAAQS. State and local regulations are developed as part of SIPs, with the goal of achieving NAAQS or state standards.
Table 4. Ambient air quality standards.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Averaging Period</th>
<th>Federal Standard(^{[a]})</th>
<th>California Standard(^{[b]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ozone (O₃)</td>
<td>1 hour</td>
<td>Revoked</td>
<td>0.09 ppm (180 µg/m³)</td>
</tr>
<tr>
<td></td>
<td>8 hour</td>
<td>0.075 ppm (147 µg/m³)</td>
<td>0.07 ppm (137 µg/m³)</td>
</tr>
<tr>
<td>Respirable Particulate Matter (PM(_{10}))</td>
<td>24 hour</td>
<td>150 µg/m³</td>
<td>50 µg/m³</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>Revoked</td>
<td>20 µg/m³</td>
</tr>
<tr>
<td>Fine Particulate Matter (PM(_{2.5}))</td>
<td>24 hour</td>
<td>35 µg/m³</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>15 µg/m³</td>
<td>12 µg/m³</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>1 hour</td>
<td>35 ppm (40 mg/m³)</td>
<td>20 ppm (23 mg/m³)</td>
</tr>
<tr>
<td></td>
<td>8 hour</td>
<td>9 ppm (10 mg/m³)</td>
<td>9.0 ppm (10 mg/m³)</td>
</tr>
<tr>
<td>Nitrogen Dioxide (NO(_₂))</td>
<td>1 hour</td>
<td>0.100 ppm</td>
<td>0.18 ppm (339 µg/m³)</td>
</tr>
<tr>
<td></td>
<td>Annual</td>
<td>0.053 ppm (100 µg/m³)</td>
<td>0.030 ppm (57 µg/m³)</td>
</tr>
<tr>
<td>Sulfur Dioxide (SO(_₂))</td>
<td>1 hour</td>
<td>0.075 ppm (197 µg/m³)</td>
<td>0.25 ppm (655 µg/m³)</td>
</tr>
<tr>
<td></td>
<td>3 hour(^{[c]})</td>
<td>0.5 ppm (1310 µg/m³)</td>
<td>---</td>
</tr>
<tr>
<td></td>
<td>24 hour</td>
<td>--</td>
<td>0.04 ppm (105 µg/m³)</td>
</tr>
<tr>
<td>Sulfates</td>
<td>24 hour</td>
<td>---</td>
<td>25 µg/m³</td>
</tr>
</tbody>
</table>

\(^{[a]}\) Federal Standards as listed on USEPA website (http://epa.gov/air/criteria.html).

\(^{[b]}\) California standards as listed on CARB website (http://www.arb.ca.gov/research/aaqs/aaqs/aaqs.htm).

\(^{[c]}\) This is a secondary standard.

These regulations often include permitting requirements for sources of air emissions. Among these requirements is the need to use Best Available Control Technology (BACT). BACT requires that a process meet emissions limits or utilize control technologies that, for a similar source, (1) are in an EPA-approved SIP, (2) have been achieved in practice, or (3) are economically and technologically feasible (USEPA, 2012). The USEPA, as well as various regional and state agencies, have BACT clearinghouses based on what has been required as BACT in air permits.

California has the most dairy cows of any State in the U.S. In addition, California generally has the strictest air emissions regulations. Although agricultural sources previously were exempt from many permitting requirements, California Senate Bill 700 (SB 700) was signed into law in 2003, removing this exemption. Now, agricultural sources in California are subject to many of the same permitting requirements as
industrial sources.

These requirements present a unique challenge for farmers seeking to beneficially use digester gas. Currently, the BACT limit for NO\textsubscript{x} in San Joaquin Valley is 9 ppmv (SJVAPCD 2012). Control devices, such as selective catalytic reduction (SCR), are available to reduce NO\textsubscript{x} emissions from combustion equipment. However, the additional trace gases in the digester gas, namely H\textsubscript{2}S, cause fouling of the catalyst in the SCR.

Because of the catalyst poisoning, a dairy would need to install a scrubber (e.g., Iron Sponge) on the engine inlet side to reduce the H\textsubscript{2}S concentration in the digester gas. This would clean the gas in an attempt to prevent catalyst poisoning in the SCR unit, as well as reduce SO\textsubscript{x} emissions. However, this places another economic burden on the farmer. In addition to the costs of the digester (which are not included here), a farmer would thus need to install the engine as well as the associated control and backup equipment. Capital costs for these pieces of equipment are estimated to be approximately $275,000 ($90,000 for the engine; $65,000 for the gas scrubber; and $120,000 for the SCR unit (Ramon Norman personal communication; CEC, 2006). There would also be annual operation and maintenance costs. These annual costs could vary widely but, at a minimum, would include replacement of the iron sponge media, which is estimated to cost $45,500 each year (CEC, 2006). Some regulatory agencies are encouraging the use of microturbines or fuel cells rather than ICEs. However, these equipment are more expensive and can be impacted by the H\textsubscript{2}S concentration in digester gas as well.

Greenhouse Gases

In addition to limitations on criteria pollutant emissions, several pieces of legislation have been passed limiting emissions of GHGs to prevent further impacts on the global climate. These regulations include EPA’s Mandatory GHG Reporting Rule, the GHG Tailoring Rule, and California’s Assembly Bill 32 (AB32).

The Mandatory Reporting Rule requires monitoring and reporting of GHGs from facilities subject to the rule. The affected facilities include a) facilities that contain any of the listed source categories (e.g., cement production, adipic acid production); b) facilities that emit greater than 25,000 metric tons (MT) of CO\textsubscript{2} equivalents (CO\textsubscript{2}eq) per year from stationary source combustion and the source categories listed in the proposed rule; or c) facilities that have an aggregate maximum heat input capacity of 20 million British Thermal Units per hour (MMBtu/hr) and emit greater than 25,000 MT CO\textsubscript{2}eq per year from stationary source combustion.

EPA’s GHG Tailoring Rule tailors the permitting requirements for emissions of GHGs only under the existing Prevention of Significant Deterioration (PSD) and New Source Review (NSR) programs. Without the tailoring rule, the thresholds would be 100 ton per
year (tpy) or 250 tpy depending on the source for attainment areas (i.e., PSD), or 10 tpy to 100 tpy depending on the source and location for nonattainment areas (i.e., Nonattainment NSR). With the Tailoring Rule, the thresholds are 100,000 tpy CO₂eq for new sources and 75,000 tpy CO₂eq for modifications to existing facilities.

AB32 requires California to reduce GHG emissions to 1990 levels by 2020. The Scoping Plan required under AB32 identifies a plan for California to reach this goal. As part of AB32, facilities are required to report emissions of GHG. Also, a cap-and-trade program was established to help meet these restrictions. The program covers major emitters of GHGs (e.g., refineries, power plants, transportation fuels) and establishes an enforceable GHG emissions limit that will decline over time (CARB, 2012).

IMPLEMENTATION

All of these regulations are aimed at restricting levels of criteria pollutants and GHGs to avoid the health and environmental impacts associated with emissions. Because of these, and other, regulations, emissions resulting from combustion of digester gas must be controlled. As discussed above, it is difficult to predict the emissions expected from combustion equipment, even with controls, burning digester gas. One method for quantifying emissions is to perform source tests on the combustion equipment. A source test will tell the operator the emissions they can expect when running the combustion equipment under the same conditions as occurred during the test. However, because of the differences in digester gas, results from source tests cannot always be extrapolated to another farm. Although source tests from one farm are not always applicable for another farm, results from previous source tests likely provide the most reasonable option for a farmer who wants to quantify what expected emissions would be. In the absence of source tests, emission factors or modeling can be used to predict emissions. But, like extrapolating source tests, these methods will likely not provide the most accurate results.

FUTURE TRENDS

In the future, new control technologies may be developed that are better suited for controlling emissions from digester gas combustion. In addition, improvements in engine technology may result in lower NOₓ emissions from engines. Most importantly, permitting agencies need to work with farmers to come to technically feasible and cost-effective requirements that allow the federal and state standards to be achieved while allowing farmers to reduce greenhouse gases and generate useful electricity. One example of a potential path forward is flexible permits that would require control technologies but would allow emissions above limitations if the limits are not met with the controls (Warner, 2009).
CONCLUSION

Anaerobic digesters can provide environmental benefits through reduced emissions as well as economic benefits through reduced electricity costs or added income. However, there are challenges to beneficially using the digester gas produced. Namely, compliance with permitting requirements that were initially set for industrial facilities can be challenging for agricultural sources. However, with mutual agreement between farmers and regulatory agencies, anaerobic digesters can continue to provide benefits for public health and the environment.

REFERENCES

California Air Resources Board (CARB). California standards as listed on CARB website (http://www.arb.ca.gov/research/aaqs/caaqs/aaqsh.htm)


USEPA. National Ambient Air Quality Standards (NAAQS). http://www.epa.gov/air/criteria.html
USEPA. RACT/BACT/LAER Clearinghouse.  


OVERVIEW OF NITROGEN REMOVAL TECHNOLOGIES AND APPLICATION/USE OF ASSOCIATED END PRODUCTS

M. Orentlicher
Resources from Waste: Management & Engineering, New York NY

SUMMARY

Anaerobic digestion of manure produces a liquid with moderate to high concentrations of ammonia. The concentrations vary with farm practices and strongly with the source of manure. It is shown in this paper that recovery of ammonia by flash distillation (such as the Ammonia Recovery Process) or hot gas stripping will produce financial benefits to farms or organic waste digesters of sufficient size. Emphasis is on dairy farms and model calculations indicate that dairies with at least 2000 cows can profitably recover ammonia fertilizer. Farms accepting organic waste for co-digestion will likely produce additional ammonia and therefore be able to profitably recover ammonia with smaller herds.

Ammonia recovery with ammonia separation effectively reduces potential losses during manure storage and normal field application. These methods produce a nitrogen fertilizer that is stable and can be sold or applied by the farmer when and in quantities beneficial to the crop, without added P which may otherwise not be necessary.

Historically, ammonia has been recovered with sulfuric acid to produce ammonium sulfate. It is shown in this paper that both in terms of net revenue and requirements for storage of the product, nitric acid will in most cases be preferable to sulfuric acid as a medium for ammonia capture.

INTRODUCTION

Wastewater streams rich in the nutrients nitrogen (N) and phosphorus (P) are produced by municipal, industrial, and agricultural processes. These are present in various forms: partially bound to solids and not immediately available to the ambient air and water, and also present in water soluble form (phosphate, nitrate, ammonia, organic nitrogen), and in the case of ammonia in a volatile form. All three forms are present in anaerobic digestion (AD) effluent known as digestate. The soluble and volatile forms of these elements are particularly prone to loss pathways and pose a variety of environmental and human health threats.

Both N and P can be transferred to surface waters through runoff and erosion processes, leached into ground water or intercepted by subsurface drainage systems and released directly to surface waters, and N as ammonia can be volatilized and add to air pollution. On the other hand both N and P are essential nutrients for plants and animals, and have been added to increase the productivity of soil for millennia through the direct placement of manure. Preventing fugitive losses through capture and reuse of nutrients can increase overall nutrient use efficiency, partially replace chemical N
and P fertilizers and reduce manufactured N and stretch P mineral resources, while also reducing adverse environmental impacts.

Pollution control and recovery of value of these elements from agricultural or other organic waste can be accomplished for both P and N. Work presented in this paper focuses on ammonia-nitrogen recovery from animal manure. While manure is the generic term for urinary and fecal excreta of domestic farm animals, the source of the manure (dairy, swine, poultry and others) and the conditions of both its generation and treatment vary greatly.

METHODS OF AMMONIA CAPTURE FROM MANURE

Potential public concerns and especially the aesthetic impact (odor) of raw manure favor its treatment prior to land application as a crop fertilizer and soil conditioner. Anaerobic digestion greatly reduces these adverse qualities of manure. The combined benefits for manure management and potential revenue generation from energy, fertilizer and other products have promoted the growing use of AD technologies. USEPA/AgStar (2012) states that 176 digesters were operating on animal manure by the end of 2011 (over 80% dairy), and there is an annual increase of 16 digesters/yr. This has created the coupled problem and opportunity of ammonia in the digestate. Several methods for recovery of this ammonia are described in this section.

Much of the ammonia can be captured for reuse by filtration of the digestate if the process includes ultrafiltration and reverse osmosis. This captures both soluble and solids nitrogen, but the product has critical characteristics of raw digestate that decrease its utility relative to chemical fertilizer.

1. Nitrogen is recovered daily and remains relatively unstable, while crop utilization occurs seasonally. This requires either storage or export of the material, both costly due to the space required for these low nitrogen content products.
2. Managing N in its various forms can be challenging, especially in low nutrient density materials encountered in manure related products. Often, N losses to both the air and ground water and transformations make high efficiency recovery by crops in the field difficult, resulting in reduced N effectiveness.
3. Since N:P ratios of these materials are generally fixed, more P may be applied than needed to deliver enough N to high N-utilizing crops like field corn.

In contrast to manure, as well as digestate and digestate solids; chemical fertilizer is available in many forms and ratios, is more concentrated, more easily managed, and in the case of N, is more easily stabilized. These features allow greater latitude for the farmer to apply fertilizer close to the time of highest crop need, and the proportion of nutrients can usually be better balanced to suit the crop and soil. The same advantages exist for methods of ammonia recovery that separate ammonia from the digestate. Ammonia recovery with ammonia separation effectively reduces potential losses during manure storage and normal field application. These methods produce a nitrogen fertilizer that is stable and can be sold or applied by the farmer when and in quantities beneficial to the crop, without added P which may otherwise not be necessary.
The following section surveys four available methods for recovery of ammonia and focuses on the two major techniques for separation of the ammonia from digestate in a form equivalent to chemical fertilizer: air stripping and flash distillation. *Struvite is a slow release P fertilizer than can be crystallized from digestate. Since struvite is an ammonium salt, some ammonia is also recovered with the P. However this is generally no more than 20% of the free ammonia in the digestate and is therefore not considered as an ammonia recovery technology in this paper.*

Costs and Benefits of Ammonia Recovery Methods

Methods of recovery of the fertilizer value of ammonia in digestate vary in efficacy and in costs. The quantitative evaluation of these methods is specific to the manure or food waste treated, site-specific factors and the choice of method of ammonia recovery. Quantitative economics are presented for ammonia recovery from dairy manure in later sections of this paper. If the NH3-N is recovered as liquid fertilizer, it is shown that a five year payback period could be conservatively estimated for the preferred method of ammonia recovery.

1. Application of digestate as a source of nitrogen fertilizer is the least efficacious of the available methods, since the NH3-N is dilute (@0.1%) and the ammonia is both soluble and volatile so that a fraction is lost in storage and after application to soil depending on placement and timing of applications and ensuing weather conditions.
2. Capture of NH3-N with the post-digestion solids incurs capital and operating costs for separation of water from dissolved as well as suspended solids, but increases both concentration and stability of the NH3-N. The fertilizer content is dilute with concomitant requirements for storage and transport of the material.
3. Stripping of ammonia from digestate produces the advantages of chemical fertilizers in terms of purity, predictability and concentration. The concentrated fertilizer requires least space for storage, and can be exported easily or used on-farm to offset fertilizer purchases. Hot gas stripping requires large power input and large contacting vessels to provide the gas/liquid contact to achieve recovery of the ammonia from the digestate. The gas is stripped of ammonia with an acid scrubber and the ammonia recovered as the ammonium salt of the acid.
4. Flash distillation of the digestate uses pH/temperature control to achieve transfer of ammonia from the digestate to the vapor phase. Heat is required to liberate the ammonia/water mixture. Vapor is condensed and the ammonia captured as described for the hot air stripper.

Each of the above could be selected for a specific application. However, consideration of the criteria of: cost for storage and transport, N-capture efficiency, and both capital and operating cost; the last two technologies will be preferred for applications sufficiently large to produce economic quantities of fertilizer. They will be discussed in detail in this paper.
Both hot gas stripping and flash distillation involve four steps in going from ammonium ion in digestate to a useful liquid fertilizer.

1. Conversion of ammonium ion to dissolved ammonia gas.
2. Movement of ammonia out of the digestate into the vapor phase
3. Capture of the ammonia in a clean liquid phase
4. Concentration of the ammonia to a useful level.

Definition of a useful level of concentration depends on the use of the product. For example, if the ammonia will be stored in a lagoon and applied with irrigation water, the ammonia would be captured in acid solution and no further concentration might be needed. If the ammonium were used as a commercial fertilizer or industrial chemical then the solution after ammonia capture would be concentrated to saturation in order to minimize storage and transportation or field-application costs. In a large-scale application the product might be dried and pelletized for commercial distribution.

Advantages of Nitric Acid for Ammonia Recovery on a Farm

The common method for step 3 is to strip ammonia from the vapor phase with sulfuric acid. Sulfuric acid is readily available and is the least-cost acid. Ammonium sulfate is a commercial fertilizer and for soils that require added sulfur, it would be the preferred N-fertilizer. Ammonium sulfate is also a relatively low-N concentration salt and therefore is less used as N-fertilizer than are various solutions of ammonium nitrate, USDA, ERS, (2011).

Table 1. ERS Sale of N Fertilizers, tons/year

<table>
<thead>
<tr>
<th>Year ending June 30</th>
<th>Ammonia</th>
<th>Ammonium</th>
<th>Nitrogen solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Anhydrous</td>
<td>Aqua</td>
<td>Nitrate</td>
</tr>
<tr>
<td>2010</td>
<td>4,045,433</td>
<td>415,049</td>
<td>719,380</td>
</tr>
</tbody>
</table>

The high N-concentration of ammonium nitrate makes it a higher value product in most areas of the United States. The “ammonium sulfate” and “ammonium nitrate” tabulated by ERS are the solid products, which are economical to produce only in large volumes. The ammonium nitrate is sufficiently high in N that it has substantial value as liquid fertilizer, often blended with urea to form UAN, USDA, National Agricultural Statistics Service (2011).
Table 2. USDA NASS Prices Paid for Fertilizer – United States: March 2011

<table>
<thead>
<tr>
<th>Fertilizer</th>
<th>$/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium nitrate</td>
<td>479</td>
</tr>
<tr>
<td>Anhydrous ammonia</td>
<td>749</td>
</tr>
<tr>
<td>Aqua ammonia</td>
<td>249</td>
</tr>
<tr>
<td>Nitrogen solutions</td>
<td></td>
</tr>
<tr>
<td>28% N</td>
<td>369</td>
</tr>
<tr>
<td>30% N</td>
<td>351</td>
</tr>
<tr>
<td>32% N</td>
<td>403</td>
</tr>
<tr>
<td>Sulfate of ammonia</td>
<td>423</td>
</tr>
</tbody>
</table>

In most cases, ammonium nitrate would be the higher value product of ammonia recovery. As noted above, the preferred product depends both on the final use of the product and the relative value of S and N if the use is as fertilizer. Fertilizer prices vary significantly over time and with region of the United States. Recent prices average about $0.70/#N for N-fertilizer. Where industrial demand for the product exists, the value of the product could be substantially higher.

The decision as to the form in which the ammonia is recovered is independent of whether the method for recovery is stripping or flash distillation. In the comparison of the two methods in the next section, it is assumed that ammonia is captured with sulfuric acid because the published study for hot gas stripping employed sulfuric acid.

The following sections will show that the 5000 cow herd would produce about 1970 dry tons/year of ammonium sulfate if ammonia is captured in sulfuric acid, and about 2400 dry tons/year of ammonium nitrate if nitric acid were used to capture ammonia. If these were stored as saturated solutions this would be 967,000 gallons per year of liquid ammonium sulfate fertilizer per year or 690,000 gallons per year of liquid ammonium nitrate fertilizer. The lower volume of stored liquid fertilizer is another reason to prefer nitric acid over sulfuric acid.

Comparison of stripping and flash distillation

Hot gas stripping of ammonia depends on contact of the gas with digestate. Generally a high ratio of gas to digestate is required to maintain the driving force for ammonia transfer. While this provides an effective recovery of ammonia, it both requires a large vessel to allow the large flow of gas and extended contact time to affect the transfer from the liquid to vapor phase. There is also a large demand for energy to force the hot gas through the liquid in the vessel. Flash distillation accomplishes the same function in a smaller vessel by forcing the liquid to form small drops that rapidly
transfer water and ammonia to the head space. In this case energy is required to pump the digestate through a mechanism to provide the small droplets.

In order to estimate the cost of removing ammonia with these two methods, calculations were performed for examples of each. An integrated system for recovery of both N and P has recently been patented by Washington State University, and reported in an AgStAR publication, Frear, et al, 2011. They report cost estimates based on field pilot testing of the system, and include a separation of costs for the nitrogen reduction (NR) portion for both capital and operating expenses. ThermoEnergy Corporation has done extensive pilot testing with their Ammonia Recovery Process (ARP) at commercial scale, and also developed cost estimates not previously reported. The ARP system has been described in conference proceedings, Orentlicher, et al., 2009.

Both systems were analyzed for a typical AD application with dairy manure with 2200 ppm of NH3-N reduced to 400 ppm in the treated digestate, for which excess heat is available. Stripper and flash distillation operation is at 80C without caustic addition. The O&M cost was estimated in both cases at 2% of installed cost. Since neither system has a commercial operation history, this rule of thumb estimate was required. Washington State results were reported on a “cow year” basis, while ARP results were calculated on “#N” recovered basis.

The dominant difference in cost between the two systems is in the electrical energy required by each. The electrical energy for moving the hot gas through the digestate is about 6x that needed to circulate liquid through the flash distillation unit. This causes the operating cost to be higher for gas stripping than for flash distillation, about $0.6/#N for hot gas stripping and about $0.4/#N recovered with ARP. This operating cost is about $2/gallon of manure treated, with no credit for the fertilizer produced. The much larger gas system is estimated to also require a higher capital cost than the flash distillation system at the same capacity of ammonia removal. The capital cost is about $2.50/#N/yr of NH3-N removal, or about $10/gpd of digestate treated.

The preceding cost analysis is for the nitrogen recovery operations only.

- Pre-treatment of digestate may be necessary and would be specific to the manure source and the AD used.
- Storage requirements would depend on whether the product was exported or used on site, and on the product properties: sulfate vs. nitrate, solid vs. saturated liquid.
Economics of Ammonia Recovery from Manure and Scale of Operation

When the ammonia reduction is required for compliance with regulations (Nutrient Management Plans, planned EPA air emissions regulations), the operation is viewed as a cost center for the farm. However for AD operation of a sufficient size and producing sufficient concentration of ammonia; this operation can be a source of revenue for the farm. These conditions could be achieved due to the number of animals (different criteria for dairy, swine, and poultry) or due to organic waste co-digested with the manure. Pre-treatment and storage costs will be case specific, so this analysis only considers the direct costs of removing ammonia from digestate and producing a concentrated product.

Sulfuric acid is more familiar and lower cost than nitric acid and most ammonia stripping has been done with sulfuric acid. However for fertilizer production, there are distinct advantages when using nitric acid. Since in most cases the nitrate product will be of higher value, the analysis assumes capture with nitric acid. Pricing is as in the previous analysis with two exceptions: product is priced at $0.7/#N, acid is nitric acid at $400/ton.

The conclusion of the economic analysis is that the Ammonia Recovery Process can be a source of revenue for farms treating manure with anaerobic digestion, if they produce sufficient ammonia. For dairy herds, that requires about 2000 cows to achieve a five year payback in the absence of co-digestion. As shown in the following figure, economics are not attractive for smaller herds, and the Payback Period is slightly better than five years for herds of 5000 cows or greater.

Figure 1. Payback Period and herd size, digestion of cow manure

Ammonia recovery as a concentrated liquid product would be beneficial for dairies with less than 2000 cows under two conditions: aggregation of digestate in a community digestion plan, or importation of organic waste in a co-digestion operation. Tipping fees
and increased energy production are major financial benefits of co-digestion with organic waste, but there could also be a substantial increase in ammonia recovery and in revenue from the liquid fertilizer produced.

THE AMMONIA RECOVERY PROCESS

The preceding narrative has demonstrated that separation and concentration of ammonia from digestate has the potential for revenue production when associated with digesters of sufficient size. Since commercial operation is not yet achieved for the technologies that produce the equivalent of chemical fertilizer, this demonstration is still speculative. Performance of ammonia separation technology to accomplish production of the fertilizer has been proven. Some detail is provided in this section regarding the Ammonia Recovery Process of ThermoEnergy Corporation and pilot data with dairy digestate.

Process Description of Ammonia Recovery Process

Anaerobic Digestion (AD) is a primary tool for recovery of value from organic waste, whether manure, industrial waste or food waste. If the organic waste requires pre-processing; that will frequently require water addition prior to the AD. The output of the AD will produce a solid and a liquid effluent. The latter can be the source of ammonia suitable for production of commercial grade fertilizer. This is shown schematically below.

Figure 2. Ammonia Recovery following Anaerobic Digestion of Organic Waste
Figure 3. Central Component of Ammonia Recovery Process: RCAST System for Flash Distillation.

Figure 2 shows the flow of digestate through the AD and ARP to produce the fertilizer product.

- Dairy application of ARP has two products: a low-ammonia liquid that could be discharged to the field or treated for other farm use, and a concentrated nitrogen fertilizer for storage or export for use as needed. Food waste AD requires a low-ammonia source of water that is typically potable water, which would be replaced with the liquid discharge of ARP.
- Waste heat from the combustion of the biogas provides the thermal input required to transfer the ammonia from AD digestate to the vapor phase.

Figure 3 shows some detail of the operation of ARP’s system to flash distill ammonia and water from the digestate. Digestate is recirculated through a heat exchanger and sprayed into the RCAST vessel to achieve the first two necessary steps in ammonia recovery.
1. Conversion of ammonium ion to dissolved ammonia gas.
2. Movement of ammonia out of the digestate into the vapor phase

Condensation of the distillate in the condenser achieves the third step and the ammonia-bearing distillate is then concentrated to the desired level, using operations that depend on the form of ammonia desired and the level of concentration desired.

3. Capture of the ammonia in a clean liquid phase
4. Concentration of the ammonia to a useful level.
5. Success of the ARP depends upon the ability of the RCAST system to remove ammonia from the digestate at a high enough rate to provide the Payback Periods previously shown. This rapid removal was first demonstrated with the municipal digestate known as centrate, Orentlicher, et al., 2009, which was the basis for New York City to contract for the first commercial ARP installation at its 26th Ward wastewater plant. RCAST has been piloted with several dairy digestates, and one series of tests is shown below for a New York State dairy digestate. The dark, opaque liquid was preheated to about 180°F prior to feeding to the vacuum distillation vessel. At a fixed temperature of 175°F, tests in triplicate were conducted for three conditions: no added caustic, 35% of full caustic and full caustic addition. Results for no-caustic and full caustic addition are shown in Figure 4. Rapid removal of ammonia from the digestate was reproducibly achieved in both cases, but addition of caustic increased the ammonia removal rate. Choice of use of heat alone or heat with caustic will be a farm-specific one, involving a balance of capital and operating costs. The preceding economic analysis was based on no use of caustic.

Figure 4. Ammonia Removal from NYS Dairy Digestate

\[ y = 933.36e^{-0.192x} \]
CONCLUSION

Whether the final product is liquid Ammonium Sulfate or liquid Ammonium Nitrate, the products can be used interchangeably with commercially purchased fertilizer materials. Either material can be used in planters outfitted with liquid application capabilities, and these materials can be mixed with commercial liquid fertilizers (such as 10-34-0 to add P or UAN to increase nutrient density). Ammonium nitrate at 36% N as solid and 25% N as saturated liquid would be equivalent to a 25,0,0 liquid fertilizer. Ammonia recovery from digestate captures significant quantities of N that are normally lost, even under optimal management conditions. A substantial portion of N used in agriculture originates in an ammonia plant that uses significant energy resources, and much of this N is lost to the environment with traditional manure management practices. Therefore, recovery of ammonia from digestate is both an economic value to the farmer and an environmental and energy benefit to society.

REFERENCES

Craig Frear, Quanbao Zhao and Shulin Chen, Department of Biological Systems Engineering, Washington State University, Pullman, WA, May 11-12, 2011
USDA, National Agricultural Statistics Service, Agricultural Prices (April 2011) 71
COMMERCIAL DEMONSTRATION OF NUTRIENT RECOVERY OF AMMONIUM
SULFATE AND PHOSPHORUS RICH FINES FROM AD EFFLUENT

S. Dvorak, PE¹ and C. Frear, PHD²
¹DVO Incorporated, Chilton WI
²Center for Sustaining Agriculture and Natural Resources, Washington State University

INTRODUCTION

Background

Anaerobic digestion (AD) is a treatment approach that mineralizes complex organic
carbon into inorganic carbon in the form of biogas, diminishing odors/pathogens and
stabilizing waste (US-EPA, 2008). Biogas can be used as a renewable energy, while AD
also allows for reductions in methane (CH₄) and overall greenhouse gas (GHG) release
(US-EPA, 2011). As a result, there has been increasing interest in AD on animal feeding
operations (AFOs) and on dairy farms in particular, with now over 150 dairy digesters in
the U.S., providing an installed generating capacity of 38 MW, and GHG emission
reductions of 1.1 MMT of CO₂e/year (US-EPA, 2010). Presently, digesters serve less
than 6 and 7% of potential dairy farms and cows, respectively (US-EPA, 2010). Barriers
to adoption include intensive capital costs (~$2,000/cow for 500-2,000 cow installation
(Andgar, 2011)) and historically low received electrical prices, which combined, can
produce low returns on investment (Bishop and Shumway, 2009). AD adoption is
additionally hampered, as AD units are unable to resolve existing farm nutrient loading
concerns (N and P are not gasified or reduced in liquid concentration during digestion).

Liquid manure is expensive to transport (Heathwaite et al., 2000) so manure is
generally land applied to nearby fields. Long-term manure application on these lands
has resulted in excess nitrogen (N) and phosphorus (P) accumulation; 36% and 55% of
AFO dairies are in a state of N and P overload, respectively (USDA-APHIS, 2004). This
has led to issues regarding ultimate fate of nutrients on these soils, in particular their
ability to contribute to nitrate leaching, eutrophication, ammonia toxicity, and nitrite
carcinogenesis (US-EPA, 1996). From an air quality perspective, AD with its partial
conversion of organic N to ammonia, only potentially exacerbates existing concerns
related to farm-based ammonia emissions; elevating levels of PM 2.5 (Archibeque et al,
2007). As a result, AFO and dairy owners identify nutrient issues as one of their most
important concerns, one with potentially negative economic impacts (Bishop and
Shumway, 2009). Meanwhile, much of the world’s cropped farmland is nutrient-
deficient, requiring fossil fuel based inorganic fertilizers: (1) whose production results in
negative impacts to the climate (fossil fuel fertilizer results in 1.2% of global GHG
emissions (IPCC, 2007)); (2) that have increased in price significantly during the last
decade (USDA ERS, 2011); and (3) which in the case of P have finite worldwide
resources (Cordell et al, 2009).
With an eye on improving overall economics, AD project developers are intensifying efforts to generate additional revenue through use and/or production of co-products. One approach that has been successful on many dairies is to accept off-farm organics and practice co-digestion, generating tipping fees for received material and producing additional biogas (Frear et al., 2012). Frear et al. (2012) showed that biogas production could be doubled and total revenues tripled by incorporating off-farm organics at a rate of 20% of the volumetric manure flow. When off-farm organics are from local sources, considerable GHG mitigation can occur via their diversion from long-distance hauls to CH4-releasing landfills (Murphy and McKeogh, 2004). However, co-digestion alone is insufficient to enhance adoption rates and GHG mitigation on AFOs, as co-digestion exacerbates nutrient loading concerns. Frear et al. (2012) showed that even limited co-digestion caused 60 and 10% increases in on-farm N and P, in one case study. It is imperative then from the perspective of AD adoption as well as environmental stewardship to incorporate nutrient recovery alongside AD, if technology improvements and new economic markets can warrant such a business approach.

