

POWER FROM ANIMAL WASTE—ECONOMIC, TECHNICAL, AND REGULATORY LANDSCAPE IN THE UNITED STATES

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ABSTRACT

Historically, livestock waste has provided beneficial use through the application of manure as fertilizer. However, the livestock industry's evolution from small, distributed farms to large concentrated animal feeding operations has affected the value of livestock waste, in some cases transforming it from a local resource as a fertilizer to a social cost as a pollutant. Examples of this transition include water-pollution events associated with over-fertilization of amended lands and waste handling from intensive animal production, driving manure-management concerns. Watershed regulations, such as the Total Maximum Daily Loads (TMDLs) section of the Clean Water Act and expanding state Renewable Portfolio Standards (RPSs) have prompted the investigation of alternative management options and uses for animal waste. One particular management policy that simultaneously addresses the reduction of social costs and increases in beneficial use of livestock waste is its application as an alternative, renewable fuel for electricity generation. This paper examines the regulatory and economic incentives and disincentives at the current state-of-technology for generating power from animal waste biomass at the utility level. The research examines the issues that drive its potential adoption and identifies areas of future research that are necessary to induce technological advances and implementation. The results of the paper's review provide a number of insights. First, anaerobic digestion can be used at the livestock integrator level to produce electricity for sale on the grid; however, experience in the United States and other countries has shown that financial subsidies are required to offset capital investments by farmers. Second, electricity generation by direct combustion of animal waste is just beginning to be adopted in the U.S. in local sub-markets where water pollution and manure-management concerns spur policy incentives to support a higher price than other renewable sources. Finally, because of the inherent difficulties in co-firing biomass with fossil fuels and the characteristics of animal waste that will only exacerbate those problems, gasification remains the only technically and economically feasible option for coal-fired utilities seeking to reduce carbon, nitrogen oxides (NO_x), and sulfur oxides (SO_x) emissions while meeting their respective RPSs.

INTRODUCTION

In the U.S., renewable energy sources, particularly biomass, have been slow to replace fossil fuels. Federal tax incentives and state regulatory mandates for renewable power generation have attempted to compensate for the lack of a national policy or carbon tax. In the utility sector, green-pricing programs that offer electricity from renewable sources at a premium (typically 1–5¢ per kilowatt hour) have been used to offset the higher generation cost associated with alternative energy. National energy legislation to expand the development and use of alternative energy sources seems imminent. The Comprehensive American Energy Security and Consumer Protection Act (H.R.6899) were passed by the U.S. House of Representatives in September 2008 and have been placed on the Senate legislative calendar. The House bill requires 15 percent of generation from retail electric suppliers to come from renewable sources by 2020, and would be the first requirement to apply to all states.¹

Replacing fossil fuels, whose carbon has been sequestered from the atmosphere, with biomass constitutes greenhouse gas emission (carbon dioxide [CO₂]) savings. The degree of offset depends on whether the biomass is considered carbon neutral (no net release of CO₂ from growth through harvest), the emissions release associated with transport of biomass and the efficiency of energy conversion. An evaluation of the carbon balance has shown that compared with coal combustion, using biomass can reduce CO₂ emissions by approximately 90 percent (Spliethoff and Hein 1998). However, at the current level of technology, the cost of electricity production from biomass remains uncompetitive with fossil fuels. Existing markets for renewable-based energy are driven by state mandates and public and industry willingness to purchase carbon offsets, i.e., a premium on electricity from green energy sources. Economic models have shown that a carbon tax above \$30/metric ton would create a significant market for agriculture-based biofuels. However, in the absence of a carbon tax, the costs of agriculture-based biofuels exceed the value of the corresponding carbon offsets (Schneider and McCarl 2003).

The intersection of pollution concerns, watershed regulations such as the Total Maximum Daily Loads (TMDLs) section of the Clean Water Act, and state Renewable Portfolio Standards (RPSs) make finding alternative uses for animal waste a pressing issue in certain areas of the U.S. Texas, California, and Iowa (the top three animal-producing states), along with Maryland and Pennsylvania are among states with a surplus of animal waste that must be managed while meeting their respective TMDLs and RPSs. Generating power from animal-waste biomass is a way to reduce water pollution and meet these mandates. Animal waste is categorized as open loop biomass, since it was not produced specifically as a bioenergy source. Manure is generally considered carbon neutral since animal feed is mainly grown from photosynthesis of CO₂. The potential renewable energy from cattle manure alone is approximately 2 percent of the total annual energy consumption in the U.S. (Priyadarsan et al. 2003). Energy production through gasification of domestic animal waste to fire a turbine-generator has been estimated at over 34,000 MWe annually (Fedler 2006).

¹ To provide context for this requirement, in 2004, biomass provided 61 billion kilowatt hours (kWh)—1.5 percent of the 3,953 billion kWh of electricity generated in the U.S. (Energy Information Administration 2005a). Surveys of available biomass resources have shown that biomass has the potential to supply approximately 28 percent of the U.S. energy consumption (Weber and Zygarlicke 2001).

The body of literature on animal waste for power generation is relatively small. Of the research available in the public domain, most studies have been bench- or laboratory-scale, focused on the technical feasibility of using animal manure to produce electricity. Unfortunately, there remain several key barriers to effective utilization of animal waste for power that have not been comprehensively reviewed in one document. It is difficult to determine to what extent animal waste is an attractive option in the commercial energy sector, particularly with regard to utility retrofits, without understanding the economic, technical, social and regulatory issues. This paper therefore reviews the state-of-technology and current economics of energy production from animal waste and discusses how water regulations and state renewable mandates may increase the attractiveness and adoption of using this renewable energy source.

The manuscript begins by providing relevant background information on the current state of technology for using animal waste to generate electricity at the utility level. Specifically, the background section describes how changes in livestock production practices and the resultant environmental degradation have produced environmental regulations that aim to reduce the social costs of point source pollution from concentrated livestock production and nonpoint source pollution from nutrients leaching into surface and groundwater. Furthermore, the paper discusses how water regulations combined with state mandates to expand the use of alternative, renewable fuels for electricity generation may augment the beneficial use of livestock waste.

The manuscript then discusses the characteristics of animal waste as fuel and reviews four technologies that can be used for utility-based, electricity generation: anaerobic digestion, direct combustion, direct co-firing with fossil fuels, and gasification. The corresponding costs of production for each technology are discussed, as well as the economic issues that must be addressed to make each a viable option. It should be noted that use of animal waste to produce liquid biofuels for subsequent utilization as an alternative fuel is beyond the scope of this paper. The manuscript then turns to the remaining barriers that exist in the adoption of these technologies identifying areas of future research for strengthening the understanding of what technical, ecological, economic, and policy issues drive adoption and how change in and across each area can help spur investment at the utility level.

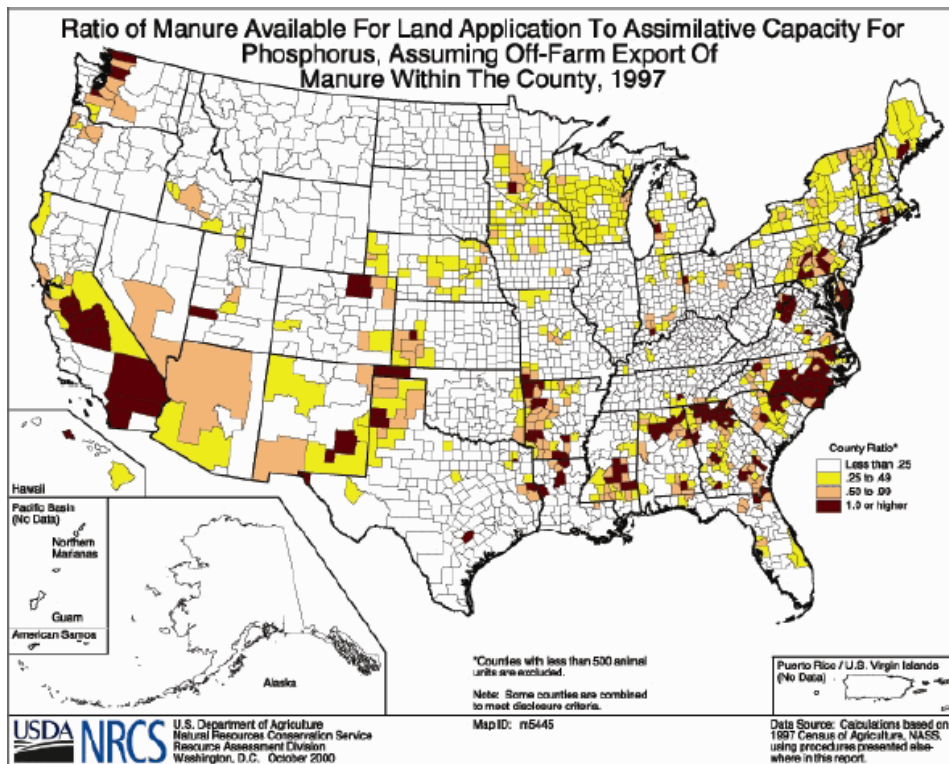
RELEVANT BACKGROUND: CONCENTRATED LIVESTOCK PRODUCTION, THE INTERSECTION OF ENVIRONMENTAL AND ENERGY POLICY

The economic efficiency of large-scale animal production and rapid growth of the industry in certain states has been accomplished by corporate livestock integrators, who contract with upward of hundreds of farmers to coordinate production vertically, resulting in larger operations that are concentrated geographically (Warrick and Stith 1995). With the evolution of the industry to these large concentrated animal feeding operations (CAFOs), the traditional use of animal manure as a soil amendment has been restricted. The size of animal operations continues to grow, and the number of animals and thus the amount of waste increases, giving rise to manure-management concerns. While the total number of farms with confined animals decreased by more than 50 percent from 1982 to 1997, the number of confined animals increased by 10 percent during that same period (Golleson et al. 2001). While demand for livestock

products from small, sustainable farms has increased in recent years, market share is small approximately five percent.

