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Comparison and analysis of energy consumption in typical Iowa swine finishing systems

by

John C. Gilbert

A thesis submitted to the graduate faculty

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MASTER OF SCIENCE

Major: Agricultural Engineering (Structures and Environment)

Program of Study Committee:
Thomas L. Richard, Major Professor
Steven Hoff
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Iowa State University

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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ABSTRACT

Fossil fuel use in agriculture is an increasingly important topic of concern. Iowa is the largest swine producing state in the United States. A systems analysis was performed to evaluate energy use in deep bedded hoop and confinement swine finishing systems for typical Iowa conditions. Energy use for feed production, facility operation, bedding production, manure application, and swine management were analyzed and the use of on-farm versus off- farm feed processing was compared. Energy for feed required 68 to 82% of the overall energy use. The hoop system required an average of 3.6% less overall energy and 47% less non-feed energy than the confinement system. On-farm feed processing reduced the overall energy an average of 9.5% when compared to off-farm feed processing. 774 MJ of non-solar energy was required to produce 104.5 kg of gain for a pig raised in a deep bedded hoop system with on-farm feed processing while 879 MJ was required in a confinement system with off-farm feed processing. Development of low external input integrated cropping and swine production systems will be key to reducing energy use in swine finishing systems.

CHAPTER 1. OVERVIEW

1.1 Introduction

Fossil fuel usage and energy conservation are increasingly important topics of concern in society. All sectors of civilization must evaluate how energy is currently used and how we plan to use energy in the future if we are to maintain our standard of living, if not improve upon current circumstances for ourselves and others. The current U.S. food system is estimated to be responsible for 19% of total U.S. energy consumption (Pimentel, 2008). Further analysis of energy consumption in all parts of the food system is needed to allow us to pursue more energy efficient methods and systems of food production.

This work analyzes a small piece of the overall food system through modeling of energy use in swine finishing operations, specifically for the state of Iowa. Swine finishing operations are the predominant supplier of pork in the United States. Pork plays an important role in the U.S. diet, with yearly per capita consumption of 23 kg (50 lbs.), 23% of U.S. meat and poultry consumption (USDA, 2009). The state of Iowa plays a major role in the production of the U.S. supply of pork, containing 19,600,000 head of swine, 30% of the total U.S. herd (USDA NASS). Two common swine finishing systems were modeled in this work; a confinement system and a deep bedded housing or hoop system. Comparison and evaluation of the energy usage in these systems allowed analysis of potential opportunities for energy savings in this part of the overall food system.

1.2 Review of Previous Work

Research into energy usage in agriculture has ranged from broad studies covering overall energy consumption (Brown et al., 2005; Carlsson-Kanyama et al., 2003; Pimentel et al., 2008; Weber et al., 2008) to studies comparing specific management practices in a production system (Fang et al, 1997; MacDonald, 2002). Recently, with the increased emphasis placed on biofuels, research into energy usage of cropping systems has been analyzed as a portion of the overall energy required for ethanol and biodiesel production (Grabowski, 2002; Hill et al. 2006; Kim et al, 2005; Shapouri et al., 2003; Sheehan et al., 1998).

Current research into energy use in swine systems has been limited and studies have generally been performed for European operations (Basset-Mens and van der Werf, 2005; Dalgaard et al., 2007; Meul et al., 2007). Lammers, 2009, evaluated energy and nutrient cycling in Iowa swine systems as part of a PhD thesis. Lammers work reported that each finished pig requires 968 MJ in a confinement system and 940 MJ in a hoop system for prototype farrow-to-finish swine systems.

1.3 Objectives

The following objectives were established for this work.

* To compare and evaluate swine finishing system energy consumption per kilogram of pig exported from the farm for a confinement system and for a deep bedded hoop system under typical management and operating conditions for Iowa using engineering principles and current research data.

* To compare and evaluate swine finishing system energy consumption per kilogram of pig exported from the farm between operations utilizing on-farm feed milling and processing with operations selling grain and receiving feed from off-farm centralized feed mills.

1.4 Thesis Organization

The information in this thesis is organized into four chapters. The first chapter provides an overview of the thesis with introduction, review of previous work, statement of objectives, and description of the thesis organization. Chapter 2 provides a description of the model development and defines the boundary of the model, attribution of energy, and energy usage for the individual components of the swine finishing systems. Chapter 3 summarizes and compares the energy usage results for the different systems. A sensitivity analysis of the input conditions is also presented in this chapter. The thesis concludes with a review of the conclusions drawn from this work, analysis of opportunities for energy conservation, and suggestions for future research on this topic. Two appendices are also included at the end of the thesis. Appendix A provides calculations and supporting information used for the model. Appendix B provides calculations and supporting information for the portion of the model used to determine heating and ventilation energy usage for the swine confinement system.

1.5 References

Basset-Mens, C., and H. M. G. van der Werf. 2005. Scenario-based environmental assessment of farming systems: The case of pig production in France. Agriculture Ecosystems and Environment 105: 127–144.

Brown E., R.N. Elliot. 2005. On-farm Energy Usage Characterizations. American Council for an Energy Efficient Economy, Report No. IE052.

Carlsson-Kanyama, A., M. P. Ekstrom, H. Shanahan. 2003. Food and life cycle energy inputs: consequences of diet and ways to increase efficiency. Ecological Economics 44:293-307.

Dalgaard, R., N. Halberg, and J. E. Hermansen. 2007. Danish pork production: An environmental assessment. DJF Animal Science 82: 1–34.

Fang Q., I. Bölöni, E. Haque, C. K. Spillman. 1997. Comparison of Energy Efficiency Between a Roller Mill and Hammer Mill. Applied Engineering in Agriculture, Vol. 13(5):631-635.

Graboski M. S. 2002. Fossil Energy Use in the Manufacture of Corn Ethanol. National Corn Growers Association, St. Louis, MO.

Hill J, E Nelson, D Tilman, S Polasky, D Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS Vol. 103 No. 30, 11206–11210.

Kim, S., B.E. Dale. 2005. Life cycle assessment of various cropping systems utilized for producing biofuels: Bioethanol and biodiesel. Biomass & Bioenergy 29 (6): 426-439.

Lammers, P.J. 2009. Energy and nutrient cycling in pig production systems. Ph.D. thesis. Iowa State University.

MacDonald, R. 2002. Saving Money by Maximizing Energy Use Efficiency in Swine Production. Advances in Pork Production, Volume 13, pg. 99.

Meul, M., F. Nevens, D. Reheul, and G. Hofman. 2007. Energy use efficiency in specialized dairy, arable, and pig farms in Flanders. Agriculture, Ecosystems and Environment 119: 135–144.