Review of Nutrient Recovery Approaches

**Phosphorus**

Studies have demonstrated that more than 80% of P in dairy AD effluent is insoluble, presenting itself as suspended colloidal particles that are difficult, especially economically, to remove through approaches that assume either its soluble nature or ability to easily be settled/-separated (Gungor and Karthikeyan, 2008a; Pastor et al., 2010). Several other studies on P extraction show that the particulates are predominantly Ca-P and/or Mg-P (Chapuis-Lardy et al., 2004; Gungor and Karthikeyan, 2005a; Zhang et al., 2008) that result from the high Ca:P molar ratio (1.66-2.43) of a dairy cow’s diet (Gungor and Karthikeyan, 2008b). Biological P removal needs readily biodegradable carbon (Tchobanogolous, 2003), which is not available after effective AD treatment. Struvite crystallization, often touted as a viable mechanism for simultaneous ammonia and P removal is significantly hampered by this chemical structure, as crystallization requires the presence of free phosphate, which in this case is only available through costly acid/chemical pre-treatment (Zhang et al, 2008). Chemical and polymer coagulation can significantly increase the size of these particles and therefore induce settling, reaching P removal efficiencies as high as 80%, however their operating costs, based on high chemical inputs, raise concerns on economic viability (Frear et al, 2012). Conversely, simple gravity settling or use of screens and/or decanting centrifuges, while representing technical solutions with vastly reduced operating costs, are, due to the small size of the particles, only partly successful (10-50% TP removal) at removing P and simply do not meet the intense reduction efficiencies needed by dairy CAFOs for attainment of their nutrient management plans.

**Nitrogen**

N recovery, whether from animal manure or from animal-manure AD effluent, poses a few problems. As such, to date, few N removal/recovery technologies have been applied at a commercial scale on operating AFOs, with or without AD. In the U.S. barriers include farm economics and the high solids concentration within manure
wastewaters, which preclude the use of the technologies commonly used in industrial and municipal wastewater settings. Thus, any existing or new technology developed for farm use must be able to simplify the recovery operation and minimize costs while also economically managing the solids. As discussed in the previous chapter, solids removal is intimately linked with P recovery. Therefore, N recovery should be combined with P recovery, allowing for mitigation of two nutrient concerns in one combined technology. Lastly, from both an economic and sustainability standpoint, recovered products must have a valued market so that farmers can offset capital and operating expenditures.

Biological ammonia removal technologies exist, however, the high concentration of ammonia and solids in the animal manure AD effluent make it difficult for biological treatment. Although conventional nitrification and denitrification can be applied to animal wastewater for N removal without AD (Choi et al., 2005; Tilche et al., 2001; Vanotti, 2005), it becomes problematic to work with AD effluent because of insufficient biodegradable carbon. A recently developed process, “anammox” does not need biodegradable carbon for N removal (Mulder et al., 1995), but anammox bacteria’s slow growth rate (Strous et al., 1999) makes it easily out-competed by other organisms, leading to poor kinetics and performance alongside process instability. Other researchers (Bolan et al., 2004; Bonmatí and Flotats, 2003; Guo et al., 2008; Liao et al., 1995; Vanotti, 2005) have opted for physical-chemical processes for N removal, including ion exchange and ammonia stripping. Ion exchange can be excluded for AD applications because it requires low solids concentrations (< 1%), which are unattainable even with effective prior solids/P removal technology implementation. However, ammonia stripping has some potential, as shown through studies on landfill leachate (Cheung et al., 1997), digester supernatant of a municipal wastewater treatment plant (Katehis et al., 1998), and digester supernatant from slaughterhouse waste (Siegrist et al., 2005). It tolerates a certain level of solids, has low energy requirements and involves relatively simple and low capital cost equipment. Ammonia stripping has already been successfully applied to municipal wastewater AD supernatant landfill leachate, and industrial wastewater at commercial scale (Janus and vanderRoest, 1997; Meyer and Wilderer, 2004; Thorndahl, 1993). It was also successfully tested under laboratory conditions for swine manure wastewater (Bonmatí and Flotats, 2003; Liao et al., 1995) and digested dilute dairy manure supernatant (Zeng et al., 2005; Zeng et al., 2006). In addition, ammonia stripping can be easily integrated with acid absorption to recover ammonia as N fertilizer. Although ammonia stripping has proven to be technically feasible for digested dairy manure, its economic feasibility has not been studied, nor has it been studied at scale utilizing concentrated scrape manure.

Although a strong potential candidate for economical recovery of N from dairy farms, ammonia stripping is not without its concerns. First, effective performance is highly dependent on temperature (US-EPA, 2000); however, the mesophilic (35°C) or thermophilic temperatures (55°C) of AD effluent can be used to overcome this concern. More problematic is the fact that, in order to strip ammonia from a wastewater, ammonia in its ionic form, must first become liberated as free ammonia. The ionic/free ammonia equilibrium is dependent upon pH with increases in pH (9.5-11) favoring the free ammonia form. AD effluent with its high alkalinity requires extensive input of chemicals
to raise the pH, thereby adding high chemical and economic costs to the process. Additionally, the traditional tower approaches used by the stripping industry are susceptible to clogging by the manure solids.

NOVEL NUTRIENT RECOVERY APPROACH

In an attempt to look at the NR problem from a new angle, the project team developed a working hypothesis that settling of the aforementioned suspended P-solids was less a problem of charge and need of coagulants and polymers, but more a problem of super-saturated gases which interfere with the natural flocculation and settling process. During AD significant amounts of CO₂ produced during the biological process can become dissolved and/or super-saturated within the effluent.

Figure 1: Microscope images of AD manure effluent with (a) micro-bubbles of gas present and evolving and (b) without gas present after aeration treatment

This is particularly true of CO₂, which is stored within the liquid effluent as aqueous CO₂, bicarbonates and carbonates. Upon release from the digester, changes in temperature, pressure, pH, air and agitation can lead to a release of these super-saturated gases (Battistoni et al., 1997; Cecchi et al., 1994). As the CO₂ partial pressure in air is much lower than that inside a digester, a hypothesis was proposed that aeration would remove the super-saturated CO₂ and enhance P removal. Figure 1a shows an image of micro-bubbles within liquid AD effluent, showing that these bubbles occur in numbers high enough to disrupt attractive forces with the buoyant forces and micro-turbulence they induce. As per the hypothesis, during aeration, supersaturated CO₂ released from liquid to gas phase (Figure 1b). In addition, analysis of chemical equilibriums shows that as aeration releases the gaseous CO₂, reactions move towards the right, generating more OH⁻ and raising the pH of the solution, especially with elevated solution temperature (Figure 2; Figure 3a). Subsequent testing of this high temperature aeration process verified that the stripping of the CO₂ and corresponding elevation in pH also allowed for enhanced ammonia stripping and P-settling without chemical addition (Figure 3bc; Figure 4). Thus, aeration treatment not only leads to the desired P-settling but also N removal through the stripping and assumed recovery of the ammonia—yielding an integrated NR process with vastly reduced chemical inputs.
Figure 2: Chemical equilibrium associated with aeration process

\[
\begin{align*}
\text{CO}_2 \text{(aq)} & \rightarrow \text{CO}_2 \uparrow \text{(g)} \\
\text{H}_2\text{CO}_3 & \rightarrow \text{H}_2\text{O} + \text{CO}_2 \text{(aq)} \\
\text{HCO}_3^- + \text{H}_2\text{O} & \rightarrow \text{H}_2\text{CO}_3 + \text{OH}^- \\
\text{CO}_3^{2-} + \text{H}_2\text{O} & \rightarrow \text{HCO}_3^- + \text{OH}^- \\
[\text{OH}^-] & \text{causes pH } \uparrow \\
\text{NH}_4^+ + \text{OH}^- & \rightarrow \text{NH}_3 \uparrow + \text{H}_2\text{O}
\end{align*}
\]

Figure 3: Effect of aeration/temperature on (a) pH, (b) NH₃ removal, and (c) TP removal

Figure 4: (a) Ability for aeration/settling to more effectively settle solids and P as compared to no aeration; (b) settled P-solids removed from settling weirs
Evolving from the base research discussed above is a novel system approach to both ammonia and P-solids recovery from digested effluent (Figure 5). Waste engine heat from the AD engine/generator sets is used to raise the temperature to 55-70°C for the necessary time duration to meet EPA Class A solids standards, thereby producing a more valuable and highly controlled pathogen-reduced fiber for bedding or off-farm sales as well as the necessary temperature to induce efficient aeration and degassing of super-saturated CO₂ and release of free ammonia. After aeration, the treated effluent is sent to a quiescent zone to allow for settling and removal of P-solids in a weir system. Stripped ammonia is then sent to an acid contact tower to convert the gaseous ammonia to ammonium sulfate solution (~35% concentration). An additional step still under development and evaluation is using the final effluent, still with a relatively high pH, as a media for scrubbing of biogas impurities, particularly H₂S.

Figure 5: Second iteration, patented, and commercial approach to economic recovery of nutrients from an AD associated NR system

PILOT TESTING AND ECONOMIC ASSUMPTIONS

Batch trials using 5,000-gallon systems were completed at dairies in Wisconsin and Indiana (Figure 6) while evaluation of aeration and settling performance was evaluated at a dairy in Idaho. During the pilot-operation, the following unit operations and conditions were followed (inputs are in italics and products are in bold):

• 100°F AD effluent from an existing commercial AD unit was heated to 160°F using an extended engine exhaust heat recovery system to further heat treat the effluent and its fibrous solids to Class A pathogen standards.
• The Class-A fibrous solids were removed through mechanical screen separation using an inclined screen with screw press, while the remaining liquid with suspended solids was sent to an aeration zone for further treatment at operating temperatures of approximately 140°F.
Aeration occurred in a dedicated plug-flow tank with a variable 10-20 hour retention time. Aeration was accomplished through the use of micro-aerators placed at the bottom of the tank to supply various degrees of aeration flow per gallon of treated effluent. Air was heated to temperature using engine exhaust heat sent through an air-to-air heat exchanger. As described before, the aeration allowed for the stripping of super-saturated CO₂ gas. High temperature enhanced the process, allowing for a more rapid release of the CO₂ and two important results. First the pH is increased and second gases, which interfere with natural settling were removed.

The increase in pH (>9.5) allowed for a portion of dissolved ammonia to shift its equilibrium towards free, gaseous ammonia and enter the air stream leaving the chamber which was then piped to a dedicated two-stage acid tower where controlled amounts of sulfuric acid made contact with the ammonia in the air and produced dissolved ammonia sulfate salt bio-fertilizer. The two-tower approach was conceived so that a neutral pH product with consistent maximum concentration (~35% by weight) could be achieved.

After return of the effluent to a quiet, settling zone, phosphorous-rich solids were then gravity settled and collected using dewatering weirs.

Figure 6: Batch testing of (a) aeration system and (b) two-tower acid contact system

Results of the testing at optimal aeration flow rates (micro-aerators, 20 gallons/cfm, and 55°C) are as described in Figure 7. While laboratory tests showed more ready stripping of ammonia, pilot-tests showed the need for considerably longer retention times, most likely due to lower operating temperatures (limited availability of waste heat energy and losses of heat due to mechanical separation of fibrous solids) and lower mass-transfer due to mixing limitations at larger scale (foaming). Results did determine a feasible temperature and aeration rate that minimized energy inputs and controlled foaming while still stripping ammonia in a reasonable retention time. At the aforementioned optimized parameters, nearly 80% of TAN was stripped during a 15-hour operation due to a consistent capability to raise the pH at or near 10.0. The two
tower acid contact system, once equilibrium at maximum solubility was attained, produced a consistent 35% by mass ammonia sulfate solution with pH at neutral.

**Figure 7:** Performance capabilities of ammonia stripping and ammonia sulfate production systems at optimized conditions during testing

The ability of aeration to settle P-solids was evaluated using only limited aeration (~40 gallons/cfm and temperature (20-35°C) and results are summarized in Table 1. As can be seen from the figure, limited aeration and temperature can keep capital and operating costs down while also retaining most of the ammonia and removing significant percentages of P from the effluent. No aeration resulted in a baseline of 40% P removal using the sequence of primary, secondary screening followed by extended weir settling while addition of 6 and 24 hours aeration resulted in 65 and 80% removal, respectively. Notably then, the system can be operated as a P-recovery system alone or as a combined system with more enhanced aeration and temperature yielding even higher P removal efficiencies.

**COMMERCIAL DEMONSTRATION—DAIRY WITH CO-DIGESTION**

After pilot evaluations were completed, design and funding were completed for demonstration of a continuous flow system at commercial scale on a Washington dairy practicing co-digestion with their dairy manure using a DVO mixed plug-flow digester. The flow rate for this farm and digester is 40,000 gallons/day. Funding for the capital construction, evaluation and performance report are provided by USDA NRCS CIG and DOE ARRA grant funds with industry and producer match. Figure 8 is a schematic for the overall design of the system while Figure 9 is an overhead image of the actual completed construction.
Table 1: Limited aeration and temperature settling of P-solids

<table>
<thead>
<tr>
<th>Effluent Pit Only Aeration Experiment</th>
<th>TS (%)</th>
<th>VS (%)</th>
<th>TKN (g/L)</th>
<th>TAN (G/L)</th>
<th>TP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure Effluent w/Fiber</td>
<td>5.15</td>
<td>3.28</td>
<td>4.03</td>
<td>2.61</td>
<td>564.53</td>
</tr>
<tr>
<td>Six hours of aeration at 35°C and 40 gal/cfm</td>
<td>4.32</td>
<td>2.65</td>
<td>4.23</td>
<td>2.58</td>
<td>613.48</td>
</tr>
<tr>
<td>Post fiber separation</td>
<td>4.33</td>
<td>2.45</td>
<td>3.78</td>
<td>2.63</td>
<td>593.90</td>
</tr>
<tr>
<td>1 day settling</td>
<td>2.51</td>
<td>1.38</td>
<td>3.18</td>
<td>2.46</td>
<td>231.69</td>
</tr>
<tr>
<td>2 days settling</td>
<td>2.43</td>
<td>1.32</td>
<td>3.18</td>
<td>2.42</td>
<td>199.06</td>
</tr>
<tr>
<td>3 days settling</td>
<td>2.41</td>
<td>1.29</td>
<td>3.18</td>
<td>2.38</td>
<td>199.06</td>
</tr>
<tr>
<td><strong>Beginning to End Reduction (%)</strong></td>
<td><strong>53.20</strong></td>
<td><strong>60.67</strong></td>
<td><strong>21.09</strong></td>
<td><strong>8.81</strong></td>
<td><strong>64.74</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effluent Pit + Extra Aeration Experiment</th>
<th>TS (%)</th>
<th>VS (%)</th>
<th>TKN (g/L)</th>
<th>TAN (G/L)</th>
<th>TP (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure Effluent w/Fiber</td>
<td>5.15</td>
<td>3.28</td>
<td>4.03</td>
<td>2.61</td>
<td>564.53</td>
</tr>
<tr>
<td>Six hours of aeration at 40 gal/cfm</td>
<td>5.37</td>
<td>3.41</td>
<td>4.09</td>
<td>2.65</td>
<td>587.38</td>
</tr>
<tr>
<td>Post fiber separation</td>
<td>4.47</td>
<td>2.49</td>
<td>3.87</td>
<td>2.64</td>
<td>600.43</td>
</tr>
<tr>
<td>Add 18 hrs aeration at 20°C and 40 gal/cfm</td>
<td>4.37</td>
<td>2.48</td>
<td>3.71</td>
<td>2.48</td>
<td>580.85</td>
</tr>
<tr>
<td>1 day settling</td>
<td>2.27</td>
<td>1.21</td>
<td>3.01</td>
<td>2.23</td>
<td>133.79</td>
</tr>
<tr>
<td>2 days settling</td>
<td>2.24</td>
<td>1.17</td>
<td>2.94</td>
<td>2.23</td>
<td>124.00</td>
</tr>
<tr>
<td>3 days settling</td>
<td>2.19</td>
<td>1.14</td>
<td>2.92</td>
<td>2.22</td>
<td>114.21</td>
</tr>
<tr>
<td><strong>Beginning to End Reduction (%)</strong></td>
<td><strong>57.48</strong></td>
<td><strong>65.24</strong></td>
<td><strong>27.54</strong></td>
<td><strong>14.94</strong></td>
<td><strong>79.77</strong></td>
</tr>
</tbody>
</table>

Figure 8: Schematic of NR system at co-digestion dairy (Green is existing AD systems while blue is new NR systems)

From Figure 8 you can see that as earlier described during description of the NR approach, manure and substrates leave their respective pits for entry to the digester. Digester effluent leaves the gas-tight vessel through a weir wall and enters an effluent pit that was retrofitted with heat exchangers to elevate the temperature of the manure for subsequent aeration and Class-A treatment. The effluent is then sent to a primary...
screen separator and dewatering auger for production of fiber product while the remaining effluent is sent to the aeration pit for micro-aeration and subsequent removal of CO₂, rise of pH and stripping of ammonia gas. The aeration pit is designed to be a plug-flow reactor capable of aeration (micro-aerators) and temperature (~50-60°C) equivalent to pilot studies using an HRT of 17 hours. Aerated effluent with foam exits the aeration reactor and enters a sump house where continuous de-foaming is accomplished using recycled effluent and spray-bars. Resulting gases exit the sump house through a hood and ducting system for entry into an acid tower. Acid is continuously pumped into the acid chamber for contact with ammonia via control of automated pH meters. Resulting ammonium sulfate solution overflows and is sent to storage tanks while treated exhaust is run through an air-to-air heat exchanger to warm input air to the aeration reactor. Effluent leaving the sump house is sent to a 2-day settling weir for settling of P-solids. An additional micro-screen is operated in a continuous loop allowing for large solids at the bottom of the weir to be removed and dewatered while small solids (primary P containing solids) that are not captured by the micro-screen return to the settled bottom of the weir for periodic removal and natural dewatering. Finally, effluent leaving the weir is sent to a large lagoon for storage until field application is allowed.

Figure 9: Image of completed system
Figure 10 is a collage of system products. Four products are produced by the system with moisture level and NPK dry values in parentheses (preliminary results): (1) Class-A fiber (74%; 1.4:0.6:0.8); (2) Fine Solids (80%; 2.5:0.8:0.8); (3) P-solids (70%; 2.2:2:1.5); and (4) Ammonium Sulfate Solution (65%; 8:0:0:10(S)).

Figure 10: NR products: (A) three solids, P-solids, Fine-solids, Fiber-solids clockwise from left; (B) 35% solution of ammonium sulfate and (C) first application of ammonium sulfate to fields

Tentative economics based on pilot scale results and demonstration system design is summarized in Table 2. From the table you can see that the system is designed to try to offset recovery costs as opposed to yielding significant profits although as markets mature and fertilizer prices potentially continue to rise, this scenario could change. For now though the system primarily uses AD outputs to more efficiently meet producer nutrient management needs and in turn the more robust system in terms of producer needs could lead to enhanced AD adoption, especially in the face of future potential more stringent nutrient regulations. Since completion of the commercial demonstration was delayed, resulting in a completed system not until late winter 2011, an updated economic evaluation has not been completed due to continued system troubleshooting. Updated economics as well as performance indicators are anticipated for this late spring and summer with some information hopefully available for the oral presentation later in the month.
Table 2: Tentative NR economics

<table>
<thead>
<tr>
<th>Costs ($/cow yr)</th>
<th>Revenues ($/cow yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Power: (Electrical purchase of 5¢/kwh; aeration rate of 20 gallons/cfm; power need of 20 cfm/ hp; 1.2x for other electrical)</td>
<td>$29.78</td>
</tr>
<tr>
<td>Sulfuric Acid: ($175/ton conc. acid; 2.9 lbs of Acid: 1 lb NH₃ recovered)</td>
<td>$56.58</td>
</tr>
<tr>
<td>Labor: (0.5 FTE salaried position with salary of $40K/yr; 2,000 cow farm)</td>
<td>$10.00</td>
</tr>
<tr>
<td>O&amp;M: (2% of capital costs at $600/cow NR only)</td>
<td>$12.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$108.36</strong></td>
</tr>
</tbody>
</table>

As stated earlier, the system is presently undergoing extensive troubleshooting and beta testing. Demonstration goals still hold at producing a final effluent that has 70% removal of ammonia, 80% removal of P and 50% total N as compared to values entering the digester. A partial list of particular concerns and lessons learned from the commercial demonstration are as follows, with undoubtedly more to follow as operation continues:

- Overall noise control
- Identification of optimal pumps, blowers, screens, etc. for conditions experienced
- Tuning of system to farm operations/sequences and vice versa
- Acid handling, storage, supply, pumping
- Acid tower operation, product quality, storage
- Product and solids dewatering, recovery and marketing
- Catalogue of regulations/permits
- Ammonia stripping operating parameters shifts under continuous flow
- Foam control

Field days, conference papers, extension papers, videos, webinars, marketing information, and techno-economic and performance evaluation report are envisioned for late summer, early fall of 2012.

COMMERCIAL DEMONSTRATION—EGG LAYER MANURE

Concerns Applying AD to Caged Layer Poultry Manure

*The problem* facing the US caged layer poultry industry and its 400+ larger CAFO-sized farms is how to annually treat 4 million tons of wet manure in a manner which responds to emerging needs in renewable energy, air/water quality improvements, and establishing new revenue streams for enhanced farm sustainability. However, next generation technology options allowing for production of renewable energy, such as gasification and anaerobic digestion (AD) have technical concerns, as applied to caged layer manure. Gasification, while suited well for dry broiler litter operations (80% solids), is poorly positioned for much wetter caged layer manure (25% solids) while AD has historically not been identified as a suitable technology for poultry manure because of its
inability to handle the higher solid content and biologically-inhibitory levels of ammonia. While digested effluent could be returned back to the front of the digester for use as grey dilution water as a means to reduce fresh water inputs, research at Washington State University (WSU) has shown that layer manure TAN levels are significantly higher than microbial thresholds and these levels become increasingly and dangerously high as AD effluent is used as reclaim water—leading to a steady decline in biogas performance with increased ammonia and use of reclaim water, especially when TAN levels exceed 4 g/L (Figure 11).

Caged poultry manure with 25% TS requires an input of dilution water in order to supply a wastewater material suitable for operation within commercially available AD technologies. On-farm, manure-based AD units within the US have traditionally used complete-mix (various European or US designs) or mixed plug-flow (DVO Inc., Chilton, WI) technology, with both technologies ideally supporting influents with TS content on the order of 4-12% (US-EPA, 2006). With caged-layer manure arriving from the belt press with TS of 25% it is clear that effective performance of the digesters require more than a 1:1 dilution with water, and at the scale of 600,000 layers for an average operation, that amounts to more than 180,000 gallons of dilution water per day—a sum that is simply not sustainable or economic, particularly in water threatened regions of the US. The conclusion, then, is that, in order for effective AD of caged layer manure to occur, an alternative to fresh water for dilution is required and that source is the AD effluent itself, which with treatment can be used as reclaim water.

AD effluent as source of reclaim water is viable, but only upon treatment and preparation. Since typical AD manure systems result on the order of 30-40% TS destruction, a system with influent of 11% TS leads to effluent with a 7% TS. Re-use of 7% TS effluent as dilution water makes poor engineering sense as every percentage point of solids that is re-introduced to the front of the digester results in the need for more reclaim water to attain the desired working TS flow rate. From a biological sense, the operation is non-optimal as well, as the non-digested solids are for the most part inert or recalcitrant in nature, which would lead to little further degradation upon extended digestion, thereby filling a fraction of the digester volume with non-reactive, non-biogas producing material. Fortunately, research and commercial demonstration have already shown that industrial separation of a significant portion of the solids can be accomplished (DVO, 2009). While, utilization of industrial separators to accomplish this requires additional capital and operating input, not to mention, parasitic use of produced electricity, it does serve to accomplish two very important goals. First, the effluent liquid to be used as reclaim water can be brought to a more desirable TS content on the order of 2% TS. Importantly, the remaining solids are suspended solids, which supply both nutrients and some biodegradable material to the digester while minimizing the volumetric impact to the digester. Of equal importance is research that shows during the digestion process, a significant portion of the organic phosphorus is converted to inorganic form and when in the presence of high Mg and Ca content manures, is chemically converted to phosphates bound as amorphous micro-solid salts (Gungor and Karthikeyan, 2008; Zhang et al., 2008). Thus, decanting centrifuge of the solids within
the effluent serves as a recovery mechanism and concentrator for P in the form of saleable organic solids (Frear et al, 2010).

While removal of solids allows for improved utilization of AD effluent as reclaim water, it does not solve an important concern regarding retention of soluble ammonia and the inhibition that it contributes to the AD process. Ammonia inhibition has been extensively studied during the AD of poultry manure, with results showing that poultry manure has levels of total ammonia nitrogen (TAN) (Itodo and Awulu 1999; Bujoczek, Oleszkiewicz et al. 2000) at times, well above levels of threshold inhibition identified as at or above 2 g/L TAN (Koster and Lettinga, 1984). Although microbial communities can adapt to higher concentrations of sustained ammonia (Frear et al, 2010; Abouelenien et al, 2009), research at Washington State University (WSU) has shown that (1) layer manure TAN levels are significantly higher than the threshold, (2) levels become increasingly and dangerously high as AD effluent is used as reclaim water, and (3) biogas performance steadily declines with increased ammonia and use of reclaim water, especially when TAN levels exceed 4 g/L (Figure 11).

Figure 11: Methane production as factor of TAN concentration and use of AD effluent as reclaim water (i.e. 20:20:60 AE:W refers to 20% seed and 20% AD effluent mixed with 60% fresh water as source of reclaim water during digestion)

An opportunity lies in demonstrating that existing commercial AD units can be effectively and economically operated using caged layer manure if the digester effluent is treated with a unique nutrient recovery and reclaim water system so as to overcome existing concerns with ammonia inhibition and intensive water usage needed for solids dilution (Figure 12).
Fortunately a demonstration commercial digester already exists at Wenning Poultry Farm in Fort Recovery Ohio (1 million layers), but one which is somewhat underperforming due to ammonia concerns discussed above. Industry, producer and grant funding have been made available to evaluate the NR system and its water recovery system at demonstration commercial scale. Design has been completed and as of this paper, construction has begun with a completion date and subsequent beta testing planned for late March 2012. It is hoped that oral presentation later this month can supply construction photos and an update on project completion.

REFERENCES


Andgar, (2011). Average digester capital cost per cow, Ferndale, WA.


SMALL-SCALE ANAEROBIC DIGESTION IN THE UNITED STATES: DESIGN OPTIONS AND FINANCIAL VIABILITY

S. Lansing and K. Klawon
Department of Environmental Science and Technology
University of Maryland, College Park, MD

INTRODUCTION

Anaerobic digesters were first widely constructed in the United States during the 1970’s energy crisis. Within the anaerobic environment inside a digester, methanogenic microorganisms, utilize organic matter, carbon dioxide, and hydrogen to produce methane, resulting in the creation of renewable energy with decreases in greenhouse gas emissions, organic pollutants, pathogens, and odor (Martin, 2004). Unfortunately, poor economic viability and technical flaws led to a 60% failure rate of these systems (Bishop and Shumway, 2009). Through improved designs, the world is currently seeing a revitalization of anaerobic digestion technology with over 30 million manure-based digesters operating globally (Chen et al., 2010; Rao et al., 2010).

The United States Environmental Protection Agency (USEPA) estimated that large-scale U.S. dairy operations (>500 cows) could produce 6.8 million MWh of renewable energy annually (AgSTAR, 2010). Derived from data in Vanhorn et al. (1994) and the US National Agricultural Statistics Service (2009), it was determined that small-scale dairy operations (<500 cows) have the potential of producing an additional 3.4 million MWh annually (780 kWh/cow).

In recent years, the number of digesters on large-scale livestock operations in the U.S. has increased from approximately 100 facilities in 2005 to 171 facilities in July 2011 (AgSTAR, 2010). With an average capital investment of 1.5 million U.S. dollars, the USEPA does not recommend biogas recovery systems for facilities with less than 500 cows. Other studies have shown at least 200-400 cows are needed for anaerobic digestion systems to be economically viable (Metha, 2002; Moser, 2011). In the United States in 2007, 89% of dairy farms had less than 200 cows, making digestion technology economically inaccessible to the majority of U.S. dairy farms (US National Agricultural Statistics Service, 2009).

Traditional sources of revenue from anaerobic digestion are the creation of biogas and the sale of electricity. While revenue from electricity sales has been successfully achieved at large-scale operations (Nelson and Lamb, 2002; Wright and Inglis, 2003), it is connected to economies of scale and thus not often profitable for small-scale systems, which are more dependent on the price of electricity (Lazarus and Rudstrom, 2007; Ghafoori and Flynn, 2007; Giesy et al., 2009). Small dairies that produce electricity at a profit credit their success to receiving additional off-farm waste, having a favorable buyer for their electricity, and dedicating substantial time to the project development stage (Millen, 2008). When electrical generation was not economically viable, the direct use of biogas was found to be economically feasible when the on-farm
heating requirements were high enough to regularly utilize the produced biogas (Barcmort et al., 2008; Bishop and Shumway, 2009).

Perhaps the greatest economic issue facing small-scale digestion is uncertainty of both traditional and non-market factors. Gloy and Dressler (2010) cited the main challenges facing anaerobic digestion financing are the lack of information regarding the initial capital investment, predicted biogas production, expected lifetime, future electricity prices and operating costs. Stokes et al. (2008) highlighted the lack of quantified data on non-market benefits as a major obstacle to widespread anaerobic digestion implementation. The AgSTAR Program, an outreach program supported by the U.S. Environmental Protection Agency (USEPA), U.S. Department of Agriculture (USDA) and U.S. Department of Energy (USDOE) to encourage the use of anaerobic digesters in the U.S., has begun to address the lack of standardized digestion performance data by releasing the report, “Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures”, but is expected to take years to collect a comprehensive database.

The Minnesota Project, evaluated six anaerobic digester designs for small dairies, 100-300 cows, ranging in cost from $105,000 - $230,000 (2010 US$) (Goodrich, 2005). The largest reduction in capital investment was achieved through the elimination of electricity generation capabilities. The Minnesota Project subsequently constructed a small-scale up-flow digester for 160 milking cows at a cost of $460,000 (US) (Lazarus, 2009. The system, while an excellent first step, has run into problems common at most dairies: engine failure and complications with manure handling.

Objectives

Of the 30 million-plus digesters operating around the world, the majority are low-cost and concentrated in the tropics where the ambient temperature is at or near the optimal digestion temperature of 35°C. In this study, low-cost digestion models from the developing world were modified to transfer this technology to small and medium scale dairy farmers in temperate climates with abundant waste resources.

The goals of the research were to make anaerobic digestion of manure more readily available, cost effective, and manageable to small dairy farmers in the United States. Specifically, the research objectives were to (1) perform an economic assessment of constructed pilot-scale research digesters, (2) perform an economic assessment on a 100-cow scale-up of the research digester design, (3) create a small-scale digester database and perform a cost analyses of these systems, (4) reevaluate the minimum size dairy farm needed for an economically feasible anaerobic digester in the U.S.
METHODS

Research site

The University of Maryland (UMD) research digesters were constructed using a modified Taiwanese digester design developed by Raul Botero and T. R. Preston for tropical climates. The traditional Taiwanese digester includes a plug-flow reactor constructed of a tubular polyethylene bag and PVC piping (Lansing et al., 2008). Modifications to this design were necessitated by the sensitivity of methanogens to the lower temperatures inherent in the temperate climate of the U.S.

There are nine plug-flow UMD research digesters located at the United States Department of Agriculture (USDA) dairy facility in Beltsville, Maryland. Each digester is 4.36 meters in length with a diameter of 0.91 meters and a total capacity of 700 gallons (2.65 m³) per digester. The digesters are fed 25 gallons (0.09 m³) of manure daily with a combined treatment volume of 225 (0.85 m³) gallons per day with a 21-day retention time.

The UMD research digesters were constructed of a PVC-based flexible material, laid in insulative foam beds surrounded by radiant barriers, and enclosed within 1.07 meter drainage culverts to both protect and maintain the desired shape of the digesters as shown in Figure 1.