Compounding the manure problem, CAFOs are often geographically separated from areas that can use the manure for fertilizer. Where land application plans are in place, use of manure as a fertilizer is typically based on nitrogen content. However, since manure contains more phosphorus relative to crop uptake than nitrogen, when manure is used as an amendment based on nitrogen content, the result is an excess of phosphorus. Since phosphorus is only moderately soluble, significant transport can occur through erosion of sediment-absorbed phosphate to surface waters. If soils have been over-fertilized, buildup of phosphates in the soil will increase runoff rates (Ribaudo et al. 2003).

Figure 1 presents the assimilative capacity for phosphorus in the U.S., based on in-county transportation of animal manure. As the figure shows, the dark red areas indicate a surplus of manure that far exceeds assimilative capacity of cropland. In some of the most intensive animal production areas of the U.S.—the Texas panhandle, California’s central valley, North Carolina’s eastern counties, and the Delmarva Peninsula of Maryland/Delaware—the quantity of manure far exceeds the land available for phosphorus uptake. The USDA Economic Research Service has estimated that only 18 percent of large hog farms and 23 percent of large dairies are currently applying manure on enough cropland to meet a nitrogen standard, and fewer than 2 percent of dairies have adequate land to meet a phosphorus-based standard (Ribaudo et al. 2003).



Source: Farm Foundation (2006)

Figure 1: Ratio of Manure to Assimilative Capability for Phosphorus in the U.S.

Over-application of manure as fertilizer and run-off from lagoons has caused damaging water pollution and incidents of water-quality problems that receive wide media attention (Mallin 2000; CBS 2003; Barringer 2007). Accidents linked to poor manure management and disposal have occurred in North Carolina, Arkansas, Oklahoma, and Alabama, among other states (Sheth and Turner 2002). Leaching of nitrates and phosphorus from animal waste can lead to eutrophication of surface waters, resulting in algae blooms and oxygen depletion and causing fish kills. Numerous disease-causing pathogens are found in animal waste, including salmonella, E. coli, listeria, and clostridium, which have been found in surface waters and groundwater (Moore et al. 1988).

Table I provides a listing of the livestock production in six selected states with either intensive animal production or water concerns related to animal waste—California, Iowa, Maryland, North Carolina, Pennsylvania, and Texas. Texas, California, and Iowa (in that order) are the top three states in the quantity of animal waste generated (total tons in 1997) (Scorecard 2005). One solution for areas with low assimilative capacity for accommodating current manure production is to transport excess waste to areas with high assimilative capacity. While simple in concept, the costs associated with disposing of the manure in higher-assimilative-capacity areas are prohibitive, resulting in the current surplus of stored manure in low-assimilative capacity areas.

Table I
Populations of Livestock in Selected States: 2006

State	Chickens (Thousands)	Broilers (Thousands)	Turkeys (Thousands)	All Cattle (Thousands)	Hogs and Pigs (Thousands)
California	23,296	^a	15,800	5,450	145
Iowa	61,605	^a	8,200	3,800	16,600
Maryland	3,514	271,800	730	230	34
North Carolina	19,201	749,000	37,500	860	9,500
Pennsylvania	28,303	144,900	10,500	1,590	1,100
Texas	24,861	628,300	^b	14,100	930

^a State production combined with other states to avoid disclosing individual operations: total for 9 states, including California and Iowa, is 859,400.

^b State production combined with other states to avoid disclosing individual operations: total for 7 states, including Texas, is 27,050.

Source: National Agricultural Statistics Service (2007)

The problem with manure storage is exemplified by events such as a 1995 lagoon rupture in North Carolina that released 25 million gallons of concentrated waste into the New River and investigative media reports of widespread lagoon leakage into groundwater (Mallin 2000; Stith and Warrick 1995). The Neuse River, which runs through the hog-intensive eastern part of North Carolina, was recently declared one of the 10 most endangered rivers in the U.S., due in part to pollution from hog waste (American Rivers 2007). North Carolina is the nation's second-largest hog producer, after Iowa. About 9.5 million hogs are raised each year on 2,300 factory farms. Waste is typically stored in open-air lagoons and then sprayed on fields. In 2007, the North Carolina state legislature banned all new hog-waste lagoons and spray fields, recognizing the potential water and air pollution associated with this type of waste handling. The measure

includes state financial incentives (up to 90 percent of cost or \$500,000 per applicant) to help farmers replace their existing waste-handling systems (Lillard 2007).

Intensive agricultural production has contributed to excessive loading of nitrogen and phosphorus in water bodies in several states. Tributaries in Iowa contribute about 25 percent of the nitrate that the Mississippi River delivers to the Gulf of Mexico. Iowa is the nation's largest hog producer, with more than 16 million swine produced each year. Agriculture accounts for 93 percent of the land use in eastern Iowa. The Mississippi's nitrate load has been implicated as the primary cause of the seasonal hypoxic zone that occurs in the Gulf of Mexico each year, known as the "Dead Zone" (Jha, Arnold, and Gassman 2006). Marine life in the Gulf, one of the nation's most important fisheries, is decimated every summer as the Dead Zone grows to an area that is roughly the size of New Jersey.

After a well-publicized outbreak of *Pfiesteria* in the Chesapeake Bay in 1997, Maryland and Delaware enacted new regulations aimed at reducing nutrient emissions from animal production, including application of manure as fertilizer. The regulations require a nutrient management plan specifying the amount of fertilizer that can be applied. A study of the economic value of poultry litter along the Delmarva Peninsula found that application to nearby cropland had the highest value among studied uses. However, three counties in that area (two in Maryland, one in Delaware) had exceptionally large numbers of broilers to corn acreage, and the litter generated would exceed what could legally be applied as fertilizer (Lichtenberg, Parker, and Lynch 2002). Further studies have concluded that the limited land base in the Chesapeake Bay watershed substantially restricts the ability for land application, and under a phosphorus-based standard would require transportation distances of more than 90 miles (Aillery et al. 2005; Ribaud et al. 2003).

To address these problems, programs have been implemented to offset the high costs associated with transporting manure from low-assimilative-capacity areas to high-capacity areas. For example, from 2001 to 2002 West Virginia implemented a subsidy program aimed at transporting poultry litter from high- to low-density poultry production areas to reduce nutrient overloading from land application. The program provided subsidies to farmers willing to purchase poultry litter. After the subsidies ended, 92 percent of participants no longer purchased poultry litter, citing the transportation cost as the reason for discontinuing use. Even in economically feasible counties, very few farmers continued to buy litter (Collins and Basden 2006).

The West Virginia subsidy program, and the resulting return to the status quo following the subsidy's termination, provides a useful example of the economic aspects of the issues associated with concentrated livestock production. Specifically, transportation costs are cited as the reason why the purchase from high-capacity areas is discontinued. While transportation costs limit the amount of manure purchased from low-capacity areas, from an economic perspective, the larger cause of the problem is that concentrated livestock producers do not have to deal with all of the costs associated with their livestock production.

Specifically, there are social costs associated with the excess manure that results from the livestock production, and the producers do not have to factor these social costs into their production decisions. These social costs include the resulting environmental degradation associated with uncontrolled manure releases or excess nonpoint source pollution as illustrated

by the previous examples. When the resulting environmental degradation affects another entity's well being—be it an individual, household, a firm or a region—an externality occurs. Externalities are situations in which the welfare of one entity is affected by the actions of another, in this case households and/or firms downstream of the CAFOs.² See Tietenberg (2003) and Freeman (2003) for a complete discussion of externalities.

In the previous examples, because the concentrated livestock producers do not bear the social costs associated with the excess manure production and storage, they are not likely to be sensitive to those costs in their production decision-making, and therefore they produce a level of livestock with resulting manure production that is inefficient. By inefficient we mean that the net benefits to society (benefits minus the costs) of livestock production are not maximized—a different level of livestock production, one with less associated manure production, would improve net benefits.

The reason net benefits are not maximized is that the resulting environmental degradation associated with production is not being accounted for. While the status quo decision maximizes the firm's profits, it does not correspondingly maximize societal welfare. Such situations reflect market failures; that is, the market has not performed in a manner relative to production and consumption decisions that maximizes social welfare. As Massey and Zering (2001) point out, the reason that these social costs and benefits are typically not accounted for is that benefit estimation of nonpoint-source pollution reduction from livestock production is problematic because of the uncertain relationship between pollutants at the farm level and transport to the area where damage may result. Moreover, estimating the monetary benefit of pollution reduction adds another layer of complexity because markets for environmental quality improvements related to nonpoint source pollution typically do not exist. Despite this difficulty, Zilbermann, Ogishi and Metcalfe (2001) conclude that "regulatory standards, waste management technology performance criteria and other policy targets should be set within a framework that simultaneously addresses as many facets of the animal waste problem as possible."