Lammers, P.J. 2009. Energy and nutrient cycling in pig production systems. Ph.D. thesis. Iowa State University.

Pimentel D., S. Williamson, C. Alexander, O. Gonzalez-Pagan, C. Kontak, S Mulkey. 2008. Reducing Energy Inputs in the US Food System. Human Ecology 36:459–471.

Shapouri H., J. A. Duffield, M. Wang. 2003. The Energy Balance of Corn Ethanol Revisited. Transactions of the ASAE, Vol. 46(4): 959–968.

Sheehan J., Camobreco, V., Duffield, J., Graboski, M. & Shapouri, H. 1998. Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus. Natl. Renewable Energy Lab., Golden, CO, NREL Publ. No. SR-580-24089.

USDA NASS. http://www.nass.usda.gov/QuickStats/PullData_US.jsp. Accessed September 24, 2009.

USDA World Agricultural Supply and Demand Estimates, #474, September 11, 2009, http://www.usda.gov/oce/commodity/wasde/latest.pdf. Accessed September 24, 2009.

CHAPTER 2. MODEL DEVELOPMENT

A computational model was created using Microsoft Excel ® to evaluate energy consumption in two types of swine finishing systems. The two systems are referred to in this thesis as confinement and hoop. The confinement housing system was assumed to be a building with pigs housed on concrete slatted floors over a manure storage pit. The building was assumed to be mechanically ventilated with supplemental heat. The deep bedded housing or hoop system was assumed to be a building with pigs housed on a thick layer of bedding with a concrete area for feeders and waterers and with a synthetic tarp cover stretched over Quonset™ shaped steel frames. The hoop system was assumed to have no supplemental ventilation or heat. Typical conditions and management practices for the state of Iowa were assumed for both systems.

The average energy required to produce a finished pig from each system was calculated by quantifying the material flows in and out of a model boundary. The model boundary was arbitrarily set around a swine finishing system including feed mill operations for the period required to produce a finished pig. Each system was modeled as part of a continuously operating farm with a steady state of production. To account for seasonal variations in conditions, systems were analyzed for a typical year of production and an average energy value to produce a finished pig calculated. An embodied energy value was assigned to each material, which was then used to quantify the energy flows to and from the model boundary. The difference in energy into and out of the model boundary was then used to calculate the energy required to produce a finished pig from each system, as represented by the equation in Figure 1. Only non-solar energy was included in the analysis.

Figure 1. Total Energy Use Equation

$$E_{pig} = E_{fuels} + E_{electricity} + E_{corn} + E_{SBM} + E_{\sup pl.} + E_{bedding} - E_{manure}$$

E_{pig}: Energy use per finished pig [MJ per pig]

$$E_{pig} = e_{pig} \times \left(m_{pig-out} - m_{pig-in}\right)$$

e_{pig}: Embodied energy of finished pig [MJ per kg of pig]

$m_{pig\text{-}out}$: Mass of pig out from system [kg per pig]

$m_{pig\text{-}in}$: Mass of pig into system [kg per pig]

E_{fuels}: Energy use per finished pig from liquid fuels [MJ per pig]

$$E_{fuels} = e_{diesel} \times m_{diesel} + e_{gasoline} \times m_{gasoline} + e_{oil} \times m_{oil} + e_{LP} \times m_{LP}$$

e_{diesel}: Embodied energy of diesel fuel [MJ per kg diesel]

m_{diesel}: Mass of diesel fuel used per finished pig [kg diesel per pig]

$e_{gasoline}$: Embodied energy of gasoline [MJ per kg gasoline]

$m_{gasoline}$: Mass of gasoline used per finished pig [kg gasoline per pig]

e_{oil}: Embodied energy of oil [MJ per kg oil]

m_{oil}: Mass of oil used per finished pig [kg oil per pig]

e_{LP}: Embodied energy of liquid propane [MJ per kg LP]

m_{LP}: Mass of liquid propane used per finished pig [kg LP per pig]

$E_{electricity}$: Energy use per finished pig from electricity [MJ per pig]

$$E_{electricity} = e_{electricity} \times n_{electricity}$$

$e_{electricity}$: Embodied energy of electricity [MJ per kWh]

$n_{electricity}$: Electrical use per finished pig [kWh per pig]

E_{corn}: Energy use per finished pig from corn [MJ per pig]

$$E_{corn} = e_{corn} \times m_{corn}$$

e_{corn}: Embodied energy of corn [MJ per kg corn]

m_{corn}: Mass of corn used per finished pig [kg corn per pig]

Figure 1. Total Energy Use Equation (continued)

E_{SBM}: Energy use per finished pig from soybean meal [MJ per pig]

$$E_{SBM} = e_{SBM} \times m_{SBM}$$

e_{SBM}: Embodied energy of soybean meal [MJ per kg soybean meal]

m_{SBM}: Mass of soybean meal used per finished pig [kg soybean meal per pig]

$E_{suppl.}$: Energy use per finished pig from feed supplement [MJ per pig]

$$E_{\sup pl.} = e_{\sup pl.} \times m_{\sup pl.}$$

$e_{suppl.}$: Embodied energy of feed supplement [MJ per kg supplement]

$m_{suppl.}$: Mass of feed supplement used per finished pig [kg supplement per pig]

E_{manure}: Energy credit per finished pig from manure [MJ per pig]

$$E_{manure} = e_{nitrogen} \times m_{nitrogen} + e_{phosphate} \times m_{phosphate} + e_{potash} \times m_{potash}$$

$e_{nitrogen}$: Embodied energy of nitrogen fertilizer [MJ per kg nitrogen]

$m_{nitrogen}$: Equivalent mass of nitrogen fertilizer in manure produced per finished pig [kg nitrogen per pig]

$e_{phosphate}$: Embodied energy of phosphate fertilizer [MJ per kg phosphate]

$m_{phosphate}$: Mass of phosphate fertilizer equivalent in manure per finished pig [kg phosphate per pig]

e_{potash}: Embodied energy of potash fertilizer [MJ per kg potash]

m_{potash}: Equivalent mass of potash fertilizer in manure produced per finished pig [kg potash per pig]

2.1 Attribution of Energy

The model was established on the basis that all materials have an embodied energy per unit of mass. For fuels, the embodied energy included the higher heating value (IEA, 2005), the maximum amount of work that can be derived from the fuel. The higher heating value is the total energy released from combustion including the latent heat of vaporization of water. The lower heating value includes energy released from combustion, but not the latent heat of vaporization. Higher heating values were used to match the values presented in Shapouri et al., 2003 and 2004. Efficiencies of production and delivery (Shapouri et al., 2003) were factored in per equations shown in Figure 2 to derive a total embodied energy value for fuels that included both the energy available in the fuel and the energy consumed to process and deliver the fuel to the model boundary. Electricity was assumed to be derived from fuels with an average production efficiency of 39.6% and a transmission loss factor of 1.087%, per the assumptions of Shapouri et al., 2003 with the embodied energy calculated per the equation in Figure 3.