Figure 1: The inside of the UMD modified Taiwanese-model plug-flow digester

Manure is pumped into a stainless steel heating kettle and warmed to 35°C before draining into the digesters. Preheating of manure influent is a technique that has shown promise in past experiments but has not been tested as a modification to the Taiwanese design. Once the manure reaches 35°C, it is released into the digester. The culverts are partially buried for added insulation and protected from the elements by a windshield structure.

The UMD research digesters are augmented with recirculation capabilities, allowing the effluent from the digesters to be reintroduced into the system through the heating
kettle. Recirculation has been shown to aid in the distribution of the microorganisms and aid in keeping warm material circulating through the system. These modifications represent a departure from the original plug-flow, unheated Taiwanese-model digestion system in an effort to create a design that is compatible with a temperate climate.

The USDA's dairy facility uses a manure scraper system to remove the waste from its 120-cow facility. The manure is separated using a solid separator. The solids are composted, while the liquid portion is treated by a mixed digester system installed in 1994 for $263,000 (1994 US$). The digester effluent is stored in a lagoon and spray applied to the fields as fertilizer. The influent to the UMD research digesters is pumped from two locations. Six of the UMD research digesters receive un-separated manure pumped from the manure storage pit located before solid separation, and three UMD research digesters receive liquid manure pumped from a manure storage pit located after solid separation. The effluent from the nine research digesters is pumped back into the storage lagoon. These influent and effluent connections were used as the boundary line for the economic analysis of the research digesters; thus, neither the solids separator nor the lagoon storage is included in the economic assessment.

The UMD research system was conceptually scaled up to supply a 100-cow dairy (referenced as UMD digester.) The scale up was performed on a component by component basis to most accurately represent real costs.

Smaller-scale anaerobic digestion systems

The UMD digester was evaluated against literature values obtained from existing and theoretical digesters for farms of 250 or less cows. The digester types include complete-mixed, plug-flow, covered lagoons, fixed film, and up-flow. The cost data were compiled from published studies and conversations with providers and farmers for actual systems. Projected costs for the theoretical systems were determined by extrapolating costs of existing components from other systems. The digestion systems used in the economic analysis are listed in Table 1. The UMD digester was evaluated under two scenarios: the first scenario was calculated without an electric generation system, and the second scenario included an electric generation system and payback from the utility.

Cash-flow analysis

In order to evaluate the economic viability of the proposed modified plug-flow system, a cash-flow approach was used, as recommended by the USEPA-AgSTAR Protocol for Quantifying and Reporting the Performance of Anaerobic Digestion Systems for Livestock Manures. The cash-flow approach tabulates and compares all annual costs and revenues. Required assumptions described by the AgSTAR Protocol are as follows: (1) initial capital for the system is considered to be a combination of internal capital and borrowed capital, (2) the interest rate on borrowed capital is assumed to be equal to the rate of return on internal capital, (3) no cost-sharing assistance is included in the analysis, (4) payments for the total capital costs occur as a uniform series of annual payments over the useful life of the system, and (5) the useful
life of the system is assumed to be 20 years and the replacement of system components with shorter lifetimes is accounted for in annual operation and maintenance costs. The discount rate on borrowed capital is assumed to equal the average effective interest rate (7.8%) on non-real-estate farm loans. All costs were converted to 2010 U.S. dollars using the Engineering News Record (ENR) Construction Cost Index. See Klavon (2011) for a detailed method of the cash-flow analysis.

Table 1. Database of small-scale digester systems in the United States, 2011

<table>
<thead>
<tr>
<th>Name</th>
<th>Digester Type</th>
<th>Digester Site</th>
<th># of cows</th>
<th>Items Included</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMD 1</td>
<td>Taiwanese-model Plug Flow</td>
<td>UMD Research Digesters, MD</td>
<td>100</td>
<td>digester, collection, excavation, gen-set</td>
</tr>
<tr>
<td>UMD 2</td>
<td>Taiwanese-model Plug Flow</td>
<td>UMD Research Digesters, MD</td>
<td>100</td>
<td>digester, collection, excavation</td>
</tr>
<tr>
<td>Theoretical 1</td>
<td>Covered Lagoon</td>
<td>Designed, not constructed</td>
<td>100</td>
<td>digester, collection, boiler</td>
</tr>
<tr>
<td>Theoretical 2</td>
<td>Plug Flow</td>
<td>Designed, not constructed</td>
<td>100</td>
<td>digester, collection, boiler</td>
</tr>
<tr>
<td>Theoretical 3</td>
<td>Upright</td>
<td>Designed, not constructed</td>
<td>100</td>
<td>digester, separator, composter, boiler</td>
</tr>
<tr>
<td>Theoretical 4</td>
<td>Upright Mixed</td>
<td>Designed, not constructed</td>
<td>100</td>
<td>digester, separator, boiler</td>
</tr>
<tr>
<td>Theoretical 5</td>
<td>&quot;Low-cost&quot; Plug Flow</td>
<td>Designed, not constructed</td>
<td>100</td>
<td>digester, collection, boiler</td>
</tr>
<tr>
<td>Theoretical 6</td>
<td>Upright Mixed</td>
<td>WA State Dairy Farm, WA</td>
<td>200</td>
<td>digester, gen-set</td>
</tr>
<tr>
<td>Digester 1</td>
<td>Upright</td>
<td>USDA Beltsville, MD</td>
<td>220</td>
<td>digester, collection, separator, boiler</td>
</tr>
<tr>
<td>Digester 2</td>
<td>Plug Flow</td>
<td>Northeast IA CC Farm, IA</td>
<td>120</td>
<td>digester, gen-set</td>
</tr>
<tr>
<td>Digester 3</td>
<td>Upflow-tank</td>
<td>Jer-Lindy Farm, MN</td>
<td>160</td>
<td>digester, collection, building, labor, excavation, boiler, gen-set</td>
</tr>
<tr>
<td>Digester 4</td>
<td>Plug Flow</td>
<td>Freund Dairy, CT</td>
<td>250</td>
<td>digester, boiler</td>
</tr>
<tr>
<td>Digester 5</td>
<td>Fixed-Film</td>
<td>JJ Farber Dairy, NY</td>
<td>100</td>
<td>digester, boiler</td>
</tr>
<tr>
<td>Digester 6</td>
<td>Covered Lagoon</td>
<td>Spring Valley Dairy, NY</td>
<td>236</td>
<td>digester, gen-set, manure storage</td>
</tr>
<tr>
<td>Digester 7</td>
<td>Fixed-Film</td>
<td>Williston Cattle Co., VT</td>
<td>250</td>
<td>digester, extra research ports, boiler</td>
</tr>
<tr>
<td>Digester 8</td>
<td>Upright Mixed</td>
<td>WA State Dairy Farm, WA</td>
<td>200</td>
<td>digester, boiler</td>
</tr>
<tr>
<td>Manure Pit 1</td>
<td>Earthen Manure Pit</td>
<td>Typical, MD</td>
<td>150</td>
<td>Pit, pumps, pipes</td>
</tr>
<tr>
<td>Manure Pit 2</td>
<td>Lagoon (no cover)</td>
<td>Typical, MD</td>
<td>250</td>
<td>Lagoon, solid separator, concrete pad, pumps, pipes</td>
</tr>
</tbody>
</table>
RESULTS

Capital costs

The most expensive components of the UMD research digesters were the digester bags, culverts, and conveyance system (piping and pumps), resulting in a total system capital cost of $83,970 (2010 US$), not including labor. Utilizing the same design but scaled up for a 100-cow facility, the capital cost of the UMD system for a 100-cow farm with electrical generation (UMD1) was calculated to be $284,150 (2010 US$) with the co-generator accounting for 36% of the total capital cost. The capital cost of the UMD system without electrical generation (UMD2) totaled $184,150 (2010 US$).

Cash-flow analysis

The cash-flow analysis found two systems had a positive cash-flow without cost sharing when all possible revenue sources were included, Theoretical 6 and Digester 8 (Tables 2, 3). Bedding reuse accounted for the greatest percentage of annual revenue. When carbon credits and bedding reuse were excluded as annual benefits, no smaller-scale digestion system had a positive cash-flow.

DISCUSSION

*Cash-flow analysis for smaller-scale digesters in the U.S.*

The UMD system did not perform well with or without electrical generation capabilities due to high initial capital costs and insufficient revenue. The system may perform better when actual operation and maintenance data are available as the system was designed to utilized less biogas for internal heating and expensive automotive capabilities that could decrease the time required for digester operation.

Of the two systems with a positive cash-flow, Digester 8 did not have electrical generation and Theoretical 6 had electrical generation capabilities. Both systems had lower initial capital costs, which was the largest factor in determining their cost effectiveness. Digester 8, a complete mixed digester with a boiler system, was installed in 1976 for $164,520 (2010 US$) (Coppinger et al., 1980). Given the age of the system, it is possible that the cost to build the same system today would be higher than is accounted for in this analysis, as the construction cost index is used for general construction costs and is not an exact inflation rate for all the materials used in construction of the digester. Theoretical 6, which is Digester 8 with added electrical generation capabilities, could have a similar inflation error as Digester 8.

Given the limited ability of traditional manure management systems to generate revenue, neither manure pit systems had a positive cash-flow. It is assumed that this cost is already being absorbed by the farm before the installation of the digester. If the cost of the manure pit were added to the cost of the digester, none of the digester systems would generate a positive cash-flow.
Table 2. Capital costs and cash flow analysis for the small-scale digestion systems. Parentheses represent a negative number, numbers are 2010 US$, rounded to $10

<table>
<thead>
<tr>
<th>System</th>
<th>Capital Costs</th>
<th>Capital Cost/Cow</th>
<th>Annual Operating Cost</th>
<th>Annual Income</th>
<th>Annual Net Cost</th>
<th>Annual Cost/Cow</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMD 1</td>
<td>$284,150</td>
<td>$2,840</td>
<td>($14,210)</td>
<td>$15,370</td>
<td>($27,780)</td>
<td>($280)</td>
</tr>
<tr>
<td>UMD 2</td>
<td>$184,150</td>
<td>$1,840</td>
<td>($5,520)</td>
<td>$15,960</td>
<td>($8,320)</td>
<td>($80)</td>
</tr>
<tr>
<td>Theoretical 1</td>
<td>$217,480</td>
<td>$2,170</td>
<td>($6,520)</td>
<td>$15,960</td>
<td>($12,710)</td>
<td>($130)</td>
</tr>
<tr>
<td>Theoretical 2</td>
<td>$192,650</td>
<td>$1,930</td>
<td>($5,780)</td>
<td>$15,960</td>
<td>($9,440)</td>
<td>($90)</td>
</tr>
<tr>
<td>Theoretical 3</td>
<td>$189,110</td>
<td>$1,890</td>
<td>($5,670)</td>
<td>$15,960</td>
<td>($8,970)</td>
<td>($90)</td>
</tr>
<tr>
<td>Theoretical 4</td>
<td>$163,110</td>
<td>$1,630</td>
<td>($4,890)</td>
<td>$15,960</td>
<td>($5,540)</td>
<td>($60)</td>
</tr>
<tr>
<td>Theoretical 5</td>
<td>$124,100</td>
<td>$1,240</td>
<td>($3,720)</td>
<td>$15,960</td>
<td>($400)</td>
<td>$0</td>
</tr>
<tr>
<td>Theoretical 6</td>
<td>$176,450</td>
<td>$880</td>
<td>($8,820)</td>
<td>$30,750</td>
<td>$3,960</td>
<td>$20</td>
</tr>
<tr>
<td>Digester 1</td>
<td>$427,990</td>
<td>$1,950</td>
<td>($12,840)</td>
<td>$35,110</td>
<td>($21,320)</td>
<td>($100)</td>
</tr>
<tr>
<td>Digester 2</td>
<td>$266,930</td>
<td>$2,220</td>
<td>($13,350)</td>
<td>$18,450</td>
<td>($22,090)</td>
<td>($180)</td>
</tr>
<tr>
<td>Digester 3</td>
<td>$487,160</td>
<td>$3,040</td>
<td>($13,390)</td>
<td>$28,790</td>
<td>($34,220)</td>
<td>($210)</td>
</tr>
<tr>
<td>Digester 4</td>
<td>$349,890</td>
<td>$1,400</td>
<td>($10,500)</td>
<td>$39,900</td>
<td>($6,240)</td>
<td>($20)</td>
</tr>
<tr>
<td>Digester 5</td>
<td>$176,140</td>
<td>$1,760</td>
<td>($31,550)</td>
<td>$17,090</td>
<td>($32,400)</td>
<td>($320)</td>
</tr>
<tr>
<td>Digester 6</td>
<td>$188,830</td>
<td>$800</td>
<td>($10,550)</td>
<td>$22,680</td>
<td>($7,100)</td>
<td>($30)</td>
</tr>
<tr>
<td>Digester 7</td>
<td>$371,070</td>
<td>$1,480</td>
<td>($11,130)</td>
<td>$39,900</td>
<td>($9,020)</td>
<td>($40)</td>
</tr>
<tr>
<td>Digester 8</td>
<td>$164,520</td>
<td>$820</td>
<td>($4,940)</td>
<td>$31,920</td>
<td>$10,220</td>
<td>$50</td>
</tr>
<tr>
<td>Manure Pit 1</td>
<td>$150,000</td>
<td>$1,000</td>
<td>($15,000)</td>
<td>$0</td>
<td>($30,280)</td>
<td>($200)</td>
</tr>
<tr>
<td>Manure Pit 2</td>
<td>$600,000</td>
<td>$2,400</td>
<td>($25,000)</td>
<td>$33,800</td>
<td>($52,310)</td>
<td>($210)</td>
</tr>
</tbody>
</table>

Impact of revenue generation on the cash-flow analysis

Given the industrial market price of natural gas in 2010-2011, $5.10/cf, and the price of electricity, $0.09/kWh, it was more cost effective to use the biogas directly than it was to convert it into electricity, even without taking into account the higher capital cost and operating cost of an electrical generation system. This gave all systems utilizing boilers a higher annual income per cow than those utilizing electrical generation. Other studies have also concluded the direct use of biogas in lieu of electrical production was economically feasible when the on farm heating requirements were high enough to regularly utilize all of the produced biogas (Bracmort et al., 2008; Bishop and Shumway, 2009). Past studies have also demonstrated that increasing the price of electricity expanded the economic feasibility of anaerobic digesters to smaller farms (60 – 650) (Metha, 2002; Bishop and Shumway, 2009; Giesy et al., 2009).

Bedding reuse was one of the highest income sources generated from digester use, ranging from $10,000 - $25,000 (2010 US$) annually. This finding is congruent with other studies, which found bedding recycling for on-farm use or for off-farm sale to be
an important income source for farms with solid separator capabilities. For existing
digestion systems where the cost of the solid separator was not included in the capital
costs, it was assumed the separator already existed on the farm.

Table 3. Annual revenue for the small-scale digestion systems (2010 US$, rounded to
$10)

<table>
<thead>
<tr>
<th>Name</th>
<th>Biogas</th>
<th>Electrical</th>
<th>Bedding</th>
<th>CO2</th>
<th>Total Revenue</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMD 1</td>
<td>$0</td>
<td>$4,700</td>
<td>$10,000</td>
<td>$670</td>
<td>$15,370</td>
</tr>
<tr>
<td>UMD 2</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$15,960</td>
</tr>
<tr>
<td>Theoretical 1</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$15,960</td>
</tr>
<tr>
<td>Theoretical 2</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$15,960</td>
</tr>
<tr>
<td>Theoretical 3</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$15,960</td>
</tr>
<tr>
<td>Theoretical 4</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$15,960</td>
</tr>
<tr>
<td>Theoretical 5</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$15,960</td>
</tr>
<tr>
<td>Theoretical 6</td>
<td>$0</td>
<td>$9,400</td>
<td>$20,000</td>
<td>$1,350</td>
<td>$30,750</td>
</tr>
<tr>
<td>Digester 1</td>
<td>$11,590</td>
<td>$0</td>
<td>$22,000</td>
<td>$1,520</td>
<td>$35,110</td>
</tr>
<tr>
<td>Digester 2</td>
<td>$0</td>
<td>$5,640</td>
<td>$12,000</td>
<td>$810</td>
<td>$18,450</td>
</tr>
<tr>
<td>Digester 3</td>
<td>$0</td>
<td>$7,520</td>
<td>$16,000</td>
<td>$1,080</td>
<td>$28,789*</td>
</tr>
<tr>
<td>Digester 4</td>
<td>$13,170</td>
<td>$0</td>
<td>$25,000</td>
<td>$1,730</td>
<td>$39,900</td>
</tr>
<tr>
<td>Digester 5</td>
<td>$5,270</td>
<td>$0</td>
<td>$10,000</td>
<td>$690</td>
<td>$17,089*</td>
</tr>
<tr>
<td>Digester 6</td>
<td>$0</td>
<td>$11,090</td>
<td>$23,600</td>
<td>$1,590</td>
<td>$22,675*</td>
</tr>
<tr>
<td>Digester 7</td>
<td>$13,170</td>
<td>$0</td>
<td>$25,000</td>
<td>$1,730</td>
<td>$39,900</td>
</tr>
<tr>
<td>Digester 8</td>
<td>$10,540</td>
<td>$0</td>
<td>$20,000</td>
<td>$1,380</td>
<td>$31,920</td>
</tr>
<tr>
<td>Manure Pit 1</td>
<td>$0</td>
<td>$0</td>
<td>$15,000</td>
<td>$0</td>
<td>$15,000</td>
</tr>
<tr>
<td>Manure Pit 2</td>
<td>$0</td>
<td>$0</td>
<td>$25,000</td>
<td>$0</td>
<td>$25,000</td>
</tr>
</tbody>
</table>

* Total revenue amount used in the cash flow analysis is based on case study data adjusted to 2010$ and
not the addition of the columns due to actual revenue data available.

Food waste and tipping fees

The negative cash-flow observed in many of the analyzed systems could be offset
by the addition of food waste and the accompanying tipping fees. To have a positive
cash-flow, UMD2 would need an additional $690 (2010 US$) in monthly tipping fees,
while UMD1 would need $2,320 (2010$) in monthly tipping fees. Taking food waste
could also increase income beyond the tipping fee by contributing additional volatile
solids to the digester, thus increasing biogas production. There is some risk to
accepting off-farm food waste, as some wastes are not well-suited for anaerobic
digestion and can decrease biogas production.

Additional funding options

This analysis assumed the farmer paid 100% of the investment, but in practice there
are multiple cost-sharing opportunities available to U.S. farmers for anaerobic digester
projects. Federal sources of funding have been known to cover 50% of the project costs, and various grants, loans, tax exemptions, and production incentives are also available on the State and local level. Giesy et al. (2009) found economic feasibility of digesters to be highly sensitive to cost-sharing opportunities. When cost-sharing opportunities were utilized to pay for 25% of the initial capital cost, three additional systems, Theoretical 5, Digester 4, and Digester 7, had a positive cash-flow. When cost-sharing opportunities were utilized to pay for 50% of the initial capital cost, nine additional systems, including UMD2, had a positive cash-flow.

CONCLUSIONS

This study demonstrates that anaerobic digesters can be cost effective for small-scale systems, although their viability must be analyzed on an individual basis, as 63% of the systems analyzed were more expensive than the AgSTAR recommended capital cost of $1,500/cow. However, with an increase in revenue, such as an increase in the price of electricity or the addition of tipping fees, a greater capital cost could be afforded by the farmer. The most cost effective method to create economically viable small-scale digesters is to lower the capital cost using cheaper materials. With a 44% drop in capital costs, the UMD system without electricity generation would have been cost neutral.

While small-scale anaerobic digestion is economical in some cases, it is farm dependent and a majority of the systems analysis did not have a positive cash-flow. In this analysis, at least half of the existing digesters are now shutdown (4 out of 8), with three cases due to the dairy closing or management changes and not specifically related to a digester failure. The longest running small-scale system has been operational for almost two decades, and there are four small-scale systems under construction, showing some success in the market. Success appears to be dependent on the willingness of farmers to invest time and personal energy into the digester with economics being only one way to gauge the success of a project. With the appearance of multiple private companies attempting to fill the niche of small-scale anaerobic digestion with modular and proprietary designs, this technology could see much greater implementation in the coming years.

ACKNOWLEDGEMENTS

This work was supported by funding from the Maryland Water Resources Research Center (Grant# 06HQGR0090) and University of Maryland Agriculture Experiment Stations. We would like to thank Jon Leith, Mike Kemp, Brad Green, and the crew at the USDA Beltsville Agricultural Research Center for their support and assistance during construction of the research system. We also wish to thank Gary Seibel and the staff at the ENST Project Development Center for their engineering assistance and component fabrication. Additional thanks are due to the Department of Environmental Science and Technology Water Quality Laboratory Team, including Faaiz Ajaz, Scott Allen, Grant Hughes-Baldwin, Ashley Belle, Anisha Gupta, Kayoko
REFERENCES


ESTIMATING FARM SIZE REQUIRED TO ECONOMICALLY JUSTIFY ANAEROBIC DIGESTION ON SMALL DAIRY FARMS

T. Shelford
Cornell University

INTRODUCTION

The benefits of anaerobic digestion (AD) of dairy manure vary from economic (reduced power costs/income from excess electricity/heat), to environmental (reduced greenhouse gas emissions, better control over field application of digestate) to social (through reduced odor during storage and application). However to realize these benefits economically, is the true challenge of AD, and a part of the reason for the slow adoption rate in the US, particularly when compared to European countries such as Germany and Denmark. According to the EPA there are currently approximately 131 dairy farm based anaerobic digesters with cogeneration operating in the United States (AgSTAR, 2012). In Germany alone there are more than 3,000 on-farm biogas plants. In the US, the average herd size is 150 lactating cows, whereas in Germany it is 50. Clearly there must be a reason for why anaerobic digestion has not flourished in the US as it has in Europe.

Anaerobic digestion of dairy manure continues the digestion process started in the cow and produces biogas. This biogas can be used to fuel a boiler to produce heat, fuel an engine-generator set to produce electricity and heat, scrubbed and used as a natural gas replacement, or even just flared off. Depending on the size of the system the engine-generator may represent one-third to one-half the capital cost. Estimates of capital costs for various systems can vary greatly depending on the type of system selected and the size of herd it is designed for. AgSTAR estimates of capital costs on a per cow basis for larger farms indicate costs at the 500-cow level of approximately $1,500 per cow for plug flow systems and $1,100 per cow for complete mix systems (AgSTAR 2012). However, analyzing existing small farm data (farms 100 to 250 cows) prices can vary from $1,000 up to $2,800 per cow. With such a significant capital investment, it is key that the revenue and benefits of the digester are capable of at least paying down capital costs.

Revenue is a major difference between the United States and Europe. Feed in tariff pricing is a common tool used worldwide to encourage renewable energy production. Under this strategy long-term contracts guaranteeing a premium price for renewable power are signed with a producer. Rates vary greatly from jurisdiction to jurisdiction and depend on the priority put on a particular form of power generation. Feed in tariff programs in Ontario, Canada are $0.195 per kWh for farm biogas-based energy for projects under 100 kW and $0.185 for projects over 100 kW, whereas solar power sources can get up to $0.802 per kWh under certain circumstances (Ontario Power Authority, 2012). Currently the feed in tariff rate for electricity produced from biogas is 0.215 Euro ($0.31 USD) per kWh in Germany.

In the Northeastern United states, Vermont provides a feed-in-tariff for AD based energy of $0.16 per kWh. Many states don’t have a feed in tariff, though they may
encourage AD based energy through net metering laws. Under net metering laws surplus energy is put onto the grid, and can be withdrawn at times when production may not meet demand. Typically however, any surplus energy at the end of the year is only paid out to the farmer at wholesale rates, which may be as low as $0.05 per kWh.

Another contributor to the revenue of European digesters are the carbon credits associated with the destruction of methane. When manure is spread on a field with plenty of aeration it decomposes aerobically and little methane is produced. However in manure storages such as pits or lagoons, the conditions are often anaerobic under which methane can be formed. According to the US EPA, (2006) methane is 21 times more potent that CO$_2$ as a greenhouse gas, and so manure storage systems can represent a large source of greenhouse gases. Carbon credits are monies paid to a project for their reduction in CO$_2$ emissions from pre project levels. Through this trading, industries that emit too much CO$_2$, or it is too expensive for them to meet emissions reductions, can "reduce" their emissions through offsets trading. The company that needs to reduce emissions can pay a different company to reduce their CO$_2$ footprint through implementing emissions reducing strategies. For farms with existing manure storage systems capturing this methane either through a cover or AD system, and then destruction of the methane either through flaring or burning in an engine generator set or boiler, reduces the methane emissions relative to not having a system and it is this difference (pre project emissions minus post project emissions) that can then be sold.

On the European Carbon Credit market these reductions have relatively recently been worth 16.5 euro ($24) per metric ton (though currently the carbon market has dropped substantially due to the economic difficulties in Greece and an influx of approved offset projects (Carbon Capitalist, 2012). Anaerobic digestion systems can lead to a carbon credit offset amount of approximately 2.5 metric tons of CO$_2$ per cow per year, or $60 per year per cow at the $24 per metric ton carbon credit pricing. Carbon markets in the US are still uncertain with the Chicago Climate Change (CCX) reaching a peak of $7.50 per metric ton in 2008, and ceasing operations in 2010 with a value of only $0.05 to $0.10 per metric ton. California is implementing a new cap and trade market exchange to reach its greenhouse gas emission targets that could help projects throughout the country.

To further maximize biogas production, many digesters in Europe and the US co-digest additional materials; from food processing and other organic waste, to crops grown specifically for use in the digester. Co-digestion represents an excellent opportunity to help the bottom line of digesters if in addition to increased biogas yield, a “tipping fee” comparable to what a waste stream producer would pay at a landfill, is paid to the digester.

Tipping fees can vary greatly depending on the availability of digestible material. Increased transportation costs of material will result in a lower realized fee. Another complication is ensuring long-term availability of the material. The difficulty in signing long-term supply contracts for co-digestion materials makes planning for their use difficult. The increased value of biogas in Europe encourages diverting organic waste streams to digesters.
The definition of small farm varies greatly depending on the region of the country considered. The average herd size of 120 dairy cows, is certainly very small when compared to the sizes of farms that presently have operating AD systems. Due to economies of scale it has generally been easier for larger operations to justify AD systems. The circumstances of each farm will vary greatly, affecting the feasibility of constructing an AD system. Location can also affect the costs associated with hooking into the grid for energy sales, and proximity to organic wastes for co-digestion. Beyond economics there are other hurdles to small dairy AD, such as:

- The time required to operate and maintain the additional systems
- The barn style (tie-stall and stanchion may not be suitable for manure collection)
- The availability of smaller scale equipment (mixers, engine generators) biogas cleanup
- permitting and local regulation compliance
- air quality standards

The goal of this paper is to present a cost-benefit analysis of the effects of benefits pricing on small farm AD coupled with power generation. A firm understanding of the costs and potential benefits of AD systems is key to making informed decisions on individual projects, and on a larger scale, the policies that regulate and encourage them. In order to achieve the goal of this paper, the following objectives were developed and implemented.

Objectives:

1. To develop a model to estimate the surplus electricity, carbon credit and co-digestion incomes possible based on farm size (number of dairy cows.)
2. To use the model to estimate farm size necessary to break even under varying capital cost and benefit pricing scenarios.

THE MODEL

The starting point of the model is the number of lactating cows. From this population a default herd size for animals contributing to manure production was estimated based on common ratios of dry cows and heifers to lactating cows found on typical farms (17 dry cows for every 100 lactating cows and 80 heifers for every 100 lactating cows). From the herd size and make-up, the volume of manure produced and the volatile solids loading was estimated using standard values (ASAE. 2005). Herd population also serves as one of the inputs to estimating the carbon credits available to the farm following digester installation. The volatile solids loading rate serves as the basis for predicting co-digestion capacity, biogas production, and electricity production.

Co-digestion

For the purposes of the model the capacity of the system to accept additional organic materials to co-digest, was based on the volatile solids loading rate of the manure. Small farm digesters are ideally as low maintenance as possible which makes
high co-digestion rates difficult. Co-digestion can require considerable effort into monitoring both the flow of materials into the digester and the health of the digester itself; a task that may be onerous for a small farm with a limited workforce. For this reason the volatile solids loading rate as a percentage of the volatile solids of the manure was limited to 25% (i.e. one quarter of the volatile solids can be from co-digested material).

The material used as an example was cheese whey, but the model could be easily adapted to incorporate other materials. Based on the fraction of volatile solids for co-digestion a volume or mass of co-digestion material was estimated based on the density and volatile solids content of the particular material.

**Electrical generation and consumption**

The biogas production of the digester was estimated based on the volatile solids loading rate from the manure and any co-digested materials. The volatile solids loading rate used to estimate biogas production assuming standard values for digestibility (Jewell, 2005).

Electricity generation was modeled by taking the estimated biogas production and assuming it was used in an engine-generator set, with a capacity factor of 0.95. Conversion efficiencies for a range of generator set sizes (20 to 250 kW) were averaged and used to estimate and develop a ratio of biogas consumed to power produced. This ratio was used to give an estimate of the required size of engine-generator set required as well as the yearly power generation.

To estimate the surplus electricity generated as a function of farm size, energy audit data from 45 small farms (ranging in size from 24 to 240 cows), was analyzed (Petersen, 2011). This dataset contained yearly energy use and herd information necessary to develop a relation (Figure 1) between farm size and energy usage on a small farm scale. In addition, 10% of the output of the generator was assumed to contribute to operating the digester itself (parasitic load).

A net metering situation was assumed such that power available for the grid was the total power generated, minus that required for on farm (and digester) use, on an annual basis. The benefit of electricity generation was then assumed to be the avoided cost of power purchasing plus the sale of any surplus power.

**Carbon credits**

The amount of carbon credits available was estimated using the Excel workbook developed by the Climate Action Reserve (2008). The data required for the workbook used assumed values for NY, for farms with existing manure storage and the same assumed herd information used to estimate biogas production. Default values for lactating, heifer and dry cows were taken from the provided table information, along with the performance of the biogas containment system. The results of this worksheet provided the yearly avoided CO2e in metric tons.
MODEL VARIABLES

The purpose of the model is to investigate what effects incentives such as feed in tariff rates, carbon credits, and tipping fees could have on the financial viability of a digester system. By varying these benefit prices in a number of scenarios it is possible to see how important they are relative to one another. By including capital and maintenance costs in a cost benefit analysis it is then possible to examine under what scenarios digesters with accompanying power generation could be viable.

Varying Energy Price

The range of electricity price analyzed in the model goes from the basic wholesale price of $0.05 per kWh, to the feed in tariff rates seen in Europe at $0.31 per kWh. An intermediate value of $0.16 as available in Vermont is also analyzed. A further important consideration is the purchase price of electricity. Avoided purchased power is an important benefit in engine generator economics. To simplify the analysis for this paper an avoided purchase price of $0.10 per kWh was used for all scenarios.

Varying Carbon Credit Price

Carbon prices have been in turmoil lately, however this uncertainty could change once the economic crisis resolves and/or the new Californian initiative begins. For this paper, carbon credit pricing of $0 (no carbon credit value) to $20 with an intermediate value of $10 per metric ton CO$_2$e were investigated.

Varying Tipping Fee

For this paper, cheese whey was assumed to have a value of $0.05 or $0.10 per gallon which represents a typical price currently received, and a higher than average
price. Additional scenarios assumed no tipping fee for the co-digestate to evaluate the
effect of increased biogas alone on the economics. Two levels of co-digestion were
considered for this paper; a lower level where 10% of the volatile solids are from co-
digestion and a higher level where the 25% are from co-digestion (the condition of no
co-digestion was also examined).

Varying Capital Costs

The capital cost of digester systems is generally cited as a major roadblock to their
adoption on farms both large and particularly small (Gloy and Dressler, 2010).
Economies of scale favor larger projects both through reduced per cow expenses and
the ability to devote specialized labor to operation and maintenance.

To examine the cost of capital costs on small farm digester feasibility two levels of
capital cost were investigated for this paper. Capital costs were expressed on a per
cow basis and were assumed to include both the construction of the digester and
purchase/installation of the engine generator. Many analyses consider the benefits of
using separated solids for bedding; however this option was left out of the analysis for
this paper as solids separated from raw manure can also be used for bedding. For the
analysis it was assumed that the installed cost of the generator set was $1,000 per kW
which is an approximate rule of thumb (Weeks, 2012.) The balance of the capital cost
was assumed to consist of the digester and other expenses associated with the project
and to have a lifespan of 20 years. The engine generator set costs were depreciated
over a 7-year lifespan. Lost opportunity cost was assumed to be 8%.

