NATIONAL RENEWABLE ENERGY LABORATORY

Milestone Completion Report

Agreement #: 29525 FY16 Level: Quarterly Progress Measure WBS #: 2.1.0.104	Completion Date: April 4th, 2016 Scheduled Completion: March 30, 2016 Platform Area: Waste to Energy
Milestone Title:	An analysis report that discusses the economic tradeoffs among multiple biogas-to-energy choices. This analysis will be provided to BETO as an NREL technical report and will identify plausible scenarios in which it is economically attractive to collect and clean biogas for distribution in pipelines.
Authors:	Daniel Inman, Ethan Warner, Anelia Milbrandt, Alberta Carpenter, Ling Tao, Emily Newes, and Steve Peterson (Lexidyne, LLC).
Participating Researchers:	Lexidyne (external consultant)
Project Title: Principal Investigator:	Waste-to-Energy System Simulation Model Daniel Inman
Keywords:	Biogas, landfill, CAFO
Reviewed By:	NA

Abstract

Conversion of biogas from organic waste materials to usable energy (electricity, compressed natural gas [CNG], pipeline natural gas [PNG], and biofuel) has received attention because the U.S. Environmental Protection Agency (EPA) categorized biogas-derived energy as a cellulosic biofuel in 2014, making it eligible to collect renewable identification number (RIN) credits under this designation. NREL developed the Waste-to-Energy System Simulation (WESyS) model to help understand the development of the waste-to-energy (WTE) system. The objective of this study is to identify barriers to energy production from waste materials, provide insights on the role of policy for this market, and identify data/modeling gaps in the existing modeling and data structure. This study is focused on biogas resources derived from landfills and from confined animal feeding operations (CAFOs) at a national level. Our results suggest that collection and conversion of biogas to energy from landfills and CAFOs has the potential to contribute as much as 400,000,000 giga joules (GJ) annually, with the largest energy potential from swine CAFOs. This study highlights the impact of system levers: development dwell time and operating costs are very important for maximizing energy production from landfills and CAFOs.

Introduction

The term "Waste-to-energy" (WTE) refers broadly to the conversion of organic wastes to fungible energy sources via a range of technologies. The WTE system, however, is composed of a number of independently functioning and technologically disparate waste streams and conversion processes; the one commonality is that the feedstock is organic waste material. Major sources of organic waste that may be effectively used to generate energy (electricity, compressed natural gas [CNG], pipeline natural gas [PNG], and liquid biofuels) in the United States are landfills, livestock operations, wastewater treatment facilities, and food waste. Depending on the chemical characteristics of the waste and the desired energy product, WTE conversion processes may include gasification, fermentation, anaerobic digestion (AD), pyrolysis, Fischer Tropsch synthesis, or combinations of these processes and others not mentioned.

There has been increased interest in waste reduction, GHG emission (i.e., CH_4) reduction, and increased production of valuable products through utilizing organic wastes as energy feedstocks. The federal government and the State of California have begun to enact programs that incentivize certain aspects of the WTE system. For example, the U.S. Environmental Protection Agency (EPA) ruled that CNG and liquefied natural gas (LNG) produced from biogas qualifies as a "cellulosic biofuel pathway" under the Renewable Fuel Standard (RFS) program and thus qualify for the renewable identification number (RIN) credits that fall under that fuel category (EPA 2014). Under the same rule changes, electricity generated from biogas that could be demonstrated (e.g., through contract) to be used in electric vehicles would also qualify for RIN credits. Along with other market incentives—such as avoided landfill tipping fees, low carbon fuel standards, and renewable electricity credits (RECs)—the investment attractiveness of WTE projects is poised to increase.

The objective of this study is to identify barriers to energy production from waste materials, provide insights on the role of policy for this market, and identify data/modeling gaps in the existing modeling and data structure. This study is focused on biogas resources derived from landfills and from CAFOs at a national level. Scenarios explored in this study assume that state-level policies are implemented at the national level.

Waste-to-Energy System Simulation Model

NREL has developed a system dynamics (SD) model of the WTE industry in the United States. SD modeling uses cause-and-effect relationships in a dynamic stock-and-flow framework to assess potential market responses resulting from changes to a system; the framework is developed using historic trends as inputs and for calibrating cause-and-effect relationships. The SD model, WTE System Simulation (WESyS), takes a high-level view of the industry and focuses on the following areas of the supply chain:

- Conversion of organic materials to biogas
- Collection of biogas
- Conversion of biogas to fungible energy sources
- Insertion of biomethane (purified biogas) into the natural gas pipeline system.

In 2015, methane in biogas is typically used to produce electricity, heat, CNG or LNG, and pipeline natural gas (PNG). Biogas can be directly converted to electricity or heat, but requires processing and cleanup before it is acceptable for use either as a vehicle fuel (i.e., CNG) or as a substitute for PNG (EPA 2015c).

At present, WESyS consists of two models, one representing landfill systems and the other representing CAFO systems. WESyS has a flexible structure to allow buildout to model additional waste resources that could be used for energy production by 2040, such as wastes from wastewater treatment or food.

WESyS: Landfill Model

There are approximately 134 million tons of municipal solid waste (MSW) that enter U.S. landfills annually (EPA 2015e). After an increase in MSW generation in the 1990s, this influx was about the same in 2013 as it was in the early 1980s, but the number of operating landfills has dropped by nearly 75% over the same time period. An NREL report estimated that the additional potential methane from landfill biogas that could be available for energy production is approximately 2.8 million tons annually, or about 2,100,000 million British thermal units (mmBtu) per day (Saur and Milbrandt 2014; Murray et al. 2014). Chemically, biogas generated from landfills is approximately 60% CH_4 and 35% CO_2.

As of 2015, 645 landfills were capturing and converting biogas to energy (EPA 2015a), which amounts to a generation capacity of 2,066 MW and an estimated 298 million standard ft^3 of landfill gas per day (EPA 2015a). For our modeling purposes in WESyS, we categorized landfills from the Landfill Methane Outreach Program (LMOP) (EPA 2015a) based on size, landfill status, and LMOP categories for landfills with and without WTE projects.

Landfills in the LMOP (2015a) were categorized by landfill size categories using definitions from the EPA (2015b). The EPA defines *small* and *large* as having an approximate landfill design capacity of less or more, respectively, than 2.8 million tons and 88 million ft^3. This is an approximation for a calculated or measured uncontrolled non-methane organic compounds

(NMOC)emission rate of at least 55 million tons per year. On average, a small landfill has a capacity of about 2.6 million tons and a large landfill has a capacity of about 8.9 million tons.

Landfills in the LMOP (2015a) were further categorized in the WESyS Model as to their project status with *active* (landfills still accepting new MSW) and *inactive* (landfills that have closed and are no longer accepting MSW). Active and inactive landfills both produce biogas, but at differing rates. Movement from *active* to *inactive* is based on projected closure rates estimated using LMOP data on landfill capacities and MSW acceptance rates.

Categorization of LMOP landfills with and without WTE projects are based broadly on LMOP (EPA 2015a) data: *Candidate* landfills for WTE projects are landfills that are accepting MSW or have been closed for five years or less, have at least one million tons of MSW, and do not have a planned, operational, or under construction WTE project. *Candidate* landfills are further subdivided into landfills with or without installed gas collection equipment for flaring. All other landfills (e.g., that have been closed for more than five years) are categorized as *potential* candidate landfills.

Landfills with WTE projects that produce electricity or biogas are tracked within the WESyS for landfills as "electricity" and "CNG". Landfills that currently produce heat, for example, are included in modeling for accounting purposes only.

Figure 1 summarizes LMOP data by the categories described above for use in the WESyS Model. Data shown in Figure 1 represent the initial model conditions and are from the EPA's LMOP database (EPA 2015), with the initial conditions in the model set to 2013.

The WESyS models landfills as they transition from a *potential* candidate to a *candidate* landfill and from a *candidate* to a landfill with a WTE project. Movement from being a *potential* candidate for energy production to being a *candidate* for energy production is based on projections of MSW acceptance at active landfills. If an active *potential* candidate landfill would gain 1 million tons of MSW by 2040 it would become a *candidate* landfill. Movement within the candidate landfill category from a *candidate* landfill without gas collection for flaring equipment to a landfill with gas collection for flaring equipment is based largely on EPA requirements to add flaring equipment to landfills that are classified as *large*.

Each WTE option has different capital and operating expenses associated with it (Table 1) and is exposed to different price signals from the market (Figure 2). The WESyS models landfills as they transition from candidate to energy producer (i.e., capturing and converting biogas to energy) based on the net present value of the technology under consideration. Candidate landfills can change over time within WESyS in the following ways:

1. Landfills remain unchanged
2. Candidate landfills without gas collection equipment for biogas flaring can add this equipment.
3. Candidate landfills with or without gas collection and flaring equipment can:
    A. Combust the biogas to generate electricity to be sold to the grid
    B. Clean (i.e., remove H_2S) and compress the biogas to be used as CNG vehicle fuel.

The WESyS model uses forecasted estimates of population, per capita MSW generation, and the organic composition of that biomass based on historic MSW data (EPA 2015e). These estimates are used to model MSW accumulation over the course of the WESyS model simulation. In contrast, the available landfills are treated as static quantities based on the LMOP (EPA 2015a).

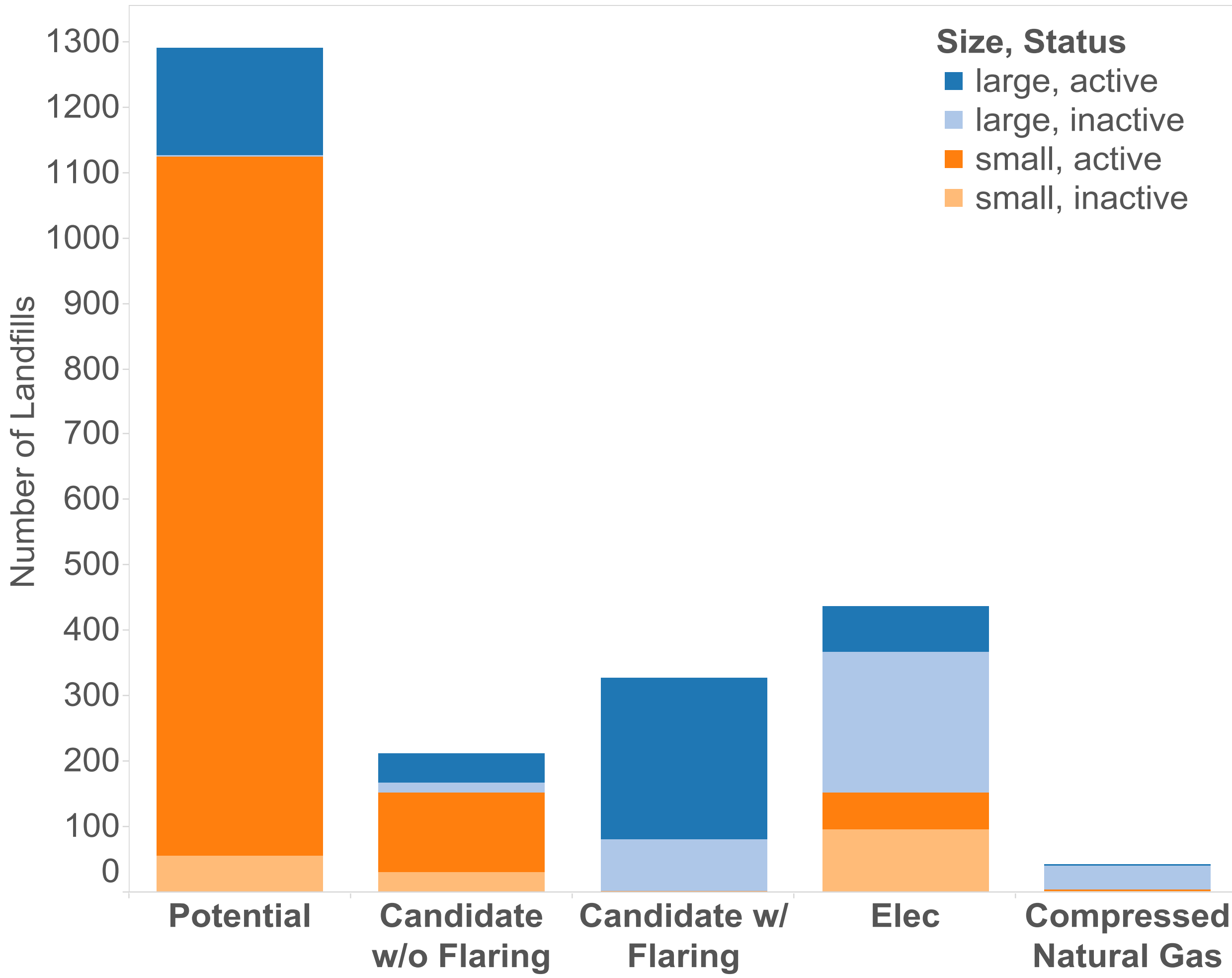

Figure 1. 2015 Landfill counts in the WESyS Model by size, activity status, and categorization of landfills with and without WTE projects. Landfills with WTE projects without electricity production or CNG production are excluded.