Again, using the West Virginia example, the subsidy is an attempt to address this social cost by distributing the excess manure in a way that reduces the environmental degradation associated with the manure remaining in the area with low-assimilative capacity. The subsidy is effectively helping to transform the manure from an economic bad, a pollutant in its concentrated level in the low-assimilative capacity area, to an economic good as a fertilizer in the high-assimilative-capacity area. However, because the benefits to the high-assimilative-capacity area farmers of purchasing manure from the low-assimilative-capacity area do not exceed the transportation costs of obtaining the manure, they will not continue to participate in the program once the subsidy is discontinued. Part of the reason for their discontinuation is that additional benefits of transporting the manure to the higher-capacity areas are not accounted for in the farmer's decision (e.g., decreasing the Dead Zone in the Gulf of Mexico by reducing leaching from hog farms along the Mississippi River in Iowa). This is an example of a positive externality in which one entity's well being is improved by the actions of another (e.g., those households and firms downstream of the CAFOs who no longer experience the environmental degradation of excess manure production because farmers in the high-assimilative-capacity areas have purchased the excess manure). If the benefiting entities can compensate the farmers in the high-assimilative-capacity areas at a rate at least equal to the transportation costs of acquiring and applying the

² By downstream we mean from an impact perspective rather than a literal regional perspective.

manure, then the status quo rate of livestock production will produce the social optimum—one that maximizes net benefits.

Regulations have been enacted at both the federal and state levels to limit the environmental impact of concentrated animal production operations, effectively trying to address the environmental degradation issue in ways similar to the West Virginia subsidy example. Concurrently, federal and state agencies are increasing their mandates of renewable energy use and production incentives. It is at the intersection of these two policy areas that we see the potential for increasing the beneficial aspect of manure to one where command and control regulations do not need to represent the only regulatory solution to the problem. Therefore, the next section presents an overview of regulations affecting animal waste management and mitigation of water body pollution and is followed by discussion of renewable mandates and production incentives.

U.S. REGULATORY CLIMATE

MANURE MANAGEMENT REGULATIONS

Concentrated Animal Feeding Operations (CAFOs) have been regulated under the National Pollutant Discharge Elimination System (NPDES) program since 1976. In February 2003, EPA promulgated new CAFO regulations to update the NPDES program to avoid and manage environmental harm from these operations’ animal manure and waste (EPA 2006a). In February 2005, the Second Circuit Court of Appeals issued its decision in *Waterkeeper Alliance et al. v. EPA* regarding legal challenges to the 2003 rule. In response to the court’s decision, EPA published the new rules in the Federal Register on November 20, 2008, which became effective on December 22, 2008. The USDA-EPA Unified National Strategy for Animal Feeding Operations requires that a Nutrient Management Plan (NMP) be developed for all animal feeding operations. According to the Strategy, the NMP should address feed management, manure handling and storage, land application of manure, land management, record keeping, runoff and erosion control from areas where manure is stored or applied, and other options for making use of manure (Fulhage 2000). The effluent guidelines apply to discharge or runoff of manure or wastewaters but do not address groundwater protection, land application, or control of air contaminants. In some cases, NPDES permits have been superseded by more stringent state regulations. Table II lists the NPDES regulations for animal manure by state.

Table II
State Regulations for Controlling Animal Manure

State	Permit Type			Permit Conditions		
	Federal NPDES	State NPDES	State Non-NPDES	Effluent Limits	Management Plan	Land Application Plan
Alabama		•		•	•	•
Alaska	•					
Arizona	•		•			•
Arkansas		•	•	•	•	•
California		•	•	•		•
Colorado			•	•	•	•
Connecticut		•	•		•	•

Delaware		•	•			
Florida		•	•	•		•
Georgia		•	•	•		•
Hawaii		•				
Idaho	•		•	•	•	•
Illinois		•	•	•	•	•
Indiana		•	•		•	•
Iowa	•	•	•	•		
Kansas		•	•		•	•
Kentucky		•	•	•	•	•
Louisiana		•	•	•	•	•
Maine	•					
Maryland		•	•			•
Massachusetts	•					
Michigan			•	•		
Minnesota		•	•	•	•	•
Mississippi		•	•	•		
Missouri		•	•	•	•	•
Montana		•	•	•		•
Nebraska		•	•	•	•	•
Nevada		•				
New Hampshire	•					
New Jersey		•				•
New Mexico	•		•		•	•
New York	•				•	
North Carolina			•	•	•	•
North Dakota		•	•			•
Ohio		•	•		•	•
Oklahoma		•	•	•	•	•
Oregon		•	•			•
Pennsylvania		•	•		•	•
Rhode Island		•				
South Carolina		•	•	•	•	
South Dakota		•	•	•		
Tennessee		•		•		
Texas		•	•	•	•	•
Utah		•				•
Vermont		•		•		•
Virginia		•	•	•	•	•
Washington		•	•	•	•	•
West Virginia		•		•	•	
Wisconsin		•	•	•		•
Wyoming		•		•	•	•
Totals	7	40	35	29	27	34

Source: USDA, Economic Research Service (2003)

A USDA Economic Research Service analysis of nutrient management plan compliance costs concluded that competition for land spreading could be severe in areas with high concentration of livestock production, and costs of producing livestock would increase and be shifted to consumers (Ribaudo et al. 2003).

While manure containment structures are designed to reduce runoff and meet permit requirements, they have often increased ammonia and methane emissions, which are not addressed with existing manure regulations (Aillery et al. 2005). Furthermore, despite discharge regulations and land application plans in place for most states, these regulations have failed to prevent groundwater contamination in many waterways of the U.S. This is in part attributable to

lack of enforcement; land application plans based on nitrogen uptake rather than phosphorus, which would be more restrictive; and failure of containment and conveyance structures. The Clean Water Act addresses those waterways impacted by pollution.

CLEAN WATER ACT REGULATIONS

The pollution-control strategies that states construct in cooperation with a broad array of stakeholders are designed to achieve the Water Quality Standards (WQS) established for the nation's rivers, lakes, estuaries, and coastal waters. More than 40 percent of the assessed waters—20,000 individual river segments, lakes, and estuaries—do not meet WQSs (EPA 2007a). The U.S. EPA estimates that the impaired waters include about 300,000 miles of rivers and shorelines and about 5 million acres of lakes, with about 218 million people living within 10 miles of impaired waters. These waters are polluted mainly by sediments, excess nutrients, and harmful microorganisms.

Section 303(d) of the Clean Water Act regulates the identification of waters that do not meet WQS even with required point-source pollution-control technology, prioritization of listed waters, and development of pollution control plans, or Total Maximum Daily Loads (TMDLs). A TMDL specifies the maximum load of pollutant that a water body can receive and still meet WQSs, and it allocates pollutant loadings among point and nonpoint sources. For each water body, a TMDL must be determined for each pollutant causing a WQS violation. While TMDLs have been required by the Clean Water Act since 1972, until recently not many states have developed them. Citizen groups have brought legal action against the EPA in 38 states, seeking the enforcement of listing of waters and development of TMDLs. In many states, EPA is under court order to ensure that either the state or the EPA establishes TMDLs (EPA 2006b, 2006c, 2007a).

TMDLs increase the scope of water-quality management to include nonpoint source pollution by requiring that the actual quality of the water body itself be considered. TMDLs are driving a holistic ecological approach to water-quality management, the perspective that all point and nonpoint sources of pollution in a drainage basin—as well as the physical characteristics of the water body itself—are inextricably linked. Historically, discharges from point sources, such as wastewater treatment plants or factories, have been most closely monitored and addressed with the best available technology. TMDLs have now shifted much of the management focus to nonpoint source pollution, such as contamination from agricultural runoff (Jarrell 1999).

Table III lists TMDL requirements for selected water bodies in six states with intensive animal production—California, Iowa, Maryland, North Carolina, Pennsylvania, and Texas. Table III is not intended to be a comprehensive listing of water-quality issues in those states, but rather identification of representative water bodies that have pollutant issues related to animal waste. The water bodies listed in Table III were selected as examples for their proximity to intensive animal production areas and TMDL targeted pollution caused in part by animal waste.

Existing NPDES and TMDL regulations do not address the variety of health threats presented by animal waste, including pathogens and heavy metals. In the case of poultry litter, organo-arsenicals are added to poultry feed to promote growth and prevent parasitic infections. These organic arsenic compounds have been shown to be converted to inorganic arsenic in soils, which

are inherently more toxic and leachable (Agency for Toxic Substances and Disease Registry 2007; Jackson and Bertsch 2001). Seventy to ninety percent of the arsenic present in poultry litter is water-soluble (Garbarino et al. 2003; Rutherford et al. 2003). Unlike other biosolids, land application of animal manure is regulated on the basis of nutrient loading, yet poultry litter can contain arsenic concentrations that are comparable to sewage sludge (Jackson and Bertsch 2001). The mobilization of poultry-derived arsenic into surface water and groundwater was shown to increase four-fold in the Pocomoke River during storm events (Christen 2001). If animal waste were classified as a hazardous waste based on arsenic content, it would be prohibited from land disposal. This issue has yet to be addressed with regulations, but studies have shown that arsenic from animal production is a serious water-pollution threat (Nachman et al. 2005; Miller et al. 2000; Rutherford et al. 2003). Approximately 70 percent of the broiler chickens produced in the U.S. are fed roxarsone, the most common arsenic additive (Environmental Science and Technology Online 2007). Tyson Foods, the U.S.'s largest poultry producer, stopped adding arsenic compounds to poultry feed in 2004. Furthermore, copper and zinc are also typically added to poultry feed as fungicides (Garbarino et al. 2003; Rutherford et al. 2003).