The per cow capital costs examined for this paper were $1,500, and $3,000 per cow.
$1,500 per cow represents a low cost for a small farm digester with an engine-generator
set and would most likely require some subsidization. A higher value is $3,000 per cow
for small farm systems with an engine-generator set and mixing. These system cost
levels were based on reviewing the project costs of the limited number of small farm
digesters both with and without cogeneration of power, and were selected to span the
likely average capital cost of a small farm AD project.

Maintenance Costs

Maintenance costs were estimated based both on the quantity of power generated,
as well as a fixed percentage of the initial capital cost. For the purposes of this analysis
it was assumed that no gas cleanup equipment was installed to reduce the
concentration of H$_2$S in the biogas. High concentrations of H$_2$S shorten the lifespan of
biogas equipment and as such the maintenance costs are higher. Maintenance costs
have been estimated to be in the range of $0.015 to 0.020 per kWh generated (Martin
2009). Assuming no gas cleanup, $0.02 per kWh was used.

General maintenance on the digester pumps/mixers and other equipment was
estimated as 5% of the initial capital cost.
RESULTS

This analysis was focused on small farms and determining what level of benefit pricing would allow them to cover the substantial capital cost investment. To answer this question a total annual cost/benefit economic analysis was performed. The sum of the annual cost savings and revenue were subtracted from the total costs to own and operate the system expressed on an annual basis. A positive value means that the system is a net economic liability to own and operate while a negative value means that the system probably is an economic benefit, but further analysis would be needed to determine its true economic benefit to the farm.

Thirty milking cows was selected as the lower limit to this analysis. The manure from a herd of this size could potentially power a 10 kW engine generator set with co-digestion. A generator set of this size designed to run on biogas may not be currently available (such systems typically start at 20kW) however, some smaller farms have utilized modified internal combustion engines to run on the biogas they produce. The upper limit for this analysis was set at 250 milking cows.

The various scenarios of benefit pricing values and initial capital cost level were input into the model, and the number of cows necessary to offset the costs from the benefits was solved for (Tables 1 and 2.) A negative value (shown in parenthesis) indicates the system is likely an economic benefit to the farm. All values are expressed on a per cow basis.

In many cases there was no solution in which the combination of benefit pricing would offset the capital and maintenance costs (this was the case in most of the scenarios with a capital cost of $3,000 per cow) and so only the scenarios with a neutral or net benefit are shown in the tables. Similarly under some scenarios even the lower limit farm size of 30 milking cows was capable of offsetting the costs.

At a per cow capital cost of $3,000 it is clear that all three benefit strategies play an important part of offsetting the capital costs. Under no scenario at this capital level was a surplus power sale price of $0.05 per kWh feasible. Only at a level of $0.16 or $0.31 per kWh did any scenario break even. Further, only scenarios that also featured a tipping fee and/or some level of Carbon Credit valuation showed a neutral or net benefit. The best options at this capital level are high usage of co-digestion (25% of the VS from co-digestables) coupled with a tipping fee. Including a carbon credit valuation dramatically reduced the size of farm necessary to break even.
Table 1. Annual cost/benefit analysis of benefit pricing scenarios resulting in a net benefit with an initial capital cost of $1,500 per cow.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cow #</th>
<th>Yearly per Cow Expenses</th>
<th>Yearly per Cow Benefits</th>
<th>Total Annual Cost/ Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Capital</td>
<td>Maint</td>
<td>Electricity</td>
</tr>
<tr>
<td>$0.31/kWh, no CC, no CD</td>
<td>254</td>
<td>$122</td>
<td>$14</td>
<td>$77</td>
</tr>
<tr>
<td>$0.31/kWh, $10 CC, no CD</td>
<td>91</td>
<td>$122</td>
<td>$14</td>
<td>$87</td>
</tr>
<tr>
<td>$0.31/kWh, $20 CC, no CD</td>
<td>53</td>
<td>$122</td>
<td>$14</td>
<td>$96</td>
</tr>
<tr>
<td>$0.05/kWh, no CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.16/kWh, no CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.31/kWh, no CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.05/kWh, $10 CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.16/kWh, $10 CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.31/kWh, $10 CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.05/kWh, $20 CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.16/kWh, $20 CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.31/kWh, $20 CC, 10% VS $0.05 TF</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
<td>$106</td>
</tr>
<tr>
<td>$0.05/kWh, no CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.16/kWh, no CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.31/kWh, no CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.05/kWh, $10 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.16/kWh, $10 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.31/kWh, $10 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.05/kWh, $20 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.16/kWh, $20 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.31/kWh, $20 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.05/kWh, no CC, 10% VS no TF</td>
<td>76</td>
<td>$123</td>
<td>$16</td>
<td>$90</td>
</tr>
<tr>
<td>$0.16/kWh, no CC, 10% VS no TF</td>
<td>100</td>
<td>$123</td>
<td>$16</td>
<td>$85</td>
</tr>
<tr>
<td>$0.31/kWh, no CC, 10% VS no TF</td>
<td>49</td>
<td>$123</td>
<td>$16</td>
<td>$100</td>
</tr>
<tr>
<td>$0.16/kWh, $20 CC, 10% VS no TF</td>
<td>32</td>
<td>$123</td>
<td>$16</td>
<td>$105</td>
</tr>
<tr>
<td>$0.31/kWh, $20 CC, 10% VS no TF</td>
<td>32</td>
<td>$123</td>
<td>$16</td>
<td>$105</td>
</tr>
<tr>
<td>$0.16/kWh, no CC, 25% VS no TF</td>
<td>129</td>
<td>$125</td>
<td>$18</td>
<td>$82</td>
</tr>
<tr>
<td>$0.31/kWh, no CC, 25% VS no TF</td>
<td>37</td>
<td>$125</td>
<td>$18</td>
<td>$110</td>
</tr>
<tr>
<td>$0.16/kWh, $10 CC, 25% VS no TF</td>
<td>31</td>
<td>$125</td>
<td>$18</td>
<td>$116</td>
</tr>
<tr>
<td>$0.31/kWh, $10 CC, 25% VS no TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.05/kWh, $20 CC, 25% VS no TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.16/kWh, $20 CC, 25% VS no TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
<tr>
<td>$0.31/kWh, $20 CC, 25% VS no TF</td>
<td>30</td>
<td>$125</td>
<td>$18</td>
<td>$118</td>
</tr>
</tbody>
</table>

* CC = Carbon Credit, TF = Tipping Fee
Table 2. Annual Cost/Benefit analysis of Benefit Pricing Scenarios Resulting in a Net
Benefit with an Initial Capital Cost of $3,000 per cow.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Cow #</th>
<th>Yearly per Cow Expenses</th>
<th>Yearly per Cow Benefits</th>
<th>Total Annual Cost/Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.31/kWh, $20 CC, 10% VS $0.05 TF</td>
<td>235</td>
<td>$236 $16</td>
<td>$77 $88 $42 $44</td>
<td>($0)</td>
</tr>
<tr>
<td>$0.16/kWh, no CC, 25% VS $0.05 TF</td>
<td>221</td>
<td>$237 $18</td>
<td>$78 $68 $0 $110</td>
<td>($0)</td>
</tr>
<tr>
<td>$0.31/kWh, no CC, 25% VS $0.05 TF</td>
<td>39</td>
<td>$237 $18</td>
<td>$107 $40 $0 $110</td>
<td>($2)</td>
</tr>
<tr>
<td>$0.16/kWh, $10 CC, 25% VS $0.05 TF</td>
<td>34</td>
<td>$237 $18</td>
<td>$112 $13 $21 $110</td>
<td>($0)</td>
</tr>
<tr>
<td>$0.31/kWh, $10 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$237 $18</td>
<td>$118 $6 $21 $110</td>
<td>($0)</td>
</tr>
<tr>
<td>$0.16/kWh, $20 CC, 25% VS $0.05 TF</td>
<td>30</td>
<td>$237 $18</td>
<td>$118 $3 $42 $110</td>
<td>($18)</td>
</tr>
<tr>
<td>$0.31/kWh, $20 CC, 25% VS no TF</td>
<td>254</td>
<td>$237 $18</td>
<td>$77 $134 $42 $0</td>
<td>$2</td>
</tr>
</tbody>
</table>

* CC = Carbon Credit, TF = Tipping Fee

The situation is quite different when the capital cost per cow is $1,500. Many more
scenarios are break even. Under this cost regime every scenario that featured
$0.31/kWh power broke even. Low (and high) power sale price scenarios with other
benefits often broke even at the lowest farm size, but this is due to the fact that at this
farm size there is no surplus power to sell (the farm has to purchase additional power)
and so the sale price does not come into play. This illustrates the point that selling to
the grid is often not enough to justify a digester and some other means of taking
advantage of the surplus energy needs to be employed.

Another clear result from this analysis is the importance of capital cost. The cost of
carrying a large initial capital investment is a significant challenge, particularly with a
small farm system. To examine the effect of how the initial capital cost affects the net
benefit of the systems, the initial capital cost was varied from $500 to $3,000 per cow
with optimistically achievable values for Feed in Tariffs, Carbon Credit pricing, and
Tipping fees (Table 3) as well as the scenario of no feed in tariffs, or carbon credit
market, with surplus power sold at the price it would be purchased for ($0.1 per kWh),
and moderate co-digestion (%10 VS from cheese whey) with a tipping fee of $0.05 per
gallon (Table 4).

The results shown in Tables 3 and 4 indicate that keeping capital costs below
$1,500 is key to achieving a net benefit as at this level even the smallest farms almost
showed a net benefit (net cost of $2 per cow per year) with very attainable tipping fee
prices. The results also show that the benefit of tipping fees and reduced capital alone
is more important for small farms than a feed in tariff, as for all the scenarios with a net
benefit, no surplus power is sold to the grid (so feed in tariff rates do not come into
play.) The avoided cost of purchased power is however a major advantage, indicating
that small farms would benefit most from sizing an engine generator set to meet their
net on farm needs, rather than aiming to sell power to the grid.
Table 3. Annual Cost/Benefit analysis of Capital Cost effect with Benefit values of $0.16 per kWh for power, $10 per tonne Carbon Credit, and co-digestion with 10% of the VS from off-farm cheese whey and a tipping fee of $0.05 per gallon.

<table>
<thead>
<tr>
<th>Capital Cost ($/cow)</th>
<th>Cow #</th>
<th>Yearly per Cow Expenses</th>
<th>Yearly per Cow Benefits</th>
<th>Total Annual Cost/Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Yearly per Cow</td>
<td>Yearly per Cow Benefits</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capital</td>
<td>Maint</td>
<td>Avoided cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$48</td>
<td>$16</td>
<td>$106 ($12)</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>30</td>
<td>$86</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>1,500</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>2,000</td>
<td>57</td>
<td>$161</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>254</td>
<td>$198</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>3,000</td>
<td>254</td>
<td>$236</td>
<td>$16</td>
</tr>
</tbody>
</table>

* CC = Carbon Credit, TF = Tipping Fee

Table 4. Annual Cost/Benefit analysis of Capital Cost effect with Benefit values of $0.10 per kWh for power, $0 per tonne Carbon Credit, and co-digestion with 10% of the VS from off-farm cheese whey and a tipping fee of $0.05 per gallon.

<table>
<thead>
<tr>
<th>Capital Cost ($/cow)</th>
<th>Cow #</th>
<th>Yearly per Cow Expenses</th>
<th>Yearly per Cow Benefits</th>
<th>Total Annual Cost/Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Yearly per Cow</td>
<td>Yearly per Cow Benefits</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Expenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Capital</td>
<td>Maint</td>
<td>Avoided cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$48</td>
<td>$16</td>
<td>$106 ($12)</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>30</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1,000</td>
<td>30</td>
<td>$86</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>1,500</td>
<td>30</td>
<td>$123</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>2,000</td>
<td>254</td>
<td>$161</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>2,500</td>
<td>254</td>
<td>$198</td>
<td>$16</td>
</tr>
<tr>
<td></td>
<td>3,000</td>
<td>254</td>
<td>$236</td>
<td>$16</td>
</tr>
</tbody>
</table>

* CC = Carbon Credit, TF = Tipping Fee

Grant programs to reduce the burden and risk to small (and large) farms are one option that has been used. The effect of grant support on the annual cost/benefit, for a 125 cow dairy is presented in Table 5. The capital costs for a 125 cow dairy (125 cows represents the approximate average size herd in the US in 2010) were estimated by averaging the capital costs for three existing small farm anaerobic digesters with associated engine-generator sets (Klavon 2011). The percentage of the total capital cost of $2,700 per cow paid by the farm was then varied from 100% down to 30% and the annual cost/benefit calculated. Benefits assumed surplus power was sold at the purchase rate of $0.10 per kWh, no Carbon Credit revenues, and tipping fees of $0.05 per gallon for cheese whey making up 10% of the Volatile solids digested.
Table 5. Annual Cost/Benefit Analysis of the Effect of % Grant Support with Benefit Values of $0.10 per kWh for power, $0 per tonne Carbon Credit, and Co-Digestion with 10% of the VS from off-farm cheese whey and a tipping fee of $0.05 per gallon, for a 125 cow dairy farm with a Capital Cost of $2,700 per cow.

<table>
<thead>
<tr>
<th>Capital Cost % Borne by Farm</th>
<th>Cow #</th>
<th>Yearly per Cow Expenses</th>
<th>Yearly per Cow Benefits</th>
<th>Total Annual Cost/Benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Capital</td>
<td>Maint</td>
<td>Electricity</td>
</tr>
<tr>
<td>100% ($2,700 per cow)</td>
<td>125</td>
<td>$213</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>90% ($2,430 per cow)</td>
<td>125</td>
<td>$193</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>80% ($2,160 per cow)</td>
<td>125</td>
<td>$173</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>70% ($1,890 per cow)</td>
<td>125</td>
<td>$153</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>60% ($1,620 per cow)</td>
<td>125</td>
<td>$132</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>50% ($1,350 per cow)</td>
<td>125</td>
<td>$112</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>40% ($1,080 per cow)</td>
<td>125</td>
<td>$92</td>
<td>$16</td>
<td>$82</td>
</tr>
<tr>
<td>30% ($810 per cow)</td>
<td>125</td>
<td>$72</td>
<td>$16</td>
<td>$82</td>
</tr>
</tbody>
</table>

*TF = Tipping Fee

The calculations show that with a grant covering 40% of the capital cost, the project is probably an economic benefit. A 40% grant on a total capital cost of $2,700 per cow and 125 cows, is $135,000.

DISCUSSION

It is clear from the results that financing small farm AD can be difficult depending on the incentive programs available to a farmer. Even with relatively generous programs it may take several benefit programs in concert to justify AD at the small farm level. It is also clear that avoided costs of purchasing power is a significant benefit, and that the sale of surplus power even with a generous feed in tariff may not be worth it.

The initial capital cost of digester systems is a significant hurdle to their further adoption and strategic policy will need to be enacted to allow small farms to participate in AD. Keeping the capital costs below $1,500 per cow whether through grant programs or improved low cost designs would likely be preferable to relying on feed in tariff and carbon credit programs where the benefits pricing may be variable or short lived.

Another consideration when deciding on whether to pursue AD on a small farm, is the valuation of non-monetary benefits such as improved flexibility in field application and odor reduction. These can be very significant reasons for installing and AD system particularly if a small farm is located near encroaching residential areas. The net cost of an AD system could be a means of assigning value to odor reduction.

The model will continue to be developed to answer further questions, and increase the scope of the analyses it can be used for. The model will be expanded to provide an estimate of the AD system capital costs based on a line item estimate of costs for digester components and construction and engine generator pricing. This estimator will
include actual costs and sizes of equipment and make use of average site development, engineering and labor costs developed from similarly sized projects. Though every project situation will be different, an approximate estimation based on average values will be of use in determining how policy decisions could affect the adoption of small farm AD.

Similarly, for power production estimation, actual available generator sizes (and prices) will be used. Any excess biogas produced beyond what that size generator can use (and the next size up could use) would then be flared and not used for power generation. This technique will more closely match real world production of power from biogas and the associated costs of doing so.

REFERENCES

REDUCING RISK OF ENTRY INTO CONFINED SPACE MANURE STORAGES

D. J. Murphy, H. B. Manbeck, J. S. Steel
Department of Agricultural & Biological Engineering
Penn State University, University Park, PA

INTRODUCTION

This project developed computational fluid dynamics protocols to simulate removal of noxious contaminant gases, by forced ventilation, from solid and slotted floor covered confined space, on-farm manure storage tanks. These simulation protocols were then used to determine ventilation requirements (air exchange rates, fan and air outlet locations, and operation times) to reduce concentrations of contaminant gases to levels below gas specific TLVs for human entry. These ventilation requirements are applicable for a wide range of manure storage facilities typical of those on farms throughout the U.S. Subsequently, an international engineering safety standard, Ventilating Manure Storages to Reduce Entry Risk, was written and approved by the American Society of Agricultural and Biological Engineers (ASABE) and the American National Standards Institute (ANSI). Finally, an educational program was developed to inform extension educators, engineers, regulators, and farmers about the standard and how to use its provisions to reduce risk when entering confined space manure storage tanks. The educational program included: (1) A large scale trailer mounted demonstration model which can be used to identify the occupational hazards associated with entry into confined space manure tanks and facilities and explain how to mitigate the hazards with proper ventilation; (2) High quality videos of educational programs, using the demonstration model, to show how to properly ventilate solid and slotted covered confined-space manure storages; (3) Comprehensive instructional manuals for “education extenders” to use the ventilation demonstration unit in the field; (4) Four Fact Sheets covering Confined Space Manure Storage Hazards, Monitoring Manure Gases, Ventilating Storages Prior to Entry, and Emergency Rescue Procedures for Confined Space Manure Storages; and (5) A website, www.manurepitsafety.psu.edu, which contains the safety standard, educational videos, and fact sheets.

THE RESEARCH PROJECT

The project team conducted research work that spanned nearly eight years. This work has been published in a series of five journal articles (Pesce, et al., 2008 ; Zhao, et al., 2007a; Zhao, et al., 2007b ; Zhao, et al., 2008a; Zhao, et al. 2008b).

In experimental studies hydrogen sulfide (H₂S) was used as an indicator gas to investigate the effectiveness of forced-ventilation strategies for eliminating the toxic and oxygen-deficient atmospheres in the confined-space manure pits. Typical H₂S concentration reduction curves during forced-air ventilation were identified in a rectangular manure tank. Based on the experimental tests conducted in the research, the most promising candidate ventilation strategies were identified for the studied rectangular confined-space manure tank with solid, totally slotted and partially slotted
covers. In addition, based on results of experimental tests, a field-based database was developed for the validation of computational fluid dynamics modeling protocols (Pesce et al., 2008). As an important input parameter of the CFD modeling protocols, manure gas emissions were measured experimentally using the same rectangular tank. The influencing factors on gas emissions were identified as well (Zhao et al., 2007a).

Computational fluid dynamics (CFD) modeling protocols to simulate H$_2$S removal from fan-ventilated confined-space manure storages were developed and validated. The CFD model was used to conduct the simulations of evacuating H$_2$S during forced ventilation for the best ventilation strategies identified in the work by Pesce et al. (2008) for a typical rectangular on-farm manure tank with three cover types (i.e., solid, totally slotted, and partially slotted) and the validation of the CFD modeling protocols based on comparisons between simulated and measured H$_2$S evacuation times. Simulated and measured evacuation times within the confined-space manure storage facilities evaluated agreed within 10% at all measuring locations except those immediately adjacent to the ventilation fan jet for all three cover types for both high (5 AC min$^{-1}$) and low (3 AC min$^{-1}$) air exchange (AC) rates. Corresponding evacuation times agreed to within 15% for all cover types and air exchange rates in the high-velocity gradient region of the ventilation fan jet. These results demonstrated that the CFD modeling protocols developed satisfactorily predict the gas concentration decay during forced ventilation in confined-space manure pits (Zhao et al., 2007b, 2007c). The validated CFD modeling protocols were applied to conduct simulations for identifying manure gas evacuation times and oxygen level recovery in the confined-space manure pits with different footprints. The factors (i.e., air exchange rate, manure gas emission rates, gas initial concentration) influencing the gas evacuation time were identified (Zhao et al., 2008a, 2008b).

An extensive literature review was conducted to identify the highest concentration levels and emission rates documented for NH$_3$, H$_2$S, CH$_4$, and CO$_2$ during typical manure operations. The highest documented concentration levels of NH$_3$, H$_2$S, CH$_4$, and CO$_2$ are, respectively, 270 ppm, 10,000 ppm, 700,000 ppm, and 450,000 ppm. For emission rates, the highest emission rates of NH$_3$, H$_2$S, CH$_4$, and CO$_2$ identified from the literature review were 0.71, 0.48, 2.35, and 7.25 mg s$^{-1}$ m$^{-2}$, respectively (Zhao et al., 2008b). Additionally, a study on the mechanism of manure gas based on the literature review shows the time taken to evacuate H$_2$S and CO$_2$ from associated high concentration levels to the safe exposure limits is longer than the time for evacuating NH$_3$ and CH$_4$ from their associated high concentration levels to safe levels. As a result, the mixture of H$_2$S and CO$_2$ may be used to represent the manure gases mixture in simulations to identify maximum evacuation times for mechanically ventilated confined-space manure pits.

CFD simulations were conducted for the manure pits with the geometries and sizes representing a majority portion of the confined-space, on-farm manure pits in the US and Canada based on an informal survey of USDA-NRCS (Natural Resource Conservation Service) waste management engineers. The simulation results show gas evacuation times or oxygen replenishment times for a wide range of manure pit
Several conclusions have been drawn from this research:

- A non-linear relationship was identified between gas initial concentration and evacuation time.
- Non-significant difference of evacuation time was identified when the inter-contamination ratio was higher than 0.40.
- The ventilation time required to replenish oxygen from 0 % to 20.5 %, by volume, was almost (difference < 5%) the same time for confined space manure pits initially filled with either H₂S, CH₄, or CO₂.
- The time to evacuate H₂S from 10,000 ppm to OSHA PEL (10 ppm) and CH₄ from 700,000 ppm (70 % by volume) to TLV (1000 ppm) was nearly the same (difference < 5%).
- There was no significant difference (<5%) of evacuation times for the confined airspace filled with a single gas or with a gas mixture.
- Ventilation time required to remove H₂S from maximum initial levels to PEL (10 ppm) was greater than or equal to time to remove other gases from maximum initial levels to their respective PELs or TLVs.
- Ventilation time required to replenish O₂ to ≥20 % by volume is less than time required to evacuate H₂S from 10,000 to 10 ppm.

The results of these simulations were used to formulate the ventilation protocols and specifications defined in the consensus engineering safety standard, ANSI/ASABE S607 “Ventilating Manure Storages to Reduce Entry Risk”.

SAFETY STANDARD DEVELOPMENT

The first engineering standard to address specific ventilation strategies, including fan location, outlet location, air exchange rates, and ventilation times required to reduce contaminant gases in confined space manure storages to below ACGIH defined TLVs for hydrogen sulfide, carbon dioxide, and methane, and to replenish oxygen levels from 0% to 20 % by volume at sea level has been developed (ASABE, 2010). The standards development project followed the protocols outlined by the American National Standards Institute (ANSI) and was managed by the Standards Department of the American Society of Agricultural and Biological Engineers (ASABE), an ANSI certified standards provider. ASABE assured that all appropriate standards writing and approval protocols were followed for a consensus ANSI standard. In brief the protocols were:

- An ASABE standards development committee, which had wide representation including, designers, researchers, users, and regulators, was formed.
- The committee developed a draft standard for comment and balloting.
- The draft standard was approved by the committee only after at least 50% of the committee responded, at least 75% of the responders voted to approve the draft
standard, and all comments from approval and disapproval ballots were addressed to the satisfaction of the critics and the entire committee.

- Once committee approval was received, the ASABE Standards Committee confirmed that all ANSI consensus standard development protocols were followed and forwarded to ANSI for approval.
- ANSI reviewed and approved S607 as a consensus engineering standard.
- ANSI/ASABE S607, Ventilating Manure Storages to Reduce Entry Risk was published by ASABE in October, 2010.

SAFETY EDUCATION PROGRAM DEVELOPMENT

The research team has developed an outreach educational program, the overall aims of which are to demonstrate the hazards associated with entry into confined-space manure storages and to demonstrate how proper ventilation mitigates the hazards. The education program includes fact sheets, workbooks, educational videos and a safety demonstration model on mitigating hazards associated with manure pit entry events. The education program is flexible and can be tailored to various audiences including farmers, regulators, builders, or designers (Tillapaugh, et al., 2010a, 2010b, 2010c).

The educational program is based on several goals which are aimed at reducing risks when entering confined-space manure storages. Specific educational program goals include:

- Explaining hazards and risks associated with confined-space manure storages, and ways to eliminate or minimize those hazards and risks.
- Providing instructions for purchasing, using and maintaining gas measurement equipment.
- Presenting ventilation design details and requirements for existing and planned facilities.
- Teaching proper procedures for planned entry and responding to emergency situations.

There are several target audiences for the educational program. These include:

- Engineers/Designers/Builders/Inspectors - Presentations for this group are focused on understanding and using calculations and recommendations for forced air ventilation systems described in ANSI/ASABE Standard S607 (Ventilating Manure Storages to Reduce Entry Risk).
- Farmers/Operators/Users/Insurance - Presentations for this group are focused on understanding, identifying and minimizing hazards; employee/worker training; understanding and using gas detection equipment; planned entry procedures; and responding to emergency situations.
- Educators - An Instructor Guidebook has been developed for cooperative extension and other educators to teach confined-space manure storage hazards and safety practices to farmers, employees, family members, manure haulers, insurance personnel and other such groups. The Instructor Guidebook includes all information developed for the other target groups.
• Emergency Services - Presentations for this group focus on procedures for safely responding to emergencies involving manure storages.

Several educational tools are used to target audience these groups and cover the wide range of topics necessary for reducing risk when entering confined-space manure storages. A portable scale model demonstration unit representative of a confined-space manure facility has been constructed. Agricultural and Biological Engineering extension publications have been created and serve as reference materials for targeted audiences. A workshop has been developed and presented to teach engineers and building planners how to design ventilation systems for manure pits to reduce entry risk. Program presentations utilize the scale model demonstration unit, a PowerPoint slide deck, printed reference materials and web-based video presentations.

**Scale Model Demonstrations.** The scale model demonstration has been designed to illustrate and reinforce toxic gas hazards and proper ventilation of confined-space manure storages. An Instructor’s Manual guides demonstrators though set up and tear down of the demonstrations, contains demonstration scripts, and contains the educational fact sheets and other handouts (Tillapaugh et al., 2011) The unit is built inside a seven foot tall by fourteen foot long enclosed trailer. Spectators watch the demonstrations through a four foot tall by twelve foot long hinged door in the side of the trailer. A PowerPoint slide presentation is used to help communicate important points. The scale model manure storage inside the trailer is constructed with a removable animal housing structure. With the barn removed, plastic floor panels can be exchanged to simulate storages with slotted or solid covers. Ventilation fans are installed at desired locations in the manure storage as well as in the barn structure (Figure 1).

Figure 1. Photograph of scale model demonstration unit

![Scale Model Demonstration Unit](image)

During presentations, the manure storage is flooded with carbon dioxide and fog to simulate and visualize accumulated toxic manure gases. Gas concentration measurements are displayed on large LED displays for the audience. A mannequin is
used to show the consequences of entering the manure facility without proper ventilation. Appropriate ventilation techniques are demonstrated. During ventilation demonstrations, audience members see gas concentrations decrease on the LED displays as the toxic gases are evacuated by forced ventilation. Simulations of manure pit ventilation are shown on a 46 inch LED television screen to help audience members visualize air flows and hazard reduction. These animations were created with SolidWorks Flow Simulation software and use color scales to show changing gas concentrations. A detailed set of instructions, complete with demonstration videos on CDs, for multiple demonstrations using the scale model have been developed.

**Extension Publications.** In an effort to organize educational program subject matter, extension publications for the targeted audiences have been developed. These extension publications are:

- **Confined-space Manure Storage Hazard.** This publication (Steel et al., 2011a) targets any person seeking general manure storage safety information. Topics covered include manure storages and confined-spaces, monitoring gas levels, positive pressure ventilation systems, regulatory issues, and planned entry into confined-space manure storage.

- **Confined-Space Manure Gas Monitoring.** This publication (Steel et al., 2011b) targets those seeking information for selecting, using, maintaining, and calibrating manure gas detecting and testing equipment. This includes the benefits of gas measurements for calculating required ventilation times, and personnel safety. Comparisons of detector tube equipment, electronic sensors and multiple gas detectors are also given.

- **Confined-Space Manure Storage Ventilation System Design.** This publication (Manbeck et al., 2011) targets designers, contractors, and inspectors. Details are based on the ANSI/ASABE S607 standard and address techniques to calculate ventilation requirements based on storage dimensions and selection of appropriate fans. These ventilation calculations are valid for designing ventilation in both existing and planned storages, as well as portable and permanently installed systems.

- **Confined-space Manure Storage Emergencies.** This publication (Hill et al., 2011) targets farmers, employees, family members, manure haulers, and emergency response personnel. The importance of using confined-space entry best safety practices to rescue victims in manure pits is explained.

**Video Presentations.** Two professional level video presentations of the confined-space manure storage ventilation demonstrations, with voice-over narration and graphics, have been developed. One video presentation addresses solid covered storages and is 24 minutes (Steel et al., 2011c). The other video covers slotted floor storages and has three parts: a) high initial gas concentration in the storage; low initial gas concentration in the storage; and c) low level of contaminant gas in the ducted ventilation air supply (Steel et al., 2011d). This video is 27 minutes long.

**Website.** A dedicated website ([www.manurepitsafety.psu.edu](http://www.manurepitsafety.psu.edu)) has been developed (Murphy et al., 2011). The website contains all of the educational information including
the video presentations, the ANSI/ASABE S607 standard, the extension publications, and links to other relevant websites. The website features an automated pre and post survey that allows us to measure impact, whenever a person visits each of the fact sheet and video sites. This allows us to understand who may be using the site, the value they assign to our educational products, and suggestions for improvement.

FUTURE WORK

Evaluation of the education program is on-going. We are in the process of conducting a baseline survey of a sample of dairy and swine farmers in several states to assess their current knowledge of manure storage hazards, current safety practices, and the ability to mitigate the hazards with properly designed and installed ventilation systems. A follow-up survey 3 to 5 years from now is anticipated to assess the effectiveness of the developed educational program to induce farmers to adopt the manure pit ventilation interventions developed in this research and development project.

A currently funded project is titled On-Line Tools for Designing Ventilation Systems to Reduce Manure Pit Entry Risk. This 5-yr project began September 1, 2011 and has as a goal the development of an on-line, web-based, computer-aided-design tool to simulate the performance of ventilation systems for removing noxious gases and to replenish oxygen prior to entry. We will validate the design tool against previously published field and simulation results. The developed on-line tool will be alpha- and beta-tested by two nationwide pools of practicing agricultural facilities planners prior to launching it on the web. A training program to teach planners how to properly use the developed design tool will be developed and delivered in webinar, on-line university and live workshop formats. A small sample of practicing facilities planners will evaluate the training session. The training program will subsequently be revised based on the critiques prior to launching the training sessions on the web. Finally, we will write and submit proposed revisions to the current consensus safety standard (ANSI/ASABE S607), Ventilating Manure Storages to Reduce Entry Risk, to include the developed on-line tool for specifying ventilation requirements for on-farm, confined-space manure storage tanks.

REFERENCES


Manbeck, H. B., D. J. Murphy and J. S. Steel. 2011. Confined space manure storage ventilation systems. E53. The Pennsylvania State University, College of Agricultural
Sciences, Department of Agricultural and Biological Engineers, University Park, PA. 4 pp.