Figure 2. Fuel Embodied Energy Equations

$$\%Efficiency = \frac{e_{fuel-HHV}}{e_{fuel-HHV} + e_{fuel-production}}$$

$$e_{fuel} = e_{fuel-HHV} + e_{fuel-production} = \frac{e_{fuel-HHV}}{\%Efficiency}$$

e_{fuel}: Embodied energy of each fuel [MJ per kg fuel]

$e_{fuel\text{-}HHV}$: Higher heating value of each fuel [MJ per kg fuel]

$e_{fuel\text{-}production}$: Energy required to mine, produce, and deliver fuel [MJ per kg fuel]

%Efficiency: Efficiency of production and delivery of fuel [%]

Figure 3. Electricity Embodied Energy Equation

$$e_{electricty} = \frac{e_{kWh}}{\%Efficiency \times (1 - TL)}$$

$e_{electricity}$: Embodied energy of each kilowatt-hour of electricity [MJ per kWh]

e_{kWh}: Energy in one kilowatt-hour [MJ per kWh]

TL: Transmission loss factor

%Efficiency: Efficiency of production of electricity from fuel sources [%]

For non-fuel materials such as corn, the embodied energy of the material was assumed to be the fuel energy used per unit mass to create, process, and deliver the material to the model boundary. The values presented in Shapouri et al., 2004, were used as a base for the analysis of agricultural materials. There are multiple studies on energy use in corn production as part analyses of ethanol energy efficiency. Values from Shapouri et al., 2004, were used as the study presented a straightforward accounting of energy use and also included specific values for the state of Iowa, updates for improvements in crop yields, and revisions based on criticisms of their previous work.

An embodied energy value for soybean meal, a major ingredient in typical swine rations, was not available in Shapouri et al., 2004. 4.60 MJ per kilogram was used based on an analysis of biodiesel production from Hill et al., 2006. Other swine ration ingredients typically include processed minerals and vitamin premixes to balance the nutrient needs of the pig (Holden et al., 1996). Lammers, 2009, provided a collection of embodied energy values for some typical swine ration supplement ingredients. These values were used with the quantities of supplement ingredients in the ration (Honeyman and Harmon, 2003), to derive an average supplement energy value of 10.49 MJ per kilogram.

Embodied energy for bedding was calculated through analysis of energy use to produce round bales of corn stalks from corn crop residue. The energy used in producing the corn crop was attributed all to the embodied energy of the corn grain. Therefore the energy used for bedding was solely from the energy required to harvest, transfer, and deliver the bedding from the field to the hoop house. Corn stalk harvest and delivery were modeled based on a yield of 4,500 kg per hectare (2 tons per acre) and field practices and delivery distances to supply three hoop buildings with 150 pig spaces each finishing two batches of pigs per year. Energy use for corn stalk harvest was modeled using the following methods. The corn stalks were chopped and raked into a windrow in one pass across the field. The stalks were then baled into 318 kg (700 lb) bales. These bales were then loaded onto a bale wagon holding 11 bales using a tractor with front end loader and bale fork. These bales were then hauled 0.8 km (0.5 mi) to a bedding storage location and unloaded using the same tractor with front end loader. The bales were then deposited by tractor into the hoop periodically throughout the year. Based on tractor PTO requirements and field efficiencies, diesel fuel and oil usage were calculated using ASAE Standard EP496.3. Table 1 provides a summary of the energy used in field practices per 1,000 kg of bedding. The embodied energy of the bedding was 0.54 MJ per kilogram of bedding.

Table 1. Bedding Field Operation Energy Use

	Diesel (liter)	Oil (liter)	Energy (MJ)
	per 1000 kg of corn stalks		
Chopping/Raking	1.42	0.01	65
Baling	2.84	0.10	135
Loading/Unloading	2.87	0.02	132
Transport	0.78	0.01	36
Deposition in Hoop	3.83	0.03	176
Total	11.74	0.17	544

The embodied energy of manure was assumed equivalent to the energy required for Nitrogen, Phosphate, and Potash synthetic fertilizer replaced in crop production. While there are different types of synthetic fertilizers that could be used to represent the energy credit for manure, embodied energies for synthetic fertilizers as presented in Shapouri et al., 2004, were used to maintain consistency with the embodied energy of corn used for this model, also from Shapouri et al., 2004. All manure was assumed to be field applied to land under a continuous corn-soybean cropping system. Energy production from the manure through

Table 2. Fuel Embodied Energy Values

Fuel	Embodied Energy		% Efficiency*	Higher Heating Value		Density		Reference
Diesel Fuel	45.71	MJ/liter	84.3%	45.66	MJ/kg	0.84	kg/liter	IEA, Energy Statistics Manual, 2005
Gasoline	43.34	MJ/liter	80.5%	47.10	MJ/kg	0.74	kg/liter	IEA, Energy Statistics Manual, 2005
Oil	46.29	MJ/liter	84.3%	44.34	MJ/kg	0.88	kg/liter	http://www.energylogic.com
LP Gas	26.44	MJ/liter	98.9%	50.08	MJ/kg	0.52	kg/liter	IEA, Energy Statistics Manual, 2005
Electricity**	8.99	MJ/kWh	39.6%	3.6	MJ/kWh			Shapouri, 2003

*Efficiency of production and delivery (Shapouri, 2003); ** 39.6% production efficiency and 1.087% transmission Loss

Table 3. Agricultural Material Embodied Energy Values

Material	Embodied Energy	
Corn[3]	1.61	MJ/kg corn
Soybean Meal[1]	4.60	MJ/kg soybean meal
Supplement[2]	10.50	MJ/kg supplement
Nitrogen Fertilizer[3]	56.86	MJ/kg nitrogen
Phosphate Fertilizer[3]	6.96	MJ/kg phosphate
Potash Fertilizer[3]	9.28	MJ/kg potash
Lime Fertilizer[3]	1.29	MJ/kg lime
Bedding (corn stalks)	0.54	MJ/kg bedding