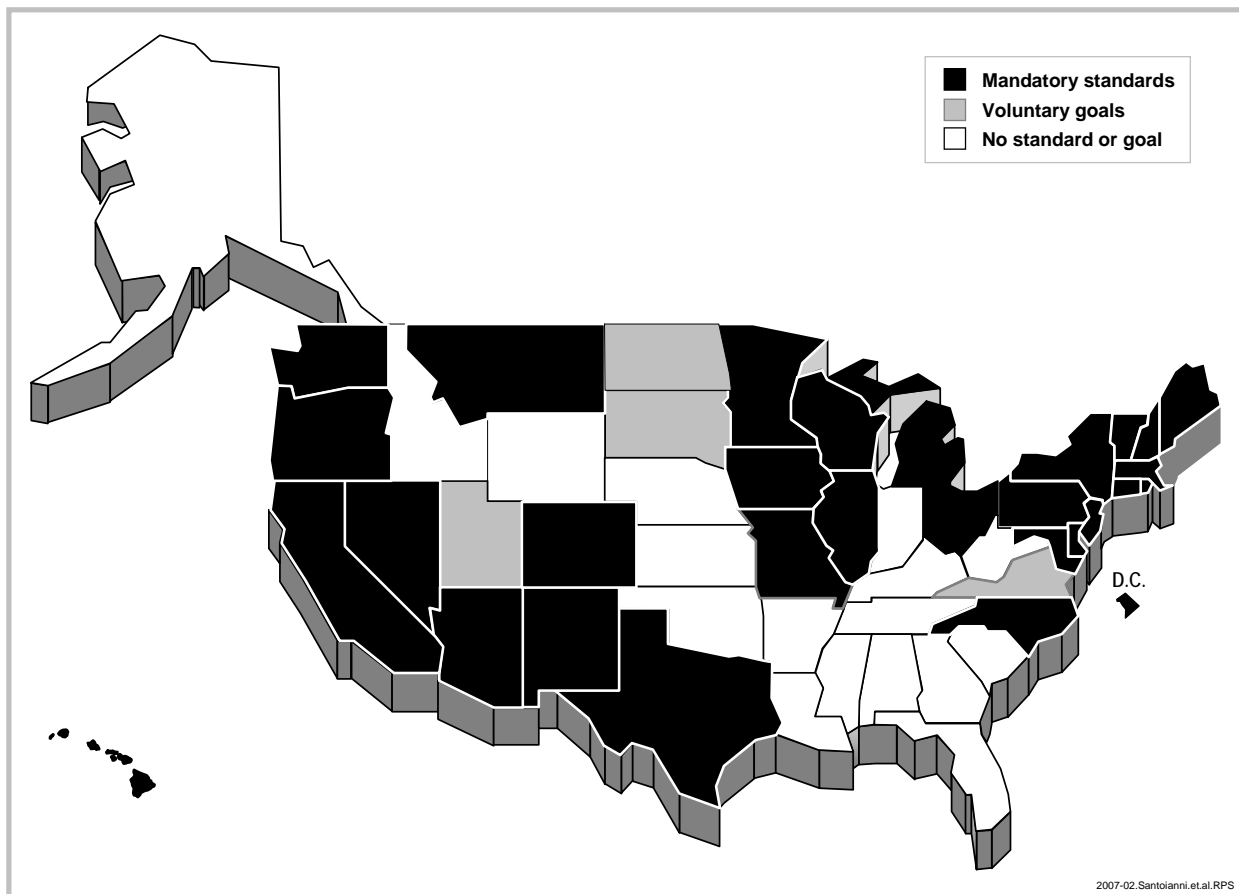
Table III
TMDL Requirements in Selected Water Bodies

State/Water Body	Pollutant or Impairment	TMDL Requirement	Comments
<i>California</i>			
Tulare Lake watershed in the Central Valley, including the Kaweah, Kern, and Kings Rivers	Ammonia, fecal coliform, pathogens	Under development, with completed TMDLs expected from 2012–2020 (State Water Resources Control Board 2006)	Many of California's most productive agricultural areas are in the Central Valley (Umbach 1997). Waivers for agricultural drainage have been granted from government permitting requirements for 20 years (Baggett 2002).
<i>Iowa</i>			
Raccoon River	Nitrate, bacteria	Water-quality improvement plan is scheduled for 2007 TMDLs are under development (Iowa Department of Natural Resources [DNR] 2007)	The Raccoon River Watershed (RRW) exports some of the highest nitrate-nitrogen loadings in the U.S. and is a major source of nutrient loadings. In fact, the RRW is the major source of nitrate loading into the Mississippi River (Jha, Arnold, and Gassman 2006).
<i>Maryland</i>			
Waters flowing into the Chesapeake Bay, including the Potomac and Susquehanna Rivers	Nitrogen, phosphorus, sediment	Have been submitted and approved for several water bodies (Maryland DNR 2007a)	Under the Chesapeake Bay 2000 Agreement, Maryland must reduce the amount of nitrogen and phosphorus entering the Bay by about 20 million pounds and 1 million pounds per year, respectively (Blankenship 2007). One of the major nutrient contributors is agricultural runoff from animal operations and farming (Maryland DNR 2007b).
<i>North Carolina</i>			
Neuse River	Nitrogen	Mandatory 30% reduction in nitrogen from point, urban, and rural sources by 2003 (U.S. EPA 2006d)	Neuse River empties into Pamlico Sound. Water quality has been a concern for more than a century. North Carolina Environmental Management Commission adopted a mandatory plan to control both point and nonpoint source pollution. Long-term nutrient data show a 27% instream nitrogen reduction in 2003 (U.S. EPA 2006e).
<i>Pennsylvania</i>			
Waters feeding into the Chesapeake Bay, principally the Susquehanna River	Nitrogen, phosphorus, sediment	Yearly discharges will be reduced to no more than: Nitrogen: 71.9 million pounds Phosphorus: 2.46 million pounds Sediment: 0.995 million tons (Pennsylvania Dept. of Conservation and Natural Resources 2005)	As part of the Chesapeake 2000 Agreement among Chesapeake Bay states and partners, Pennsylvania agreed to reduce annual discharges to the Bay (Pennsylvania Dept. of Conservation and Natural Resources 2005).

<i>Texas</i>			
Sabine River	Bacteria	TMDL development is under way or will be studied further (Texas Commission on Environmental Quality (2007)	The Sabine River empties into the Gulf of Mexico (Texas Commission on Environmental Quality 2007). Large poultry farms are located in several counties within the river's watershed.

RENEWABLE PORTFOLIO STANDARDS AND TAX INCENTIVES

While environmental policies are being developed to address the environmental degradation associated with concentrated livestock production, energy policies are simultaneously being developed to increase the use of renewable energy sources. Currently, 29 states and the District of Columbia have mandatory RPSs (Figure 2) and several more have voluntary goals or legislature in progress. As a result of the expanding enactment of RPSs in the U.S. and as utilities look for ways to meet these mandates and reduce nitrous oxides (NO_x), sulfur oxides (SO_x), mercury, and greenhouse gas emissions, biopower is becoming more attractive. Biomass is second only to hydropower in renewable electricity production, accounting for 75 percent of the non-hydropower renewable generation. Generation from biomass in the electric power sector is expected to increase by 140 percent within the next decade, with the majority of that increase in production provided by co-firing (U.S. Department of Energy [DOE] 2007; Energy Information Administration 2007).



Source: Interstate Renewable Energy Council (2007)

Figure 2: Renewable Portfolio Standards by State

Note that the states listed in Table III for intensive animal production all have an RPS. North Carolina's renewable and energy efficiency mandate was signed into law in August 2007. Seven states have production incentives for renewable energy, including California, Minnesota and South Carolina. Twenty-four states have corporate tax incentives for renewable generation. For example, Maryland's Clean Energy Incentive Act of 2006 provides a tax credit of 0.85¢/kWh for biomass (0.5¢/kWh for co-fired electricity) (Maryland General Assembly 2006, 2007; North Carolina State University 2007).

Absent a comprehensive energy bill, federal incentives take the form of tax credits and loans. The Section 45 Renewable Electricity Production Tax Credit provides a per-kilowatt-hour federal tax credit of 1¢/kWh, adjusted annually for inflation, for electricity generated by open-loop biomass, including agricultural livestock waste. It is important to note that in co-fired situations, the tax credit is only applicable to the percentage of electricity generated from qualified biomass sources. The Section 45 Production Tax Credit, which had expired for new projects in 2003, was amended in 2005 to reauthorize appropriations for fiscal years 2006 through 2026 (DSIRE 2007a, 2007b). The Renewable Energy Production Incentive provides a credit of 1.5¢/kWh to tribal, municipal, rural cooperative, and state/local government utilities that produce electricity from qualified sources, including biomass.

CHARACTERISTICS OF ANIMAL WASTE AS FUEL

Animal waste biomass differs substantially from woody or herbaceous biomass, notably in the amount of chlorine and alkali compounds present. The moisture content of animal manure varies widely, depending on production conditions and manure clean-out procedure. Poultry litter typically contains a mixture of bedding materials (straw, wood chips, corn husks) and manure, along with feathers. Analyses of poultry litter have reported moisture contents varying from 7 percent to 49 percent (Abelha et al. 2003; Henihan et al. 2003; Kirubakaran et al. 2005; Kelleher et al. 2002; Priyadarsan et al. 2004; Mukhtar et al. 2002). In one study, samples of poultry litter collected at 16 regional farms ranged in moisture content from 17.2 to 48.1 percent (Harter-Dennis 2002). Similarly, cattle raised in feed pens can have a variety of bedding material. Soil-surfaced feedlot manure will have significantly higher ash content than when bedding materials are used (Priyadarsan et al. 2003). Cattle raised in feed pens produce manure with an average of 35 percent moisture, although moisture levels exceeding 60 percent have been measured. Hog waste that is flushed and stored in lagoons has very low solids content, approximately 3 percent.