Table 1. Capital and Operating Costs by Landfill size. Costs are in 2011 dollars.

Parameter	Collection Equipment	Conditioning Unit	Compressor Unit	Total	Collection Electricity Use	Collection Operation and Maintenance (O&M)	Conditioning O&M	Compressor O&M	Total
Units	---------------------$$10^6$ ---------------------------				------------------------------- $$10^3$ yr^{-1} ---------------------------------				
Small, Add Flaring	1.2	0	0	**1.2**	52	2.6	0	0	**55**
Large, Add Flaring	3.3	0	0	**3.3**	150	7.5	0	0	**160**
Small, Flaring to Elec.	0	3	0	**3**	0	0	130	0	**130**
Large, Flaring to Elec.	0	5.2	0	**5.2**	0	0	530	0	**530**
Small. Add Elec.	1.2	3	0	**4.2**	52	2.6	130	0	**180**
Large, Add Elec.	3.3	5.2	0	**8.5**	150	7.5	530	0	**690**
Small, Flaring to CNG	0	3	0.23	**3.2**	0	0	130	46	**190**
Large, Flaring to CNG	0	5.2	0.45	**5.6**	0	0	530	190	**720**
Small, Add CNG	1.2	3	0.23	**4.4**	52	2.6	130	46	**230**
Large, Add CNG	3.3	5.2	0.45	**9.1**	150	7.5	530	190	**880**

Murray et al. (2014), the source of information in the table above, derived the data from Prasodjo et al. (2013). On average, a small landfill corresponds to about 42,000 ft^3 per hour and large landfill corresponds to about 120,000 ft^3 per hour.

Figure 2. Pricing scenarios used for electricity, CNG, and PNG in the WESyS Model.

Data are from DOE 2015a and EIA 2015.

WESyS: Concentrated Animal Feeding Operation

Production of biogas from CAFOs requires the use of digesters where the process of AD takes place. Biogas derived from CAFOs is estimated to have a maximum economic production potential of approximately 2.1 million tons per year or 1,750,000 mmBtu) per day (Saur and Milbrandt 2014; Murray et al. 2014). Chemically, biogas from the AD) of animal manure is approximately 65% CH_4 and 35% CO_2 and requires processing and cleanup before it is acceptable for use either as a vehicle fuel (CNG) or injection into the natural gas pipeline as PNG (Murray et al. 2014).

In 2015, there were about 247 CAFOs capturing and converting biogas to energy (EPA 2015e). which amounts to a generation capacity of 1,670 MW (EPA 2015f). For our modeling purposes in WESyS, we categorized landfills from AgStar (EPA 2015f) based on AgStar and Murray et al. (2014) methods. Categorization is based on CAFO type, size, and the anaerobic digester used coupled with the WTE project.

We consider all dairy cattle, beef cattle, and swine operations with over 500 head to be *candidate* biogas producers (Murray et al., 2014). From the potential WTE candidates, we classify them into *small*, *medium*, and *large* CAFO operations (Table 2). Dairies are the largest potential source of biogas, from CAFOs in the United States (Murray et al. 2014). As compared to other types of CAFOs, dairies routinely confine and concentrate animals and have additional organic waste streams from the production and collection of milk that are included in the slurry.

Biogas yield varies depending on the type of animal manure and anaerobic digester used. Anaerobic digesters can be classified by the way in which the manure slurry is handled and fed to the system. Batch systems (e.g. *covered lagoon [CL]*) store the slurry in holding ponds or lagoons to be loaded into the anaerobic digester in batches. In contrast, continuous feed systems (i.e., *continuous mix [CM]*, *plug flow [PF]*) allow the slurry to enter the anaerobic digester. Based on Murray et al. 2014, continuous slurry feed anaerobic digesters using dairy manure have the highest biogas yields. Anaerobic digesters can produce viable amounts of biogas from swine and beef operations.

Once an AD system is installed and producing the biogas and the biogas has been cleaned up (removing H_2S) to standard, we assume three marketable options:

1. Combust the biogas to generate electricity to be used on-site or sold to the grid
2. Compression of the biogas to be used as CNG vehicle fuel
3. Further upgrade the biogas to 99% CH_4 for distribution in existing natural gas pipelines.

The WESyS CAFO model uses a nested logit function to represent farmer adoption of anaerobic digester equipment. A nested logit function represents choices among several similar options (Figure 3). CAFOs are classified by the type of animal and the size of the operation (Table 2). Within each farm base, operations are categorized as being an adopter (of anaerobic digester equipment), a potential adopter, and not adopting based on expected relative per-operation revenues.

The techno-economics of converting animal wastes to biogas via AD vary considerably among the type of CAFO, the size of the CAFO, and AD system being used (Table 3). Costs associated with biogas derived via AD of animal manure include the fixed capital associated with the installed anaerobic digester system, operating costs of the digester, solids removal, and utility costs. Table 3 also presents costs associated with the installation and operation of compressor equipment needed for CNG and PNG as well as pipeline costs associated with PNG.

The farm bases are typically treated as static quantities over the course of a simulation run. The WESyS Model can run scenarios that represent changes (+/-) in the total number of CAFOs, in operation size, and in distribution among types of CAFOs. Forecasts of the potential build out of CAFOs at the appropriate level of detail were not found that could be used in this study.

Table 2. CAFO Number and size Classes used in the WESyS Model

Size Class (head)	Total Number of Animals (million head)		
	Dairy	Swine	Beef
Small (500 – 999)	2.2	1.3	11
Medium (1,000 – 1,999)	2.4	6.5	3.9
Large (> 1,999)	3	58	9.7
	Total Number of Operations		
	Dairy	Swine	Beef
Small (500 – 999)	1600	2300	4200
Medium (1,000 – 1,999)	950	3300	1100
Large (> 1,999)	780	9000	320

Total animal counts (head) per class for four types of animal operations in the United States. Source: Murray et al. 2014

Table 3. Techno-economic Characteristics for the AD Systems and CAFO Combinations used in the WESyS Model

Farm Type	Size	AD System	Methane Production	Methane Collected (85%)	Fixed Capital Investment for AD	Utility Costs	AD Operating Costs	Gas (H_2S) Clean-Up	Post-Digestion Solids Clean-Up
			$10^6 m^3 yr^{-1} op^{-1}$	$10^6 m^3 yr^{-1} op^{-1}$	--------- $\$10^6$ ---------		---------------- $\$10^3 yr^{-1}$] --------------		
Dairy	Small	CL	0.41	0.34	0.9	0.048	36	28	58
	Medium	CL	0.79	0.67	1.2	0.062	47	36	75
	Large	CL	2.2	1.9	2.2	0.120	88	68	140
Swine	Small	CL	0.18	0.16	0.71	0.038	28	22	0
	Medium	CL	0.36	0.31	0.8	0.042	32	25	0
	Large	CL	1.6	1.3	1.6	0.084	64	49	0
Dairy	Small	CM	0.48	0.41	0.73	0.039	29	23	47
	Medium	CM	0.94	0.8	1.1	0.059	45	35	71
	Large	CM	2.7	2.3	2.6	0.140	100	79	160
Swine	Small	CM	0.18	0.16	0.46	0.025	19	14	0
	Medium	CM	0.36	0.3	0.59	0.031	24	18	0
	Large	CM	1.6	1.3	1.7	0.090	68	53	0
Dairy	Small	PF	0.48	0.41	1.0	0.054	41	32	65
	Medium	PF	0.94	0.8	1.4	0.076	58	45	92
	Large	PF	2.7	2.3	3.0	0.160	120	94	190
Swine	Small	PF	0.18	0.16	0.73	0.039	29	23	0
	Medium	PF	0.36	0.3	0.87	0.046	35	27	0
	Large	PF	1.6	1.3	2.1	0.110	83	65	0
Beef	Small	PF	0.085	0.072	0.7	0.037	28	22	45
	Medium	PF	0.17	0.14	0.82	0.044	33	26	53
	Large	PF	0.41	0.35	1.5	0.079	60	46	96

CL = covered lagoon, CM = continuous mix, PF = plug flow. The source of information in the table above, Murray et al. (2014), derived the data from Prasodjo et al. (2013).

Table 4. Compressor Equipment and Operational Costs for Three Types of AD Systems. Costs are in 2011 dollars.

System Size	Capital Investment	Operating Cost
	$\$10^6$	10^3 yr^{-1}
Small	130	9.5
Medium	130	9.5
Large	200	16

CL = covered lagoon, CM = continuous mix, PF = plug flow. Source: Prasodjo et al. (2013)

Table 5. Pipeline and Transmission Costs in 2011 dollars.

Transmission Cost	Pipeline Cost	Assumed Average Pipeline length	Pipeline costs
$ mmBtu^{-1}	10^3 mile^{-1}	miles	10^6
1.2	180	5	0.900

Source: Prasodjo et al. (2013)

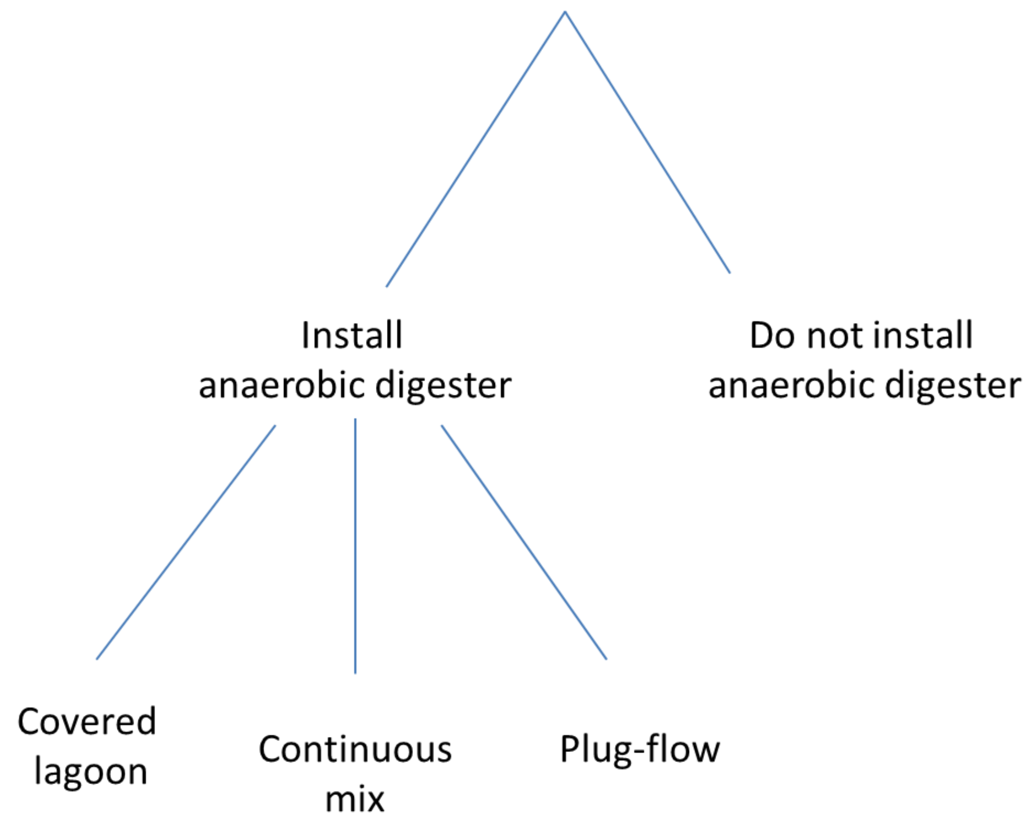

Figure 3. Example of the nested logic function for representing the adoption of AD equipment in the WESyS Model

Major Current Policies Supplying Revenue to WTE in the United States

Major current U.S. and California policies examined in this report that can generate revenue for WTE projects using biogas are summarized in Table 5. The REC is a credit for renewable electricity generation in many states with a market price. The average market price has been around $1.00 per MWh generated (Informa Economics 2013). The revenue from a REC is small relative to the $11/MWh generated U.S. Production Tax Credit (PTC) (EPA 2015d). The PTC is a national policy for renewable electricity that includes production from biogas.