Steel, J. S, D. J. Murphy and H. B. Manbeck. 2011b. Confined space manure gas monitoring. E52. The Pennsylvania State University, College of Agricultural Sciences, Department of Agricultural and Biological Engineers, University Park, PA. 5 pp.


Steel J. S., Murphy D. J., Manbeck H. B. 2011d. Video: Reducing Entry Risk - Slotted Floor Storage. 27 minutes. Agricultural Safety & Health Program, Department of


MONITORING OF ANAEROBIC DIGESTION PROCESS TO OPTIMIZE PERFORMANCE AND PREVENT SYSTEM FAILURE

R. A. Labatut and C. A. Gooch
Department of Biological and Environmental Engineering
Cornell University, Ithaca, NY

ABSTRACT

Although anaerobic digestion (AD) is a rather mature technology, poor anaerobic digester performance and system failure are still frequent around the world. Most of these problems occur as a result of inadequate operational management and lack of process control. Digester upsets are usually temporary, and in most cases can be solved by taking simple measures, such as adjusting the influent co-digestion ratio and/or the frequency of influent pumping. If prompt and adequate measures are not taken, the digester operation will eventually fail. Recovery of a digester can take several months, during which, energy generation and waste treatment are not possible, resulting in increased operational costs for the farm. The importance of well-trained and qualified personnel to operate AD systems and properly control and monitor the process is essential, not only to prevent digester upsets and potential system failures, but also to ensure efficient organic waste stabilization and constant and stable biogas production. Analytical laboratories were installed on selected farm-based anaerobic digester systems in NYS to regularly monitor key process parameters and to evaluate performance and stability of the operations. Preliminary results of the monitoring confirmed that analytical labs are essential to detect process upsets more efficiently, and to identify and correct the source of the problem before system failure occurs.

INTRODUCTION

Anaerobic digestion (AD) systems are extremely sensitive to changes in environmental variables. Correct design and control of the system’s parameters are essential to maximize process efficiency, increase stability, and prevent system failure. Up to 1998, failure rates of on-farm anaerobic digesters in the U.S. were at a staggering 70% and 63% for complete-mixed and plug-flow reactors, respectively (Lusk, 1998). Today, with improved system design, better construction practices, and an increased number of qualified companies to develop AD projects, the probability of long-term system failure is likely to be somewhat lower. Nevertheless, underperformance and short-term failure are still a common problem in on-farm AD systems across the U.S. Last year, three on-farm co-digestion operations in the Midwest (MI and OH) receiving thick stillage, a by-product of the ethanol distillation process, failed and presented

1The performance of the anaerobic digester process decreases to a point where the entire operation, including combined heat and power (CHP) unit, needs to be shut down for an undetermined amount of time, which can last from a few days, or weeks (short-term), to several months (long-term)

2The CHP unit operates below its nominal power capacity
depressed biogas production for a period of two to three weeks. Although many times not reported, in New York State the same problems are seen.

THE CASE OF NEW YORK STATE

In a year-long study conducted between 2008 and 2009, seven of the 22 on-farm AD systems currently in operation in New York State were monitored (Gooch et al., 2011). The average online efficiency\(^3\), which represents the percent of time the CHP system was in operation during this same period, was found to be as high as 88% across the seven AD operations (Figure 1). However, the average capacity factor\(^3\), which indicates the ratio of electrical energy produced by the combined heat and power (CHP) unit relative to its potential capacity, was found to be 0.57 across the same AD operations (Figure 1). This means that, even though the CHP units were running most of the time, the power output was only slightly higher than half of their potential capacity.

Figure 1. Average capacity factor and online efficiency of seven on-farm anaerobic digestion systems in New York State obtained from a 12- to 15-month operational period (Gooch et al., 2011)

Low CHP performance could be caused by several conditions:
1. Decreased/unstable biogas production
2. Decreased/unstable biomethane content in biogas
3. Downtime of CHP unit due to AD system failure
4. Decreased efficiency of CHP system
5. Over-dimensioning of CHP system
6. Downtime of both AD and CHP systems due to maintenance

\(^3\) See Appendix for definition and formulae
However, conditions related to the AD system performance (i.e., 1 – 3), rather than the CHP unit in itself (i.e., 4 and 5), are likely to be the main causes of low CHP performance. Indeed, episodes of AD system failure and fairly unstable biogas production were observed throughout the monitoring period in the AD operations with the lowest capacity factors (Figure 2). Such behavior is attributed to digestion process upsets, which are usually the result of inadequate operational management and poor process oversight. This is not surprising, considering that nearly all active on-farm AD systems in New York State are operated by a farm worker, who usually has no previous experience or training in anaerobic digestion. Furthermore, this person has to operate, maintain, and monitor both AD and CHP systems in addition to his/her daily farm-related activities.

Figure 2. Biogas production (ft³/min) of five on-farm anaerobic digestion systems in New York State throughout a 12- to 15-month operational period (Gooch et al., 2011)

KEY PROCESS INDICATORS TO PREVENT DIGESTER UPSETS

The anaerobic digestion of complex organic matter is a highly dynamic, multi-step process, where physicochemical and biochemical reactions take place in sequential and parallel ways. The main biochemical conversion pathways of anaerobic digestion are depicted in Figure 3. The delicate balance between such reactants and products is what primarily determines how stable and efficient the anaerobic digestion process is. When the concentration of a particular intermediate reaches the homeostatic equilibrium of certain organism or group of organisms, such balance is disrupted. Intermediate products further accumulate and the digestion process becomes upset. Substrate stabilization and biogas production progressively decrease, and eventually the entire system fails.
To prevent process upsets, proper system configuration and a rigorous control of the operational parameters are critical to maintain environmental variables steady and within the optimal ranges. Because of their central role in methanogenesis, propionate, acetate and hydrogen are probably the most important intermediate products of anaerobic digestion, and therefore the key process indicators to monitor in the system. About 64% of the methane produced during anaerobic digestion comes from acetate, while the remaining 36% comes from hydrogen (Batstone et al., 2002). Propionate is an important precursor of acetate and hydrogen – approximately 30% of the electron flow directly related to methane production goes through propionate (Jeris & McCarty, 1965; McCarty & Smith, 1986). In addition, propionate, acetate and hydrogen are more sensitive to process upsets than biogas production, methane content, or pH. The most important process parameters to monitor in AD systems are described below.

**Volatile fatty acids (VFA)** – As a process performance indicator, VFA concentration is probably the most sensitive parameter to monitor. They can be inhibitory of the digestion process which can lead to system failure. VFAAs encompass a group of six compounds, i.e., acetic acid/acetate, propionic acid/propionate, butyric acid/butyrate,
valeric acid/valerate, caproic acid/caproate, and enanthic acid/enanthate, from which acetate is predominant. In a correctly designed and well-operated digester, the concentration of total VFA is typically below 500 mg/L as acetic acid. However, if the digester is undersized for the organic load this concentration can be higher. At VFA concentrations over 1,500 – 2,000 mg/L, biogas production might be limited by inhibition. However, rather than a specific concentration, it is a sudden and steady increase of VFAs in the effluent what can be a sign of a digester upset. Thus, it is essential to monitor VFAs periodically (e.g. bi-weekly) in order to detect problems on time, and make the necessary operational changes before digester failure occurs.

Molecular hydrogen – Together with VFAs, molecular hydrogen is maybe the most sensitive parameter of process upsets. The energy available for the degradation of propionate is very small, and requires partial pressures of hydrogen below \(10^{-4}\) atm at 25°C (McCarty & Smith, 1986; Schmidt & Ahring, 1993). Such low hydrogen partial pressures in AD systems are only possible by the syntrophic relationships between hydrogen-producing bacteria to hydrogen-oxidizing methanogens (Bryant, 1979). The balance between these two groups of organisms is of foremost importance to prevent digester upsets (Demirel & Yenigün, 2002). As opposed to other parameters, molecular hydrogen is more difficult to measure due to the low levels found in AD systems, and requires specialized equipment to determine it.

\textit{pH} – Maintenance of the system pH in the proper range is required for efficient anaerobic digestion. The generally accepted values are in the neutral range, between 6.5 and 7.6. The anaerobic digestion of complex organic substrates requires the joint work of several groups of microorganisms, from which methanogens are the most sensitive to low pH. Changes in digester operating conditions or introduction of toxic substances may result in process imbalance and accumulation of volatile fatty acids (VFA). Unless the system contains enough buffer capacity (alkalinity), the pH will drop below optimal levels and the digester will become “sour”. Depending on the pH magnitude and the duration of the drop, the biogas production will decrease to a point where it may completely cease. On the contrary, in a well-operated system, a slight increase of the digester’s effluent pH is expected, because organisms produce alkalinity as they consume (protein-rich) organic matter.

\textit{Alkalinity (Alk)} – The buffering capacity of an anaerobic digester is determined by the amount of alkalinity present in the system. The bicarbonate ion (\(\text{HCO}_3^-\)) is the main source of buffering capacity to maintain the system’s pH in the range of 6.5 – 7.6. The concentration of \(\text{HCO}_3^-\) in solution is related to the percent of carbon dioxide in the gas phase. In a typical manure-only digester with a pH 7.4 and a percent CO\(_2\) of 35%, the bicarbonate alkalinity is about 5,500 mg/L as CaCO\(_3\). Such alkalinity usually provides enough buffering capacity to withstand moderate shock loads of volatile fatty acids. In fact, cow manure can play an important role in co-digestion operations by increasing the pH and buffering capacity of the influent mixture when high-strength, easily degradable industrial wastes are used as co-substrates.
**Total ammonia-nitrogen (TAN)** – Ammonia is produced during the digestion of protein-rich substrates, such as swine or cow manure. Likewise VFAs, ammonia can inhibit the digestion process and decrease its overall performance. Concentrations over 1,500 mg/L of ammonia-N have been reported to be inhibitory for the digestion process at high pH (i.e., > 7.4); however, acclimation to higher ammonia levels (>5,000 mg/L) has been also reported in manure systems.

**Temperature** – The optimal temperature for mesophilic anaerobic digestion is 37°C (100°F) (VanLier et al., 1997). Although some variation is considered normal, digester temperature should be always maintained between 35°C (95°F) and 40°C (105°F). Operating at temperatures outside the normal range will result in decreased biogas production and organic matter stabilization. In addition, long periods of time under these conditions may eventually stop biogas production and cause digester failure. Furthermore, the process will be generally more affected at higher temperatures than at lower ones.

**Biogas production** – The biogas production is probably the most important parameter to monitor in anaerobic digesters. Biogas is almost completely composed of methane gas and carbon dioxide gas, but it also includes traces of ammonia nitrogen, hydrogen sulfide, and other gases. Methane is the final product of anaerobic digestion, and its production is a measure of how well the digester is performing. The amount of methane produced during digestion is directly related to the amount of organic matter (VS) that has been stabilized (destroyed). More importantly, the more methane is produced, the more energy (electricity and heat) that can be generated. Biogas production should be fairly stable over time. If the biogas production drops below the average daily values, it is most likely that other indicators, as discussed above, have changed as well, and it is a strong indicator of a digester upset.

**Methane content** – Biogas is composed of two main gas components, methane (CH₄) and carbon dioxide (CO₂). The percent of methane in a well-operated/designed anaerobic digester treating dairy manure is in the range of 58 – 65%, with the remaining gas consisting mostly of carbon dioxide. When manure is co-digested with high-strength substrates, such as food wastes, this percent is usually higher. The methane content of biogas should be fairly stable over time unless there is a problem with the digester. A steady drop of methane below the digester’s average daily values is usually an indicator of a digester problem. However, if substrate is fed intermittently, short-time drops may be observed at times of digester loading.

**Volatile solids (VS)** – Total volatile solids (VS) provide a measure of the organic matter content of the waste. The amount of digester influent being pumped and the percent VS of the waste are a measure of the digester’s organic loading rate (influent mass per time). The difference between the VS concentration in the influent and that of the effluent indicates the percent of waste that has been stabilized (destroyed) through the digestion process. For an influent of constant characteristics, the higher the VS stabilized, the lower the solids found in the effluent and the greater the reduction of odors. The extent (percent) of organic matter stabilization primarily depends on the
system configuration and the substrate's physicochemical characteristics. The percent VS stabilization in manure-only digesters is in the range of 30-42% (Gooch et al., 2011). In systems co-digesting manure and additional high-strength substrates, the percent stabilization of the waste is typically higher, but its magnitude varies according to the co-substrates employed.

THE IMPORTANCE OF PROCESS CONTROL AND MONITORING

Proper system operation and careful process control and monitoring are not only necessary to ensure efficient organic waste stabilization and constant and stable biogas production, but also to prevent digester upsets and potential system failure.

Digester upsets are the result of process perturbations caused by the digester operational parameters and/or the influent substrate characteristics (Figure 4). Preventing digester upsets will depend on the relative time taken to implement correcting actions to resolve the original cause of the perturbation (Figure 4).

Depending on the system configuration and the influent substrate, some operations are more or less susceptible to digester upsets. The two most common types of anaerobic digesters used in NYS are the continuously-stirred tank reactor (CSTR) and the plug-flow reactor (PFR). CSTRs are continuously (or periodically) mixed via impellers or sometimes pump mixed, so that the influent substrate material is theoretically diluted in the entire reactor's volume. In contrast, PFRs are not mixed – the influent material is pumped in one end of the reactor and advances as a plug-flow throughout its length until it exits at the other end. This fundamental difference makes CSTRs more suitable for high-strength substrates as shock loads can be minimized due to dilution. PFRs are better handling low-strength, stable-substrates, such as livestock manure. Indeed, anaerobic digestion of livestock manure usually presents a relatively low risk for upsets, regardless of the reactor. Its chemical properties (e.g., low-strength, optimal alkalinity, high nutrients) and particularly consistent nature over time, makes it a rather safe substrate for digestion. However, in farm-based co-digestion operations, livestock manure is usually co-digested with imported substrates coming from the food industry. The very same characteristics that make these type of substrates highly energy yielding, i.e., high chemical strength and increased biodegradability, make these operations especially susceptible to digester upsets.

In general, since changes in the system operational parameters and/or influent substrate characteristics are usually unintended, rather than scheduled, any type of operation is susceptible to process perturbations resulting in digester upset. Therefore, periodic monitoring of the process’ key parameters is always recommended – it is essential for early detection of process perturbations, on-time resolution of digester upsets, and prevention of system failure.

4 See Appendix for description
IMPLEMENTATION OF ANALYTICAL LABORATORIES IN ANAEROBIC DIGESTERS IN NEW YORK STATE

The role of the AD operator not only requires exclusive dedication, but also formal training on the fundamentals of system operation and process control. Motivated by such need, the Manure Management Program at Cornell University, as a part of a NYSERDA-founded project, has created a program to educate and support a workforce of AD operators and technicians. This project involves the implementation of analytical laboratories on selected farm-based anaerobic digester systems across NYS. The purpose of these labs is to periodically monitor key process parameters to develop a baseline for each AD system and to evaluate performance and stability of the operations. This will help operators to detect process upsets more efficiently, and to identify and correct the source of the problem before system failure occurs.

Five on-farm AD systems were implemented with analytical labs, i.e., Sunnyside, Roach, Sheland, Noblehurst, and SUNY Morrisville. The labs were equipped with instrumentation to measure the parameters listed on Table 1.

Table 1. Parameters measured in the analytical laboratories and the methods used

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Determination method</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>pH meter/single-junction electrode</td>
</tr>
<tr>
<td>Temperature</td>
<td>pH meter/thermocouple</td>
</tr>
<tr>
<td>Alkalinity (Alk)</td>
<td>Titration of sample with sulfuric acid 0.1 N to pH 4.0</td>
</tr>
<tr>
<td>Volatile fatty acids (VFA)</td>
<td>Distillation of sample and titration of distillate with sodium hydroxide 0.1 N to pH 8.3</td>
</tr>
<tr>
<td>Total solids (TS)</td>
<td>Drying sample in gravity convection oven at 105°C overnight (&gt; 8 h)</td>
</tr>
<tr>
<td>Total volatile solids (VS)</td>
<td>Ashing sample in muffle furnace at 550°C for 1 h</td>
</tr>
<tr>
<td>Methane content</td>
<td>By difference of carbon dioxide content, measured using sensidyne tubes</td>
</tr>
<tr>
<td>Total ammonia-nitrogen (TAN)</td>
<td>Ion meter/ion selective electrode</td>
</tr>
</tbody>
</table>

pH, Alk, VFA, TS, VS and TAN are measured both in the influent and the effluent of the AD systems. Analyses should be conducted weekly; however, at least bi-weekly analyses of VFA in the effluent of the anaerobic digester are recommended due to the role of this parameter as an early indicator of digester upsets.

All the labs were equipped with the exact same equipment to facilitate the instruction and training, and to promote cooperation between the operators. Figure 5 shows the setup of two of such labs and part of the equipment used.
Figure 4. Main causes of process perturbation leading to AD system failure; the relative time assumes that no actions have been taken to correct the original cause of the perturbation.

Digester operational parameters
- Organic loading rate (OLR)
- Loading frequency
- Temperature regime/variability
- Mixing frequency
- Mixing speed

Substrate/feedstock characteristics
- Dry matter content (TS)
- Organic matter content (VS)
- Substrate(s) chemical strength
- Substrate(s) biodegradability
- Co-digestion ratio

Process perturbation
- Steady increase VFA concentrations
- Increase $H_2$ partial pressure

Digester upset
- High VFA (e.g. acetate, propionate)
- High $H_2$ concentrations
- Lower pH (sour digester)
- Decreased biogas production
- Decreased methane content
- Decreased VS stabilization

AD system failure
- Biogas production stopped
- AD system failure
- CHP system down
The capability of the AD analytical labs and the importance of monitoring are well demonstrated by the preliminary data obtained at one on-farm AD system in particular. The actual name of the AD system is not disclosed here to maintain the farm’s privacy – it is referred here as the Alpha AD system. The Alpha AD system is a co-digestion operation treating the manure produced by approximately 3,000 cows and an average of 35,000 gallons of cheese whey every week. The anaerobic digester is a unique reactor design, a hybrid between a PFR and a CSTR. It consists of two separate U-shaped plug-flow reactors running in parallel, each one with an independent inlet and outlet. Mixing is conducted by recirculating biogas through defined sections along the reactor’s length axis, one section at a time.

Figure 6 shows the power output of the CHP system and biogas production of the AD system observed from 2011 to date. As shown in the figure, although biogas production is somewhat irregular, its range of variability is fairly constant over time.
Furthermore, since the Alpha AD system produces twice as much biogas as the CHP needs to operate at full capacity, stability of electricity generation is not affected by such variability. There are three downtime periods of the CHP system. The first two were scheduled shutdowns of the system due to maintenance. However, the last downtime period (enclosed inside a box in the graph) was an unexpected shutdown due to AD system failure, as clearly evidenced by the coincidental decrease of biogas production.

Figure 7 shows the daily power output of the CHP system and daily biogas production of the AD system right before and after the system failed. These data are contrasted with the most relevant parameters obtained from the analyses performed at the AD analytical labs from samples at the effluent of the AD system, i.e., pH, volatile fatty acids (VFA), and volatile solids (VS). A seen in the graph, the AD system failure occurs shortly after the start of the monitoring (only one sample had been analyzed). A steady decrease in the biogas production (and methane content) forced the operator to shut down the CHP system – no electricity or heat was produced for two weeks. During the AD system failure, biogas production dropped 70% from its moving average, i.e. 320 to 100 ft³/min, and methane content decreased from an average 65% to 52% (data not shown). Unfortunately, due to the additional responsibilities of the AD system operator, lab analyses could not be conducted as frequent as expected, and VFA levels were already at critical levels before any correcting actions could have been taken. From all the parameters measured in the lab, VFAs were certainly the only true early indicator of the digester upset. Indeed, before the biogas production showed any evidence of decreasing, VFAs show a two-fold increase in concentration, from 0.5 to 1.5 g/L (based on the projection of its first and second measurements, i.e. 10/13 and 11/01, respectively). Furthermore, by the third measurement, VFA concentrations are nine times higher than their baseline.

Interestingly, pH is many times taken as a sole indicator of a digester upset. Although this is true in certain cases, in farm-based co-digestion operations, pH does not always change during process perturbations, as shown in Figure 7. This is because cow manure provides increased buffering capacity to the digestate due to its high alkalinity. As opposed to VFAs, pH, biogas production, and methane content are a result of process perturbations, rather than a direct cause; therefore, it is not recommended to use them as early indicators (or predictors) of digester upsets.

Several (coincidental) operational problems in the Alpha AD system were the possible causes of the failure. One (of the two) pump located in the influent pit was out of service for two weeks during the same period, making the influent material highly inconsistent and stratified. Furthermore, almost twice as much volume of cheese whey (58,100 gal) was received by the farm for co-digestion the previous week to the upset than an average week (35,000 gal). In addition, the proportion of corn silage in the cow’s feed was doubled during the same period. Considering that cheese whey and corn silage are highly biodegradable and acidic (pH = 3.3 and 3.5, respectively), and the fact that the influent material was not properly mixed during the same period, it is very possible that an increased in the rates of biodegradation had produced a shock load of VFAs and imbalanced the AD process resulting in the digester upset.
A simplistic, but conservative analysis of the costs resulting from not receiving cheese whey and not selling electricity to the utility company during the two-week downtime period of the Alpha AD system results in about $10,000 in tangible economic losses. This estimation does not consider the additional expenses incurred by the farm for extra fuel required to heat its facilities and the digester, or the losses in income from carbon credits.

CONCLUSIONS

Although anaerobic digestion is a rather mature technology, system failures are still frequent around the world. In New York State, a study revealed that some AD systems generate less than 60% of their electric energy potential due to poor anaerobic digester performance and system failure. Most of these problems occur as a result of inadequate operational management and lack of process control.

The importance of well-trained and qualified personnel to operate AD systems and properly control and monitor the process is essential, not only to prevent digester upsets and potential system failures, but also to ensure efficient organic waste stabilization and constant and stable biogas production.

Analytical laboratories were installed on selected farm-based anaerobic digester systems in NYS to periodically monitor key process parameters to develop a baseline for each AD system and to evaluate performance and stability of the operations. The preliminary results of the monitoring confirmed that these facilities are essential to detect process upsets more efficiently, and to identify and correct the source of the problem before system failure occurs.

LESSONS LEARNED

One essential aspect to consider when monitoring AD systems is the selection of the point where samples and/or measurements are taken. The influent pit is probably the most adequate location to obtain a representative sample of the influent material. On the other hand, the effluent of the AD system is the appropriate sampling point to evaluate efficiency of treatment (e.g., organic matter stabilization), or to perform an overall mass balance (e.g., COD, nutrients) around the anaerobic digester. However, to monitor process parameters, the effluent of the reactor is not always the optimal location. As newly added material undergoes mostly hydrolytic and fermentation reactions during the first days of digestion, in PFRs, for example, VFA and other key parameters observe their peak concentrations in the first segment of the vessel, rather than near the effluent. Thus, it seems apparent that in these types of reactors, process monitoring should be conducted within the first section of the vessel, in a specific point (or points) to be established through sampling trials. This would allow PFRs, such as the Alpha AD system, to identify upsets much more quickly, i.e., during the first days of digestion as opposed to after 20 (or more) days of retention time. Conversely, in an efficiently-mixed CSTR, process parameters can be monitored in its effluent, because
the concentration of metabolites in the digestate should be (nearly) the same as that determined in the effluent.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the following farms for their willingness to participate in this project: Sunnyside, Roach, Sheland, Noblehurst, and SUNY Morrisville. Also, special thanks to the lab operators, Don Kulis, Gary Mutchler, Doug Shelmadine and Sons, Paul Tobias, and Ben Ballard and his students, for their motivation, and all the hard work they have done for this project, and will continue doing for their farms. Finally, the authors would like to thank the New York State Energy Research and Development Authority (NYSERDA) for funding in support of this work.
Figure 6. Power output and biogas production obtained daily from farm records at the Alpha AD system; box shows the downtime period of the CHP system due to the AD system upset.
Figure 7. Preliminary results of the on-going monitoring at the Alpha AD system; power output and biogas production obtained daily from farm records; effluent pH, VFA, and VS obtained with the analytical laboratories
APPENDIX

Capacity factor
The capacity factor is the ratio of the actual electrical energy produced by the CHP system over a given period of time and the electrical energy that potentially could have been produced if the CHP had been running at nominal capacity over the same period of time.

\[
\text{Capacity factor (decimal)} = \frac{\text{Electricity generated over time period (kW \cdot h)}}{\text{Time period (d) \cdot 24 \left(\frac{h}{d}\right)} \cdot \text{Nominal power capacity (kW)}}
\]

Online efficiency
The online efficiency indicates the percent of time the CHP system was operating over a given period of time.

\[
\text{Online efficiency (%) = } \frac{\text{Electricity generation system run time during period (h)}}{\text{Time period (d) \cdot 24 \left(\frac{h}{d}\right)}} \times 100
\]

Plug flow reactors (PFR)
Most PFRs are long, rectangular-vessels. The influent material is loaded in one end and exits the other end. Inside the vessel, the material advances as a plug and no mixing takes place.

Continuously-stirred tank reactors (CSTR)
The majority of CSTRs in Europe are upright circular tanks that are continuously mixed with one or two impellers fixed to an inclined shaft. Another type of CSTR, which is common in NYS, is a square tank. The tank includes several, but separate, mixers located on the sides of the vessel, which are turned on and off in shifts (i.e., one at a time).
REFERENCES


ON-FARM ANAEROBIC DIGESTION: MESSAGES AND METHODS TO EDUCATE A LAY AUDIENCE

J. Pronto¹ and B. Meyer²
¹Department of Biological and Environmental Engineering, Cornell University
²American Dairy Association & Dairy Council Inc, Syracuse, NY

INTRODUCTION

Farm-based anaerobic digestion (AD) technology has been gaining in popularity over the past 15 years in the United States and has seen more rapid rates of implementation in European countries like Germany and Denmark. This manure treatment strategy that incorporates concurrent renewable energy generation is well known to the constituents of applicable industries, namely, dairy and swine. However, it remains a poorly understood technology by the public and is normally absent from dialogue on renewable energy. Anaerobic digestion is rarely, if ever, called out as a strategy to generate renewable energy, as are wind and solar; if ‘biomass’ is included at all, it is assumed to encompass AD.

Since AD technology has proven to be an effective manure management strategy and one of the most reliable and efficient ways to generate renewable electricity, it is essential to educate the public and increase awareness of the benefits of this technology. If more people are aware of the technology and the multitude of benefits it offers, legislative and funding support mechanisms are likely to emerge, and consequently, expanded adoption opportunities.

This paper provides the main concepts to be publicized in order to 1) increase awareness of the role anaerobic digestion plays in a dairy farm setting, 2) educate people on the ability of AD to generate renewable energy, and 3) foster legislation that supports different aspects of on-farm AD and associated renewable energy generation. The paper also outlines several proven methods for encouraging positive public perceptions of on-farm AD, beginning with effectively educating a lay audience.

Relevant background

Anaerobic digestion technology has not caught on as quickly for the United States as it has elsewhere, for example in Europe, specifically in Denmark and Germany. There, government policies as well as high electricity pay-back prices have encouraged adoption of the technology, whereas the United States has relatively low prices for small electricity-generators that sell power back to the grid. The technology however, is proven effective at reducing manure-related odors and capturing the mainly methane-based biogas produced from the anaerobic breakdown of manure and other substrates. It is important to demonstrate the reasons for low rates of adoption thus far in the U.S., so this is not construed as inadequacies of the technology.
It is important that producers and their advisors be prepared and confident to
discuss technical aspects of on-farm AD. This paper includes information and
techniques to be used by producers and their advisors when interacting with the public,
media and law makers and when discussing on-farm AD. Foremost, they should be
well versed in demonstrating the advantages AD has for the farm compared with
conventional manure management.

It is important that not only producers, but also extension educators and others, be
aware of the positive aspects of on-farm AD, and be able to disseminate this information
to different audiences with varying knowledge levels.

MESSAGES FOR EDUCATING A LAY AUDIENCE

There are many positive messages to convey regarding on-farm use of AD
technology both from the standpoint of treating manure and of generating renewable
energy. Messages directed to the public need to be made audience-appropriate; additional details on this are discussed later in the paper. Brief overviews of the major
benefits attributed to AD are provided below.

- **Odor reduction**: Incorporating dairy manure to an anaerobic digester significantly
decreases the odor causing compounds in the manure, and allows farmers the
flexibility of how and where to store the digested manure and how and when to
apply it on cropland.

- **Greenhouse gas mitigation**: An anaerobic digester system on a farm captures the
methane that is produced from anaerobically degraded manure and combuts it
to reduce it to carbon dioxide, which is 23 times less potent as a greenhouse gas
in the atmosphere.

- **Water quality improvement**: Contamination of local bodies of water is significantly
reduced when digested manure can be applied at the agronomically optimal time,
minimizing runoff and leaching.

- **Renewable energy generation**: Biogas that is produced from manure degrading
anaerobically is captured and can be used to generate heat and electricity. Anaerobic digesters used to generate renewable electricity also have much
higher capacity factors than other forms of renewable energy generation, since
manure is consistently available and biogas is continually produced, fueling
energy generation.

- **Nutrient availability**: The nutrients contained in manure are conserved through
the anaerobic digestion process. Applying digested manure to cropland at the
agronomically optimal time means that a growing crop is readily able to uptake
and utilize nutrients.
• **Pathogen reduction:** Research at Cornell University has demonstrated a 99.9 percent reduction of indicator organisms (those that are commonly used to evaluate the success of a system’s performance relative to killing other pathogens) in manure. Johnes disease, a disease found in dairy cows, is reduced 99 percent by anaerobic digestion of manure.

• **On-farm financial savings:** Utilizing certain by-products from the digestion process can lead to a reduction in purchase costs for electricity, heat and bedding.

• **Improved neighbor and community relations:** By reducing odors from storing manure long-term and applying manure to cropland, it has been shown that neighbor complaints decrease, and fewer complaints to be mediated means overall improved community relations.

In addition to the direct benefits listed above that anaerobic digester systems provide to the immediate farm and surrounding lands, there are also by-products of the digestion process that can be sold to generate revenue on the farm. Electricity generated by combusting biogas in an engine-generator set can be first used to offset purchased electricity on the farm and excess can be sold back to the utility grid. In most states there are laws that regulate the sale of electricity back to the grid, for example, in New York, electricity may be sold back under the provisions of the New York State Net Metering Law. Post-digestion, the effluent can be separated and the solids can be sold as-is or can be further treated by composting them, and then sold as bedding to other farms or as a soil amendment. Receiving food waste for inclusion to the anaerobic digester also generates revenue through tipping fees paid to deliver food waste to the farm. Incorporating food waste substrates to the anaerobic digester also significantly enhances biogas production by 3-5 times that of manure alone.

There are many original revenue generation schemes that can be integrated with an on-farm anaerobic digester system. Secondary to using the by-products of the system to offset costs on-farm, excess heat, manure solids and biogas can be used for several innovative, synergistic enterprises. Presenting these potential scenarios further demonstrates the opportunities AD technology presents to the farm and community.

There is a company in Connecticut that manufactures a product called CowPots™ - a biodegradable alternative to plastic seedling pots - which are made by molding digested manure solids into seed-starting pots that biodegrade when placed in the ground with a growing seedling. Manufacturing potting plants is a step beyond simply composting manure solids – but simply selling cured compost is another revenue generation strategy. There is a farm in New York that currently bags and sells composted manure solids as a soil amendment to commercial and residential consumers, which have actually been approved for organic food production.

Many options exist for generating revenue with the excess heat produced by the combined heat and power system (CHP) when generating electricity. While there are
no examples in operation in New York State, heat-intensive and potential synergistic applications include: a car wash, a grain dryer, a maple sugaring operation, a greenhouse, or an aquaculture operation.

AD systems reduce the greenhouse gas emissions associated with manure stored long-term, and farms normally opt to trade these carbon credits and receive payment for them when the credits are retired. However, rather than trade them, they could potentially be used to offset the carbon emissions from the production of fluid milk. The resulting added-value product could be sold as ‘carbon-neutral’ or ‘green milk’. Selling carbon-neutral milk has not been attempted thus far, but with the recent spike in interest towards greenhouse gas reductions, it is a product that would likely have higher value than conventional milk.