Although all of the animal wastes have a considerably lower energy content compared with coal (one-third to one-half the higher heating value), hog waste is above average, with a higher heating value and ash content comparable to lignite coal. Table IV presents an ultimate and proximate analysis for chicken litter, cattle manure, belt-harvested hog waste, and three different rank coals for comparison. Collected directly from the hog, fresh manure contains 60–85 percent moisture. Belt-harvesting of hog waste is a process to separate solids from the liquid component of the manure. Studies with published elemental analysis of animal manure show significantly higher levels of potassium, phosphorus, and sodium compounds, compared with coal. Potassium content of animal waste is particularly noteworthy when compared with coal. An in-depth investigation of ash deposition in biomass power plants undertaken by Baxter et al. (1996)

showed that potassium and chlorine were major factors in ash formation. Chlorine content influences the amount of alkali vaporized during combustion, thus enhancing the mobility and deposit formation. Furthermore, potassium salts were found to be more difficult to remove than calcium deposits and affected furnace operation to a greater extent.

Table IV
Ultimate and Proximate Analysis of Animal Waste Compared with Coal

	Chicken Litter ^a	Cattle Feedlot Manure ^b	Belt-Harvested Hog Waste ^c	Bituminous Coal	Subbituminous Coal	Lignite Coal
<i>Proximate analysis: as received</i>						
Moisture (%)	43.0	36.6	23.2	2.7	24.8	30.1
Volatile matter (%)	38.9	31.6	57.4	35.9	32.7	30.5
Fixed C (%)	1.7	6.6	10.0	52.8	36.4	29.5
Ash (%)	16.4	25.2	9.4	8.6	6.1	9.9
<i>Ultimate analysis: dry basis</i>						
Carbon (%)	39.6	19.2	45.0	74.5	68.6	60.7
Hydrogen (%)	5.1	2.2	6.9	4.8	5.1	3.7
Nitrogen (%)	5.3	1.5	4.0	1.4	0.9	0.9
Sulfur (%)	0.8	0.5	0.3	2.9	0.4	1.1
Oxygen (%)	48.3	14.7	24.0	7.6	16.8	20.1
Higher heating value (kJ/kg)	10,620	7,865	19,700	31,015	27,830	22,685

Sources: ^aAbelha et al. (2003); ^bSami, Annamalai, and Wooldridge (2001); ^cKoger et al. (2002)

The chlorine content of the various animal wastes has only sporadically been reported in the literature. This is important because chlorine will enhance alkali vaporization and subsequent fouling. Furthermore, under certain combustion conditions chlorine can contribute to dioxin and furan formation. A study of the partitioning of alkali and chlorine compounds in a fluidized bed combustor found that ashes collected from a cyclone accounted for 70 percent of the chlorine input. The HCL measured in the stack gases was 56 ppm at 11 percent oxygen (O₂). The cyclone ash was also enriched with heavy metals; however, the amount of metals present in the litter was not high enough to be of concern (Abelha et al. 2003). A notable omission in all the poultry-litter studies surveyed was the fate of arsenic in the combustion or gasification process.

Currently, four main technologies are used to generate electricity from biomass—anaerobic digestion, direct combustion, direct co-firing with fossil fuels, and gasification. A brief description of each of the technologies is presented, along with discussion of the unique technical challenges specific to animal-waste biomass.

ANAEROBIC DIGESTION

Anaerobic digestion is a biochemical method of converting waste into a biogas that subsequently can be used for electricity generation. Bacterial decomposition of organic waste under anaerobic

conditions produces a biogas containing 60–70 percent methane and 30–40 percent carbon dioxide, with small amounts of hydrogen sulfide (H_2S), ammonia (NH_3), and other noxious gases (Hansen 2007). The biogas has an energy content of about 20–40 percent of the lower heating value of the feedstock, or about half that of natural gas. Since about half of the energy produced is used to maintain digester temperature, the overall conversion efficiency from waste-to-electricity in spark ignition gas engines has been estimated as 10–16 percent (McKendry 2002). A significant advantage of the process is the ability to treat wastes with high moisture content, those exceeding 80 percent (Engler et al. 1999).

The efficiency of conversion to methane is dependent on digester loading rate (retention time), characteristics of the waste, and environmental conditions of the digester. Most digesters in the United States operate in the mesophilic range, between 30 and 40°C (Flora and Riahi-Nezhad 2006). Mesophilic digesters are less sensitive to feedstock variances, have moderate processing time (typically 12–30 days), and have moderate input heating requirements (Van Haren and Fleming 2005). However, mesophilic digesters are not as effective at destroying pathogens as digesters operating at higher temperatures. Complete eradication of fecal coliforms and salmonellae has been reported with thermophilic digesters (50°C), but only partial destruction was observed with a comparable mesophilic digester (Salminen and Rintala 2002).

Depending on the technology utilizing the biogas, some treatment of the raw biogas may be necessary. For example, H_2S is corrosive in small concentrations and must be removed before using the biogas in a fuel cell or conventional internal combustion engine. Some waste streams are more amenable to anaerobic digestion than others. Manure left on pasture or range is not economically collectable. Conversely, most poultry litter is collected in bulk, but it contains feathers and bedding that can clog digesters (Van Dyne and Weber 1994). Because poultry litter has high nitrogen content, excessive ammonia production during digestion can inhibit the process, thus requiring significant amounts of water for digestion, an approximately 10:1 ratio of water to manure (Hansen 2007; Flora and Riahi-Nezhad 2006). The highest solids content at which digestion of poultry litter can still proceed has been reported as 10 percent (Kelleher et al. 2002). Since covered lagoons are not typically heated, they are used only in warm climates and solids content is limited to about 3 percent (U.S. EPA 2002). For a more thorough review of anaerobic digestion, see Van Haren and Fleming (2005); and Barker (2001).

ECONOMICS OF ANAEROBIC DIGESTION

The number of operational digesters has grown to 125 biogas recovery systems on U.S. livestock and poultry farms (U.S. EPA 2007b). The U.S. EPA AgSTAR program, aimed at commercialization of digesters, documented installation costs averaging \$178,000 for swine waste systems and nearly \$250,000 for dairy waste systems. Revenue streams from sale of electricity and/or byproducts of digestion were on the order of \$50,000 annually, yielding payback in 3–7 years (Balsam 2002). Since few farmers will have the capital to invest in digestion systems without subsidies or loans, replacement of existing manure containment facilities has been slow.

Biogas recovery systems are estimated to be technically feasible at about 7,000 dairy and swine operations in the U.S. alone. Biogas recovery systems at these facilities have the potential to generate up to 6 million MWh yearly (U.S. EPA 2006f). While its use in the U.S. is increasing,

several European nations, notably Germany, have a significant number of digester installations attributable to legislation that promotes biogas production (European Anaerobic Digestion Network 2005; Duff undated). Germany alone has more than 1,900 biogas facilities, ranging in size from small farm installations to centralized plants using other organic wastes to boost production (Van Haren and Fleming 2005; European Anaerobic Digestion Network 2005).

The reported cost of producing electricity from anaerobic digestion varies widely and depends on the size of the installation and amount of animal manure processed. Costs from 6.5¢/kWh upwards to 10.3¢/kWh have been estimated, which is significantly more than utilities pay for renewable energy in most areas of the U.S. (Palmer 2004; Van Dyne and Weber 1994; Flora and Riahi-Nezhad 2006). In North Carolina, Progress Energy and GreenCo Solutions, a non-profit organization representing electric cooperatives, are investigating the feasibility of selling electricity generated by methane capture from hog waste lagoons. Progress Energy had previously negotiated with the state's pork producers to purchase electricity at an elevated cost (18¢/kWh) that would enable farmers to cover the capital investment and operating costs of such systems (Murawski 2007). A pilot program was approved by North Carolina legislators to enclose lagoons on 50 farms and capture methane, generating 25 MW, enough to power 15,000 homes (Rawlins 2007).

DIRECT COMBUSTION

STATE-OF-TECHNOLOGY

Direct combustion is thus far the simplest and most developed biopower technology. The existing biopower sector comprises nearly 1,000 plants, which include combined heat and power and electricity-only plants in the commercial and industrial sectors. Currently, the majority of biomass electricity generation comes from direct-combustion plants with only a small amount of co-firing with coal (approximately 400 MWe total from 106 plants). Installed capacity at biomass plants averages only 20 MWe, with a typical biomass-to-electricity conversion efficiency of about 20 percent (U.S. Climate Change Technology Program 2005).

Prior to 2007, only bench- and pilot-scale demonstration projects used animal waste as a feedstock in combustion systems. The first U.S. commercial installation is a 55 MW power plant fired with turkey litter in Benson, Minnesota, operated by Fibrominn LLC. The plant went on-line during the summer of 2007. Fibrominn is a subsidiary of Fibrowatt LLC, the U.S.-based company founded by one of the developers of the poultry-litter-fired installations in the United Kingdom (U.K.). Operational animal biomass-fired power facilities abroad include the world's first poultry litter-fueled plant at Eye, U.K. and Europe's largest biomass-fueled electricity generator at Thetford, U.K. Both are now operated by Energy Power Resources Limited (EPR) (2007).