The renewable information number (RIN) credit and California's Low Carbon Fuel Standard (LCFS) credits are for renewable transportation fuels (such as CNG) only. If PNG and electricity are being used by electric and gas vehicles there are revenue opportunities from RIN and LCFS credit. There is an excise tax credit for renewable gas, but it is slightly offset by the tax on alternative fuels (DOE 2015b).

CAFO operators may need to pay tipping fees to dispose of animal waste. Another potential revenue source is avoiding these tipping fees through installation of an AD system. Table 6 summarizes the waste generation per animal and by CAFO size, along with the expected tipping fee costs associated with that waste generation. The decision to build an AD system (described above) factors into the avoided tipping fee cost if an AD system with lower AD post-digestion solids cleanup costs (see Table 3) were installed.

Table 6. Sources of Potential Additional Revenue for U.S. Biogas.

Revenue Source	Energy Product	Value	Range	Units	Source
REC	electricity	U.S.: $1.00 CA: $4.25	U.S.: $0.25 to $3.00 CA: $4.25 - $12.75	USD per MWh	Informa Economics 2013
PTC	electricity	$11	N/A	USD per MWh	EPA 2015d
RIN	transportation electricity, CNG, and PNG	Average for 2015: $0.7	Historically $0 – $2	USD per RIN*	Foody 2015
California LCFS credit	transportation electricity, CNG, and PNG	Range Average: $45	$18 – $73	USD per ton CO_2-e	NRDC 2015
Excise Tax Credit (minus alternative fuel tax)	CNG	$0.5 - $0.18 = $0.32	N/A	USD per gge	DOE 2015b

*A RIN is equal to ethanol gallon equivalent of fuel.

Table 7. Sources of Potential Additional Revenue for U.S. Biogas Producers

Farm Type	Size	Animal Waste per Operation	Tipping Fee
		[thousand tons/yr]	[mil $2011/yr]
Dairy	Small	16	0.8
Dairy	Medium	30	1.5
Dairy	Large	86	4.3
Swine	Small	1.5	0.075
Swine	Medium	2.9	0.15
Swine	Large	13	0.65
Beef	Small	-	-
Beef	Medium	-	-
Beef	Large	25	1.3

Tipping fees have been estimated to range between $24 – 91 per ton of waste. Source: Clean Energy Projects 2015; Barker and Walls 2002

Scenario Development

In this study, WESyS is used to evaluate the potential economic development of WTE projects on landfills and at CAFOs in the United States under different policy conditions. Alternative policy conditions from a business as usual (BAU) scenario were developed on the bases of potential policy changes that could be implemented at the national level. Alternative scenarios were developed on the basis of policies being implemented or discussed for implementation in individual states, such as California.

1. Baseline

The baseline scenario is a BAU scenario based on national policies or policies that impact many U.S. states, such as RECs. The BAU policies are reflected in Table 5 with the exception of the LCFS.

National policy conditions are extended out into 2040 in the BAU scenario. Though optimistic, this consistency in assumptions was implemented to simplify comparisons between other scenarios so that changes in results could be directly linked to a single policy change.

In the BAU, it is assumed that by 2040, about 20% of generated electricity and 20% of PNG will be used by electric and gas vehicles. This assumption influences how much of an impact RINs have on electricity WTE projects. In our assumptions, this means that at most, the impact of RIN on electricity and PNG relative to CNG will be about 20%.

2. California Low Carbon Fuel Standard

We examined a scenario in which a policy similar to the California's LCFS was implemented for the entire United States. We did not dynamically model a LCFS credit market and we did not examine multiple LCFS credit prices.

Table 7 summarizes implementation of the alternative scenario with an LCFS. Table 8 shows how life cycle GHG emission estimates of landfill and CAFO biogas is compared to the 10% life cycle GHG emission reduction of diesel fuels. The difference, multiplied by the credit price, indicates the potential revenue impact of an LCFS credit after 2020 if implemented in the United States.

3. California State Flaring Requirements Applied Nationally (Landfill Model only)

We examined a landfill scenario in which national policy set a lower threshold for requiring the installation of gas collection and flaring equipment. We based this alternative scenario on California policies.

The EPA (2015b) has general guidelines that control emissions landfills install gas collection and flaring equipment for landfills with a capacity >2.8 million tons. In the BAU scenario, this information is used to gradually add gas collection and flaring equipment to all *large* landfills. Requiring the installation of this equipment greatly reduces the overall costs to install WTE projects due to gas collection being a major expense.

Beginning in 2010, California requires installation of gas collection and flaring equipment for landfills with a capacity >500,000 tons of waste (CARB 2014c); the intent is to reduce GHG emissions in support of California's GHG emission reductions goals (CA Legislature 2008).

We developed a scenario that assumes gradual implementation of a similar policy for the entire United States. Forecasting landfill waste acceptance out to 2040 using LMOP (2015a) data shows that a large number of candidate landfills would be >500,000 tons of waste. By 2040, about an additional 25% of landfills would need to install gas collection and flaring equipment. Thus, we increased the WESyS Model's rate of conversion of candidate landfills to flares to gradually add gas collection and flaring equipment to 25% more landfills by around 2040.

A. No RIN and no Flaring (Landfill Model only)

To examine the impact of RINs and flaring requirements, we developed a scenario that has the baseline conditions without any RINs and without any requirements to flare biogas emitted from landfills.

B. No Price Incentives

This scenario removes the price incentives that are assumed to exist in the baseline scenario.

C. Fixed Capital Investment (FCI) Grants

Capital investment costs can be a barrier to takeoff in similar industries (e.g., biofuels). This scenario examined the impact of a generous FCI grant level of 50%.

D. Loan Guarantees

Having loan guarantees reduces the risk associated with financing emerging industries, such as biofuels. This scenario examined the impact of assuming a 50% loan guarantee for debt financing of each project.

E. FCI and loan Guarantees

This scenario examined the combined impact of both FCI grants and loan guarantees, both at a 50% level.

F. Organic Waste Diverted from Landfills (Landfill Model only)

We examined a landfill scenario in which national policy focused on increased diversion of the organic portion of MSW for composting and recycling rather than landfilling. We have based this alternative scenario on California's and other states' policies that seek to reduce waste generation.

In 2010, the U.S. organic portion of waste was about 50% (EPA 2015d). Based on historic trends and all else being equal, this organic portion of MSW that is landfilled should decrease to about 40% by 2040. We created a scenario in which by 2040, only 20% of the waste generated is organic in order to model the potential impact of state policies further reducing the organic portion of the waste.

Table 8. Estimation of the Impact of the LCFS on WTE Projects

Description	Life Cycle GHG Emissions	Life Cycle GHG Emissions for the Fossil Fuel Comparison in 2020	LCFS Credit Price	Assumed LCFS Impact
	lb CO_2e mmBtu^{-1}	lb CO_2e mmBtu^{-1}	\$ ton^{-1}	\$ mmBtu^{-1}
Landfill Biogas	26	200	45	4.10
CAFO Biogas	31	200	45	3.90

Source: CARB 2014a; CARB 2014b; NRDC 2015

G. RINs

The BAU scenario includes a $0.7/RIN credit, as documented in Table 5, but we did not dynamically model a RIN market. Therefore, we examined scenarios where RIN market prices have varied from the historic highs and lows of $0 to $2.00 per RIN (Foody 2015).

Sensitivity Analysis

In addition to the scenarios described above, we also performed a variance-based sensitivity study of both the Landfill and CAFO models. Sensitivity analysis is complementary to the scenario analysis because it examines the impact of a large number of system inputs across a wide range of plausible values.

Sensitivity analysis is the assessment of how uncertainty in modeled output can be apportioned to uncertainty in the model's input factors (Saltelli et al. 2008) (i.e., how variance in the model's input can explain variance in the model's output). Sensitivity analysis and uncertainty analysis have distinctly different objectives (Saltelli et al. 2008); understanding what inputs most influence a model's output contributes to model validation and provides insights into the expected behavior, across a broad range of conditions, of the system being modeled.

In this study, we focus on using a factor fixing approach. Factor fixing approaches are designed to identify which factors, among all model factors, can be fixed (i.e., assigned any value within its range) without any appreciable impact on the model's output. We decided to use Sobol's variance-based sensitivity method (Sobol 1993). Variance-based methods have many desirable features such as independence in the estimates of sensitivity indices (i.e., the order of input in the model does not affect its sensitivity index), ability to assess a very broad range of input settings, and the assessment of interaction effects (Sobol 1993). Depending on the sample size and number of factors being assessed, variance-based sensitivity methods can be computationallyintensive, particularly for higher-order effects. Using best practices, sensitivity analysis is approached systematically. For variance-based sensitivity analysis, this process involves identifying the factors of interest and their ranges, choosing a sample size and sampling approach, and deciding on which indices to compute (e.g., total effects, first-order, nth-order).

Results and Discussion

Results are presented by individual model (landfill, CAFO operations) for the scenarios evaluated.

Landfill Model: Total production of CNG and electricity by scenario and by active landfill is presented in Figure 3 and participating active landfills are presented in Figure 4. In general, CNG production has more potential than that of electricity production. Electricity production is not very responsive to the scenarios examined here while CNG production is responsive to the scenarios examined—in particular, the FCI grant has the largest impact on both CNG and electricity production. CNG production is more capital-intensive and requires higher operating costs than electricity production. Once incentivized, the CNG option quickly gains attractiveness. Incentives play an important role in terms of increasing the attractiveness of producing CNG from landfill biogas.