Many times, an opportunity to connect with an audience will be brief, and messages aimed at providing educational insight will need to be short and focused. Realizing the need for short, accurate, anaerobic digestion-related facts prompted the development of the following list, organized by topic. These facts are great for use in visual resources as well as for media articles and outreach materials.

**Renewable energy**

- Digesting the manure from half of the dairy cows in New York State would produce over 70-MW annually.

- Digesting the manure from half of the dairy cows in New York State, in addition to the food waste from all active food and beverage manufacturers would produce enough energy to allow the city of Rochester to take its coal-fired power plant (Russell Station, 253-MW) out of service.

- If the manure from half of the dairy cows in New York State was digested, it would offset 2,250 railcars full of coal destined to be burned in coal-fired power plants annually.

- If the manure from half of the dairy cows in New York State was digested in addition to the food waste from all active food and beverage manufacturers, it would offset more than 8,000 railcars full of coal destined to be burned in coal-fired power plants annually.

- Assuming the manure from half of the dairy cows in New York State was digested, enough power could be produced to power 45,000 residences per year.

**Greenhouse gases**

- New York State contributes 1% of global greenhouse gas emissions

- The reduction in greenhouse gas emissions by 16 of the 20 operating digesters in New York State is equivalent to removing 7,775 cars from the road per year
• The 20 operating digesters in New York State yield a total greenhouse gas reduction of 155,000 TCO$_2$e/year, which, at $6.00 per ton, is equivalent to a potential revenue of $930,700.

• If half of the cows’ manure in New York State were digested, it would yield a total greenhouse gas reduction of 2.5 million TCO$_2$e/year, which, at $6.00 per ton, is equivalent to a potential revenue of $14,858,000.

Transportation
• 1 car is removed from the road for every 2 cows’ worth of manure digested

• If 40% of the manure in New York State was digested, it would be equivalent to removing 215,000 cars from the road

Solid waste and nutrients
• One on-farm digester co-digesting manure and food waste could displace the average food waste deposited in a landfill by more than 8,000 people per year.

• One centralized AD accepting dairy manure from 25 farms and several food waste substrates has the ability to offset 11 million gallons per year of synthetic fertilizer, after meeting the fertilizer needs of all participating farms.

• One centralized AD accepting dairy manure from 25 farms and several food waste substrates has the potential to generate $226,000 per year in revenue from the sale of AD effluent to be used in place of synthetic fertilizer.

METHODS TO EDUCATE A LAY AUDIENCE

There are several ways to encourage positive publicity for on-farm applications of AD. Effectively educating a lay audience is foremost in increasing the knowledgebase the public has with regards to this technology. Additionally, presenting information in a manner that is engaging will attract attention and enhance education efforts. These efforts are important in order to reach an audience that includes potential funding organizations and legislative entities that have the potential to create legislation in support of different aspects of on-farm AD.

In order to increase awareness of AD, a group must first have the knowledgebase to understand the topic and related issues. The first step in educating the public on AD technology, is to synthesize the information to be concise, jargon-free, easy to understand, and easy to relate to. Making information concise, jargon-free and easy to understand are common methods of translating technical information to make it easier for a lay audience to understand. However, it is also important to create an aspect of audience-specific content that will make the audience able to relate to the information. Several parties involved with the implementation of on-farm AD have the responsibility
to disseminate information to the public, including: extension educators, producers and research groups.

In addition, local media outlets have an interest in serving their audiences and presenting information in a way that is meaningful and useful to their viewers/readers. Since milk and other dairy foods are an important part of most families’ diets, stories about dairy farming easily fit into this category. Although this may be contrary to commonly-held public perception, reporters are looking for positive stories to tell; with increased interest in both how food is produced and the generation of renewable energy; AD makes a well-suited candidate.

There are various materials that can be designed to effectively provide information at a basic level, including: case studies, websites, posters, articles and videos, among many other visual formats. Another way to directly present introductory material on the topic of on-farm AD is being pursued by the PRO-DAIRY Dairy Environmental Systems group at Cornell University, who are currently offering one-day workshops that target a lay audience and local media outlets. The workshop begins with a classroom-based instruction session in the morning and concludes with a tour of an existing on-farm anaerobic digestion operation in the afternoon. This format exposes participants to information in a lecture-style format for half a day, presented in both printed and visual formats (i.e., use of a workbook and slide presentation) and also exposes participants to a hands-on learning experience by viewing an actual operation, the second half of the day.

Extension educators can provide tools to producers in order for them to be able to reach the public and when they do have a public audience present on the farm, to be able to distribute concise information in a positive light. Simply equipping producers with materials for a lay audience can greatly improve the education of a public group when visiting a farm. In addition, workshops can be designed to teach producers, first, the complete set of benefits AD technology has to offer the farm and the community, and second, how to effectively present farm visitors with this information.

It is also important to have advanced research information available in a lay format. More importantly than educating the general public on current research issues, research groups should realize the benefit of making technical information available to both legislators and potential funding sources.

Many times simply making a document non-technical is not enough to accurately convey scientific information to a lay audience. There are some terms that incorrectly convey an idea to the public, as is shown in Figure 1. Using better word choices with clear intentions can more effectively communicate concepts.
Figure 1. Terms that have different meanings for scientists and the public (Somerville, 2011)

<table>
<thead>
<tr>
<th>Scientific term</th>
<th>Public meaning</th>
<th>Better choice</th>
</tr>
</thead>
<tbody>
<tr>
<td>enhance</td>
<td>improve</td>
<td>intensify, increase</td>
</tr>
<tr>
<td>aerosol</td>
<td>spray can</td>
<td>tiny atmospheric particle</td>
</tr>
<tr>
<td>positive trend</td>
<td>good trend</td>
<td>upward trend</td>
</tr>
<tr>
<td>positive feedback</td>
<td>good response, praise</td>
<td>vicious cycle, self-reinforcing cycle</td>
</tr>
<tr>
<td>theory</td>
<td>hunch, speculation</td>
<td>scientific understanding</td>
</tr>
<tr>
<td>uncertainty</td>
<td>ignorance</td>
<td>range</td>
</tr>
<tr>
<td>error</td>
<td>mistake, wrong, incorrect</td>
<td>difference from exact true number</td>
</tr>
<tr>
<td>bias</td>
<td>distortion, political motive</td>
<td>offset from an observation</td>
</tr>
<tr>
<td>sign</td>
<td>indication, astrological sign</td>
<td>plus or minus sign</td>
</tr>
<tr>
<td>values</td>
<td>ethics, monetary value</td>
<td>numbers, quantity</td>
</tr>
<tr>
<td>manipulation</td>
<td>illicit tampering</td>
<td>scientific data processing</td>
</tr>
<tr>
<td>scheme</td>
<td>devious plot</td>
<td>systematic plan</td>
</tr>
<tr>
<td>anomaly</td>
<td>abnormal occurrence</td>
<td>change from long-term average</td>
</tr>
</tbody>
</table>

After preparing the actual information and messages to be conveyed following the methods described above, the materials should be presented in a format that is easily accessible, appealing, and entertaining.

When developing materials to educate the public, there are several keys to making the information you are presenting not only easier to understand, but easier to retain as well (List adapted from (AAAS, 2012):

- **Do not use jargon:** Do not use acronyms (i.e., CAFO, NCRS) or jargon that is specific only to a select industry.

- **Focus on a few points:** Think about what is important for a specific audience and accordingly what the major points are to highlight; do not attempt to explain everything beyond what the target audience is concerned with.

- **Use numbers sparingly:** Numbers can be very effective at making a point, but do not overuse numbers; when using number values be sure to provide a context (i.e., “This 1,000 cow dairy can generate enough energy to heat all the homes in Liverpool for the entire winter”).

- **Anticipate questions:** Attempt to formulate the questions you think the target audience will ask and focus on the answers in the outreach materials.
• **Provide visuals:** Include visuals where appropriate in all outreach materials; visuals help in explaining processes and make points easier for people to relate to (i.e.; show images of dairy cows when discussing manure generation).

• **Fact sheets:** Provide people with a fact sheet for a particular case study and if possible, include a glossary of terms.

A great way to publicize information about AD technology or a particular project is to involve the media, with the goal of developing positive and informative news articles. Working with the media can provide accurate, informative updates about your research or project to stakeholders. Specifically, taking the time to work with the media can help to:

• **Reach a wider audience:** Journalists can help to reach the broader public, legislators, and funding organizations, not just those actively seeking information.

• **Raise awareness:** Consistent and accurate news coverage could increase public awareness of a project.

• **Create positive attitudes:** Bringing current successes and future goals of dairy farming to the attention of the public could help generate enthusiasm for research and for funding support.

Holding farm tours to see firsthand how anaerobic digester technology operates on a farm helps people connect with the processes involved with treating manure, producing biogas and generating renewable energy. It is advisable to keep tour groups to a very specific audience so that material can be targeted toward one knowledge level and so that the needs of each group can be met effectively. Offering tours and/or a press conference to announce the ground breaking of a new project can be appealing to media and legislators as well as the general public. Tours can also be held to showcase new and unique designs or changes to standard uses of the technology. Legislators might view a farm tour of an operating anaerobic digester as an opportunity to demonstrate their support for dairy farming, renewable energy or other AD-associated issues. Legislators and politicians are also prime audiences to target when seeking funding or regulatory support for a certain issue. Offering tours and educational materials for school-age children helps increase awareness of renewable energy, dairy farming and responsible manure management, and over time undoubtedly increases the number of people interested in pursuing these fields. Other children's groups and organizations (i.e., Boy and Girl Scouts of America) may be interested in farm tours to use as the basis for a specific project or learning initiative.

An unconventional method of promoting on-farm anaerobic digestion in the past has included the use of sculptures to depict anaerobic digestion technology on a farm. In 2010, the famous butter sculpture at the New York State Fair featured a farm with an anaerobic digester as well as a poster highlighting the process. In 2012, the butter
sculpture from the Pennsylvania State Fair was donated to a local dairy farm with an operating anaerobic digester to be co-digested with the farm’s manure. This made for a great example of a sustainable full circle where the products used to make the sculpture were returned to the farm for a beneficial use (in this case, heating the farm).

Participating in state fairs, environmental and agriculture focused fairs, provides an outlet to educate many attenders with quick fun facts about dairy farming and renewable energy generation. Visuals for this type of event should be light on textual information and heavy on images that attract attention and are easy to understand. Technical information is best presented verbally in this context to especially interested individuals.

CONCLUSION

In order to make AD and biogas consistently present on the list of major renewable energy technologies, alongside wind and solar, public awareness of the technology needs to be increased, and positive, informative news stories need to be encouraged. Producers are constantly in contact with audiences in the community that stand to benefit from an education on the use of farm-based AD and the ways it improves aspects of dairy farming both on and off the farm. Extension educators and others involved in supporting on-farm manure treatment strategies like AD can greatly support farmers in their mission to educate community members.

With the recent increase in attention to sustainable management of organic waste from industrial, commercial and residential sources, anaerobic digestion is likely to be mentioned more frequently. Education efforts aimed at stakeholders in these industries can improve understanding of the technology and increase adoption rates.

Overall, anaerobic digestion technology stands to benefit farms, agriculture communities, and the general public through responsible manure management techniques and the generation of high-efficiency renewable energy. Reaching the public with the messages contained in this paper and pursuing effective methods for communicating those ideas will lead to increased public awareness and an improved knowledgebase for understanding the technology.

REFERENCES


THE BUSINESS CASE FOR CARBON MANAGEMENT: NEW OPPORTUNITIES FOR OFFSET REVENUES FROM MANURE DIGESTERS

S. Hernandez
Business Development Manager
Climate Action Reserve

INTRODUCTION

One of the many benefits of using anaerobic digestion for management of livestock manure is the destruction of methane (CH₄), a highly potent greenhouse gas with a global warming potential 25 times greater than that of carbon dioxide (CO₂).¹ For more than a decade it has been possible for livestock operations to generate carbon offsets for this methane reduction when they replace their open manure lagoon systems with a biogas controls system (BCS) to capture and destroy methane. With such a BCS in place, a dairy operation should be able to generate, on average, between 2 and 4 offset credits per cow per year. Unfortunately, historically, the carbon market has been beset by a great deal of variability and instability, resulting in financial uncertainty for farmers, project developers and investors in digester projects.

MARKET OVERVIEW

Over the last couple of years, however, more voluntary buyers of carbon offsets have entered the market, and they have been shifting their preferences towards offset programs that utilize stringent standards and operate in an open and transparent manner. In addition, there have been significant steps forward in the formal development and implementation of compliance markets for carbon offsets. In particular, the state of California finalized the regulations for its cap-and-trade program, creating a new market for carbon offsets to be used for compliance. For livestock operators this means significant increases in the growth and stability in the demand for their credits, resulting in upward pressure on prices. Prices for livestock offset credits (Climate Reserve Tonnes or CRTs) have recently been trading in the range of $9-10 each (as of late January 2012; this is subject to change). This price premium is marked in comparison to non-compliance offset credits which are currently trading in the range of $1-2, reflecting perceived demand for offsets for use in compliance markets.

The Climate Action Reserve is a non-profit carbon offsets program that develops high-quality, conservative standards and maintains a project registry through which serialized CRTs are issued, transferred, and retired. The initial Livestock Project Protocol was developed in 2007, and has received periodic updates and revisions since that time. There are currently 60 dairy and swine manure digester projects that have been submitted from 16 states throughout the United States, as well as 18 projects submitted from Mexico. Together these projects have generated upwards of a half of a

million CRTs, and more are on the way. Please see Figure 1 for a detailed map of the Reserve’s projects located throughout the United States and Mexico.

Figure 1. US-Mexico Project Map

The Compliance Market – Greater Certainty for Farmers, Developers and Investors

In 2006, the state of California adopted Assembly Bill 32 (AB32), the California Global Warming Solutions Act, which requires the state to reduce statewide greenhouse gas emissions (GHGs) to 1990 levels by 2020.

In order to achieve the ambitious emissions reductions targets mandated under AB32, the California Air Resources Board (CARB) developed a Scoping Plan to detail the actual regulations that would be put in place. A statewide cap-and-trade regulation was developed and formally adopted by the CARB in October of 2011, becoming law in December following approval by the State’s Office of Administrative Law. This program is scheduled to begin in 2013 and run through 2020, with the first compliance period running from 2013-2014.
The main component of California’s compliance market will be tradable emissions permits known as allowances. However, the regulation also includes a provision that allows emitters to use carbon offsets for up to 8% of their emissions for each year. So far the ARB has adopted four of the Reserve’s project protocols for use in creating these compliance offsets: Livestock, Forestry, Urban Forestry, and Ozone Depleting Substances. These projects may be located anywhere in the United States. This means that a dairy manure digester project in Wisconsin (or any other state) may generate offsets and sell them into the California market.

Table 2. Forecasted Compliance Offset Demand (2013-2020)

<table>
<thead>
<tr>
<th>Compliance Period</th>
<th>Year</th>
<th>Allowance Budget (mt CO$_2$e)</th>
<th>Total Offset Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First</strong> (narrow scope)</td>
<td>2013</td>
<td>162,800,000</td>
<td>26,800,000</td>
</tr>
<tr>
<td></td>
<td>2014</td>
<td>159,700,000</td>
<td></td>
</tr>
<tr>
<td><strong>Second</strong> (broad scope)</td>
<td>2015</td>
<td>394,500,000</td>
<td>91,784,000</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>382,400,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>370,400,000</td>
<td></td>
</tr>
<tr>
<td><strong>Third</strong></td>
<td>2018</td>
<td>358,300,000</td>
<td>83,104,000</td>
</tr>
<tr>
<td></td>
<td>2019</td>
<td>346,300,000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2020</td>
<td>334,200,000</td>
<td></td>
</tr>
</tbody>
</table>

Source: CARB Final Cap-and-Trade Regulation, October 2011

As illustrated in Table 1 (see above), the CARB anticipates the market demand for offset credits to be used for compliance in California will be 13 million tonnes per year for the first two years, rising to approximately 27 million tonnes at the start of the second compliance period in 2015. The regulation includes a minimum price (“price floor”) of $10.00 per tonne for allowances, so offset projects can expect similar prices when they sell their credits. That said, many market analysts predict robust demand for compliance offsets to drive prices to upwards of $70. For example, Barclay’s Capital estimates that prices for compliance offsets will reach $68 during the third compliance period (2018-2020). If such forecasts are realized, then the prices for compliance offsets, such as those generated by the Reserve’s Livestock Project Protocol, should provide ample incentive for dairy operations to invest in biogas control systems such as anaerobic digesters.

---

2 California Code of Regulations. Subchapter 10 Climate Change, Article 5: CALIFORNIA CAP ON GREENHOUSE GAS EMISSIONS AND MARKET-BASED COMPLIANCE MECHANISMS. § 95841, Table 6-1: California GHG Allowances Budgets. (A-72)

PROGRAM DETAILS – HOW TO GET STARTED

The Reserve’s Livestock Project Protocol (currently on version 3.0) outlines all of the eligibility requirements for livestock methane projects. Only new digester projects are eligible (you must submit the necessary paperwork to the Reserve no later than six months after your project is operational), and the manure must have previously been managed in an open, uncontrolled anaerobic lagoon (or storage tank). The biogas that is generated by the digester may be destroyed on-site or off-site, there is no prescription about how it is utilized. For example, if a dairy operator wishes to combust the biogas in an engine or boiler to generate renewable energy to power other farm operations or to sell into the electricity grid, it still meets our standards for an acceptable project under our protocol. In order to receive offset credits under the Livestock Protocol, the key requirement is the capture and destruction of methane in a biogas control system – whether you flare the methane or use it for renewable energy is a decision that is left to the individual project operator.

Moreover, facilities that have the capacity to co-digest manure with other organic waste can do so and earn additional credits for the digestion of other eligible feedstocks under the Reserve’s Organic Waste Digestion Project Protocol. However, the project must satisfy both the Livestock and Organic Waste Digestion Project Protocols in order to receive additional CRTs for co-digestion livestock manure and organic waste and/or organic loaded wastewater.

The Livestock protocol gives guidance about monitoring and metering requirements, and it will be much easier to comply with these if they are incorporated into the design of the digester project. The major monitoring and metering requirements are the following: (1) Total flow of biogas from the digester; (2) Methane concentration of the biogas; and (3) the flow of biogas to each approved destruction device. For more information please refer to the monitoring diagram in Figure 2. Start early on the development of a monitoring plan to make sure that you have the proper equipment for metering gas flow and methane concentration, as well as the operating hours of your engine, flare or other destruction system. At least every two years, each individual livestock project must go through verification by an independent third-party which cost in the range of $10,000 to $12,000. It is only after this verification is successful that CRTs are issued, and this process is much easier if the project is prepared from the outset. To this end, the Protocol should serve as a step-by-step guide to walk the developer through the process of listing, verifying and registering the project.

Additional Resources

There are a number of resources available to learn more about carbon offsets and the Livestock Project Protocol on the Reserve website, www.climateactionreserve.org/. There you can download the protocol, as well as the Program Manual which outlines the processes and procedures that must be adhered to in order to successfully implement an emission reduction project according to the Reserve’s standards.
Figure 2: Livestock Project Monitoring and Metering Diagram

For more information regarding past presentations and videos from previous workshops and webinars related to livestock carbon projects, they can also be found on the Reserve’s website (Click the link provided: Presentations). For information related to the various participants in the carbon markets, please visit the CRT Marketplace, which provides links to companies involved with buying and selling CRTs, who can help a project learn more about accessing the financial markets for their CRTs. It is important to note, that the Reserve is not a broker, retailer or otherwise a seller of CRTs; the Reserve simply acts as a publically-accessible database for registering projects and the credits they generate.

CONCLUSION

The carbon markets are strong and have a high demand for livestock CRTs, and digester technology has matured greatly in the past few years. There are many resources available to farmers who want to learn more and get involved. The timing has never been better for livestock operations that wish to install manure digesters.
HOW CARBON DIOXIDE OFFSETS AND OTHER POLICIES IMPACT THE
FINANCIAL FEASIBILITY OF ANAEROBIC DIGESTION SYSTEMS ON U.S. DAIRY
FARMS

B. A. Gloy
Department of Agricultural Economics
Purdue University, West Lafayette, IN

Anaerobic digestion (AD) of livestock waste presents a potential technological
solution to the challenges of renewable energy production, greenhouse gas mitigation,
and livestock waste management. While AD systems have been commercially
available for many years, they have not been widely adopted on U.S. livestock
operations. Among livestock species, AD systems have been more rapidly adopted by
dairy operations. According to the U.S. EPA’s AgSTAR program website,
http://www.epa.gov/agstar/projects/index.html, in 2011 dairy operations accounted for
140 of the 171 active AD sites.

While the technology of AD is relatively well understood, it is not clear how many
dairy farms could realistically be expected to adopt AD systems. As a result little is
known about how much renewable energy could be created from AD systems installed
on U.S. livestock operations or how much methane emissions associated with manure
management on U.S. livestock operations could be reduced by adoption of AD systems.
These are both critical questions as it is clear that government incentives would be
required to encourage adoption of AD systems on a wide scale. The few analyses that
have been undertaken to date have been developed from aggregate data and only
considered a few of the many of the factors that will likely limit the deployment of this
technology.

A variety of factors make dairy farms attractive candidates for AD. Dairy farms
produce considerable amounts of waste and many of the operations confine livestock to
barns where manure is collected and stored in anaerobic conditions. These manure
handling systems could technically be converted to include an AD system and the
installation of an AD system. Further, such an installation would likely result in a
reduction in the amount of methane, an important greenhouse gas, that is emitted to the
atmosphere. This is achieved when methane that is normally emitted to the
atmosphere is captured and combusted.

Once biogas has been created by the AD system, a variety of options exist for
converting the biogas to energy. Today, this is most commonly accomplished by
combusting the biogas in an internal combustion engine which is used to power and
electrical generator. The electricity can then be used to meet on-farm electrical needs
and/or sold onto the power grid. Gloy and Dressler (2010) provide a more thorough
description of the various energy conversion options and their potential benefits and
challenges.
Although AD systems have many potential benefits, it is obvious from the small number of operating systems present in the U.S. that many hurdles to adoption exist. These include both technical feasibility as well as economic viability. For instance, it is clear that due to economies of scale, AD systems are more likely to be economically viable on larger dairy farms. Additionally, factors such as the current manure handling systems in place on the farm, the energy demands that are experienced by the farms, the farm’s plans to continue to operate into the future, and capital constraints faced by the farms all influence the likelihood that an AD system could be adopted by a dairy farm.

The purpose of this paper is to examine the viability of AD systems on U.S. dairy farms and produce an estimate of the potential for AD adoption that takes into consideration how a variety of constraints might impact AD adoption. In addition, this paper provides some insight into the potential methane emission reductions that could be achieved through the use of AD systems. Readers interested in a detailed analysis of the this issue should consult recent work by Gloy (2011) and Key and Sneeringer (2011) who develop estimates of aggregate supply curves for greenhouse gas emission reductions from AD systems.

The analysis makes use of the most comprehensive farm level data set available regarding the economic condition of U.S. dairy farms, the Economic Research Service’s Agricultural and Resource Management Survey, version 4 (ARMS). The ARMS survey contains detailed information on the production, financial and management characteristics of U.S. dairy farms. This study uses the 2005 special dairy costs and returns version of the ARMS to develop estimates of the potential for AD adoption on U.S. dairy farms.

The next section describes the various factors that influence the technical feasibility and economic viability of potential digester systems. Then previous estimates of the potential for AD on U.S. dairy farms are discussed. The data and methodology used to create the estimates is then presented and finally the results are developed and discussed.

FACTORS INFLUENCING THE VIABILITY OF AD SYSTEMS

There are several significant technical barriers that must be considered in developing an estimate of the potential for AD adoption on U.S. dairy farms. AD systems are designed to handle wet feedstocks with moisture content that is typically at least 85 percent. While the moisture content of excreted dairy manure is acceptable for AD systems, how the farms handle manure plays a role in determining the viability of AD systems. Farms that do not collect excreted manure, because animals are grazing or because animals are not kept in confinement, are unable to adopt an AD system. As a result, farms whose manure handling systems utilize lagoon or liquid slurry storage systems are typically the best candidates for AD systems.
Further, the inclusion of inorganic materials such as sand or dirt greatly reduces the feasibility of AD systems. If dirt or sand is not removed prior to digestion, it tends to settle out of suspension in the digestion tank and quickly fills the reactor. Once substantial amounts of inorganic material has settled in the digester it must be opened and cleaned, greatly reducing the amount of energy that the system generates. Thus, farms that bed with sand or farms that utilize a dry lot housing system are typically not good candidates for AD systems.

While many farms face some technical constraints that impact the potential for AD system adoption, almost all farms face significant economic hurdles to AD adoption. It is clear from previous research that AD systems tend to exhibit large economies of scale (Enahoro and Gloy; Gloy, 2011; Leuer, Hyde, and Richard). A major source for these economies of scale arises due to the fact that AD takes place in large containers or tanks whose construction costs are proportional to surface area and whose revenues are proportional to volume.

Additionally, the AD system requires active management for optimal production, and larger systems are more likely able to justify the managerial expertise necessary to achieve high levels of production. Finally, there are many other capital installation costs such as utility interconnection that have fixed cost elements which make them more suitable for installation on larger farms and prohibitively expensive for smaller operations. While there is no exact farm size at which AD systems become viable alternatives, many previous analyses assume that the system will handle the manure from at least 500 cows and larger farms are likely even more attractive candidates for system installation (Gloy and Dressler 2010).

In addition to the size necessary to achieve viability, there are a number of other economic realities that can significantly impact the potential profitability of AD systems. First, the energy price that the farm currently pays for its electricity and its level of demand is a critical element of potential profitability. Farms that face higher electrical prices will have a better chance at achieving AD system profitability because they are able to off-set higher retail electrical prices. Likewise, the price that the farm receives for any excess electricity sold back to the electrical grid also plays a key role in economic viability. As Gloy and Dressler point out, these factors tend to be very site specific because different utilities have different pricing policies for electricity purchased from AD system operators. Further, some utilities, utility regulators, and state and local governments offer incentives that are designed to enhance the economics of AD systems. An example of these incentives is the production incentives offered to AD systems by the New York State Energy Research and Development Authority (NYSERDA).

The economics of AD systems can be greatly enhanced with the inclusion of additional organic waste streams or substrates such as waste fats and oils. These waste streams sometimes generate “tipping fees” which are payments received by AD operators for taking the wastes. These substrates also often produce biogas which greatly increases the amount of energy that the system is capable of producing. A
detailed discussion of these and other economic considerations is available in Enahoro and Gloy.

Finally, AD systems require a substantial capital outlays that will only be recaptured over an extended period of time. In other words, AD systems are long-term capital investments. This means that farms that adopt an AD system must expect to remain in operation for a considerable period of time in order to justify the capital outlay. Likewise, because many dairy farms are capital constrained, the availability of financing for the capital intensive AD projects is a significant economic barrier to AD system installation.

With respect to economic viability at current energy prices and capital requirements for AD systems, most AD systems exhibit marginal profitability at best (Gloy 2011). In fact, most AD systems are not economically viable without government incentives that encourage their adoption. However, the economics of AD systems can be enhanced with government policies such as enhanced electrical pricing, grants to reduce capital expenditures, and/or loan guarantees.

It is also possible that government incentives for AD adoption could be constructed around the idea of paying farmers for greenhouse gas (GHG) reductions achieved by reducing manure methane emissions. At times these incentives have been available in voluntary carbon markets like the Chicago Climate Exchange (CCX). At current carbon off-set prices the revenue stream that would be created by a typical AD system would be trivial. However, if AD systems were qualified to provide carbon off-sets to a larger regulated carbon market created through a cap and trade carbon regulations, the revenue stream might increase substantially.

In order to evaluate the potential impact that the sale of carbon off-sets might have on digester adoption, it is necessary to understand how many AD systems might qualify for carbon off-set credits. Under current rules for the CCX a farm qualifies for GHG emission reduction credits or off-sets if it utilizes a liquid slurry or anaerobic lagoon manure storage system. These systems create methane emissions because manure is stored in anaerobic conditions. However, the amount of methane generated by the manure storages is dependent on a variety of conditions such as temperatures and length of storage.

In summary, there are a variety of technical and economic constraints that should be taken into consideration when estimating the potential for AD adoption on U.S. dairy farms. The following analysis will incorporate many of these technical and economic constraints in assessing the potential for adoption on U.S. dairy farms. Important technical and economic constraints include appropriate animal housing and manure handling systems. Likewise, the farms should be of sufficient size so as to achieve economies of scale in the AD system. Additionally, the farm must have an expected life suitable for AD system payback and the farm must be in a financial condition that allows them to make the capital investment necessary to install the AD system.
DATA AND METHOD

This study relies upon a variety of data collected from the 2005 special dairy costs and returns of the USDA/ERS Agricultural Resource Management Survey (ARMS) version 4. The sample for the ARMS survey is developed from a complex survey sampling methodology designed to produce estimates that are statistically representative of the population of U.S. dairy farms that milk more than 10 cows in the 24 important dairy states in the U.S.\(^1\) The ARMS survey is administered by paid, professional enumerators. For the 2005 dairy costs and returns study, a total of 1,815 questionnaires were completed. Details of the survey and the methodology used to develop and collect results are available at [http://www.ers.usda.gov/data/arms/](http://www.ers.usda.gov/data/arms/).

The ARMS 2005 Dairy Production Practices and Costs and Returns Report questionnaire contained a large number of questions about the characteristics and financial condition of U.S. dairy farms. These questions were used to develop estimates of the number of digesters that could potentially be developed in the U.S. dairy industry. Several different characteristics of the dairy operation were considered in developing the estimates. These included factors such as the farm size, characteristics of the manure handling and housing system, and financial condition. Each of these items is explained in detail in the following sections.

Farm Size

Because AD systems typically exhibit economies of scale, farm size is an important consideration in understanding the number of farms that could potentially adopt AD systems (Enahoro and Gloy; Leuer, Hyde, and Richard). The amount of manure that is available for the AD system is determined by the number of animals on the farm.

The ARMS survey contains information about the average number of dry and lactating milk cows on each farm. It does not directly ask farms to estimate the total annual manure production on the farm. Instead, it asks questions about the volume of different manure storage structures. In order to estimate the total manure production on the farm, the calculation in equation 1 was calculated for each farm.

\[
(1) \text{Manure} = M_l \times 365 \times \text{lactating} + M_d \times 365 \times \text{dry}
\]

Where \text{manure} is the annual total quantity of manure produced by each farm, \(M_l\) is a parameter for the average daily pounds of manure produced by lactating cows, \text{lactating} is the average number of lactating cows, \(M_d\) is a parameter for the average daily pounds of manure produced by dry cows, and \text{dry} is the average number of dry cows. In accordance with estimates produced by the ASAE, the parameters for manure production were set to 150 and 83 pounds per animal per day for lactating and dry cows.

---

\(^1\)The states covered by the survey are AZ, CA, FL, GA, ID, IL, IN, IA, KY, ME, MI, MN, MO, NM, NY, OH, OR, PA, TN, TX, VT, VA, WA, WI
respectively (ASAE). The estimates of total manure production are on an as excreted basis and include both feces and urine.

The structure of the dairy industry continues to undergo a shift toward larger operations (LaDue, Gloy, and Cuykendall; MacDonald and McBride). As a result, the nearly half of all of the milk and manure produced in the U.S. comes from the approximately 5.3 percent of dairy farms that milk in excess of 500 cows (Table 1).