1- Hill et al, 2006
2- Lammers, 2009
3- Shapouri et al., 2004

Table 4. Manure Embodied Energy Values per Finished Pig

	Nutrients- As Excreted (kg)		Nutrient Losses		Applied Nutrients (kg)		Energy Credit (MJ per pig)	
	Hoop	Confinement	Hoop	Confinement	Hoop	Confinement	Hoop	Confinement
Nitrogen (N)	1.88	1.88	50%	25%	2.4	3.5	133.6	200.4
Phosphate (P_20_5)	0.46	0.46	30%	5%	1.2	1.7	8.5	11.5
Potash (K_2O)	1.20	1.20	30%	5%	1.7	2.3	15.7	21.3
						Total	157.8	233.3

anaerobic digestion or other processes was not considered. Typical manure nutrient quantities of Nitrogen (N), Phosphate (P_2O_5), and Potash (K_2O) produced per finished pig as excreted were used from ASABE Standard D384.2 March 2005. The net value for use of manure as fertilizer is less than the excreted value due to environmental losses. For the confinement system, environmental losses were assumed for a manure storage pit below slatted floor with injected field application based on the Ag Waste Management Field Handbook Tables 11-5 and 11-6. For the deep bedded hoop system, environmental losses from the bedded pack and composting were based on Tiquia et al., 2002, for a system where manure was stockpiled outside during cleanout with a loader and then field applied at a later date after some composting had taken place.

2.2 Model Boundaries

With the embodied energies of materials identified, the inputs and outputs through a defined boundary were analyzed to determine the unknown embodied energy of the production of a finished market hog. The boundary for the model was defined as around a swine finishing operation including the feed milling operations. Farrowing, gestation, and nursery swine operations were not considered as part of the model. Field operations other than manure application were also not included in the model as embodied energies of corn and soybean meal already included the energy used for crop field operations.

Figure 4 provides a graphical representation of the model. Pigs were assumed to enter at 16 kg (35 lbs.) and exit to market at 120 kg (265 lbs.). Transport of pigs to and from the finishing housing was not included in the model. Corn, soybean meal, and supplements were assumed to enter the boundary from similar sources with the same embodied energy value for both the confinement and hoop systems. The manure was assumed applied to land as part of a corn-soybean crop rotation with the fuel used to apply the manure considered as part of the model. The manure nutrient values for the applied manure were taken as a credit reducing energy for synthetic fertilizers replaced in the corn and soybean production. Bedding for the hoop system was brought into the model with an embodied energy value required to produce the bedding. The amount of fuel and electricity used in the model was defined by the processes performed within the swine finishing systems' model boundary for operations such as the heating and ventilation of the confinement building and application of manure.

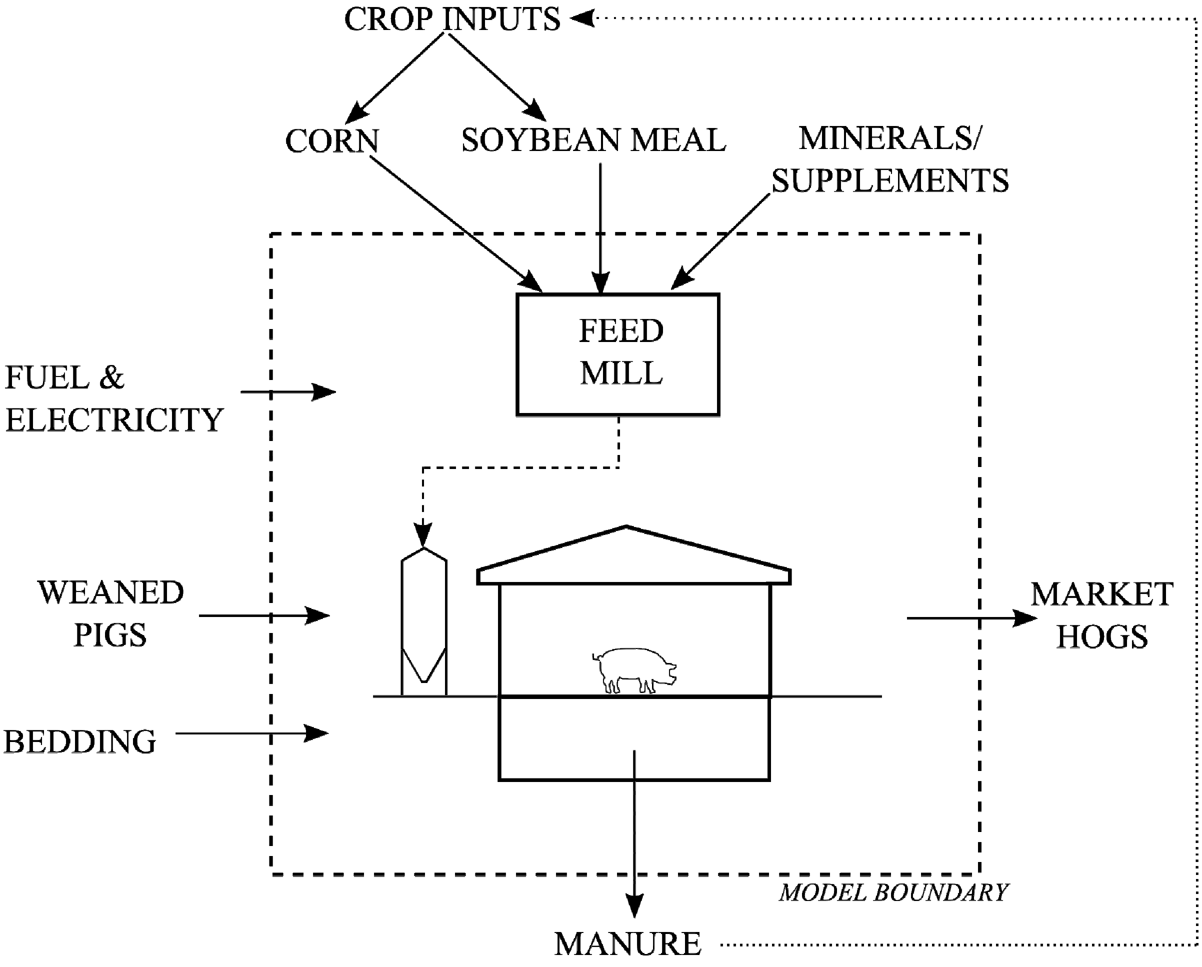

Figure 4. Model Boundary

2.3 Energy in Swine Feed

The energy used in providing feed for the finishing pig was calculated as the sum of energy used to process and deliver the ration and the product of the embodied energy and the quantity consumed of each ingredient. The quantities of the feed ingredients were determined by their proportions in the ration and the required amount of feed per weight of gain of the pig.

Swine performance can vary with many factors including genetics, ration, management, and environment. As a basis for the model comparison of two housing systems, swine performance and feed efficiency from a study comparing deep bedded hoop housing with confinement systems was used (Honeyman and Harmon, 2003). The Honeyman and Harmon study compared a deep bedded hoop system with a confinement system with both facilities at the same site in central Iowa using the same genetics and rations, minimizing effect of factors other than housing type for comparison of swine performance.