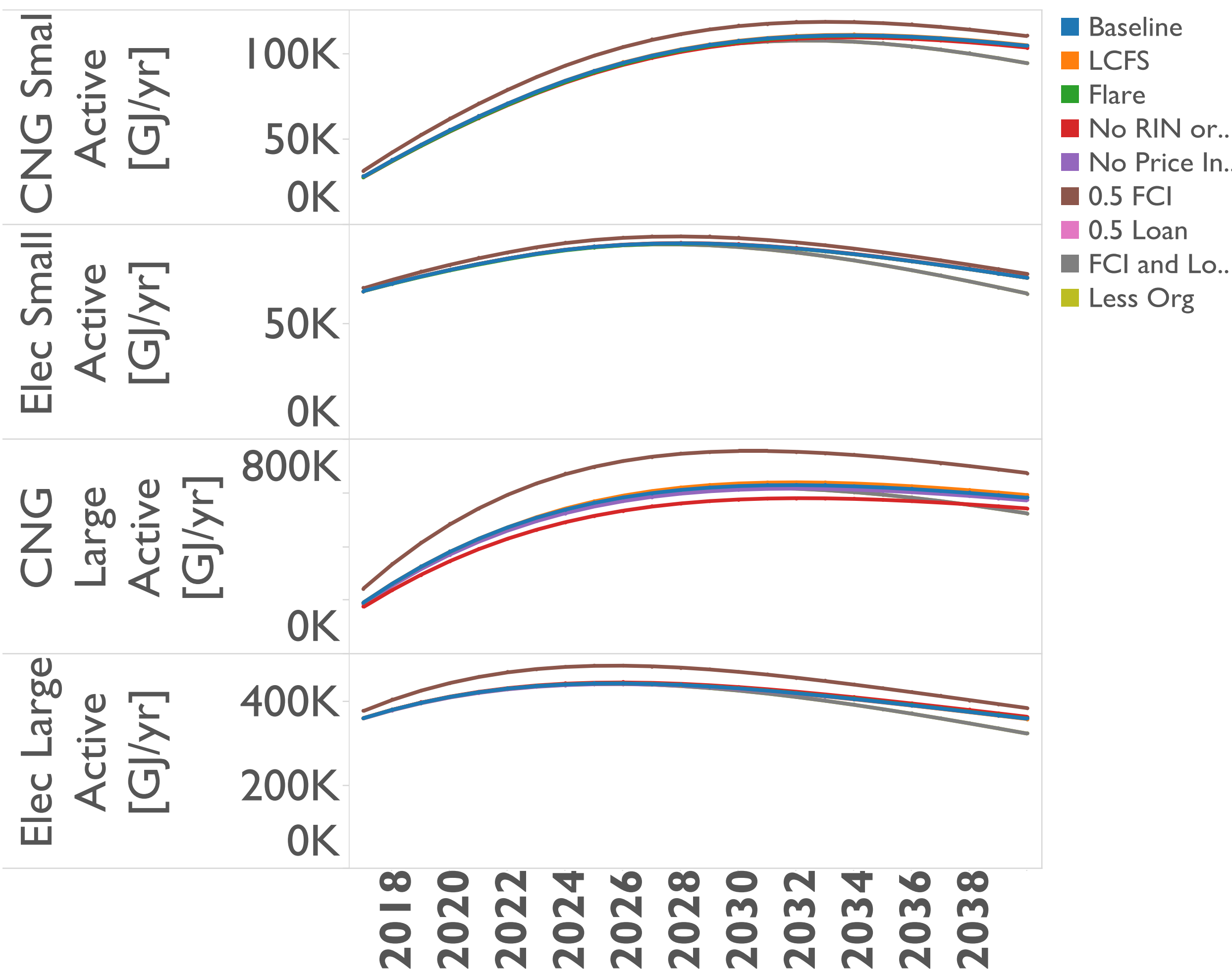

Figure 3. CNG and electricity production from small and large active landfills in response to nine scenarios

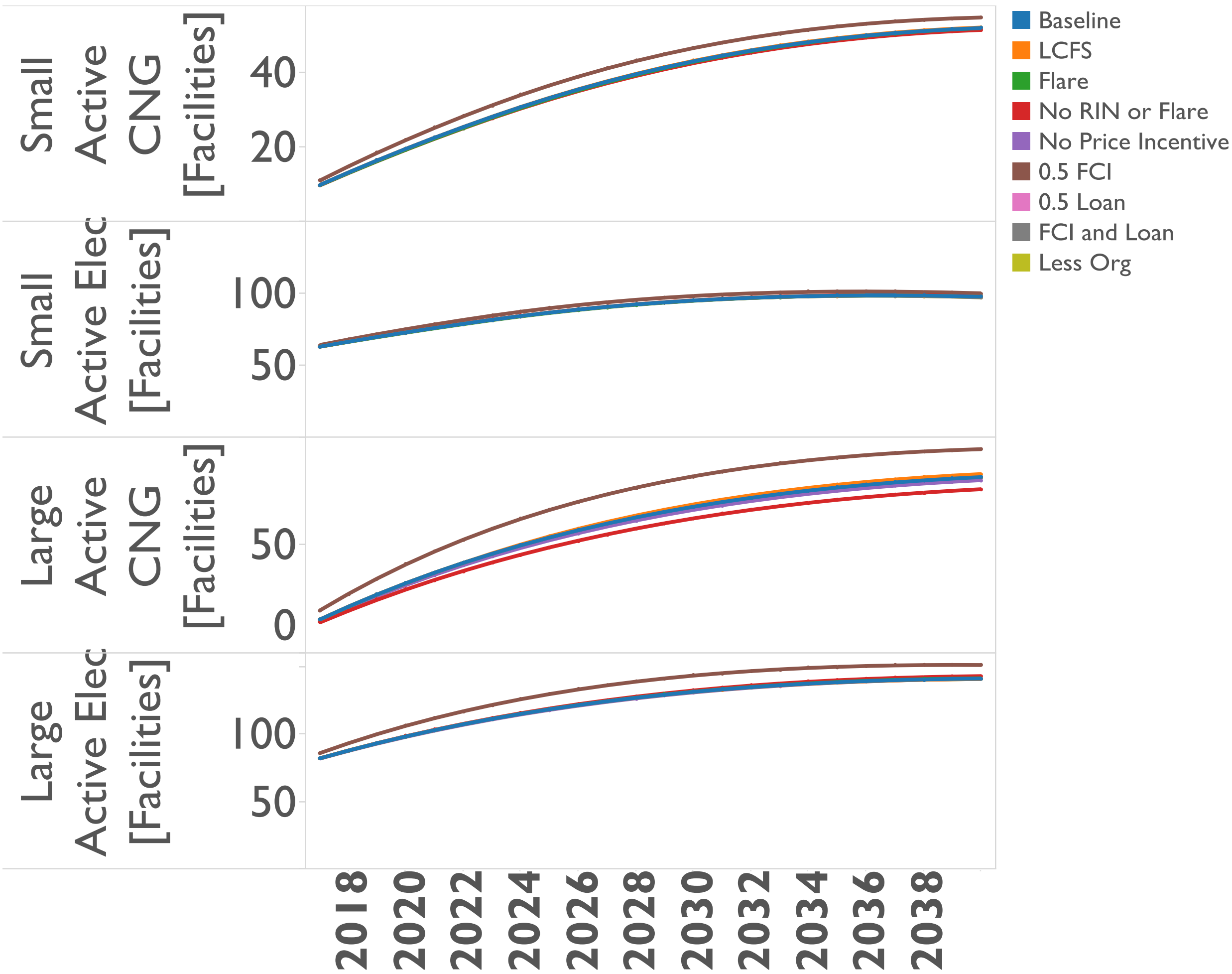

Figure 4. Number of active landfills, by class, producing electricity and CNG in response to nine scenarios

Sensitivity Results: Landfill Model

Histograms of maximum CNG and electricity production are presented in Figures 7 and 8. Across all variable combinations and ranges tested, the most likely maximum electricity output from all landfills is between 1,800,000 and 1,900,00 GJ/yr. For CNG, the probable maximum production is between 1,400,000 and 1,700,000 GJ/yr. Time series of simulated electricity and CNG production from landfills for all sensitivity runs are presented in Figures 9 and 10. Both CNG production and electricity production are responsive to the range of parameters evaluated in this sensitivity study. Overall, the most important parameters for maximizing production of CNG and electricity are development dwell time and operating costs, respectively. Development dwell time is the amount of time between making the decision to invest in a particular conversion option and having that operation up and running. The longer the dwell time the longer before a given investment begins to produce a return on investment. The operating costs are important for landfills because the capital costs are relatively low and offset for those facilities that are required to install capture and flaring equipment.

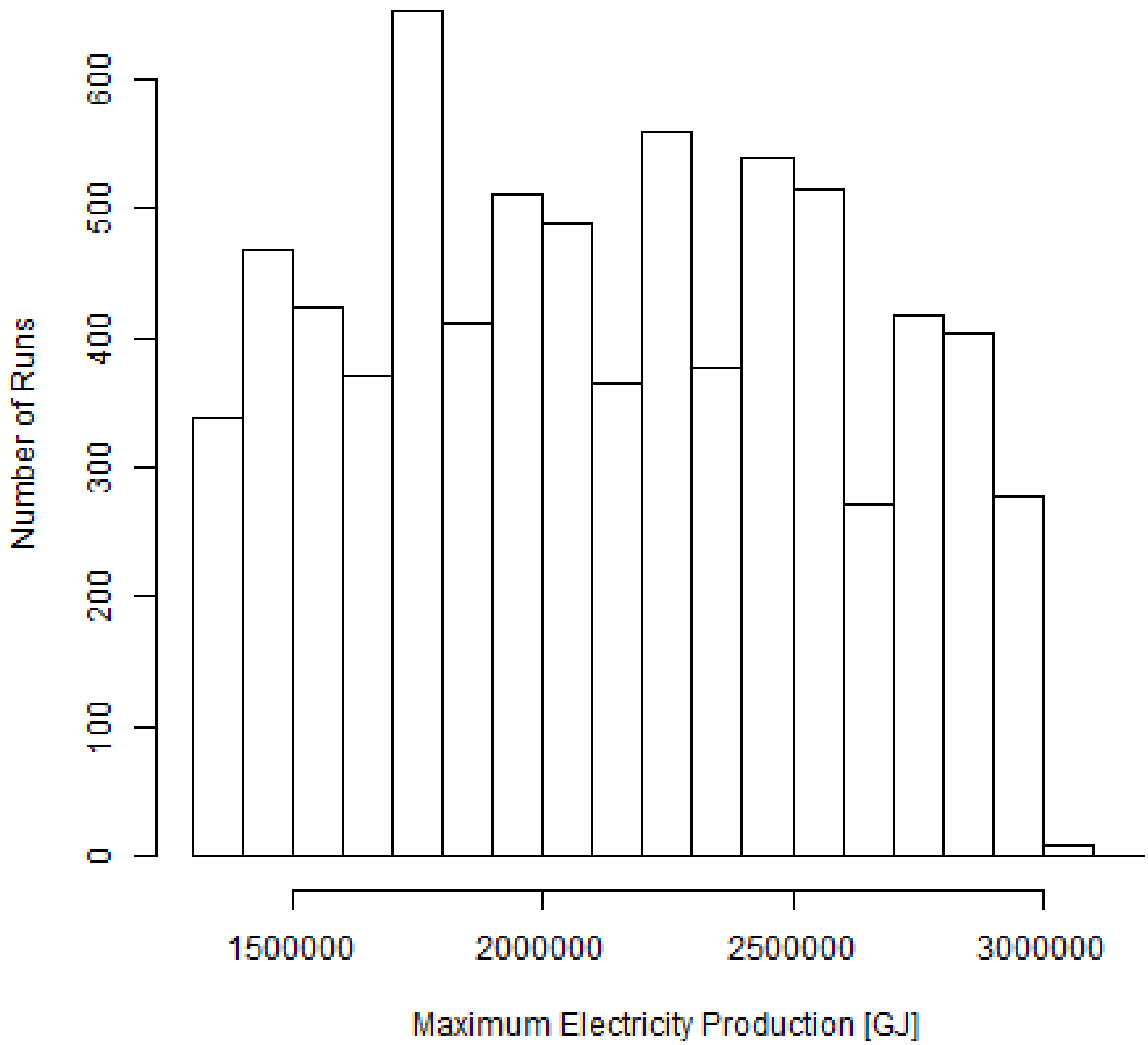

Figure 7. Histogram of maximum electricity production from all landfills types.