Table 1. Percent of milk production, manure production, and farms, U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>Size Category</th>
<th>Milk</th>
<th>Manure</th>
<th>Farms</th>
</tr>
</thead>
<tbody>
<tr>
<td>less than 100 cows</td>
<td>19.4</td>
<td>22.7</td>
<td>66.2</td>
</tr>
<tr>
<td>100 to 500</td>
<td>33.9</td>
<td>34.4</td>
<td>28.5</td>
</tr>
<tr>
<td>500 to 1000</td>
<td>14.5</td>
<td>13.3</td>
<td>3.1</td>
</tr>
<tr>
<td>1000 to 2000</td>
<td>14.5</td>
<td>13.4</td>
<td>1.5</td>
</tr>
<tr>
<td>2000 to 3000</td>
<td>7.3</td>
<td>6.6</td>
<td>0.4</td>
</tr>
<tr>
<td>3000 and over</td>
<td>10.4</td>
<td>9.6</td>
<td>0.3</td>
</tr>
</tbody>
</table>

While any size farm could technically install an AD system, it is likely that larger farms will find an AD system more economical. This study considers how herd size constraints of at least 500 cows, 1,000 cows, and 2,000 cows would impact the number of operations that might adopt an AD system. It is possible that incentives could be developed so as to make AD system installation on smaller operations economically viable. Likewise, technology could be developed that would allow digestion to be viable at smaller farm sizes. An estimate is also made assuming that there are no size restrictions to adoption of an AD system.

Housing and Manure Handling

The method that the farm uses to collect and store manure has an important impact on the potential feasibility of installing an AD system. First, if the animals spend considerable amounts of time grazing, collecting manure is not likely to be feasible. For this reason, all estimates of digesters excluded farms that were primarily grazing operations. Second, if manure is deposited in a dry lot system it is likely to dry and be contaminated with dirt and other foreign materials that make digestion problematic. Likewise, manure handled on a dry basis is unlikely to be of the appropriate moisture content for an AD system. Additionally, manure that is stored dry produces significantly fewer methane emissions than manure stored in anaerobic or slurry systems (US-EPA, 2009). If policy is designed to encourage digester installation on the basis of reducing methane emissions, it should be targeted toward systems that currently produce methane emissions from manure handling.

Farms with manure handling systems that would be conducive to AD system installation were determined by examining the type of manure storage systems used by the farm. The ARMS survey asks respondents to identify the various types of manure
storages on the farm. Table 2 shows the percentage of farms with various types of manure storages on their farms. Because some farms have multiple types of storages, the total percentage of farms does not add to 100. The second most common type of storage is for farms that have no storage system (34.4 percent). This includes farms that spread manure daily or graze their herds.

<table>
<thead>
<tr>
<th>Number of Different Manure Storage Systems</th>
<th>Percent of Farms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slab or Shed</td>
<td>25.2</td>
</tr>
<tr>
<td>Pond or Lagoon</td>
<td>17.9</td>
</tr>
<tr>
<td>Slurry/pit</td>
<td>36.9</td>
</tr>
<tr>
<td>No Storage</td>
<td>34.4</td>
</tr>
</tbody>
</table>

a The total exceeds 100 percent because some farms use more than one type of storage system.

Farms with pond or lagoon or slurry/pit systems were identified as possible candidates for AD systems. The types of storage that are appropriate for AD systems are slurry based systems or lagoon systems. Either one of these or both of these systems are present on approximately 55 percent of dairy farms.

Information about the type of manure storage on the farm was used to estimate the carbon dioxide equivalent (CO2e) emissions of the farm from manure in metric tons. The estimates were developed by characterizing the overall manure handling system as an anaerobic lagoon based system, a slurry/pit system, or neither. The Chicago Climate Exchange (CCX) uses these classifications and the state the farm is located to determine the potential methane emissions from manure under its ex ante approach to calculated emission reduction associated with methane destruction (Chicago Climate Exchange). These calculations are part of the process that the CCX uses to calculate offsets for agricultural methane collection and combustion.

The procedure used to estimate the methane emissions for each farm follows the ex-ante procedure and parameter estimates developed by the CCX. As such, the approach used is to identify farms with either a slurry/pit system or an anaerobic lagoon based system. Once these are identified the CCX methane emission factors for each state and the number of dairy cows on the farm are used to calculate the total CO2e methane emissions for the farm. The procedure used in this paper does not consider dairy animals other than cows. To the extent that animals identified in ARMS as milking cows are actually heifers, this approach would overestimate methane emissions from the farm. However, it should be noted that CCX makes no distinction between lactating and dry dairy cows. Because the manure production from lactating animals is nearly twice that of dry animals, the CCX protocol likely overestimates methane emissions as well.

Additionally, when a farm has both pit/slurry systems and anaerobic systems, the CCX protocol would require that the emissions be calculated accordingly. The approach in this paper is to use the estimate from anaerobic lagoons when both types of storages are available. This was done because it was not possible to accurately
determine the relative proportion of manure held in the various storages. As such, the process in the paper will likely overestimate methane emissions from manure handling. In total, the methane emissions estimates are believed to be as accurate as can be possible with the level of data that is available at the national level.

Specifically, methane emissions are estimated for each farm according to equation 2.

\[
(2) \text{Manure Emissions}_{S,T} = \text{EF}_{S,T} \times \text{Cows}
\]

Where Manure Emissions\(_{S,T}\) is the carbon dioxide equivalent emissions of methane in metric tons/farm/year for a farm in state \(S\) with manure storage type \(T\), \(T\) is the type of manure storage (either anaerobic lagoon or slurry/pit), \(\text{EF}_{S,T}\) is the emission factor for each state and type of manure storage in metric tons of \(\text{CO}_2\)e per cow per year, and Cows is the average number of dairy cows on the farm. The emissions factors (\(\text{EF}_{S,T}\)) are taken from the Chicago Climate Exchange protocols for agricultural methane gas projects.

The installation of an AD system should enable the farm to significantly reduce the methane emissions associated with manure management. In order to determine the potential methane emission reduction that could be achieved by AD installation the calculation procedure in equation 2 was used to estimate the CO2e methane emissions from manure for U.S. dairy farms (Table 3).

Table 3. Carbon Dioxide equivalent emissions of methane from manure management on U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>All Farms</th>
<th>All Farms</th>
<th>Farms With Manure Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of Farms (%)</td>
<td>100</td>
<td>50.25</td>
</tr>
<tr>
<td>Manure CO2e (MT/farm/year)</td>
<td>412.28</td>
<td>820.47</td>
</tr>
<tr>
<td>Manure CO2e per cow (MT/cow/year)</td>
<td>1.378</td>
<td>2.741</td>
</tr>
<tr>
<td>Manure CO2e per cwt (MT/cwt/year)</td>
<td>0.0086</td>
<td>0.0171</td>
</tr>
<tr>
<td>Average Number of Cows</td>
<td>155</td>
<td>220</td>
</tr>
<tr>
<td>Average Rate of Milk Production (lbs/cow/year)</td>
<td>16,544</td>
<td>17,827</td>
</tr>
</tbody>
</table>

Based upon the manure storage structures present on the farm approximately half of the dairy farms generate methane emissions from manure storages. Considering all farms, including those with no estimated methane emissions from manure storages, the average dairy farm in the U.S. generates 412 metric tons of CO2e methane emissions from their manure storage. Considering only farms that generate emissions, the average CO2e manure methane emission climbs to 820 MT per farm. For farms with manure emissions, each hundred weight of milk production produces roughly 0.0171 MT’s of CO2e methane emissions. As one can see, the typical farm with manure methane emissions is larger than average and has a higher average rate of milk production per cow per year.
In order to provide some context with which to understand the CO2e emission levels one can compare them to some more basic activities. For instance, the U.S. EPA (2005) estimates that the typical passenger vehicle in the U.S. generates greenhouse gas emissions of 5.5 MT of CO2e annually. In other words, considering farms with manure methane emissions, the average U.S. dairy farm has manure methane emissions equivalent to 149 passenger vehicles. Likewise, the EPA estimates that roughly 4 MT of CO2e per person per year are emitted from U.S. homes, making the average CO2e emissions from manure equivalent to roughly 205 U.S. homes. Clearly, these comparisons are only intended to be illustrative.

Financial Condition

Because AD systems require substantial amounts of capital, the financial condition of the farm will play a key role in system adoption. The major capital expenditures associated with an AD system include construction of the AD reactor, the electrical generator (or other energy conversion device), and modifications to the existing manure handling system. While there is little publically available data regarding the magnitude of these costs, several studies have estimated these expenses for feasibility studies and the estimates of capital costs have varied widely.

For example, Enahoro and Gloy examine installation of an AD system on a 1,000 cow New York farm. They used studies from the Cornell Manure Management Program to estimate capital expenses at $940 per cow. They also note that the US-EPA’s FarmWare AD evaluation tool produces a capital expense estimate for the same system of $788 per cow. Continuing with the large disparity in capital budgets for AD systems, Lazorus and Rudstrom estimate capital costs at roughly $530 per cow for an 800 cow system in Minnesota. Reflecting the economies of scale described earlier, Leuer, Hyde and Richard estimate that the capital costs at $1,608 and $887 per cow for 500 and 2000 cow installations respectively.

Kramer reports the capital costs for several AD systems noting a range of installed costs of $417 to $763 per head. Additionally, Kramer notes that simple covered lagoon digesters can be installed at substantially lower cost, from $57 to $78 per head. Ultimately, the capital cost of an AD system is dependent upon the type of digester installed and producing an exact estimate applicable to all digesters is not realistic. However, it is clear from previous studies that the digester is a substantial capital investment and one should consider whether dairy farms are in a position to make such an investment.

A number of measures were calculated in order to assess how financial condition would influence the likelihood that a farm would be able to adopt an AD system. Because the payoff to an AD system occurs over a relatively long period of time, it is important to consider how long the farm plans to operate. Table 4 shows the expected operating life of U.S. dairy farms by herd size. Over 20 percent of all U.S. dairy farms plan to operate for less than 6 additional years. These farms would be unlikely to adopt an AD system because it is unlikely that they would receive enough financial benefits to
justified adoption. Slightly more than 30 percent of all operations expect to operate for more than 20 years. As one would expect, the data in the table also indicate that as opposed to farms with fewer than 500 cows, a much greater proportion of larger farms expect to have a lifespan in excess of 20 years.

Table 4. Expected life of dairy farm by farm size, percent of U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>Expected Farm Life</th>
<th>Number of Cows</th>
<th>Refused</th>
<th>Less than 100 Cows</th>
<th>100 to 500</th>
<th>500 to 1,000</th>
<th>1,000 to 2,000</th>
<th>2,000 to 3,000</th>
<th>Over 3,000</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>More than 20 years</td>
<td></td>
<td>22.7</td>
<td>41.8</td>
<td>63.1</td>
<td>64.9</td>
<td>57.9</td>
<td>85.3</td>
<td>30.4</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>66.2</td>
<td>28.5</td>
<td>3.1</td>
<td>1.5</td>
<td>0.4</td>
<td>0.3</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

N = 52,237 U.S. Dairy Farms, based on sample of 1,814 observations

In addition to expectations about operating lifespan, one should also consider the financial condition of the dairy farms when examining the potential for AD adoption. Farms with substantial debt and poor cash flow are unlikely to have the financial capacity necessary to make the significant investment that would be required to install and AD system. Table 5 shows how the proportion of assets financed with debt (debt to asset ratio) in 2005. Farms with greater proportions of existing debt are less likely to be able to adopt as they are more financially constrained.

Table 5. Debt to asset ratio for U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>Debt to Asset Ratio</th>
<th>Percent of Farms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 20%</td>
<td>71.7</td>
</tr>
<tr>
<td>20% to 40%</td>
<td>21.8</td>
</tr>
<tr>
<td>40% to 60%</td>
<td>4.5</td>
</tr>
<tr>
<td>Over 60%</td>
<td>2.0</td>
</tr>
</tbody>
</table>

The debt coverage ratio was calculated in order to measure the cash flow generation of U.S. dairy farms relative to their debt servicing requirements (Table 6). The debt coverage ratio is a measure of the farm's cash flow position and describes how well the farm produces cash flow to service its debts. Here, larger values indicate larger amounts of cash flow relative to debt servicing requirements, placing the farm operation in a more comfortable financial position. Slightly over half of the farms had a debt coverage ratio in excess of 3 meaning that they had cash flow sufficient to cover their debt service requirements 3 times over.

<table>
<thead>
<tr>
<th>Debt Coverage Ratio</th>
<th>Percent of Farms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater than 6</td>
<td>38.4</td>
</tr>
<tr>
<td>3 to 6</td>
<td>18.0</td>
</tr>
<tr>
<td>2 to 3</td>
<td>13.2</td>
</tr>
<tr>
<td>Less than 2</td>
<td>30.6</td>
</tr>
</tbody>
</table>

Criteria for Digester Adoption

The various criteria discussed above were used to construct a variety of constraints that were used to evaluate the potential adoption of AD systems on U.S. dairy farms. Five different scenarios were developed ranging from restrictive to just identifying farms that would be eligible for manure methane reductions by installing an AD system under CCX rules (Table 7). After the application of the constraints for each scenario, the number of farms eligible to adopt AD systems were identified and the manure methane emissions associated with these farms were calculated.

In order for a farm to be able to adopt an AD in the restrictive scenario, the farm must be eligible for CCX (store manure in slurry or anaerobic conditions), expect to operate for at least 20 years, have a debt to asset ratio less than 20%, and a debt coverage ratio (DCR) greater than 3. The less restrictive scenario relaxes the debt coverage ratio requirement and only focuses on the debt to asset ratio. This was done because the debt coverage ratio can vary substantially from year to year and some farms in very sound financial condition could easily experience a year in which the debt coverage ratio was less than 3.

The first unrestricted scenario requires that the farm be eligible for CCX, expects to operate for at least 10 years, and have a debt to asset ratio less than 40%. This scenario identifies farms in relatively strong financial condition and farms that expect to operate for a considerable period of time. The scenario labeled unrestricted A eliminates the condition that the farm plans to operate for at least 10 years. The final scenario, CCX, considers only whether farms store manure in anaerobic conditions.

Table 7. Summary of constraints applied to various scenarios for AD system adoption, U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>Constraint</th>
<th>Restrictive</th>
<th>Less Restrictive</th>
<th>Unrestrictive</th>
<th>Unrestrictive A</th>
<th>CCX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eligible for CCX</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Farm Life ≥ 20 Years</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Farm Life ≥ 10 Years</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D/A Ratio ≤ 20%</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D/A Ratio ≤ 40%</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCR ≥3</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RESULTS

The scenarios in Table 7 were applied to the 2005 ARMS dairy data. The results indicate the number of farms able to adopt AD systems under various constraints (Table 8). Here, one can see that if no farm size constraints are considered and the least restrictive constraint set is applied, anaerobic manure storage (CCX), nearly 26,248 could technically reduce manure methane emissions through the installation of an AD system (final column of Table 8). However, one can see that most of these farms are smaller in size. If only farms over 500 cows are considered under the anaerobic storage requirement, the number of potential farms drops to 2,256 farms.

As one applies more restrictive assumptions about the characteristics required for adoption, the number of farms able to adopt an AD system declines rapidly. For instance, under the most restrictive assumptions and assuming that a 500 cow farm is the minimum efficient scale for an AD system only 318 farms would be good candidates for AD systems. In other words, the number of AD systems currently installed on U.S. dairy farms is about one third of the total potential. If one were to assume that any size farm could adopt, then the potential number would increase to 2,883 farms.

Overall, several important findings can be derived from these results. First, the role of farm size is critical in determining the number of farms that could potentially adopt an AD system. As the minimum farm size increase, the number of potential AD systems declines rapidly. These results indicate that if one hopes to achieve widespread adoption of AD systems that it is important to develop technology that can be applied on smaller dairy farms.

Second, the financial and operating characteristics of the farms are critical considerations in AD adoption. While there are 2,256 farms over 500 cows that store manure in anaerobic conditions, many are unlikely to adopt because they either do not expect to remain in operation much longer or their financial condition is such that they would be unlikely to adopt an AD system at this time. This means that either the profitability of AD systems will have to be improved greatly to encourage adoption and/or financing incentives or grants will likely be required for broader adoption.

Once the number of farms able to adopt AD systems were determined, it was possible to calculate how adoption of digesters on these farms would influence the total amount of CO2e emissions from manure storages (Table 9). The calculations in Table 9 were completed using the methane emission factors developed by the CCX. These factors include only methane that would normally be emitted from these storages, not the amount of methane that would be produced by the AD systems.

The results show that even with only a modest adoption of AD systems, it is possible to achieve relatively significant reductions in the amount of methane produced by U.S. dairy farms. For instance, even under the most restrictive assumptions, nearly 15 percent of the manure methane emissions of the U.S. dairy sector could be reduced through the adoption of AD systems on only 2,883 dairy farms. If only farms over 500
cows were to adopt under the most restrictive constraints, nearly 11% of the methane emissions could be eliminated.

Table 8. Number of dairy farms able to adopt digesters under various viability assumptions, U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>Farm Size (Cows)</th>
<th>Restrictive(^a)</th>
<th>Less Restrictive(^b)</th>
<th>Unrestrictive(^c)</th>
<th>Unrestrictive A(^d)</th>
<th>CCX(^e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 500</td>
<td>318</td>
<td>630</td>
<td>1,322</td>
<td>1,675</td>
<td>2,256</td>
</tr>
<tr>
<td>Over 1,000</td>
<td>155</td>
<td>261</td>
<td>523</td>
<td>691</td>
<td>922</td>
</tr>
<tr>
<td>Over 2,000</td>
<td>52</td>
<td>74</td>
<td>146</td>
<td>187</td>
<td>288</td>
</tr>
<tr>
<td>All Farms</td>
<td>2,883</td>
<td>5,598</td>
<td>13,275</td>
<td>23,441</td>
<td>26,248</td>
</tr>
</tbody>
</table>

\(^a\)Restrictive = Farm life at least 20 years, eligible for CCX, debt to asset ratio less than 20 percent, and a debt coverage ratio greater than 6.
\(^b\)Less restrictive = The same as above with no debt coverage restriction.
\(^c\)Unrestrictive = Farm life greater than 10 years, eligible for CCX, debt to asset ratio less than 40 percent.
\(^d\)Unrestrictive A = Eligible for CCX and a debt to asset ratio less than 40 percent.
\(^e\)CCX = Farms eligible for CCX.

The results indicate that technical and financial constraints are likely to be a barrier to widespread adoption of AD systems. Economic constraints related to the financial condition of the dairy farms, greatly reduce the number of farms that are able to adopt systems. If these constraints were lessened through either grants or increased returns to AD systems, it is possible that substantial amounts of the manure methane emissions of the sector could be reduced. These incentives would allow one to move to the right in Tables 8 and 9 where larger numbers of farms were able to adopt, and greater amounts of manure methane emissions captured.

One method in which this could be accomplished would be to compensate dairy producers for methane emission reductions produced by AD systems. Here, the question becomes how would various price levels for CO2e emission reductions influence adoption?\(^2\) While the analysis of that question in detail is beyond the scope of this paper, it is possible to illustrate how different carbon prices would influence the revenue generated by the AD system. Table 10 shows the potential CO2e offset revenue that would be generated at different carbon offset prices.

---

\(^2\) For a detailed analysis of this question, readers should consult Gloy (2011) where a thorough analysis with a supply curve which shows how digester adoption varies with carbon offset prices is presented.
Table 10. Average potential offset revenue (\$/s) under various CO2e offset prices ($/Mt), U.S. dairy farms, 2005.

<table>
<thead>
<tr>
<th>Farm Size (Cows)</th>
<th>$13/Mt</th>
<th>$20/Mt</th>
<th>$40/Mt</th>
<th>$60/Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over 500</td>
<td>84,084</td>
<td>129,360</td>
<td>258,720</td>
<td>388,080</td>
</tr>
<tr>
<td>Over 1,000</td>
<td>148,473</td>
<td>228,420</td>
<td>456,840</td>
<td>685,260</td>
</tr>
<tr>
<td>Over 2,000</td>
<td>310,154</td>
<td>477,160</td>
<td>954,320</td>
<td>1,431,480</td>
</tr>
<tr>
<td>All Farms</td>
<td>11,258</td>
<td>17,320</td>
<td>34,640</td>
<td>51,960</td>
</tr>
</tbody>
</table>

These results indicate that under different carbon prices offset revenues could provide a substantial revenue stream for some dairy farms. The more thorough analysis of this issue in Gloy (2011) indicates that roughly 2,300 farms would be able to economically justify AD adoption at offset prices between $10 and $20 per Mt. Further, he found that a price of $20 per Mt for CO2e offsets would results in approximately a 60% reduction of manure methane emissions from 2005 levels.

SUMMARY

Anaerobic digestion (AD) systems provide a number of potential benefits for dairy farmers and society in general. However, their adoption has been slowed by a number of economic and technical constraints. This article illustrated how several technical and financial constraints influences the potential adoption of AD systems. If more farms are to adopt AD systems, it will be necessary to improve the economics of AD systems on smaller farms, and/or improve the financial incentives associated with adoption.

One possible approach is to provide greater financial grants to ease the capital constraints associated with AD adoption. This would allow more farms to adopt AD systems. In addition, providing a price for manure methane emission reductions would improve the economics of AD adoption, although relatively high prices are likely required to make AD widely adopted.

Given the economic concentration in the dairy industry, it is possible to achieve a large reduction in the manure methane emissions of the sector by installing digesters on a relatively small number of the largest U.S. dairy farms. For instance, manure methane emissions could be reduced by nearly 25% with the installation of AD systems on less than 1% of U.S. dairy farms. However, it is very important to realize that many of these farms would require substantial financial assistance in order to justify adoption.
REFERENCES


FINANCIAL FEASIBILITY OF BIODIGESTER DEVELOPMENT IN WASHINGTON STATE

N. Lake-Brown
David Paul Rosen & Associates
Irvine, CA

INTRODUCTION AND METHODOLOGY

David Paul Rosen & Associates (DRA) was retained by the Washington State Housing Financing Commission (WSHFC) to analyze the financial feasibility of anaerobic biodigester development in Washington State. DRA interviewed biodigester developers, operators, contractors and consultants to identify issues and obstacles regarding the feasibility of biodigester development in the State.

DRA found that the biodigester industry in Washington State is rapidly changing as new sources of feedstocks and new revenue sources from biodigester by-products are tested and developed. In addition, funding sources that assisted development of the first six operating dairy-based biodigesters in the State are in flux.

Under State law, certain anaerobic biodigesters are allowed to operate without a solid waste permit, provided operators meet certain conditions. Anaerobic biodigesters located on or near dairies that co-digest organic wastes with manure may qualify for this permit exemption if other conditions are met. In order to qualify for the exemption, the digester must use at least 51 percent livestock manure and may include up to 30 percent pre-consumer organic waste. On-farm wastes may comprise the other 20 percent. Other conditions must also be met.

DRA modeled the financial feasibility of two prototypical dairy biodigester projects, with 2,000 and 750 cows, respectively, assuming the biodigester owner sells the electricity it produces to the local utility provider.

DRA modeled the supportable first mortgage debt based on the projected net operating income from the biodigester prototype assuming a 1.5 debt coverage ratio, a maximum loan-to-value ratio of 80%, and an interest rate of 8.0%, with a 20-year amortization period, based on input from the biodigester interviews. We also modeled a second alternative assuming tax-exempt bond financing at a 5.0% interest rate.

We then calculated the amount of equity that may be raised assuming a required internal rate of return (IRR) for the equity investment of 20 percent. DRA also modeled a second alternative assuming an IRR of 15 percent.

The difference between the total development cost of the prototype and the combined total of debt and equity equals the funding shortfall that would need to be filled by subsidized gap financing sources.
All six of the currently operating biodigesters in Washington State received
government financial assistance, such as federal stimulus funds, the 30% Treasury
grant in lieu of an investment tax credits, and USDA Rural Energy for America (REAP)
grants to close the gap between the amount of serviceable debt and total development
costs. However, given the demise of these funding sources, DRA analyzed financial
feasibility of digester development without gap financing to determine if, and under what
conditions, biodigester development is financially feasible without subsidy. The
assumptions used in DRA’s financial analysis are described below.

EXISTING OPERATING DIGESTERS IN WASHINGTON STATE

DRA gathered information in June 2011 on the six dairy-related anaerobic
biodigesters currently operating in Washington State.¹ Characteristics of these
biodigesters are described in Table 1 and summarized as follows:

- Three of the biodigesters are located in Whatcom County, with one each in Skagit,
  Snohomish and Yakima counties.
- Two of the biodigester projects are owned by Farm Power Northwest, three are
  owned by the dairies on which they are located, and one is owned by a nonprofit
corporation involving representation from local dairy owners, the Tulalip Tribe, and a
salmon recovery organization.
- Five of the biodigesters were designed by GHD/Andgar; the sixth biodigester was
designed by DariTech.
- Production capacity of the biodigesters ranges from 400 kW to 1.2 MW.
- The number of cows feeding the biodigesters ranges from 1,000 to 5,300.

FINANCIAL ANALYSIS ASSUMPTIONS

Electricity Prices and Generation

In Washington, the three investor-owned utilities (IOUs) – Pacific Power, Avista
Corporation, and Puget Sound Energy – are required to set and publish tariffs for their
purchase of renewable energy at its avoided cost. Avista and Pacific Power’s avoided
cost rates apply to qualified renewable energy projects that are 1 MW of rated capacity
or less. Puget Sound Energy’s rates apply to qualified projects that are up to 2 MW. For
contracts executed in 2010, Puget Sound Energy paid $0.08467 per kWh for power
produced in 2010 and increases the purchase price throughout the term of the contract
until it reaches $0.10838 in 2020.

¹ Does not include all biodigester operations in Washington. Wastewater treatment plants and industrial
facilities also use biodigester technology.
### Table 1: Currently operating agricultural/dairy anaerobic biodigesters, Washington State, July 2011

<table>
<thead>
<tr>
<th>Digester Name</th>
<th>FPE Renewables</th>
<th>George DeRuyter &amp; Sons</th>
<th>Qualco Energy</th>
<th>Farm Power Rexville</th>
<th>Farm Power Lynden</th>
<th>Van Dyk-S Holsteins</th>
</tr>
</thead>
<tbody>
<tr>
<td>Town</td>
<td>Lynden</td>
<td>Outlook</td>
<td>Monroe</td>
<td>Rexville</td>
<td>Lynden</td>
<td>Lynden</td>
</tr>
<tr>
<td>County</td>
<td>Whatcom</td>
<td>Yakima</td>
<td>Snohomish</td>
<td>Skagit</td>
<td>Whatcom</td>
<td>Whatcom</td>
</tr>
<tr>
<td>Number of Cows Feeding Digester</td>
<td>1,100 (2 dairies)</td>
<td>5,300 (2 dairies)</td>
<td>1,100 (1 dairy)</td>
<td>1,200 (2 dairies)</td>
<td>2,000 (1 dairy)</td>
<td>1,000 (1 dairy)</td>
</tr>
<tr>
<td>Digester Designer</td>
<td>GHD/Andgar</td>
<td>GHD/Andgar</td>
<td>GHD/Andgar</td>
<td>GHD/Andgar</td>
<td>GHD/Andgar</td>
<td>DariTech</td>
</tr>
<tr>
<td>Digester Type</td>
<td>Hybrid plug flow-complete mix</td>
<td>Hybrid plug flow-complete mix</td>
<td>Hybrid plug flow-complete mix</td>
<td>Hybrid plug flow-complete mix</td>
<td>Hybrid plug flow-complete mix</td>
<td>Complete mix</td>
</tr>
<tr>
<td>Additional solids treatment</td>
<td>None</td>
<td>Addition of bacteria</td>
<td>Two DariTech composters</td>
<td>None</td>
<td>None</td>
<td>DariTech composter</td>
</tr>
<tr>
<td>Rated production capacity</td>
<td>600 kW</td>
<td>1200 kW</td>
<td>450 kW</td>
<td>750 kW</td>
<td>750 kW</td>
<td>400 kW</td>
</tr>
<tr>
<td>Products sold/used from digester</td>
<td>Electricity</td>
<td>Electricity</td>
<td>Electricity</td>
<td>Electricity</td>
<td>Electricity</td>
<td>Electricity</td>
</tr>
<tr>
<td></td>
<td>Solids (bedding)</td>
<td>Solids (peat moss replace.)</td>
<td>Tipping fees</td>
<td>Solids (bedding)</td>
<td>Tipping fees</td>
<td>Solids (bedding)</td>
</tr>
<tr>
<td></td>
<td>Tipping fees</td>
<td>Tipping fees</td>
<td>Carbon credits</td>
<td>Tipping fees</td>
<td>Carbon credits</td>
<td>Tipping fees</td>
</tr>
<tr>
<td></td>
<td>Carbon credits</td>
<td>Carbon credits</td>
<td>Carbon credits</td>
<td>Carbon credits</td>
<td>Carbon credits</td>
<td>Carbon credits</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Heat</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Avista’s avoided cost for a project beginning operation in 2010 was $0.06276 per kWh for a one-year contract. The rate increases with the length of the PPA signed with the renewable energy producer until it reaches $0.06454 per kWh for a 5-year contract. Pacific Power’s avoided cost rate is $0.06133 per kWh plus $1.46 per kW per month for power delivered in 2010.

The three IOUs’ avoided cost tariff schedules show annual increases in the tariffs. The average annual increase for the three schedules is 2.1 percent. We have used this figure as the annual electricity purchase price inflation factor.

DRA estimates electricity output from manure alone at 0.25 kW per cow. Adding 10% food waste is estimated to increase electrical production by 25%. Adding 20% food waste is estimated to increase electrical production by 50% compared to manure alone. A dairy that uses a flush disposal process for manure is estimated to produce 20% less electricity.

Estimations for biogas production were as follows. For scrape dairy manure, 0.25 kW/WCE where WCE refers to a Wet Cow Equivalent, or the manure production from a mature lactating Holstein. Production for flush dairy operations was slightly reduced to 0.20 kW/WCE as present systems require various forms of manure concentration for suitable energy balance, with concentration causing a corresponding loss of some of the energy value in the manure. Co-digestion is a more difficult scenario to obtain a suitable rule of thumb. Braun et al (2003) and Kumke et al (2000) in their review of European dairy manure digesters have stated that biogas production can be elevated by a range of 20-400% depending upon degree and type of supplementation with outside organics. Frear et al (2011), during a long-term analysis of a Washington State dairy biodigester, have shown that a 20% pre-consumer food processing wastes with dairy manure resulted in approximately a 100% increase in biogas production as compared to a manure-alone control. Historical review of European co-digestion practices and economics as well as early findings in localized environments with Washington State have shown that availability, distribution forms and received prices can be strongly affected over time with development of a mature industry with increased biodigester concentration. In particular, many digesters in Europe have turned to digestion of less energy-intensive supplementary organics such as field grasses, grains and residues and away from high-energy food processing waste, fats and greases. This lowers their biogas increase to the lower end of that stated by Braun et al (2003) and Kumke et al (2000).

In anticipation of industry changes for future farm-based biodigester projects and with an eye on conservative evaluation, a generalized rule of thumb for co-digestion with dairy manure has been used in this study. That rule is for 10% volumetric supplementation, an increase in biogas production of 25% and for 20% supplementation, an increase of 50%. While these numbers are half of that shown in the case study of Frear et al (2011), we believe it is a fair but conservative value reflecting future organic waste distribution and form.
Renewable Energy Credits

Renewable energy credits (RECs) are purchased from renewable energy producers at a set rate per kWh of electricity produced. The REC purchase price is set in a contract negotiated and executed annually between the buyer and seller of the REC. The Bonneville Environmental Foundation estimates that a renewable energy system that begins operations in 2012 can sell its RECs at a rate of $0.012 per kWh in the project’s first year in service, increasing by $0.001 per kWh per year until it reaches a negotiated, pre-determined cap.

State law (RCW 19.285.040) allows RECs purchased from distributed generation facilities to count at double the facilities’ output for the utility company purchasing the RECs. Anaerobic biodigesters with a rated capacity of 5 MW or less qualify as distributed generation facilities under this section. Therefore, one would expect that anaerobic biodigester owners should be able to sell the RECs associated with their facilities at double the market REC price.

The biodigester operators we interviewed sell their RECs along with their produced electricity to the local utility provider. They report receiving rates in the $0.01 per kWh range for their RECs.

DRA initially assumes that the biodigester prototype sells RECs at a rate of $0.01 per kWh in its first year of operation, increasing by $0.001 annually. We analyze the sensitivity of the financial feasibility of the prototype to doubling the REC price.