Table 5. Swine Performance

	Hoop	Confinement
Average Daily Gain	0.82 kg per day	0.80 kg per day
%Carcass Yield	74.9%	75.8%
% Fat Free Lean	51.1%	52.1%
Fat Free Lean Growth Rate	0.313 kg per day	0.318 kg per day
Feed to Gain Ratio	3.04	2.94
(Honeyman and Harmon, 2003)		

Swine rations can vary based on available feedstuffs and management to match stage of growth and fat free lean growth. Rations as presented in Honeyman and Harmon, 2003, were used to evaluate the quantities of feed ingredients used. Table 5 identifies the percentage of each ingredient for each stage of the suggested ration. A constant feed to gain ratio was used to approximate the amount of feed used at each stage for hoop and confinement systems. A weighted average of the percentage of corn, soybean meal, and supplement portion of the ration was then calculated. The total feed required was then calculated by multiplying the total pig weight gain by the feed to gain ratio. The feed to gain ratio from Honeyman and Harmon accounted for feed use by mortalities and culls in the swine herd. The quantity of each ingredient was then calculated by multiplying the weighted average percentage of the ration by the total feed required. The quantities of feed ingredients used in the model are shown in Table 7.

Table 6. Ration Formulation

Stage	1	2	3	4	5	Overall
Pig Start Weight (kg)	16	29	44	63	86	16
Pig End Weight (kg)	29	44	63	86	120	120
Corn	61.7%	67.0%	73.2%	77.4%	81.6%	74.6%
Soybean Meal (SBM)	35.0%	30.0%	24.0%	20.0%	16.0%	22.7%
Supplement	3.3%	3.0%	2.8%	2.6%	2.4%	2.7%

Table 7. Feed Use

	Hoop	Confinement
Feed to Gain Ratio	3.04	2.94
Pig Start Weight (kg pig)	15.9	15.9
Pig End Weight (kg pig)	120.4	120.4
Total Pig Weight Gain (kg pig)	104.5	104.5
Feed Use Total (kg feed)	317.8	307.4
Corn Use Total (kg corn)	237.0	229.2
Soybean Meal Use Total (kg soybean meal)	72.2	69.9
Supplement Use Total (kg supplement)	8.6	8.3

The energy required to provide feed ingredients was then calculated by multiplying the embodied energies of the feed ingredients by the quantities used. Table 8 shows the total energy use per finished pig from feed for the hoop and confinement systems.

Table 8. Feed Energy Use per Finished Pig

	Hoop	Confinement
Corn	381.5 MJ per pig	369.0 MJ per pig
Soybean Meal (SBM)	332.2 MJ per pig	321.3 MJ per pig
Supplement	90.5 MJ per pig	87.6 MJ per pig
Total	804.3 MJ per pig	777.8 MJ per pig

The second component of swine feed energy use considered in the model was the processing of the feed ingredients to a ground and mixed swine feed and delivery of the feed from the feed mill to the swine housing. Two scenarios were evaluated in the model for comparison: an on-farm feed mill and an off-farm centralized feed mill.

The scenario where a swine producer has ingredient storage and a feed mill on the farm was modeled as the base case for each system. The on-farm feed mill eliminates the need for corn to be shipped from the farm and then delivered back to the farm as ground corn, therefore conserving the energy used in hauling. The soybean meal and supplements were assumed delivered from outside the farm. A typical on-farm feed mill system as shown in Figure 5 was used to evaluate the energy required for processing the feed on farm. Table 9 identifies the components of the system and their assumed characteristics. Screw augers were modeled for feed and ingredient transfer. Energy use for screw augers was calculated using equations presented in Chapter 14 Conveying of Agricultural Materials from Engineering Principles of Agricultural Machines, 2nd Ed (Srivastava et al.). Drive efficiencies and motor efficiencies were based on typical equipment and 230 volt single phase motors. Energy use in grinding of corn and mixing of the feed was calculated by using equipment manufacturer's throughput data and motor sizes for a hammer mill and mixer in sizes typical for an on-farm feed mill. Energy use from all equipment was normalized to the equivalent energy per kg of feed produced and summed to a total kilowatt-hour per kg of feed. Table 10 shows the processing energy requirement per 1,000 kg of feed.

Energy use for hauling and unloading of feed to the swine housing was assumed to be performed by a tractor with a PTO driven auger unloading wagon. Diesel fuel usage was calculated using equations from ASAE Standard EP496.3 based on hauling the feed 0.8 km (0.5 miles) from the feed mill to the swine housing.

An energy credit was calculated to account for the savings in energy from not hauling the corn from the farm to a local elevator and from the local elevator to a centralized feed mill. Shapouri et al., 2004, identifies the energy used to haul corn from the elevator to an ethanol facility as 0.23 MJ per kg of corn. This hauling energy was assumed the same as required for hauling from the elevator to a centralized feed mill. Shapouri et al., 2004, did not identify an energy requirement for hauling corn from the farm to the local elevator. The energy required to haul corn to the local elevator was calculated based on the assumption of a tractor hauling wagons containing 14,200 kg (600 bushels) of corn a distance of 8 km (5 miles). This resulted in a 0.08 MJ per kg credit which, combined with the credit for hauling from elevator to feed mill, provided a total credit of 0.31 MJ per kg of corn from the embodied energy used from Shapouri et al., 2003. Multiplying the credit times the corn used in the hoop and confinement systems provided a total credit per finished pig of 73.2 MJ and 70.8 MJ, respectively.