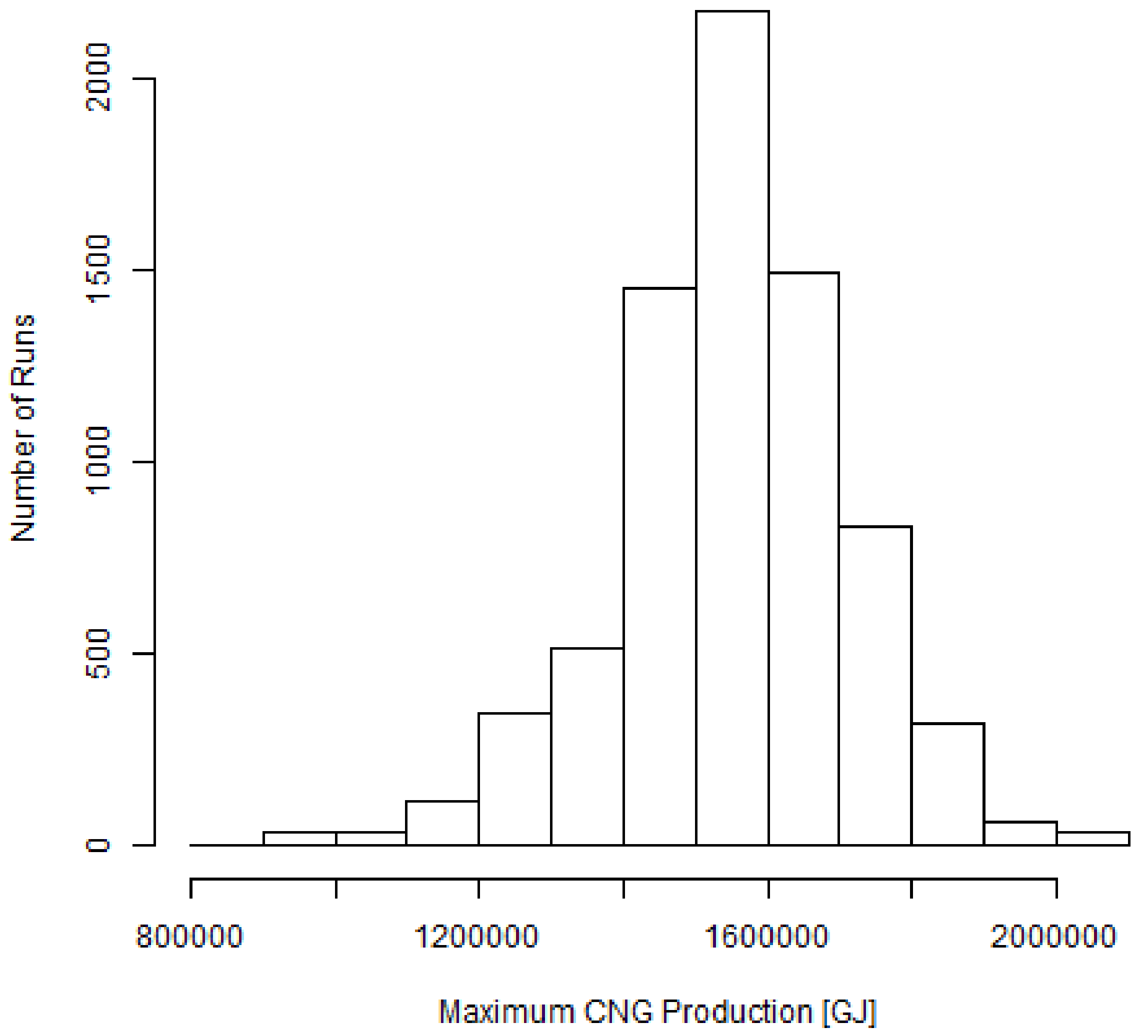

Figure 8. Histogram of maximum CNG production from all landfills types.

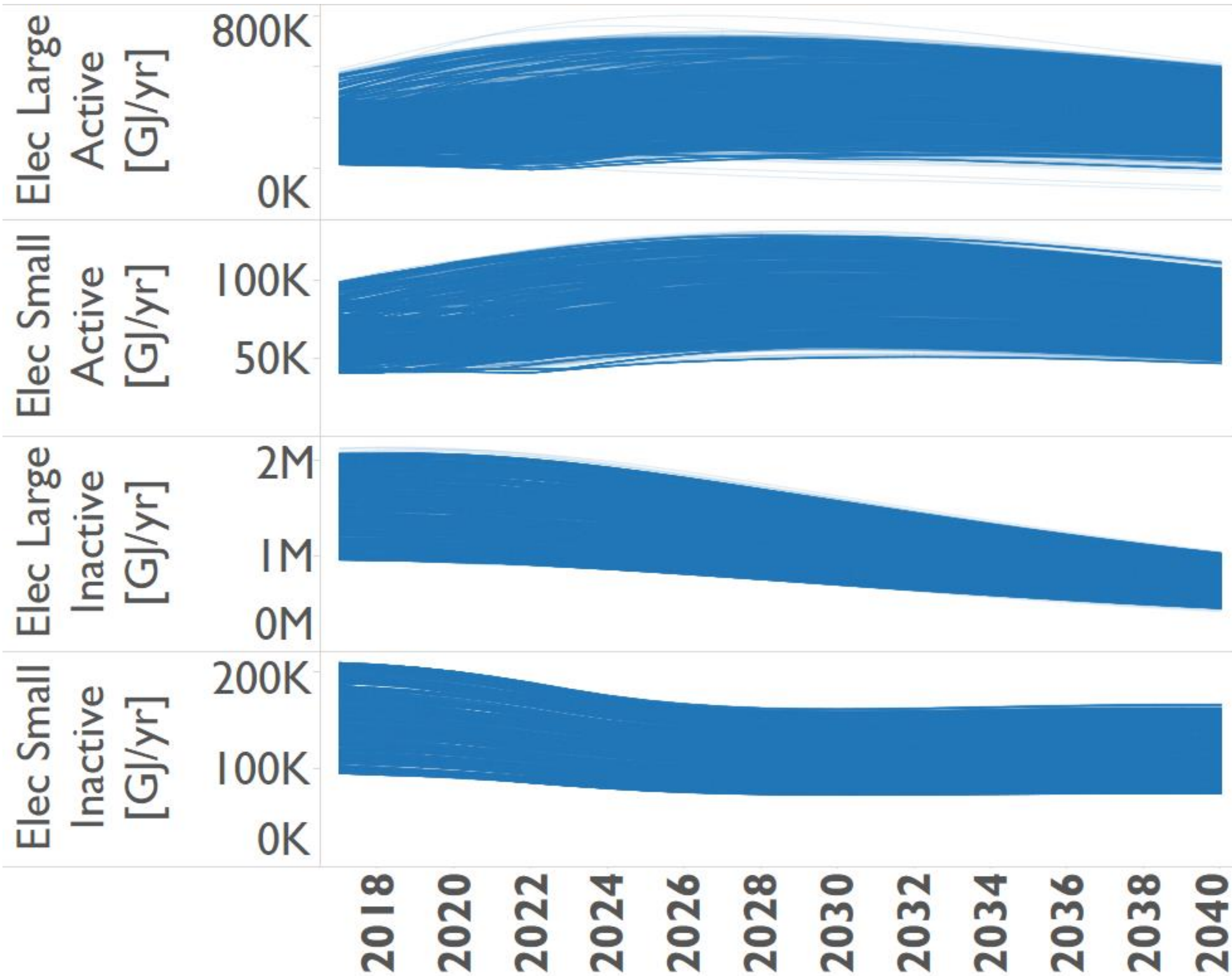

Figure 9. Simulated electricity production from landfills from 2017 to 2040.

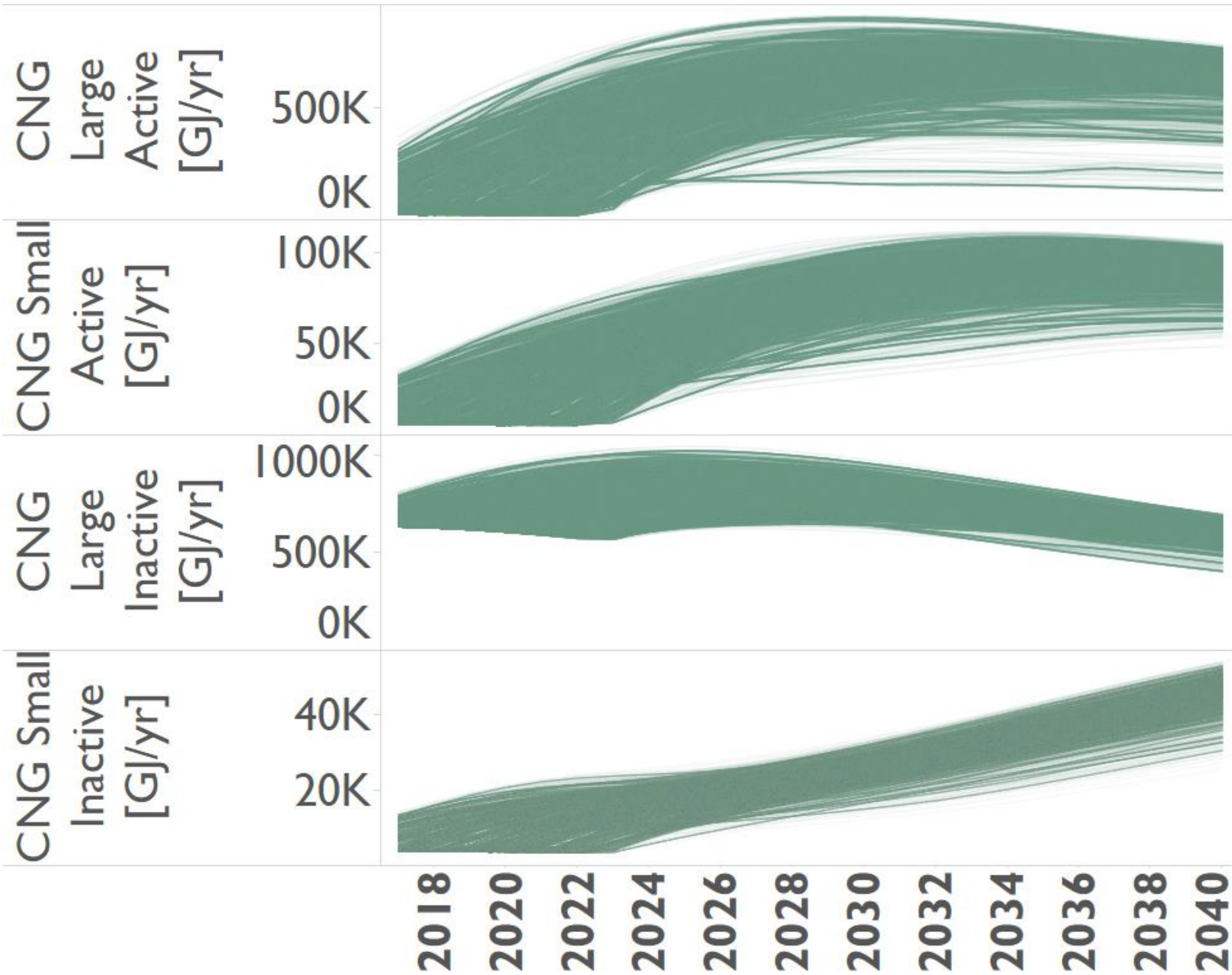

Figure 10. Simulated CNG production from landfills from 2017 to 2040.

Using Monte Carlo filtering (Saltelli et al., 2008) we are able to determine, which input factors are significantly different for a set of results. We investigated CNG production levels in excess of 1,800,000 GJ yr^{-1} and found that the runs that met or exceeded this level were different in terms of the following model parameters: duration for loan guarantee incentives, development dwell time for flare to CNG, and expected operating costs for Large CNG facilities. For these high producing runs, the mean start time for loan guarantees is 2017, the mean dwell time is 2 years, and the mean operating costs are 12% lower than the assumed value in the model. For electricity production, runs that exceed 2,900,000 GJ yr-1 had significantly different development dwell time for flare to electricity and electrical conversion efficiency. For these highly productive runs, the mean development dwell time was 2.4 years and the mean electrical conversion efficiency was 53%.

CAFO Model: Total production of CNG, electricity, and PNG in response to the seven scenarios explored is presented in figures 11 and 12. Based on the scenarios explored, CNG has the greatest market potential from CAFOs as compared to both electricity and PNG. Of the types of CAFOs explored, dairy CAFOs have the highest potential for CNG as well as electricity and PNG. There are some interesting impacts from the seven scenarios explored in this study. The impact of RINs favors certain technologies. In the absence of RINs, electricity production is favored whereas the presence of RINs has a large impact on CNG production. CNG production drops by nearly a third, as compared to the baseline scenarios, when RINs are not included.