The Fibrominn and EPR facilities employ fuel reception and storage areas operated under negative pressure to ensure biosecurity and prevent fugitive odors and emissions. The Eye power station employs a conventional moving grate boiler and a condensing turbine-generator (Dagnall 1993). Combustion of biomass with moisture content higher than 50 percent, such as

animal waste, can be problematic (McKendry 2002). The Fibrominn facility mixes poultry litter with wood waste to ensure more uniform feedstock moisture content. The plant at Eye experienced combustion problems attributable to higher-than-expected moisture content in the litter feedstock. A spreader stoker was subsequently employed at Thetford to blow the fuel into the boiler. The Thetford facility uses a cyclone and baghouse to control particulate emissions and lime injection to minimize SO₂ and HCl (Kelleher et al. 2002). The ash produced from the combustion at the EPR facilities is sterile and rich in phosphate and potash, and it is marketed as an agricultural fertilizer by Fibrophos. Fibrowatt LLC has plans to build additional poultry-litter-fueled power plants in Mississippi, Arkansas, and along the Delmarva Peninsula in Maryland, and three plants in North Carolina (Karnowski 2007).

Fluidized bed combustion has been proposed as the best available technology for handling non-standard waste materials, especially those with high moisture and ash content (Murphy 2000). Scotland's first biomass power plant is a 9.8 MW facility that uses bubbling fluidized bed combustion of poultry litter, and it is operated by EPR. Earth Resources Inc., a Georgia-based waste-to-energy company, is planning a 20 MW poultry-litter and woody-biomass-fueled power station in Carnesville, Georgia that will use a bubbling fluidized bed boiler. Earth Resources (2006) had previously secured a USDA/DOE grant to study using chicken litter as a fuel at a pilot plant, utilizing solid oxide fuel cell technology to generate electricity (Physorg.com 2005). Pennsylvania State College of Agricultural Sciences has a grant to study incineration of poultry litter, in collaboration with local turkey growers (Muhollem 2007).

COMBUSTION PROBLEMS ASSOCIATED WITH ANIMAL WASTE

The lessons learned from operational biomass power plants foretell some of the problems inherent in using animal waste as a fuel. Feeding of animal waste biomass can be problematic. Due to the high moisture content of animal manure, compaction of the fuel and blockage of the discharge has been reported with screw feeders processing poultry litter (Abelha et al. 2003) and cattle manure (Annamalai, Ibrahim, and Sweeten 1987). Pre-drying of the animal waste was subsequently required in those studies.

Perhaps the most significant issue that arises in the combustion of some types of biomass is unmanageable ash deposition and slagging, which can result in frequent, costly boiler shutdowns for maintenance. Because manure has a high proportion of potassium, and some animal waste such as poultry litter contains chlorine, there is a significant potential for ash deposition and slag. Ash deposition in conventional grate systems can reduce boiler efficiency and increase emissions. Optimizing fluidized bed combustion can avoid these issues as the bed materials provide a significant store of energy to drive off moisture and sustain combustion, while the turbulence created in a fluidized bed can help prevent ash deposition onto fuel particles (Overend 2004; Murphy, 2000).

Combustion temperature in fluidized bed systems needs to be controlled to minimize ash sintering. Maintaining operational temperatures of 800–850°C were found to prevent significant slagging and ash accumulation (Henihan et al. 2003; Abelha et al. 2003; Annamalai, Ibrahim, and Sweeten 1987). Scanning electron microscopy studies on agglomeration during biomass combustion in a fluidized bed showed that a homogeneous 10–50 µm coating was formed around all bed particles. Deposition of small ash particles onto bed materials, condensation of alkali

species, and chemical reaction of gaseous alkali on particle surfaces were identified as mechanisms for agglomeration. The melting behavior of the coating materials was sensitive to the amounts of potassium and calcium in the fuel, with higher potassium fraction lowering the melt temperature (Ohman 2000). This is particularly significant for animal wastes because both cattle manure and poultry litter contain significant percentages of potassium, compared with coal.

The emissions performance of fluidized bed combustors is another reason this technology is promising. Sorbents for SO_x control, such as limestone, can be introduced in the bed to eliminate the need for back-end removal equipment (Overend 2004). The combustion process using fluidized bed technology must be optimized to suit the nature of the waste, which contains a high percentage of volatiles in the case of animal manure. These volatiles are released rapidly, and if proper mixing with sufficient combustion air is not provided, high levels of carbon monoxide (CO) are produced. A study of fluidized combustion of cattle manure reported CO levels of 4–6 percent in the exhaust (Annamalai, Ibrahim, and Sweeten 1987). Experimental and modeling studies showed that carbon monoxide emissions from poultry litter combustion decreased with the correct ratio between fluidizing and secondary air, staging of secondary air, and the degree of turbulence with which secondary air is introduced (Abelha et al. 2003; Henihan et al. 2003).

Animal waste has a significant percentage of fuel nitrogen, which is present as both inorganic nitrogen and ammonia. With lower operational temperatures in the fluidized bed compared with conventional boilers, the primary source of NO_x should be fuel-bound nitrogen. NO_x generation levels between 10 and 30 percent of the potential nitrogen conversion suggest that fuel nitrogen in the form of ammonia or urea is creating a reducing atmosphere and abating NO_x rather than creating more (Murphy 2000). Air staging tests during fluidized combustion of poultry litter suggested that only 15 percent of fuel nitrogen is converted to NO_x (Abelha et al. 2003). Modeling studies predicted that without the use of secondary air, 30 percent conversion of fuel nitrogen to NO_x occurs; staging with secondary air decreases that amount to 15–18 percent (Henihan et al. 2003).

THE FIBROMINN MODEL

Fibrowatt's economic performance in Minnesota is being watched as a test case for whether animal waste-derived power can be profitable by independent suppliers utilizing direct combustion. Pollution concerns associated with manure management influenced state policy, causing a shift toward economic feasibility for animal waste-to-electricity projects. In an effort to promote renewable electricity generation, Minnesota passed a 1994 mandate requiring Xcel Energy, the largest state utility, to purchase 125 MW of closed loop biomass-fueled electricity. An important provision of the original mandate was that co-fired generation was excluded (later allowed in 2003). To address pollution from livestock production and attract Fibrowatt to the state, legislation in 2000 directed that up to 50 MW of the biomass mandate "be provided by a facility that uses poultry litter as its primary fuel source" (Morris 2005). Fibrominn has a 20-year contract with Xcel Energy to sell the poultry litter-generated power for 8.6¢/kWh, with production cost of 5.9¢/kWh. A 2002 study of the value of poultry litter in alternative uses estimated net costs of poultry-litter-generated electricity between 5.1¢ and 9.5¢/kWh (Lichtenberg, Parker, and Lynch 2002). That study was specific to the Delmarva Peninsula

where even with a 1.7¢/kWh tax credit for production of green energy from poultry litter, a power utility would need a subsidy or tipping fee ranging from \$7 to \$49 per ton of litter in order to break even. Fibrominn has contracts with Minnesota poultry producers to purchase turkey litter for \$3–\$7/ton, which is the wholesale value as fertilizer (Saulny 2007). However, the company reportedly received \$500 million in state incentives to offset feedstock costs (Morris 2005).

Similar mandates to solve problems of water pollution and surplus of stored manure have been debated at the state legislature level in Oklahoma, Arkansas, Mississippi, and North Carolina. For example, in the Lake Eucha watershed in Oklahoma, land application of poultry litter has previously been banned due to excess of phosphorus from runoff of amended lands (Oklahoma House of Representatives 2003). In other states, winter application of manure is prohibited because of the increased potential for runoff. The important point is that currently at the state level, and potentially at the national level, energy policy is being shaped by not only energy independence and fossil fuel-related pollution reduction goals, but also by water quality and manure management concerns.

CO-FIRING

With coal-fired electric utilities seeking ways to meet state standards for using renewable energy sources, reducing NO_x emissions, and offsetting a percentage of their greenhouse gas emissions, some utilities have turned to co-firing biomass with coal as a low-cost way to meet these mandates. Approximately 2.7 to 3.15 tons of fossil CO₂ emissions are avoided per ton of biomass burned (Tillman 2000). Biomass can also be used as an in-situ NO_x reduction method. Most of the fuel-bound nitrogen in biomass is converted to NH radicals, mainly ammonia, during combustion, which reduces nitric oxide (NO) to nitrogen (N₂). With staged combustion, co-firing wood waste with coal may not lead to significant reductions in NO_x unless co-firing ratios exceed 50 percent (Sami, Annamalai, and Wooldridge 2001). A 90/10 blend of coal and feedlot biomass in a laboratory-scale burner decreased NO_x emissions by 10 percent, but also increased CO emissions compared with coal (Annamalai, Thien, and Sweeten 2003). This reduction is comparable with what has been reported for co-firing coal with wood waste (Gold and Tillman 1996; Sami, Annamalai, and Wooldridge 2001). However, significant NO_x reduction has been demonstrated using animal waste biomass as a reburn fuel. Laboratory-scale studies of cattle manure co-fired with coal showed that manure was highly effective as a reburn fuel, with a maximum reduction in NO_x of 62 percent (Arumugam et al. 2005). In that study, cattle manure was more effective than coal as a reburn fuel for NO_x reduction at all equivalence ratios tested. For a comprehensive review of co-firing biomass with coal, see Sami, Annamalai, and Wooldridge (2001) and Sondreal et al. (2001).

Typically the amount of biomass used at electric utilities co-firing with coal has been about 1 percent of the heat input (Energy Information Administration 2005b). There are several significant reasons for the small percentage of biomass use in co-firing situations, each of which is discussed in more detail below:

- feeding issues

- heating value and volatility of animal-waste biomass
- ash deposition and fouling
- fly ash non-compliance.