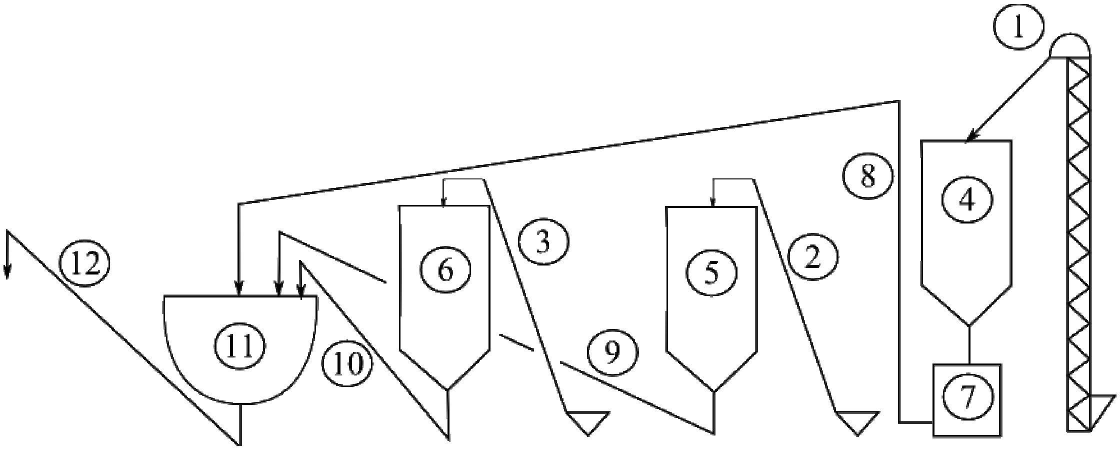

Figure 5. On-Farm Feed Mill Diagram

Table 9. On-Farm Feed Mill Components

#	Function	Equipment
1	Corn Delivery to Storage	100 ft. Grain Leg
2	SBM Delivery to Storage	30 ft. long 6" Screw Auger
3	Supplement Deliver to Storage	30 ft. long 6" Screw Auger
4	Corn Storage	
5	Soybean Meal Storage	
6	Supplement Storage	
7	Corn Milling	5 hp Hammer Mill
8	Ground Corn Transfer to Mixer	10 ft./30 ft.4" Horizontal/Vertical Screw Auger
9	SBM Transfer to Mixer	15 ft. long 4" Screw Auger
10	Supplement Transfer to Mixer	15 ft. long 4" Screw Auger
11	Mixing of Feed	3,000 lb. 10 hp Mixer
12	Transfer of Feed to Delivery Wagon	30 ft. long 8" Screw Auger

Table 10. On-Farm Feed Mill Processing Energy Use per 1,000 kg of Feed

Corn Delivery to Storage	0.0819	kWh/1,000 kg feed
SBM Delivery to Storage	0.0051	kWh/1,000 kg feed
Supplement Deliver to Storage	0.0006	kWh/1,000 kg feed
Corn Milling	5.7528	kWh/1,000 kg feed
Ground Corn Transfer to Mixer	0.0315	kWh/1,000 kg feed
SBM Transfer to Mixer	0.0019	kWh/1,000 kg feed
Supplement Transfer to Mixer	0.0002	kWh/1,000 kg feed
Mixing of Feed	1.6283	kWh/1,000 kg feed
Transfer of Feed to Delivery Wagon	0.0161	kWh/1,000 kg feed
Total Processing	7.52	kWh/1,000 kg feed
Feed Hauling and Delivery	2.03	L diesel fuel/1,000 kg feed
Total Energy Use	**160.9**	**MJ/ 1,000 kg feed**

The second scenario evaluated the use of a centralized feed mill that receives corn and feed ingredients from surrounding elevators, farms, and suppliers and then delivers feed to the surrounding swine units. In contrast to the on-farm feed mill, the off-farm mill was modeled as a vertical system relying primarily on gravity flow of materials with much greater throughput capacities. Figure 6 shows the configuration of the off-farm feed mill and Table 11 identifies components and their characteristics. Motor efficiencies were based on three-phase power and typical data available from motor manufacturers for the modeled motor sizes. Other electrical use such as lighting, controls, compressed air systems, and dust control systems were assumed negligible for each kilogram of feed produced and ignored in the model. Table 12 shows the processing energy requirement per 1,000 kg of feed produced for the off-farm feed mill.

Hauling of feed from the centralized feed mill to the swine unit was assumed done by a semi tractor and 18-ton hopper wagon with unloading auger. An average roundtrip distance of 97 km (60 miles) was assumed. Diesel fuel usage for the hauling was calculated as the trip distance times average semi fuel mileage of 2.2 km per liter (Bureau of Transportations Statistics, 2007).

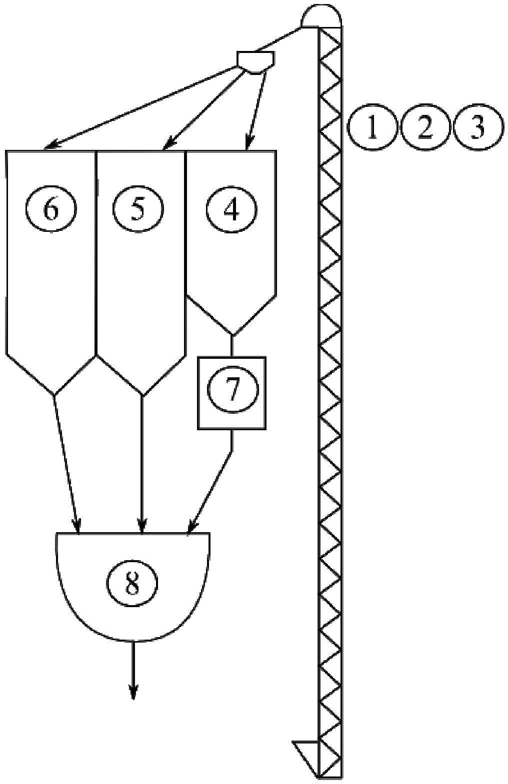

Figure 6. Off-Farm Feed Mill Diagram

Table 11. Off-Farm Feed Mill Components

#	Function	Equipment
1	Corn Delivery to Storage	140 ft. Leg
2	SBM Delivery to Storage	140 ft. Leg
3	Supplement Deliver to Storage	140 ft. Leg
4	Corn Storage	
5	SBM Storage	
6	Supplement Storage	
7	Corn Milling	100 hp Hammer Mill
8	Mixing of Feed	12,000 lb. 75 hp Mixer

Table 12. Off-Farm Feed Mill Processing Energy User per 1,000 kg of Feed

Corn Delivery to Storage	0.1050	kWh/1,000 kg feed
SBM Delivery to Storage	0.0320	kWh/1,000 kg feed
Supplement Deliver to Storage	0.0038	kWh/1,000 kg feed
Corn Milling	3.7879	kWh/1,000 kg feed
Mixing of Feed	0.9084	kWh/1,000 kg feed
Total Processing	4.84	kWh/1,000 kg feed
Feed Hauling and Delivery	2.72	L diesel fuel/1,000 kg feed
Total Energy Use	**168.7**	**MJ/1,000 kg feed**

The total energy of feed processing and delivery per finished pig was calculated by multiplying processing energy use per weight of feed times the weight of feed consumed per finished pig in the hoop and confinement systems. Table 13 summarizes the total energy usage for providing feed for each finished pig for the on-farm and off-farm feed mill scenarios for the hoop and confinement systems.