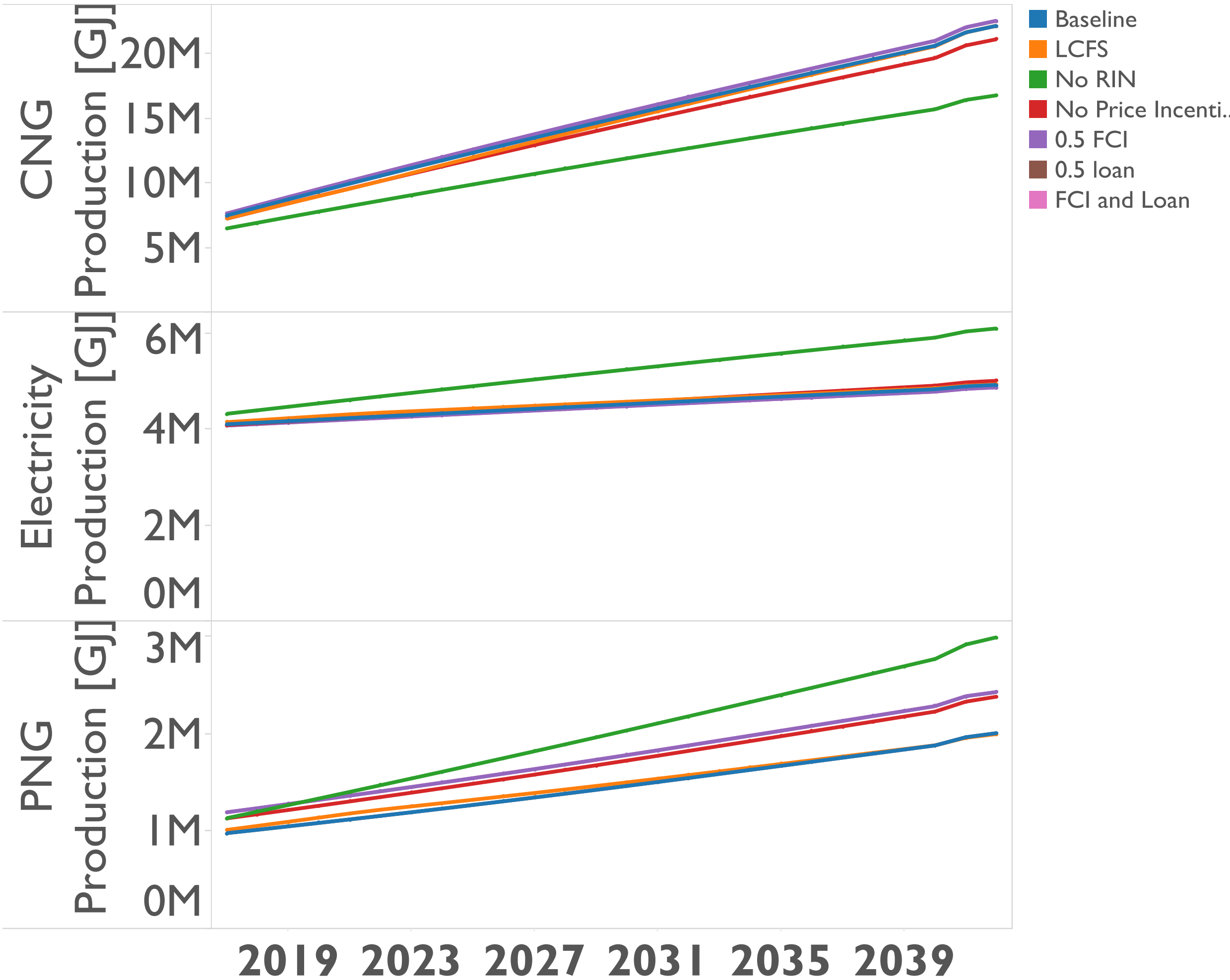

Figure 11. Compressed natural gas (CNG), electricity (Elec), and pipeline natural gas (PNG) production from confined animal feeding operations (CAFOs) in response seven scenarios.

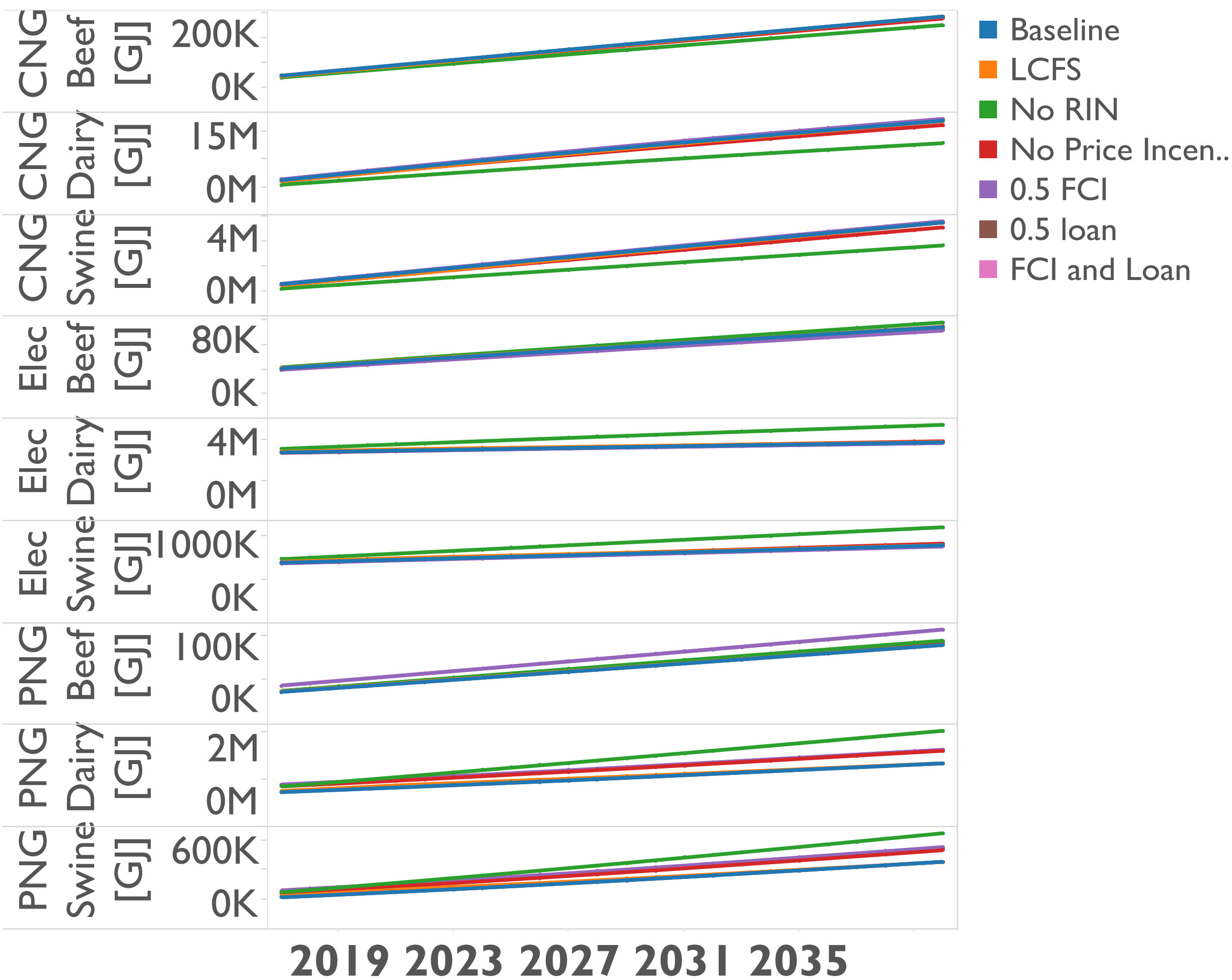

Figure 12. Compressed natural gas (CNG), electricity (Elec), and pipeline natural gas (PNG) production from beef, dairy, and swine confined animal feeding operations (CAFOs) in response seven scenarios.

Sensitivity Results: CAFO Model

Histograms of maximum CNG, electricity, and PNG production are presented in Figures 13, 14, and 15. Across all variable combinations and ranges tested, the most likely simulated maximum CNG output from CAFOs is between 20,000,000 and 25,000,000 GJ/yr. For electricity production, the probable simulated maximum production is 4,700,000 and 5,700,000 GJ/yr. Pipeline natural gas (PNG) from CAFOs has a probable simulated maximum between 2,200,000 and 2,500,000 GJ/yr. Time series of simulated CNG, electricity, and PNG production from CAFOs for all sensitivity runs are presented in Figures 16,17, and 18. Overall, CNG has the largest market potential of the energy production technologies examined given the types and ranges of model parameters explored. Electricity production is not particularly responsive to the parameters and ranges examined in this study. Pipeline natural gas production is responsive to the parameters and ranges tested, however; the production potential is low compared to both electricity and CNG production because of the capital costs associated with the PNG pathway (Figure 18). The PNG pathway requires investment in a pipeline connection to the nearest natural gas pipeline (Table 5). In terms of most influential parameters, the per ton tipping fees, development dwell time, operating costs, and duration of the FCI support rank as the top model parameters for all three CAFO pathways. Using Monte Carlo filtering, we examined the highest production runs for each to determine what parameter settings were different from the rest of the runs. For CNG production in excess of 25,000,000 GJ yr^{-1}, we found that these runs had dwell times less than 1.6 years long and high tipping fees ($88 per tonne). Runs that produced electricity production greater than 5,400,000 had very high tipping fees ($96 per tonne). The highest PNG production levels were observed for runs that had high tipping fees coupled with low operating costs.

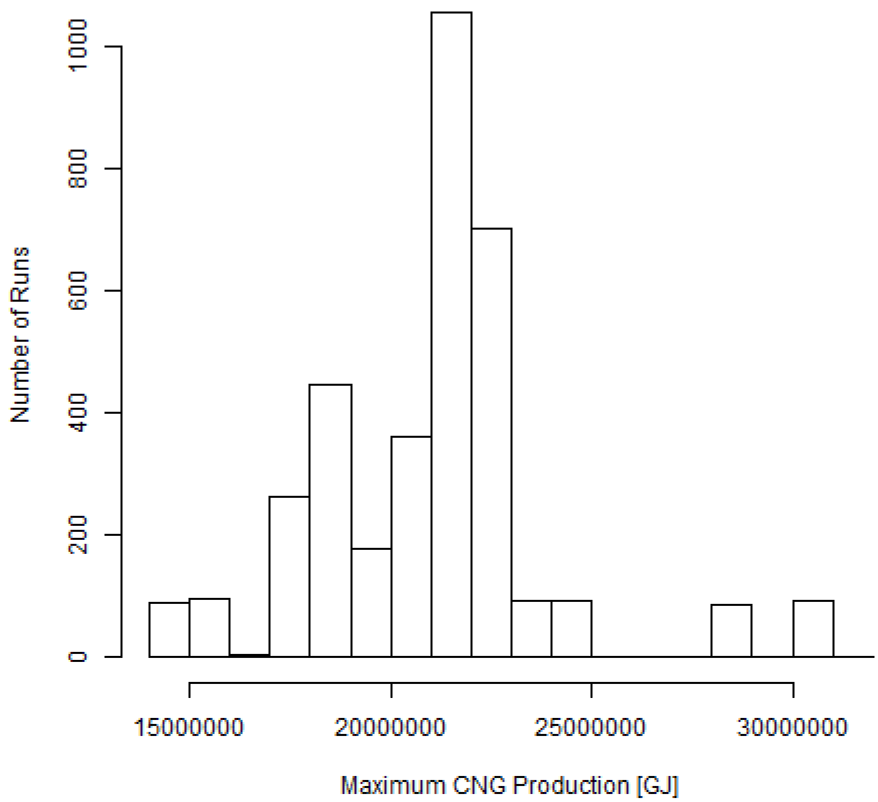

Figure 13. Histogram of maximum compressed natural gas (CNG) production from all types of confined animal feeding operations (CAFOs).