FEEDING ISSUES

One of the first issues to resolve when co-firing is processing and feeding of biomass to the boiler. Biomass is notoriously difficult to grind because of its fibrous nature. The lowest-cost approach is to use the same feed system for both the biomass and the coal. In wood co-firing tests performed at Tennessee Valley Authority pulverized coal power plants, biomass could substitute about 10–14 percent by mass or about 5 percent by heat input before limitations attributable to pulverizer amps or feeder speeds (Gold and Tillman 1996). One study noted that feedlot biomass (cattle manure) could not be ground as fine as coal because of undigested fibers that compress in the pulverizer (Annamalai, Thien, and Sweeten 2003). In cyclone boilers, which do not employ pulverizers, the limiting issue is speed of the cyclone feeder.

Co-firing with separate fuel processing and injection systems bypasses the pulverizer or feeder limitations, affords the ability to change the blend of fuel to match operational needs, and allows better control over feed rates. Use of a single swirl burner to mix the two fuel streams may be problematic, however. Feeding one of the pulverized fuels in the swirling secondary air is likely to cause damage to swirl blades (Sami, Annamalai, and Wooldridge 2001). Capital costs associated with retrofitting coal-fired plants to use biomass are estimated at \$40–\$50/kW for blending through cyclone or pulverizer and \$175–\$230/kW with a separate feed system (Sondreal et al. 2001).

HEATING VALUE AND VOLATILITY OF ANIMAL-WASTE BIOMASS

Biomass has higher moisture content and lower energy content than coal. The higher heating value of animal-waste biomass is approximately 30–50 percent that of coal, and moisture content can vary widely. Biomass with a heating value of less than 8,100 KJ/kg would be of little value to a suspension or grate-fired plant because it would require a net energy input to sustain combustion (Weber and Zygarlicke 2001). In order to compensate for the lower energy content of biomass, increased feeding rates are required to maintain capacity and avoid boiler derating. This will affect flame stand-off distances, which may cause flame instabilities and affect combustion efficiency (Sami, Annamalai, and Wooldridge 2001). Boiler efficiency loss during biomass co-firing at 15 percent (heat input basis) has been reported as 1.5 percent or less (Gold and Tillman 1996).

The combustion consequences of biomass fuel composition, particularly the fuel volatility, change the kinetics in any type of equipment. Volatilization and gas-phase combustion become the dominant reaction sequence, rather than char formation and gas-solids oxidation as with coal combustion (Tillman 2000). The percentage of volatiles in most biomass fuels will be problematic for boilers designed for low-volatile fuels. Rapid release of volatiles will locally increase the temperature near the burner. Higher initial heat-release rates at the grate can cause

clinkering and slagging because of higher temperatures. Rapid loss of volatiles, including vaporization of alkali and chloride compounds, can cause condensation on rear walls and heat-exchange tube bands in the convective pass of the stoker, which leads to considerable fouling (Weber and Zygarlicke 2001).

ASH DEPOSITION AND FOULING

In a National Renewable Energy Laboratory study of lessons learned from biomass plants, most plants reported significant investment during the first year or two of operation when resolving problems related to excessive equipment wear and wide variation in moisture content of the feedstock (Wiltsee 2000). Many of the surveyed plants reported ash fouling and slagging problems. Ash deposition problems have been found to be more severe when co-firing biomass with coal, to the extent that some biomass plants chose to burn 100 percent coal during peak and 100 percent biomass during other times rather than deal with issues related to biomass/coal interactions. The increased feeding rates required to prevent derating will also cause an increase in ash production, posing the potential to overload pollution control equipment or exceed permit particulate levels.

The high alkaline content in animal waste tends to lower ash-melting temperatures, with a greater potential for fouling. Ash-related problems are seen more in stoker boilers and fluidized bed boilers, where agglomeration causes serious issues (Sami, Annamalai and Wooldridge 2001). High chlorine content in some biomass streams caused serious corrosion of superheater tubes and the high alkaline content can deactivate the catalyst in selective catalytic reduction (SCR) systems (Wiltsee 2000; Sondreal et al. 2001; Tillman 2000). Poultry litter can contain problematic chlorine levels attributable to pharmaceutical feed additives.

A study of feedlot manure-coal co-firing in a pilot-scale boiler found that molten, fused-type deposits on slag panels and probes were difficult to remove even with the highest soot-blowing pressures (Annamalai et al. 2003). Operational data suggested that fouling was more severe with the blend because of high alkali content of the feedlot manure and almost twice the ash output, compared to coal alone. Ash constituents present in animal waste, such as chlorine, silica, and phosphorus can change emissions, generating greater quantities of fine particulate (Weber and Zygarlicke 2001).

FLY ASH NON-COMPLIANCE

One other significant ash-related problem that arises from co-firing is the impact on the residue ash. For many coal-fired utilities, the fly ash generated from combustion represents secondary revenue, as it is sold to concrete manufacturers as a cement substitute. The American Society for Testing and Materials (ASTM) has an existing standard specification (C618) for 100-percent coal fly ash for use in concrete. While studies have demonstrated that coal-biomass fly ash can meet the technical specifications for strength and setting behavior, the definition in the standard precludes any fly ash produced from biomass (Wang and Baxter 2006; Wang and Baxter 2007; Tillman 2000). While updating the standard for incorporating fly ash generated from woody-type biomass is being debated, there are no published studies regarding fly-ash properties from

animal-waste combustion. To date, there are no public domain reports on co-firing coal and animal waste other than laboratory and pilot-scale studies.

GASIFICATION

EMERGING TECHNOLOGY

Given the various problems of co-firing biomass with coal, an alternative approach is to use gasification as a front-end “processing” for biomass. Gasification is a low-temperature conversion process for breaking down a fuel into a combustible gas mixture by partial oxidation. The first step in the gasification process is to break down the feedstock into char and volatiles. The devolatilization and pyrolysis reactions are endothermic, which can come in the form of direct or indirect heating. In the second gasification step, char reacts with air, oxygen, or steam to form product gas that contains hydrogen (H₂), CO, CO₂, and CH₄ (Jones and Sheth 1999). Gasifiers operate in the range of 700–1000°C in a sub-stoichiometric environment; typically around one-third required air for complete combustion. That operational temperature range is high enough for pathogen destruction (Koger et al. 2002).

Using air in the gasification process will result in a lower-energy product gas diluted with nitrogen, which may be unacceptable because of the potential for formation of thermal NO_x. Thus, steam or oxygen gasification is preferred (Maschio, Lucchesi, and Stoppato 1994). During steam gasification, the reducing condition will cause the formation of mostly ammonia, and the production of NO_x in the gasifier will be small (Sheth and Turner 2002). The gasification unit can be directly or indirectly heated. With indirect heating, partial oxidation of the biomass produces heat to sustain the process and addition of air or oxygen is unnecessary. The moisture present in animal waste provides the steam for gasification, eliminating dilution effects and enhancing the heating value of the product gas (Koger et al. 2005). Adjusting the water-to-biomass ratio will affect product gas composition, with higher ratios resulting in greater H₂ formation (Maschio, Lucchesi, and Stoppato 1994). Bench-scale catalytic steam gasification of broiler litter showed that reaction rates and carbon conversion are enhanced with addition of an alkali catalyst (potassium salts) (Sheth and Turner 2002). The low-to-medium Btu gas produced from gasification can subsequently be used to produce electricity in a gas turbine, combusted in a co-fired scenario, or used as a reburn fuel. Compared with low-energy conversion efficiencies common with direct combustion, electricity generation via integrated gasification combined cycles holds promise for efficiencies near 50 percent (Overend 2000; McKendry 2002).

Another advantage of gasification over feeding biomass in a co-fired scenario is that there is no intermingling of ash, producing two separate and valuable ash streams. The ash collected from the gasifier will be laden with alkali compounds from the biomass and can be used subsequently as a fertilizer. If the product gas from gasification is then used to co-fire with coal, the fly ash generated from combustion in the main boiler will still meet ASTM C618 (concrete) specifications. Using gasification to co-fire addresses all the problems associated with biomass co-firing, while requiring minimal modification to existing boiler systems.

UTILITY GASIFICATION CO-FIRING

The most successful installation of front-end gasification co-firing with coal is in Lahti, Finland. The Kymijarvi power plant in Lahti is a PC-fired steam plant that generates up to 167 MWe of electricity and 240 MWth of district heat. The plant uses a 45 MWth gasifier (about 15 percent of the boiler's heat input) to process high-moisture biomass, including wood, paper, cardboard, and plastics. Feedstock with moisture content up to 60 percent can be successfully gasified. The low Btu-gas produced in the gasifier passes through a cyclone, an air preheater, and on to two local burners below the coal burners in the boiler. Only small modifications were made to the boiler, fouling and corrosion have not occurred, and disturbances to the gasifier do not shut down the power plant. The gasifier has had an availability of 98 percent (Wiltsee 2000; Engstrom 1999). The Kymijarvi gasifier has reduced NO_x emissions by 5–10 percent, and particulate emissions decreased resulting from increased moisture in the flue gas, enhancing performance of the electrostatic precipitator (Tillman 2000). Another example of co-fired biomass gasification is the McNeil Generating Station in Burlington, VT, which produces 8 MWe, and notably, kept the lights on in Burlington during the Northeast Blackout of 2003.

Several other coal and wood waste gasification demonstration projects have been undertaken. Various configurations for biomass co-firing at Tennessee Valley Authority (TVA) coal-fired power plants were studied, including blending wood with coal in the pulverizer, a separate feed system for biomass, use of biomass as reburn fuels, and installation of a front-end gasifier. The study concluded that gasification would not interfere with SCR use or require an additional baghouse (Gold and Tillman 1996).