Fiber Sales/Avoided Costs

Substantial research has and is occurring in Washington State regarding the potential use of fiber produced as a by-product to a biodigester operation. Currently, most of the existing dairies that own or contribute manure to biodigesters use the fiber as bedding for their dairy cows, or sell it as bedding to neighboring farmers. We calculate the avoided bedding cost to the farmer at 10 cubic yards per cow per year, with 50% of the fiber used as bedding at an avoided cost of $9.00 per cubic yard.

Fertilizer Sales/Avoided Costs

Research is also being done on nutrient extraction from biodigester effluent, which may be sold as fertilizer in liquid or pelleted form. Currently, most dairies that own or contribute manure to biodigesters use the liquid effluent on their own fields. Since the use of fertilizer by-products from the biodigester may just replace the use of manure itself, the benefit is difficult to quantify. We have not assumed any sales revenue or avoided cost from fertilizer in our financial modeling.
Tipping Fees

The feasibility of the prototype is analyzed with and without tipping fees. Tipping fee revenue, when included, is estimated at $12 per ton of food waste used in the biodigester each year.

Carbon Credits

The carbon credit market is in flux and has yet to be stabilized. Our baseline financial analysis assumes no revenue from carbon credits, while our sensitivity analysis examines the effect of carbon credit sales assuming 3.5 tons of carbon credits per cow, and a carbon credit price per ton of $8.00.

Operating Costs

Operating costs are estimated at $0.028 per kWh based on our research and interviews. This includes maintenance on equipment in the engine room at $.007 per kWh, maintenance on the separator at $.007 per kWh, and long-term maintenance agreement for major problems at $.008 per kWh, and sinking fund at $.006 per kWh. It also includes daily monitoring costs and insurance costs estimated at $20,000 per year.

Escalation Rates

As noted above, electricity rates are escalated at 2.10 percent annually. Other revenues (from fiber, tipping fees and carbon credits) are escalated at 2% annually. Operating costs are escalated at 4% annually.

RESULTS

The findings of the financial sensitivity analysis are summarized in Table 2, for the 2,000 cow biodigester, assuming an internal rate of return on equity of 20%, and Table 3 assuming a 15% IRR on equity. The table shows whether each scenario is feasible without additional gap financing. The findings are summarized as follows:

- With tipping fees, the prototype is feasible at the Puget Sound Energy electricity purchase rate assuming 10% waste feedstock and a 20% IRR on equity.
- At the Pacific Power electricity rate, the prototype is feasible with 10% waste feedstock, tipping fees, carbon credits, and a lower interest rate.
- The prototype is close to being feasible with 20% waste feedstock without tipping fees at the lower Pacific Power electricity rate.
Table 2: Financial Sensitivity Analysis Scenarios, 2000 Cow Dairy Anaerobic Biodigester, 20% Return on Equity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Puget Sound</td>
<td>Puget Sound</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Carbon Credits</td>
</tr>
<tr>
<td>Equity</td>
<td>$900,000</td>
<td>$953,101</td>
<td>$700,000</td>
<td>$850,000</td>
<td>$1,000,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$2,613,759</td>
<td>$3,046,899</td>
<td>$1,926,055</td>
<td>$2,359,196</td>
<td>$2,731,143</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$486,241</td>
<td>$0</td>
<td>$1,373,945</td>
<td>$790,804</td>
<td>$268,857</td>
</tr>
<tr>
<td>Total Sources/Uses</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
</tr>
<tr>
<td>Annual Loan Interest Rate</td>
<td>8.00%</td>
<td>8.00%</td>
<td>8.00%</td>
<td>8.00%</td>
<td>8.00%</td>
</tr>
<tr>
<td>Amortization Period (Years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required Debt Coverage Ratio (DCR)</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Max. Loan to Value Ratio (LTV)</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Max. Ann. Debt Service Based on DCR</td>
<td>$262,350</td>
<td>$305,826</td>
<td>$193,324</td>
<td>$236,799</td>
<td>$274,132</td>
</tr>
<tr>
<td>Debt Serv. Based on Min. of DCR/LTV</td>
<td>$262,350</td>
<td>$305,826</td>
<td>$193,324</td>
<td>$236,799</td>
<td>$274,132</td>
</tr>
<tr>
<td>Min. Required Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Projected Return on Equity (IRR)</td>
<td>20%</td>
<td>22%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Table 2 (Continued): Financial Sensitivity Analysis Scenarios, 2000 Cow Dairy Anaerobic Biodigester, 20% Return on Equity

<table>
<thead>
<tr>
<th>Scenario:</th>
<th>Scenario 6</th>
<th>Scenario 7</th>
<th>Scenario 8</th>
<th>Scenario 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>20%</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
</tr>
<tr>
<td>Other</td>
<td>Double REC Price</td>
<td>Carbon Credits</td>
<td>Carbon Credits</td>
<td>Carbon Credits</td>
</tr>
<tr>
<td>Equity</td>
<td>$900,000</td>
<td>$1,000,000</td>
<td>$650,000</td>
<td>$800,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$2,660,294</td>
<td>$2,752,199</td>
<td>$2,336,872</td>
<td>$3,200,000</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$439,706</td>
<td>$247,801</td>
<td>$1,013,128</td>
<td>$0</td>
</tr>
<tr>
<td>Total Sources/Uses:</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
</tr>
<tr>
<td>Annual Loan Interest Rate</td>
<td>8.00%</td>
<td>8.00%</td>
<td>5.00%</td>
<td>5.00%</td>
</tr>
<tr>
<td>Amortization Period (Years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required Debt Coverage Ratio (DCR)</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Max. Loan to Value Ratio (LTV)</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Max. Ann. Debt Service Based on DCR</td>
<td>$267,021</td>
<td>$276,246</td>
<td>$185,068</td>
<td>$307,377</td>
</tr>
<tr>
<td>Debt Serv. Based on Min. of DCR/LTV</td>
<td>$267,021</td>
<td>$276,246</td>
<td>$185,068</td>
<td>$253,423</td>
</tr>
<tr>
<td>Min. Required Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Projected Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>31%</td>
</tr>
</tbody>
</table>
Table 2 (Continued): Financial Sensitivity Analysis Scenarios, 2000 Cow Dairy Anaerobic Biodigester, 20% Return on Equity

<table>
<thead>
<tr>
<th>Scenario:</th>
<th>Scenario 10</th>
<th>Scenario 11</th>
<th>Scenario 12</th>
<th>Scenario 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Flush Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Puget Sound</td>
<td>Puget Sound</td>
<td>Pacific Power</td>
<td>Puget Sound</td>
</tr>
<tr>
<td>Other</td>
<td>Carbon Credits</td>
<td>PTC</td>
<td>PTC</td>
<td>PTC</td>
</tr>
<tr>
<td>Equity</td>
<td>$800,000</td>
<td>$800,000</td>
<td>$750,000</td>
<td>$625,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$3,200,000</td>
<td>$3,200,000</td>
<td>$3,200,000</td>
<td>$2,981,892</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$0</td>
<td>$0</td>
<td>$50,000</td>
<td>$1,193,108</td>
</tr>
<tr>
<td>Total Sources/Uses:</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,800,000</td>
</tr>
<tr>
<td>Annual Loan Interest Rate</td>
<td>5.00%</td>
<td>5.00%</td>
<td>5.00%</td>
<td>5.00%</td>
</tr>
<tr>
<td>Amortization Period (Years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required Debt Coverage Ratio (DCR)</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Max. Loan to Value Ratio (LTV)</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Debt Serv. Based on Min. of DCR/LTV</td>
<td>$253,423</td>
<td>$253,423</td>
<td>$253,423</td>
<td>$236,150</td>
</tr>
<tr>
<td>Min. Required Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Projected Return on Equity (IRR)</td>
<td>34%</td>
<td>29%</td>
<td>32%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Table 3: Financial Sensitivity Analysis Scenarios, 2000 Cow Dairy Anaerobic Biodigester, 15% Return on Equity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Puget Sound</td>
<td>Puget Sound</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Carbon Credits</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Equity                    | $1,300,000     | $953,101       | $950,000       | $1,100,000     | $1,268,857     |
| Loan Financing            | $2,613,759     | $3,046,899     | $1,926,055     | $2,359,196     | $2,731,143     |
| Gap Financing Required    | $86,241        | $0             | $1,123,945     | $540,804       | $0             |
| Total Sources:            | $4,000,000     | $4,000,000     | $4,000,000     | $4,000,000     | $4,000,000     |

Financing Assumptions

| Annual Loan Interest Rate | 8.00%          | 8.00%          | 8.00%          | 8.00%          | 8.00%          |
| Amortization Period (Years) | 20             | 20             | 20             | 20             | 20             |
| Required Debt Coverage Ratio   | 1.50           | 1.50           | 1.50           | 1.50           | 1.50           |
| Maximum Loan to Value Ratio   | 80%            | 80%            | 80%            | 80%            | 80%            |
| Max. Ann. Debt Service Based on DCR | $262,350     | $305,826       | $193,324       | $236,799       | $274,132       |
| Debt Service Based on Min. of DCR/LTV | $262,350     | $305,826       | $193,324       | $236,799       | $274,132       |
| Min. Required Return on Equity (IRR) | 15%           | 15%            | 15%            | 15%            | 15%            |
| Projected Return on Equity (IRR) | 15%           | 22%            | 15%            | 15%            | 16%            |
Table 3 (Continued): Financial Sensitivity Analysis Scenarios, 2000 Cow Dairy Anaerobic Biodigester, 15% Return on Equity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 6</th>
<th>Scenario 7</th>
<th>Scenario 8</th>
<th>Scenario 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>20%</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
</tr>
<tr>
<td>Other</td>
<td>Double REC Price</td>
<td>Carbon Credits</td>
<td>Carbon Credits</td>
<td>Carbon Credits</td>
</tr>
<tr>
<td>USDA Value Added Producer Grant (4)</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Equity</td>
<td>$1,250,000</td>
<td>$1,247,801</td>
<td>$900,000</td>
<td>$800,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$2,660,294</td>
<td>$2,752,199</td>
<td>$2,336,872</td>
<td>$3,200,000</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$89,706</td>
<td>$0</td>
<td>$763,128</td>
<td>$0</td>
</tr>
<tr>
<td>Total Sources:</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
</tr>
</tbody>
</table>

Financing Assumptions

- **Annual Loan Interest Rate**: 8.00% 8.00% 5.00% 5.00%
- **Amortization Period (Years)**: 20 20 20 20
- **Required Debt Coverage Ratio**: 1.50 1.50 1.50 1.50
- **Maximum Loan to Value Ratio**: 80% 80% 80% 80%
- **Max. Ann. Debt Service Based on DCR**: $267,021 $276,246 $185,068 $274,132
- **Debt Service Based on Min. of DCR/LTV**: $267,021 $276,246 $185,068 $253,423
- **Min. Required Return on Equity (IRR)**: 15% 15% 15% 15%
- **Projected Return on Equity (IRR)**: 15% 17% 15% 30%
<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 10</th>
<th>Scenario 11</th>
<th>Scenario 12</th>
<th>Scenario 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Flush Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Puget Sound</td>
<td>Puget Sound</td>
<td>Pacific Power</td>
<td>Puget Sound</td>
</tr>
<tr>
<td>Other</td>
<td>Carbon Credits</td>
<td>PTC</td>
<td>PTC</td>
<td>PTC</td>
</tr>
<tr>
<td></td>
<td>Lower Int. Rate</td>
<td>Lower Int. Rate</td>
<td>Lower Int. Rate</td>
<td>Lower Int. Rate</td>
</tr>
<tr>
<td>USDA Value Added Producer Grant (4)</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
</tr>
<tr>
<td>Equity</td>
<td>$800,000</td>
<td>$800,000</td>
<td>$800,000</td>
<td>$850,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$3,200,000</td>
<td>$3,200,000</td>
<td>$3,200,000</td>
<td>$2,981,892</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$0</td>
<td>$0</td>
<td>$0</td>
<td>$968,108</td>
</tr>
<tr>
<td>Total Sources:</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,000,000</td>
<td>$4,800,000</td>
</tr>
</tbody>
</table>

Financing Assumptions

- Annual Loan Interest Rate: 5.00% 5.00% 5.00% 5.00%
- Amortization Period (Years): 20 20 20 20
- Required Debt Coverage Ratio: 1.50 1.50 1.50 1.50
- Maximum Loan to Value Ratio: 80% 80% 80% 80%
- Debt Service Based on Min. of DCR/LTV: $253,423 $253,423 $253,423 $236,150
- Min. Required Return on Equity (IRR): 15% 15% 15% 15%
- Projected Return on Equity (IRR): 34% 29% 30% 15%
• Reducing the interest rate to 5% eliminates the need for gap financing for most of the scenarios modeled, except for the Pacific Power electricity rate and 0% waste feedstock.

• Modeling a flush dairy, as opposed to a scrape dairy, with its assumed higher development costs and lower electricity production, generates a gap even at the Puget Sound Energy power rate, a production tax credit and the lower interest rate.

• Reducing the required IRR on equity to 15% makes almost all of the scenarios modeled feasible.

Table 4 shows the results for the 750-cow biodigester, assuming an internal rate of return on equity of 20%. All of the scenarios generate a gap at both a 20% internal rate of return and a 15% internal rate of return.

REFERENCES

Table 4: Financial Sensitivity Analysis Scenarios, 750-Cow Dairy Anaerobic Biodigester, 20% Return on Equity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
<th>Scenario 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Puget Sound</td>
<td>Puget Sound</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
</tr>
<tr>
<td>Equity</td>
<td>$320,000</td>
<td>$360,000</td>
<td>$225,000</td>
<td>$275,000</td>
<td>$330,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$917,892</td>
<td>$1,080,319</td>
<td>$660,003</td>
<td>$822,431</td>
<td>$961,911</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$1,762,108</td>
<td>$1,559,681</td>
<td>$2,114,997</td>
<td>$1,902,569</td>
<td>$1,708,089</td>
</tr>
<tr>
<td>Total Sources/Uses</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
</tr>
<tr>
<td>Annual Loan Interest Rate</td>
<td>8.00%</td>
<td>8.00%</td>
<td>8.00%</td>
<td>8.00%</td>
<td>8.00%</td>
</tr>
<tr>
<td>Amortization Period (Years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required Debt Coverage Ratio</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Maximum Loan to Value Ratio</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Debt Service Based on Min. of DCR/LTV</td>
<td>$92,131</td>
<td>$108,435</td>
<td>$66,246</td>
<td>$82,550</td>
<td>$96,550</td>
</tr>
<tr>
<td>Min. Required Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Projected Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>

Carbon Credits
Table 4: Financial Sensitivity Analysis Scenarios, 750-Cow Dairy Anaerobic Biodigester, 20% Return on Equity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 6</th>
<th>Scenario 7</th>
<th>Scenario 8</th>
<th>Scenario 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>20%</td>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
<td>Pacific Power</td>
</tr>
<tr>
<td>Other</td>
<td>Double REC Price</td>
<td>Carbon Credits</td>
<td>Carbon Credits</td>
<td>Carbon Credits</td>
</tr>
<tr>
<td>Equity</td>
<td>$315,000</td>
<td>$350,000</td>
<td>$220,000</td>
<td>$375,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$935,342</td>
<td>$969,807</td>
<td>$797,408</td>
<td>$1,376,560</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$1,749,658</td>
<td>$1,680,193</td>
<td>$1,982,592</td>
<td>$1,248,440</td>
</tr>
<tr>
<td>Total Sources/Uses</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
</tr>
<tr>
<td>Annual Loan Interest Rate</td>
<td>8.00%</td>
<td>8.00%</td>
<td>5.00%</td>
<td>5.00%</td>
</tr>
<tr>
<td>Amortization Period (Years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required Debt Coverage Ratio</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Maximum Loan to Value Ratio</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Max. Ann. Debt Service Based on DCR</td>
<td>$93,883</td>
<td>$97,342</td>
<td>$63,150</td>
<td>$109,016</td>
</tr>
<tr>
<td>Debt Service Based on Min. of DCR/LTV</td>
<td>$93,883</td>
<td>$97,342</td>
<td>$63,150</td>
<td>$109,016</td>
</tr>
<tr>
<td>Min. Required Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Projected Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>
Table 4: Financial Sensitivity Analysis Scenarios, 750-Cow Dairy Anaerobic Biodigester, 20% Return on Equity

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Scenario 10</th>
<th>Scenario 11</th>
<th>Scenario 12</th>
<th>Scenario 13</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Food Waste</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Tipping Fees?</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Dairy Manure Disposal System</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Scrape Dairy</td>
<td>Flush Dairy</td>
</tr>
<tr>
<td>Electricity Purchaser</td>
<td>Puget Sound</td>
<td>Puget Sound</td>
<td>Pacific Power</td>
<td>Puget Sound</td>
</tr>
<tr>
<td>Other</td>
<td>Carbon Credits</td>
<td>PTC</td>
<td>PTC</td>
<td>PTC</td>
</tr>
<tr>
<td></td>
<td>Lower Int. Rate</td>
<td>Lower Int. Rate</td>
<td>Lower Int. Rate</td>
<td>Lower Int. Rate</td>
</tr>
<tr>
<td>Equity</td>
<td>$435,000</td>
<td>$325,000</td>
<td>$250,000</td>
<td>$250,000</td>
</tr>
<tr>
<td>Loan Financing</td>
<td>$1,340,132</td>
<td>$1,320,770</td>
<td>$993,917</td>
<td>$1,035,081</td>
</tr>
<tr>
<td>Gap Financing Required</td>
<td>$1,224,868</td>
<td>$1,354,230</td>
<td>$1,756,083</td>
<td>$2,314,919</td>
</tr>
<tr>
<td>Total Sources/Uses</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,000,000</td>
<td>$3,600,000</td>
</tr>
<tr>
<td>Annual Loan Interest Rate</td>
<td>5.00%</td>
<td>5.00%</td>
<td>5.00%</td>
<td>5.00%</td>
</tr>
<tr>
<td>Amortization Period (Years)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Required Debt Coverage Ratio</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
<td>1.50</td>
</tr>
<tr>
<td>Maximum Loan to Value Ratio</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
<td>80%</td>
</tr>
<tr>
<td>Max. Ann. Debt Service Based on DCR</td>
<td>$106,131</td>
<td>$104,598</td>
<td>$78,713</td>
<td>$81,973</td>
</tr>
<tr>
<td>Debt Service Based on Min. of DCR/LTV</td>
<td>$106,131</td>
<td>$104,598</td>
<td>$78,713</td>
<td>$81,973</td>
</tr>
<tr>
<td>Min. Required Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>Projected Return on Equity (IRR)</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
<td>20%</td>
</tr>
</tbody>
</table>
On-Farm Co-Digestion of Food Waste with Dairy Manure

M.S Lisboa, S. Lansing and C. Jackson
Department of Environmental Science and Technology
University of Maryland, College Park, MD

INTRODUCTION

Sustainable management of biowastes is currently a major concern in the United States. As of 2007, the United States had over 1 million livestock and poultry operations, 6.6% of which were dairy facilities - 69,890 dairy farms (US NASS, 2009). A variety of methods are used to collect, store, and treat manure. As concerns over water quality and other environmental factors increase, improved methods for manure treatment, including anaerobic digestion, are being utilized.

Anaerobic digestion is a biological technology for the treatment of organic wastes and the production of biogas, which can be used as a fuel for heating or co-generation of electricity and heat. In addition to renewable energy production, the utilization of anaerobic digestion technology results in other benefits: (1) improved water quality, (2) decreased odor, (3) reduced greenhouse gas emissions, and (4) increased income from non-market benefits (tipping fees, digested fiber, and carbon trading) (Archer and Kirsop, 1990; Powers et al., 1999; USEPA, 2004; Clemens et al., 2006; Klavon, 2011).

Anaerobic digestion of animal manure has been extensively researched and demonstrated. However, based on investment returns from energy production, the economics of dairy digesters are not always favorable due partly to the relatively low biogas yield of dairy manure, as compared to many other types of organic wastes such as food waste. One approach for improving the economics of dairy digesters is to increase their biogas production rate by co-digesting the manure with more degradable wastes, provided that there are appropriate off-farm wastes available in the vicinity of dairy farms and the farm land is capable of incorporating additional nutrients and salts in the off-farm wastes (El Mashad and Zhang, 2010). Nevertheless, the type and ratio of food waste used in the co-digestion process needs to be carefully considered in order to prevent an adverse reduction in biogas production. The purpose of this research was to study the methane production potential of different food waste as a co-digestion substrate with dairy manure.

Study Site

Food waste samples were taken from a dairy farm in Rising Sun, MD that accepts food waste in a covered lagoon digester. The digester input consists of 98% of cow manure and the remaining 2% is a mixture of wastes from cranberry, ice cream, turkey and meatball production processing. The chicken fat and ice-cream wastes are introduced into the digester once a week and the cranberry and meatball fat wastes are adding on alternate weeks.
METHOD

Sample Characterization

The samples were collected in October 2011 and transported to the laboratory on ice. Once reaching the laboratory, the samples were characterized for pH, total solids (TS), volatile solids (VS), and chemical oxygen demand (COD), according to Standard Methods (APHA, 1998).

Specific Methanogenic Activity Test (SMA)

Specific methanogenic activity tests (SMA) were used to characterize available inoculum sources, prior to incubation, as developed by Zeeuw (1984). In this study, the SMA was conducted based on the methods of Sorensen (1993) and used to determinate if the inoculum of the effluent of Kilby farm (co-digestion system) was a better inoculum source for the laboratory testing compared to a inoculum source from a digestion system that does not utilize food waste co-digestion. Effluent and Influent from Kilby digester and the effluent from a dairy manure-only digester at the USDA Beltsville Agricultural Research Center (BARC), located in Beltsville-Maryland, were analyzed.

The SMA test determines accumulated methane in serum bottles (70ml) spiked with acetate over a 48-hour test period. The bottles were filled with 50 ml of the respective test inoculum source and 2 ml of acetate (30 g/l), purged with O₂-free gas (N₂/CO₂ at 70/30), sealed with butyl rubber stoppers and aluminum crimps and placed on a shaker in an environmental chamber at 35°C (Table 1). Gas sampling began three hours after incubation and was determined every three hours for the first 24 hours, and three times per day for the remainder of the 48-hour test period. Bottles without acetate substrate were included as controls and prepared and tested in the manner described above.

### Table 1: SMA test design

<table>
<thead>
<tr>
<th>Inoculum source (ml)</th>
<th>Acetate (ml)</th>
<th>DI water (ml)</th>
<th># Bottles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manure Control</td>
<td>50</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Manure Acetate</td>
<td>50</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Kilby Effluent Control</td>
<td>50</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Kilby Effluent Acetate</td>
<td>50</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>BARC Control</td>
<td>50</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>BARC Acetate</td>
<td>50</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Triplicate samples from each substrate were taken to determinate the TS and VS content of the biomass prior to incubation. To estimate the pH change of the biomass due to gassing and/or addition of substrates, the pH was measure after the addition of each substrate and after purging with the N₂/CO₂ mixture. Additionally, the pH in the bottles at the end of the experiments was measured to check if any significant changes had occurred.
Anaerobic Toxicity Assay (ATA)

Through Anaerobic Toxicity Assays (ATAs), the four industrial food wastes were analyzed in order to determine their potential toxicity as possible co-digestion substrate. Anaerobic inoculum and the standard feedstock were assayed without food waste as controls and in combination with varying percentages of four potential toxicants, as shown in Table 2. The feedstock was prepared based on feedstock requirement reported by Moody (2011).

Table 2: Assay Volume for potential toxicant (2-30% inclusion)

<table>
<thead>
<tr>
<th>Toxicant</th>
<th>2%</th>
<th>5%</th>
<th>15%</th>
<th>30%</th>
<th>0% - control</th>
<th>0% - Glucose Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pot. Toxicant (mL)</td>
<td>0.6</td>
<td>1.6</td>
<td>4.8</td>
<td>9.6</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>DI water (mL)</td>
<td>31.4</td>
<td>30.4</td>
<td>27.2</td>
<td>22.4</td>
<td>34.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Inoculum (mL)</td>
<td>32.0</td>
<td>32.0</td>
<td>32.0</td>
<td>32.0</td>
<td>32.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Feedstock (mL)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>0.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Total Vol.</td>
<td>66</td>
<td>66</td>
<td>66</td>
<td>66</td>
<td>66</td>
<td>66</td>
</tr>
<tr>
<td>Total Gas space</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>94</td>
<td>94</td>
</tr>
<tr>
<td># of Bottles</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

The inoculum for the ATA was the effluent of Kilby farm digester, as identified in the SMA results. The headspace in each bottle was purged with a mix of 30% CO₂ and 70% N₂ to establish anaerobic conditions after the substrates were added to the bottles. The bottles were incubated under mesophilic conditions (35°C) for four days. All assays, including the feedstock and inoculum control, were performed in triplicate. Biogas production and biogas methane content were measured daily. The results were used to calculate the percent inhibition of methane production for each substrate inclusion rate. Biogas production was measured via volume displacement using a 50-mL wetted glass, gas tight graduated syringe with two mL gradations. The methane content of the biogas was determined using an FID Gas Chromatography.

RESULTS

The initial characterizations of the substrate (TS, VS, pH) are provided in Table 3.

Table 3: Characterization of the waste substrates. TS=Total Solids, VS=volatile solids.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>TS (mg/g)</th>
<th>VS (mg/g)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meatball</td>
<td>127</td>
<td>119</td>
<td>4.42</td>
</tr>
<tr>
<td>Chicken</td>
<td>283</td>
<td>271</td>
<td>5.79</td>
</tr>
<tr>
<td>Cranberry</td>
<td>227</td>
<td>227</td>
<td>2.85</td>
</tr>
<tr>
<td>Ice-Cream</td>
<td>5.7</td>
<td>11.6</td>
<td>4.39</td>
</tr>
<tr>
<td>Kilby's Effluent</td>
<td>7.2</td>
<td>6.3</td>
<td>6.88</td>
</tr>
<tr>
<td>BARC Inoculum</td>
<td>15.8</td>
<td>7.9</td>
<td>7.66</td>
</tr>
</tbody>
</table>
SMA Results

The SMA test results showed that the difference between methane production using the Kilby Farm effluent inoculum source and the BARC manure-only digester inoculum source were not significantly different (Figure 1), with the Kilby Farm effluent having a slightly higher methane production compared to the BARC manure-only digester inoculum source, and therefore in the remainder of this study, Kilby’s effluent was chosen as the inoculum source.

Figure 1: Methane production comparing the digester BARC (B) and Kilby’s effluent (E) as inoculum sources with acetate (A) and without acetate (C).

ATA Results

The cumulative daily methane productions for the ATA experiments are shown in Figure 2. After graphing the cumulative production, the linear segment of the resulting curve was selected (between Days 2 and 3) and percent inhibition (I) was calculated for each potential toxicant’s inclusion rate using Equation 1, a modification from the one proposed in Moody et al. (2011).

Equation 1:

\[ I = 1 - \left[ \frac{(VolCH_4test) - (VolCH_4Con)}{(VolCH_4FeedCon) - (VolCH_4Con)} \right] \times 100 \]
Where \( \text{VolCH}_4\text{test} \) is the methane volume produced per milliliter of toxicant added at the selected time (48 hours) for each potential toxicant percentage inclusion, \( \text{VolCH}_4\text{Con} \) is the volume of methane produced at the selected time for the inoculum control, and \( \text{VolCH}_4\text{FeedCon} \) is the volume of methane produced at the selected time for the feedstock control. A negative value for percent inhibition indicates there was no inhibition; a positive value indicates the percentage inhibition related to the potential toxicant.

For all the four substrates tested, the ATA results showed effects of toxicity (Table 4). For cranberry waste and meatball fat, the methane production for each inclusion rate was lower than the feed control (only containing standard feedstock and inoculum) (Figure 2a & 2b). For chicken fat and ice cream wastes, the methane production was lower than the feed control for all the inclusion rates, except the 2% where the methane production was greater (Figure 2c & 2d).

Table 4: Inhibition percentage for each substrate analyzed with four different inclusion rate (2, 5, 15 & 30%). (A negative value indicates no inhibition; a positive value indicates the percentage inhibition related to the potential toxicant)

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Percent Inhibition (I) based on each Inclusion rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2%</td>
</tr>
<tr>
<td>Cranberry</td>
<td>11.2</td>
</tr>
<tr>
<td>Chicken</td>
<td>-5.79</td>
</tr>
<tr>
<td>Meatball</td>
<td>-22.4</td>
</tr>
<tr>
<td>Ice-cream</td>
<td>-66.1</td>
</tr>
</tbody>
</table>

The percent inhibition for cranberry waste ranged from 11 to 25%, for meatball fat inhibition ranged from -5 to 25%, while the chicken and ice cream waste had inhibition values ranging between -22 to 26%.

DISCUSSION

Literature has shown that the inclusion of food waste as a co-digestion substrate can greatly increase methane production (Lansing et al., 2008; El Mashad and Zhang, 2010; Rongping et al., 2010). However, in the case of the four substrate analyzed in this study, the inclusion percentage above the 5% begin to exhibit signs of toxicity. Toxicity in co-digestion of pig manure and grease and fats wastes were also shown in Lansing et al. (2010) when the percentage was 5%, with no toxic effects at 2.5%. These findings show the importance of performance ATAs before possible co-digestion food products are introduced into anaerobic digestion environments.
Figure 2a: Anaerobic toxicity assay result analysis for the cranberry waste (CR), cumulative methane production for each inclusion rate (2, 5, 15 & 30%) in comparison to the feedstock control (Feed_Con) and inoculum control (In_CON).

![ATA Cumulative Methane production for Cranberry waste](image)

Figure 2b: Anaerobic toxicity assay result analysis for the Meatball fat (MB), cumulative methane production for each inclusion rate (2, 5, 15 & 30%) in comparison to the feedstock control (Feed_Con) and inoculum control (In_CON)

![ATA Cumulative Methane production for Meatball fat](image)
Figure 2c: Anaerobic toxicity assay result analysis for the Chicken fat (CK), cumulative methane production for each inclusion rate (2, 5, 15 & 30%) in comparison to the feedstock control (Feed_Con) and inoculum control (In_CON)

![ATA Cumulative Methane production for Chicken fat](image)

Figure 2d: Anaerobic toxicity assay result analysis for the Ice-Cream (IC), cumulative methane production for each inclusion rate (2, 5, 15 & 30%) in comparison to the feedstock control (Feed_Con) and inoculum control (In_CON)

![ATA Cumulative Methane production for Ice-cream waste](image)
CONCLUSION

These findings show the importance of performance ATAs before possible co-digestion food products are introduced into anaerobic digestion environments. This study is being complemented with an on-going 60-day biochemical methane potential assay (BMP) to analyze the potential biogas production when both substrates (cow manure and industrial food waste, in this case) are digested together.

REFERENCES


ADDITIONAL PROCEEDINGS ORDER FORM

Order online: http://www.ansci.cornell.edu/dm/proceedings_orders.html

For additional copies of the Got Manure? conference proceedings, complete and return this form, with check payment, to:

PRO-DAIRY Conference Proceedings Orders
Attn: Dairy Management Proceedings
272 Morrison Hall
Ithaca, NY 14853-4801 USA
Fax: (607) 255-1335

Please send me __________ copy(ies) of the Got Manure? conference proceedings proceedings at $20.00 each ($40.00 outside of USA). PAYMENT MUST ACCOMPANY ORDER.

Name: ____________________________________________

Company/Firm Name: ____________________________________________

Address: ____________________________________________

City: __________________________ State (Province): ___________

Zip/Postal Code: ______________ Country: __________________________

Business Phone: ______________ Cell Phone: ______________

Fax: ______________ Email: __________________________

Method of Payment: Note: Locations outside USA must pay by credit card online.

As a result of changes in credit card security and compliancy guidelines, Cornell University Department of Animal Science is transitioning away from the use of credit card payments by phone, fax, or mail. Online payments are a secure way for payments to be made using a credit card. We encourage you to place your order online at

www.ansci.cornell.edu/dm/proceedings_orders.html.

☐ Check (payable to Cornell University)  Check Number: __________________________

Order Inquiries: Lorissa Haines  dmcds@cornell.edu
(607) 255-2060