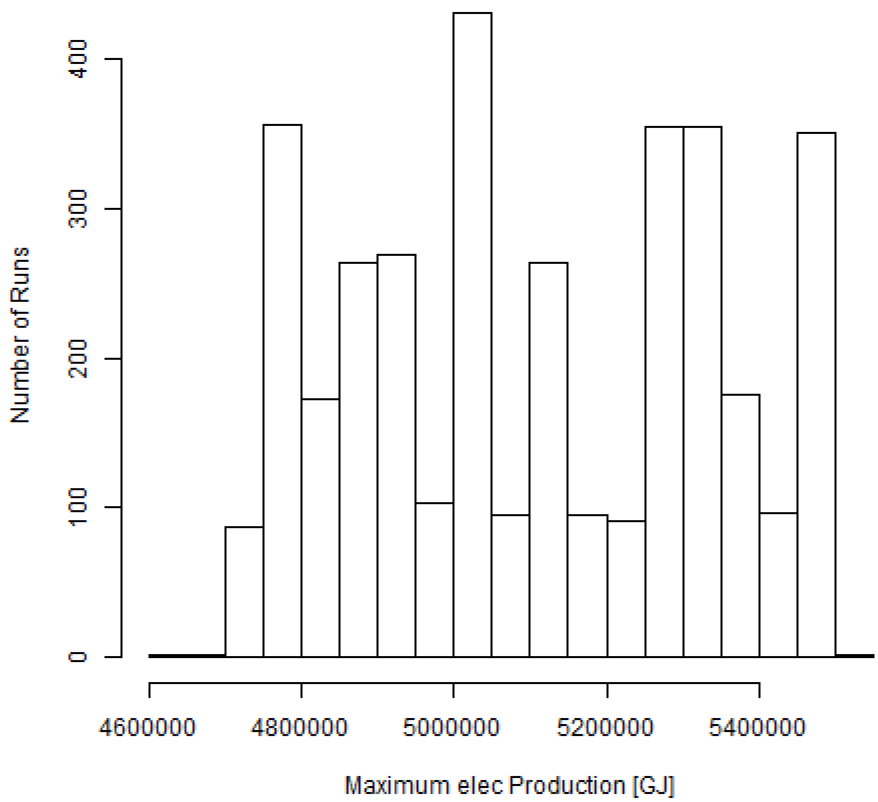

Figure 14. Histogram of maximum electricity production from all types of confined animal feeding operations (CAFOs).

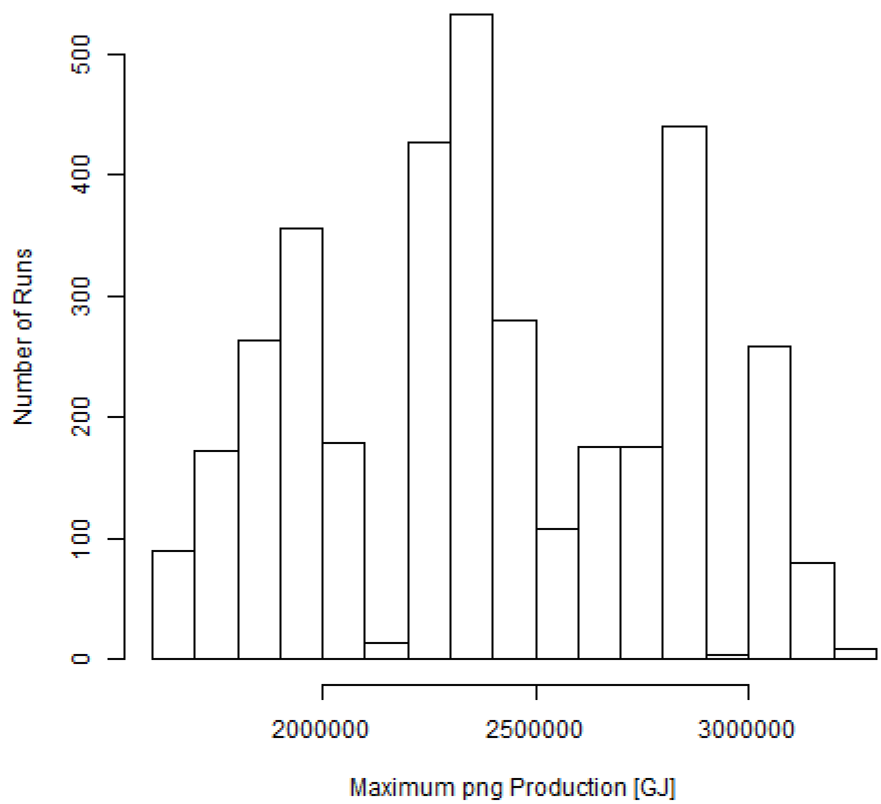

Figure 15. Histogram of maximum pipeline natural gas (PNG) production from all types of confined animal feeding operations (CAFOs).

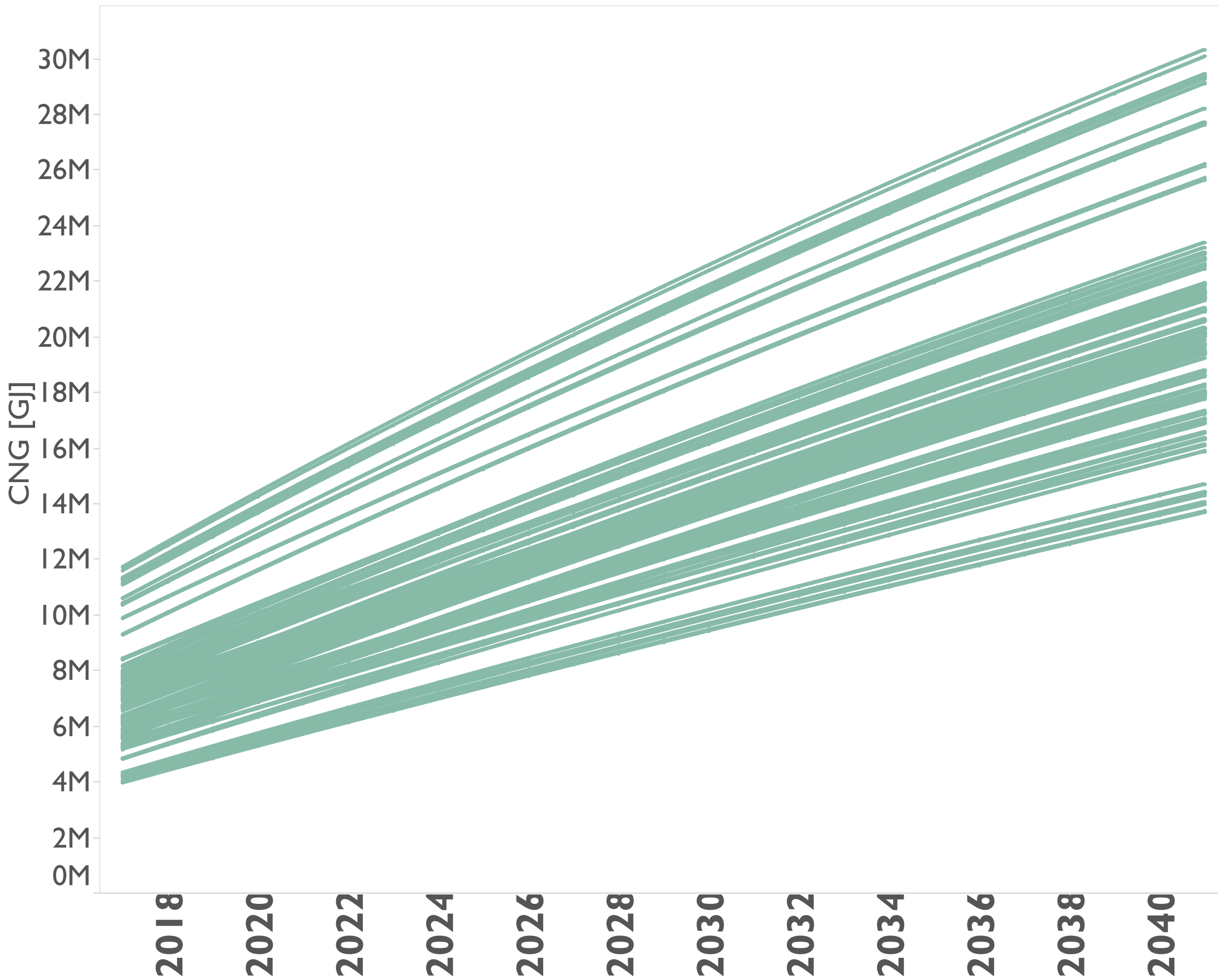

Figure 16. Simulated CNG production from confined animal feeding operations (CAFOs) from 2017 to 2040.

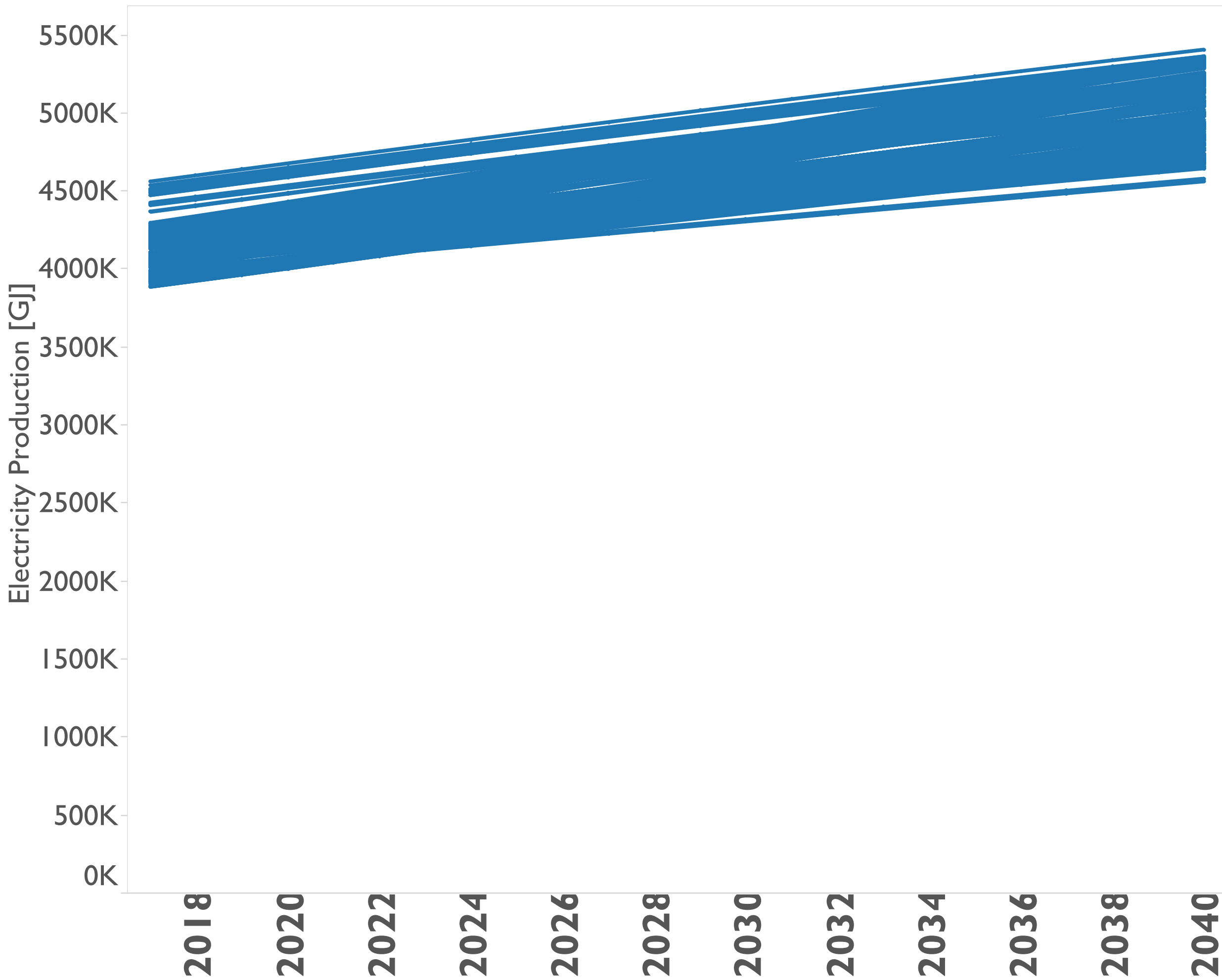

Figure 17. Simulated electricity production from confined animal feeding operations (CAFOs) from 2017 to 2040.