GASIFICATION OF ANIMAL WASTE

Gasification is an attractive option for animal waste characterized by variable (high) moisture content and grinding difficulties. The significant amount of moisture present in most animal wastes provides the steam for gasification. Some filtration of the product gas may be necessary, but unlike conventional particulate-removal systems common with direct combustion, cooling of the gas is unnecessary (Patel et al. 2002). In a study of counter-current fixed-bed gasification of chicken litter and feedlot (cattle) manure, the process was insensitive to airflow disturbances and moisture content of the fuel, producing a product gas with nearly uniform heating value regardless of airflow rate or particle size. The product gas had a heat value about 10–15 percent that of natural gas (Priyadarsan et al. 2005, 2003).

Potential problems with gasification such as slag formation, dioxin production, and ash vitrification can be avoided by temperature control. Gasification studies on hog waste determined an optimal temperature of 800°C, which was well below the ash fusion temperature, at which no dioxins were detected and NO_x formation was minimized (Koger et al. 2005). Higher-alkaline content wastes, such as poultry litter, have been found to cause more agglomeration in a fixed-bed gasifier than feedlot biomass (cattle manure) (Priyadarsan et al. 2004). Xcel Energy has provided funding for research demonstration of turkey litter gasification through their Renewable Development Fund (mandated by Minnesota energy policy) to Coaltec Energy (Coaltec 2006).

ECONOMICS OF GASIFICATION

Gasification is the most capital-intensive approach to co-firing, but it allows the most flexibility in feedstock, base fuel (coal, natural gas, oil), and boiler system used (Tillman 2000). While gasification provides promise for converting animal waste to energy, the economics of scale work against small installations and on-farm utilization. A stationary gasification unit producing fuel gas would require a minimal feed rate of 500 tons of poultry litter per day to remain profitable, according to one economic analysis (Sheth and Turner 2002). Another study estimates costs of \$1,350/kW for a small modular gasification unit (Reardon et al. 2001). Economic studies of biomass conversion technologies have shown that only gasification is likely to be commercially viable at large scales (McKendry 2002; Kirubakaran et al. 2005; Dornburg and Faaij 2001). These studies note that integration of gasification and combustion/heat recovery can result in high biomass-to-energy conversion efficiencies of 40–50 percent.

A study of energy production from poultry manure in South Carolina showed that only gasification had a positive rate of return for a 10-year time frame, with costs of production rivaling the average retail electricity price for that term (Flora and Riahi-Nezhad 2006). Although that study took into account capital, operations and maintenance, cleanout, transportation, and levelized costs, the authors concluded that a full systems economic analysis must be performed that is site- and technology-specific.

A study comparing the potential energy production from cattle manure and broiler litter found that among various technologies, gasification had the highest net energy produced for broiler litter because of the high solids content (Chang 2004). For animal wastes with moisture levels exceeding 40 percent, that study concluded anaerobic digestion had a higher net energy production because of the input energy required to dry the manure to a partial oxidation state for thermal treatment. Feedlot manure with a moisture level less than 40 percent, as is readily available in warm climates such as Texas and California, would produce higher net energy through gasification. To give some perspective, based on the volume of cattle waste generated in Texas alone, gasification of feedlot manure could generate 400 MWe of power each year, while anaerobic digestion of that same amount of manure would yield 180 MWe and would also require the addition of over 7 million gallons of water to process the waste into a biogas (Fedler 2006).

REMAINING BARRIERS TO USING ANIMAL WASTE

ECONOMIC BARRIERS

There remain significant technical and economic barriers to using animal waste as a fuel source. One of the major barriers to using animal manure for energy production is costs associated with acquiring feedstock, particularly transportation. For many operational biomass plants in the U.S. using wood waste, feedstock transportation has been one of the greatest investments, with prohibitive transportation costs beyond 100 miles (Wiltsee 2000). An economic feasibility study for poultry litter power on the Delmarva Peninsula study found that negative or zero delivery

costs for litter, or offsetting ash value as fertilizer were required for the economics of a retrofit to compete with market electricity prices (Antares Group 1999). The net value of poultry-litter ash, accounting for transportation and processing costs, has been estimated at \$25–\$75/ton (Bock 2000), while other studies estimate \$32–\$38/ton for broiler litter and \$52/ton for turkey litter (Antares Group 1999, McCallum Sweeney 2002). Gasifier manufacturer Primenergy's poultry-litter granulation process produces fertilizer with an estimated value of \$50/ton (Primenergy 2007).

A National Energy Technology Laboratory study of poultry-litter gasification and subsequent co-firing at existing PC-fired power utilities in Texas and Western Kentucky concluded that there was not an economic incentive to proceed with even a demonstration phase, with capital investment costs ranging from \$9–\$15 million and the cost of producing electricity approximately 4–5¢/kWh (Patel et al. 2002). In that study, poultry litter feedstock costs were factored, acknowledging that a zero or negative-cost fuel supply would change the economics. A thorough cost-effectiveness study taking into account Texas' RPS mandate or water quality issues was not performed, however.

Other than a few feasibility reports evaluating planned poultry-litter-fueled installations, there is a general lack of economic analysis of using animal waste to produce electricity. Furthermore, these reports have failed to account for social and environmental welfare costs, namely existing TMDLs and land amendment restrictions, or state policy incentives. Economic analysis of utility-scale power from hog and cattle manure is lacking, despite efforts to mitigate water pollution associated with CAFOs in some states. Externalities such as water pollution concerns, greenhouse gas mitigation, and renewable mandates can drive policy to dramatically alter the economic feasibility of power production from animal waste. Following the Minnesota model for poultry litter-fired power generation, Fibrowatt's plans for new power plants in North Carolina, Arkansas and Mississippi are likely contingent upon those states passing RPSs or other renewable mandates (which has now been done in North Carolina), providing tax credits and possibly other subsidies to offset feedstock and production costs.

For example, the possible adoption of a carbon tax would change the relative economics, as it incorporates a social welfare cost (greenhouse gas emissions) into the cost of fossil fuel-based power generation. A \$50/ton carbon tax would bring the costs for biomass-produced electricity into line with coal (Sondreal et al. 2001). Furthermore, if the prohibitive economic factor of using poultry litter for energy production is the cost of the feedstock, existing TMDLs may shift manure-disposal costs to the point of introducing tipping fees or state subsidies.

TRACE METALS IN ANIMAL WASTE

One issue that has not been addressed, and for which Fibrowatt has encountered not-in-my-backyard (NIMBY) resistance, is the arsenic prevalent in chicken manure (Ewall 2002; Blue Ridge Environmental Defense League 2006). The fate of manure-bound arsenic during the combustion process has yet to be evaluated, with no published measurements of air concentrations of arsenic at or near poultry-waste incinerators. A study prepared for Maryland Environmental Service on the expected emissions from a proposed Fibrowatt poultry-litter-fired plant estimates arsenic emissions based on projections from the Thetford plant in the U.K. (Alternative Resources Inc. 2001). That study estimates arsenic and dioxin emissions at an order

of magnitude less than emissions from a coal plant. Since the European Union declared the use of roxarsone undesirable in 1999 and has abandoned its use, it is unclear how the levels of arsenic in poultry litter in the U.S. compare with those in the U.K. and how the measurements made at the Thetford facility are relevant. Mercury emissions were not estimated, as poultry-litter samples were yet to be analyzed for background concentrations.

CONCLUSIONS

Historically, livestock waste has seen beneficial use through the application of manure as fertilizer. However, the livestock industry's evolution from small, distributed farms to large concentrated animal feeding operations has impacted the value of this application. The rapid and concentrated growth of the industry has contributed to water-quality issues in many states. It is clear that in many areas of the U.S., an alternative manure-management approach is necessary to meet more stringent water-quality regulations. Concurrently, concern with both the availability and environmental impacts of fossil fuels has re-awakened interest in renewable fuels for electricity generation. These factors indicate that the potential for generating electricity from animal waste could be environmentally beneficial when compared with spreading for fertilizer (or otherwise disposing of it) in many areas.

An important consideration is the social desirability of using animal waste to generate electricity relative to local environmental and cost conditions. For example, areas that support intensive animal production and have associated water-quality issues are likely to receive the highest environmental and social benefits from manure-to-electricity applications. However, economic factors such as the proximity of a proposed facility (or existing plant for co-firing) to livestock or poultry producers and availability of state incentives determine whether beneficial use of manure can be achieved cost effectively for any given location. Thus, absent regulations, what appear to be socially optimal projects might not be adopted because of recognized shortcomings in how unregulated markets price externalities.

When socially optimal projects are not undertaken for economic reasons, public policy can induce their adoption. The slow adoption of animal-waste biomass for electricity generation has been previously analyzed from an energy and sustainable policy perspective (Buckley and Schwarz 2003). However, watershed-level regulations, such as TMDL standards and state RPSs, may combine to indicate that manure-to-electricity projects are economically viable in certain areas. Site-specific considerations, such as the environmental impact of traditional manure disposal methods, possibility of tax incentives and subsidies, and selection of technology will determine the viability of energy generation from animal waste.

The poultry litter-fired power plant in Minnesota and those planned for other states are test cases demonstrating the viability of animal manure-to-electricity projects, provided local water-pollution concerns and state mandates combine to spur their adoption. Thus, modeling of regulatory goals, social costs of existing energy production and manure management strategies, and social benefits of using manure-based energy production are necessary to determine locations and technologies that are viable for deployment. An integrated economic feasibility model that includes alternative manure-management strategies, available renewable energy sources and the impacts of relevant energy, environmental, and agricultural policies is needed.

This paper has provided background information for feasibility and economic analysis of manure-based electricity generation. The review indicates that direct combustion holds promise and is beginning to see some development. However, front-end gasification with co-firing has been lightly adopted despite its promise for utilities trying to accomplish environmental objectives without the operational problems associated with co-firing biomass.

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