Table 13. Summary of Energy Use in Swine Feed

On-Farm Feed Mill		
	Hoop	Confinement
Feed Components Embodied Energy (MJ per pig)	804.3	777.8
Feed Processing Energy (MJ per pig	21.5	20.8
Feed Delivery Energy (MJ per pig)	29.6	28.7
Credit to Feed for Corn Hauling Savings(MJ per pig)	-73.2	-70.8
Total Energy Use (MJ per pig)	**782.2**	**756.4**
Off-Farm Feed Mill		
	Hoop	Confinement
Feed Components Embodied Energy (MJ per pig)	804.3	777.8
Feed Processing Energy (MJ per pig)	13.8	13.4
Feed Delivery Energy (MJ per pig)	39.8	38.5
Credit to Feed for Corn Hauling Savings(MJ per pig)	0.0	0.0
Total Energy Use (MJ per pig)	**857.9**	**829.7**

2.4 Facility Energy Use

Energy use from the housing facilities was analyzed for heating and ventilation, lighting, feed delivery, water use, and embodied energy of construction materials. No typical heating and ventilation energy usage data was found for confinement housing systems in Iowa, so a model was created to estimate the energy usage per finished pig, as detailed below. Ventilation and supplemental heating are not generally used in hoop finishing systems as the bedding allows the pig to modify their environment to maintain warmth during periods of cold weather. Pigs also will eat greater amounts of feed during cold weather for added energy to maintain body temperatures, which is reflected in the feed efficiencies used from Honeyman and Harmon, 2003.

An energy use model created for the confinement system analyzed the energy usage per pig for heating and ventilation. The model calculated energy use through a time series evaluation of ventilation and heating requirements to maintain a suitable interior environment for the pigs based on exterior weather data for a typical meteorological year (NREL). The typical meteorological year data sets were available for 39 weather station locations in the state of Iowa. Average heating and ventilation energy use was calculated for each of these weather stations. Pig numbers per county (USDA-NASS 2007 Ag Census) were then used with heating and ventilation energy use from the weather station location nearest to the center of the county to produce weighted average energy use values for the state of Iowa.

The suitable interior environment for the pig was based on maintaining temperature ranges (PM 1586) and minimum cold weather ventilation rates (PM 1780) as recommended by Iowa State University Extension. Pig growth was modeled in the time series evaluation assuming a constant rate of gain. The suitable temperature ranges, minimum cold weather ventilation rates, and heat and humidity produced from the pigs were modeled relative to pig weight. The pig housing cycle was incorporated into the model. Pigs were assumed to be cycled through the building 2.6 times per year. Each cycle, the pigs were assumed to grow from 15.9 to 120.5 kg (35 to 265 lbs.) body weight at a constant rate of gain of 0.80 kg (1.77 lbs) per day (Honeyman and Harmon, 2003) for 130 days. The building was assumed to be filled with 1,000 head of pigs at the beginning of each cycle. A 2.0 % reduction in pig numbers was taken at the midpoint of the cycle to account for mortalities. Load out for sale of the pigs was simulated by removing one third of the pigs on a day each week of the last three weeks of the growth cycle. A period of four days with no pigs in the building was left at the end of each cycle to account for the time used for power washing and maintenance between pig groups. The scheduling of pig entry and the seasonally changing temperatures in Iowa has an impact on the total yearly heating and ventilation energy usage. Therefore, energy usage was analyzed by evaluating the pig housing and growth cycle for the cycle start date set from day 1 to day 365 of the year and then taking the average of the 365 iterations.

To determine energy use required to maintain interior environment set point temperatures, an engineering analysis of the heat balance at each time step was calculated. Heat loss or gain for the building envelope was calculated based on the difference between interior and exterior temperatures at each building surface and the R-value of the assumed building construction. A 12.2 m by 68.6 m (40’-0” by 225’-0”) 1,000 pig-space building was used as the basis for the analysis. The confinement building was modeled as a stud-frame building with ribbed metal roof, insulated ceiling, ventilation curtain sidewalls, and concrete slatted floors with manure storage pit below. A summary of the building components are shown in Table 14. Solar heat gain was accounted for through calculation of sol-air temperature at each surface. The sol-air temperature, the equivalent temperature of the exterior air at the building surface to account for solar radiation heat gain, was calculated using solar declination and angle for the latitude and longitude of the weather station location for each hour of each day along with solar radiation and cloud cover figures from the typical meteorological year weather data. Surfaces were assumed white with a surface absorptivity of 0.3. The model was run for North-South and East-West building ridge orientations as the orientation of the building has an effect on solar gain. The energy use values were then averaged for the two ridge orientation cases for each location. Variable effects of wind speed and direction on convective heat transfer were not factored into the model.

Table 14. Building Construction

End Wall Construction		
Wall Area	29.73	sq m
Average U-value	3.85	W/sq m - deg C
End Wall Peak Construction		
Peak Area	12.39	sq m
Average U-value	9.31	W/sq m - deg C
Side Wall Construction		
Wall Area	167.23	sq m
Average U-value	3.85	W/sq m - deg C
Ceiling		
Ceiling Area	836.13	sq m
Average U-value	0.15	W/sq m - deg C
Roof		
Roof area (one side)	440.68	sq m
Average U-value	9.31	W/sq m - deg C
Slatted Floor		
Floor Area	836.13	sq m
Average U value	3.34	W/sq m - deg C
Room Volume	2,039	cu m
Attic Volume	850	cu m

(U-Value = 1 / R-Value)

Ventilation heat gain and loss was calculated at each time step for a set ventilation rate based on management and control sequences. Three ventilation scenarios were incorporated into the model with implementation of each scenario based on the exterior air temperature. Below the minimum ventilation set point, the sidewall curtains were assumed fully closed and ventilation provided through pit fans and end wall fans with supplemental heat used to maintain the interior set point temperature. Pit fans were modeled to provide the minimum ventilation rates per the management requirements shown in Table 15. Natural ventilation was used for exterior temperatures above the minimum ventilation temperature set point and below the tunnel ventilation temperature set point. The sidewall curtains were assumed open with pit fans continuing to run and the interior temperature following the exterior temperature. Above the tunnel ventilation temperature set point, tunnel ventilation was provided between a minimum and maximum ventilation rate to maintain the interior temperature at 2.8 degrees Celsius (5.0 degrees Fahrenheit) above the exterior temperature.