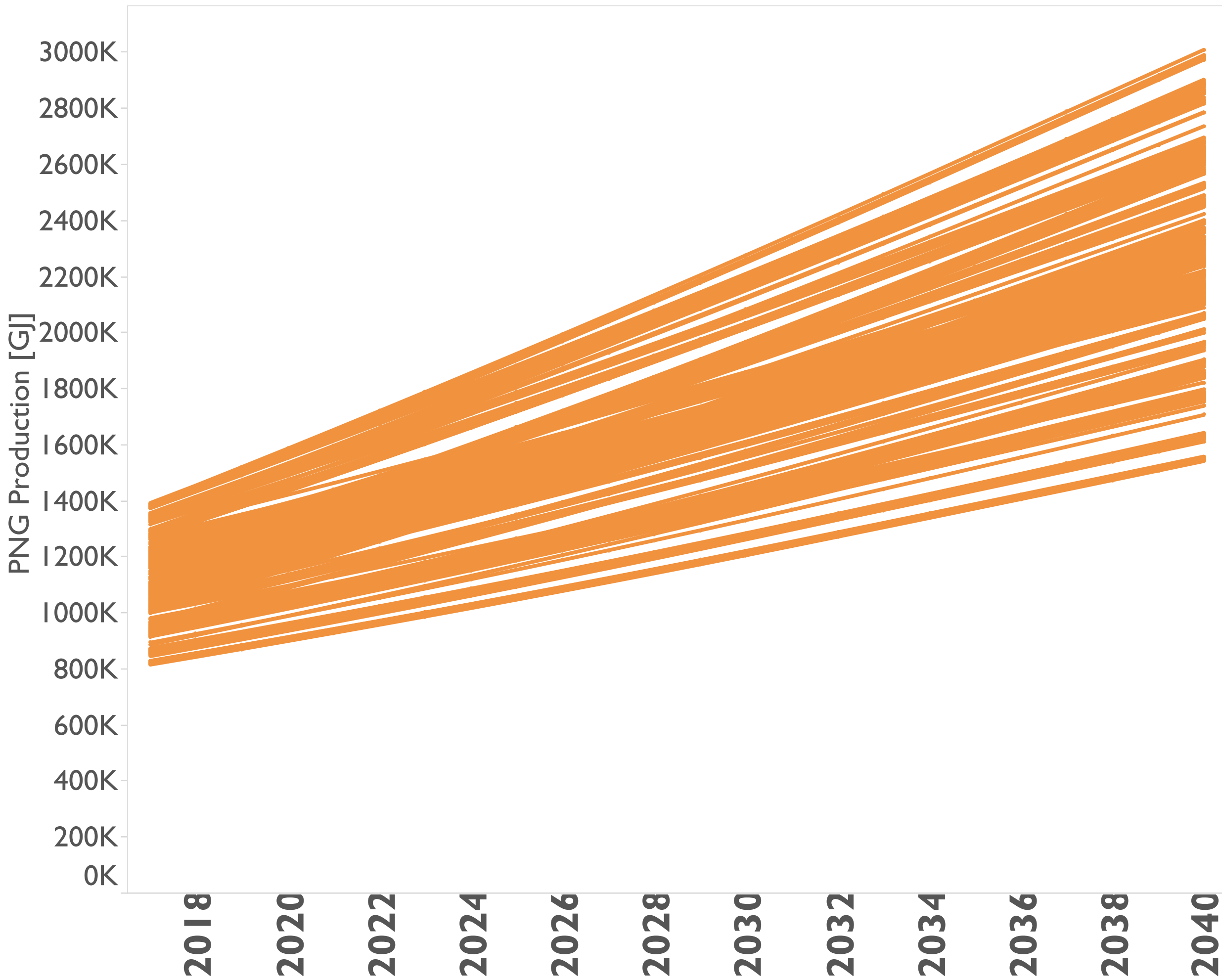

Figure 18. Simulated pipeline natural gas (PNG) production from confined animal feeding operations (CAFOs) from 2017 to 2040.

Summary

Our simulation suggests that collection and conversion of biogas to energy from landfills and CAFOs has potential to contribute as over 30,000,000 GJ annually. The largest energy potential is from CAFOs, specifically dairy operations. This study highlights the impact of certain system levers on the overall production of energy from biogas. For energy production form both landfills and CAFOs, the development dwell time has considerable influence on the type and amount of energy produced. In general, minimizing the amount of time between making the decision to invest in a given energy conversion route and having installed capital will maximize energy production from landfills. Operating costs are also important for energy production from both landfills and CAFOs; relative to the capital costs, operating costs are impactful and even modest reduction can have increase energy production, particularly for CNG. The tipping fees assumed were highly influential for energy produced from CAFOs. When manure from CAFOs is used to produce energy, tipping fees associated with the disposal of the manure are avoided. Higher tipping fees promoted energy production from CAFOs, the highest tipping fees favored the higher operating and capital intensive technologies (CNG, and PNG).

Data and Modeling Gaps

Developing the WESyS Model required substantial landfill and CAFO literature and data review. This process highlighted several areas where information was unavailable or there were barriers to the use of the data or modeling.

A full analysis of the future potential of WTE from landfills and CAFOs was not possible due to the lack of available data or analysis on anticipated or future buildout of those systems. Such an analysis could focus on linking historic and anticipated future trends in MSW generation and diet, respectively, to buildout of landfills and CAFOs. Existing information on historic trends that could help inform future scenario development in the WESyS Model for how the buildout might develop. For example, historically fewer, but larger landfills have been built over time (EPA 2015a).

Addressing several gaps in techno-economic analyses would refine current and in-progress technical potential assessment of resources. These improvements would allow for refinement of landfill and CAFO technical potential assessments to more economic potential-oriented assessments.

In general, robust design cases and the supporting techno-economic data were not available for WESyS modeling. The Murray et al. (2014) and Prasodjo et al. (2013) papers are a good first step, but are limited in several respects. For example, fixed capital costs only incorporate the costs of equipment and not any soft costs (e.g., contingency). Another example: variable costs (and some capital costs) are not based on a bottom-up assessment, but rather on an approximation based on a percentage of the capital costs of the AD system. Finally, the techno-economic data available are for fairly conventional cases and do not consider potential uses for biofuels or other products.

A related limitation to WTE project economics are data gaps related to all WTE projects moving energy offset. The costs and benefits of WTE projects that are producing and using energy offsetsite are not very clear. Some important questions that arose from this study are related to the costs associated with infrastructure buildout or transport of energy offsite and policy and social barriers to transporting the energy offsite.

Finally, the incidence of credit prices on bioenergy production continues to be an understudied area. For the purposes of this study and simplicity, we assume RINs and the LCFS have a direct impact on biogas production. However, initial research into this topic area for other fuels indicates that there are barriers to fuel producers capturing the full benefit of the credit (Knittle et al. 2015).

References Barker, J.C., and F.R. Walls. 2002. "Livestock Manure Production Rates and Nutrient Content." In the *2002 North Carolina Agricultural Chemicals Manual*. Accessed March 2016, http://agrienvarchive.ca/bioenergy/download/barker_ncsu_manure_02.pdf.

CA Legislature. 2008. Final Regulation Order: Methane Emissions from Municipal Solid Waste Landfills. Accessed March 2016, http://www.arb.ca.gov/regact/2009/landfills09/landfillfinalfro.pdf

CARB. 2014a. Table 7. Carbon Intensity Lookup Table for Diesel and Fuels that Substitute for Diesel. Accessed March 2016, http://www.arb.ca.gov/fuels/lcfs/lu_tables_11282012.pdf

CARB. 2014b. *Final Regulation Order*. Accessed March 2016, http://www.arb.ca.gov/fuels/lcfs/CleanFinalRegOrder112612.pdf.

CARB. 2014c. Implementation Guidance Document for the Regulation to Reduce Methane Emissions from Municipal Solid Waste Landfills. Accessed March 2016, http://www.arb.ca.gov/cc/landfills/docs/guidance0711.pdf

Clean Energy Projects, Inc. 2015. "Landfill Tipping Fees in USA." Accessed March 2016, http://www.cleanenergyprojects.com/Landfill-Tipping-Fees-in-USA-2013.html.

DOE. 2015a. *Clean Cities Alternative Fuel Price Report*. Accessed September 2015, http://www.afdc.energy.gov/uploads/publication/alternative_fuel_price_report_october_2015.pdf.

DOE. 2015b. "Federal Laws and Incentives for Natural Gas." Accessed March 2016, http://www.afdc.energy.gov/fuels/laws/NG/US.

EIA. 2015. "Real Prices Viewer." Accessed September 2015, http://www.eia.gov/forecasts/steo/realprices/.

EPA. 2014. *Regulation of Fuels and Fuel Additives: RFS Pathways II, and Technical Amendments to the RFS Standards and E15 Misfueling Mitigation Requirements*. Federal Register Vol 79 number 139.

EPA. 2015a. Landfill Methane Outreach Program (LMOP) Database. Accessed October 2015, http://www3.epa.gov/lmop/projects-candidates/.

EPA. 2015b. "LMOP FAQ." Accessed September 2015, http://epa.gov/lmop/faq/public.html.

EPA. 2015c. *Complete LFG Energy Project Development Handbook*. Accessed September 2015, https://www3.epa.gov/lmop/publications-tools/handbook.html.

EPA. 2015d. "Renewable Electricity Production Tax Credit." Accessed September 2015, https://www3.epa.gov/lmop/publications-tools/funding-guide/federal-resources/treasury.html.

EPA. 2015e. “Advancing Sustainable Materials Management: Facts and Figures 2013. Accessed October 2015, http://www.epa.gov/smm/advancing-sustainable-materials-management-facts-and-figures-report.

EPA. 2015f. “AgSTAR: Biogas Recovery in the Agriculture Sector.” Accessed Decemeber 2015, http://www.epa.gov/agstar.

Foody, P. 2015. “Outlook and Strategies for Cellulosic Biofuel RINs (Iogen Corporation).” Presented at the OPIS RFS2, RINs and Biodiesel Forum, Chicago, IL, 15-Oct-2015.

Informa Economics. 2013. National Market Value of Anaerobic Digester Products. Accessed March 2016, http://www.americanbiogascouncil.org/pdf/nationalmarketpotentialofanaerobicdigesterproducts_dairy.pdf

Knittel, C.R., B.S. Meiselman, and J.H. Stock. 2015. *The Pass-Through of RIN Prices to Wholesale and Retail Fuels under the Renewable Fuel Standard*. Accessed March 2016, http://scholar.harvard.edu/files/stock/files/pass-through_of_rin_prices_1.pdf?m=1435796200.

Murray, B.C., C.S. Galik, and T. Vegh. 2014. *Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future*. Duke University, Nicholas Institute. NI R 14-02.

NRDC. 2015. *California's Low Carbon Fuel Standard: Evaluation of the Potential to Meet or Exceed the Standards*. Accessed March 2016, http://docs.nrdc.org/energy/files/ene_15012801a.pdf.

Prasodjo, D., T. Vujic, D. Cooley, K. Yeh, and M. Lee. 2013. A Spatial-Economic Optimization Study of Swine-Waste Derived Biogas Infrastructure Design in North Carolina. Durham, NC: Duke University, Duke Carbon Offsets Initiative. Accessed October 2015, http://www.hr.duke.edu/media/sustainability/SwineBiogas.pdf .

Saltelli, A., M. Ratto, T. Andres, F. Campolongo, J. Cariboni, G. Gatelli, M. Saisana, and S. Tarantola. 2008. *Global Sensitivity Analysis, The Primer*. John Wiley and Sons, Ltd. ISBN 978-0-470-05997-5.

Saur, G., and A. Milbrandt. 2014. *Renewable Hydrogen Potential from Biogas in the United States*. NREL/TP-5400-60283. Golden, CO: National Renewable Energy Laboratory.

Sobol, I.M. 1993. “Sensitivity analysis for non-linear mathematical models.” *Mathematical Modeling and Computational Experiment* 1: 407 – 414.