Table 15. Ventilation Management Settings

Pig Weight (kg)	Minimum Ventilation Rate (cu. m per s)	Min Ventilation Set Point Temperature (deg. C)	Tunnel Ventilation Set Point Temperature (deg. C)
15.9	1.42	25.0	28.9
26.4	1.42	21.1	27.8
36.8	3.30	18.9	26.7
47.3	3.30	16.7	26.7
57.7	3.30	14.4	26.7
68.2	4.72	13.3	26.7
78.6	4.72	13.3	26.7
89.1	4.72	12.2	26.7
99.5	4.72	12.2	26.7
110.0	4.72	11.1	26.7
120.5	4.72	11.1	26.7

The other heat gain considered in the model was that produced by the pigs. Pig heat production was calculated per equations from Pederson, 2002, that incorporated effects of pig body weight and interior temperature. The heat energy change from the building envelope, ventilation, and pig were summed at each step. If the sum of these values totaled a heat loss that would change the temperature to below the minimum set point level, a supplemental heating value was included to maintain the minimum set point temperature. Supplemental heat was assumed to be provided by direct fire propane gas unit heaters. The sum of the supplemental heating values provided the heating energy use value for the building. Energy use for ventilation was calculated by dividing the ventilation rate by the fan efficiency (BESS Labs, 2009) for each type of fan modeled in the system and summing the total fan electrical usage. Table 16 provides a summary of the per pig energy use for heating and ventilation for the confinement system.

Table 16. Confinement Heating and Ventilation Energy Use Summary

Heating and Ventilation Run Time Ranges[1]				
Minimum Ventilation	5,007	to	6,040	hours
	(57.2%)		(69.0%)	
Natural Ventilation	2,125	to	2,774	hours
	(24.3%)		(31.7%)	
Tunnel Ventilation	265	to	1,020	hours
	(3.0%)		(11.6%)	
Empty Ventilation			192	hours
			(2.2%)	
Heater Run Time	404	to	1,902	hours
	(4.6%)		(21.7%)	
Weighted Average Energy Use per Pig Space				
Heating			9.27	liters Propane per pig space
Ventilation			15.08	kWh per pig space
Weighted Average Energy Use per Finished Pig				
Heating			**94.3**	**MJ per pig**
Ventilation			**52.2**	**MJ per pig**
Total			**146.5**	**MJ per pig**

1-Range of values for 39 TMY3 weather station locations

Energy use for lighting of the pig housing area was also considered. There was no data found on total energy or hours per year of lighting typically used for either system. Average wattage of lighting per area from MWPS-8 and area per pig (Honeyman and Harmon, 2003) were used to calculate lighting loads. The confinement system was assumed to use fluorescent lights and the hoop system was assumed to use incandescent lights due to the cold temperatures experienced in the hoop building that makes the use of fluorescent lights impractical. An assumption was made that the lights were used for 90 hours per year for each system. The total lighting energy usage was then calculated per pig based on multiplying the number of days spent in the building per year times the total yearly lighting energy usage. Table 17 shows the values used for lighting energy usage.

Table 17. Lighting Energy Use

	Hoop		Confinement	
Lighting Wattages per Area	8.61 0.8	W/sq. m W/sq. ft.	2.15 0.2	W/sq m W/sf
Area per pig space	1.11 12	sq. m sq. ft.	0.74 8	sq. m sq. ft.
Wattage per pig space	9.6	W	1.6	W
Lighting Use	90	hours/year	90	hours/year
Days per pig in building	127	Days	126	days
Average Lighting Energy Use per Pig	**0.30**	**kWh per pig**	**0.05**	**kWh per pig**
Average Energy Use per Pig	**2.7**	**MJ per pig**	**0.4**	**MJ per pig**

Feed was assumed delivered by a flexible auger system from the feed bin to the pig feeders. The energy required was estimated by multiplying feed auger delivery efficiency by the weight of feed consumed per pig by the average length traveled. The feed auger delivery efficiency was calculated from typical product data for a 8.9 cm (3.5 inch) diameter flexible auger system. Average feed delivery lengths were based on assumed building dimensions. Table 18 summarizes the input variable and energy usage for feed delivery.

Table 18. Feed Delivery Energy Use

	Hoop		Confinement	
Feed Auger Delivery Efficiency	50.7	J/kg-m	50.7	J/kg-m
Total Feed per Pig	317.8	Kg	307.4	Kg
Average Length of Auger	9.1	M	45.0	M
Feed Delivery Energy Use per Pig	**0.15** **0.04**	**MJ per pig** **kWh per pig**	**0.70** **0.19**	**MJ per pig** **kWh per pig**

Water was assumed provided on site from a groundwater well. Energy usage was calculated based on multiplying the total water use per pig by the energy required to pump the water from the well. The well was assumed 45.7 m (150 feet) deep with average system pressure of 345 kPa (50 psi). The well pump was modeled as 70% efficient with a 90% efficient motor. Water usage per pig was estimated for drinking water, water used for cooling, and water used for power washing as shown in Table 19. Drinking water was assumed 2.5 times the feed consumed (Nutrient Requirements of Swine, 1998) plus 5.0% wastage. Sprinkler cooling was utilized only in the confinement system and water usage was based off of typical flow rates (MWPS-8) for a 1 to 4 on/off cycle (Edstrom) for the period of time when temperatures are above 27 degrees Celsius (80 degrees Fahrenheit) (PM1586). The total cooling water usage was then multiplied by the average inclusion of cooling sprinkler systems in confinement buildings of 61% (Harmon, 1998). Power washing water usage was estimated and energy usage for pressurizing the power washing water and heating the water was calculated.

Table 19. Water Usage and Energy Consumption per Pig

	Hoop		Confinement	
Drinking Water	834	kg per pig	807	kg per pig
Cooling Water	0	kg per pig	872	kg per pig
Power Washing Water	0	kg per pig	80	kg per pig
Total Water Usage	834.3	kg per pig	1,759	kg per pig
Water Energy Usage	**1.11**	**MJ per pig**	**2.34**	**MJ per pig**
Power Washing Energy Usage	**0**	**MJ per pig**	**9.27**	**MJ per pig**
Total Energy Usage	***1.11***	***MJ per pig***	***11.61***	***MJ per pig***

Energy of materials used in construction of finishing facilities was estimated for the hoop and confinement systems. Lammers et al., 2009, estimated quantities of construction materials required in a comparison of confinement and hoop systems and included a reference of embodied energies of construction materials (Hammond et al., 2008). Using these quantities and embodied energies for a facility life of 15 years for both the hoop and confinement finishing systems, the resulting energy per finished pig was 14.5 MJ for the hoop system and 30.6 MJ for the confinement system.

A summary of the total facility energy usage is provided in Table 20 below.

Table 20. Facility Energy Use Summary

	Hoop (MJ per pig)	Confinement (MJ per pig)
Heating	0.0	94.3
Ventilation	0.0	52.2
Lighting	2.7	0.4
Feed Delivery	0.4	1.8
Water Use	2.8	5.8
Power Washing	0.0	23.1
Construction Materials	14.5	30.6
Total	**20.4**	**208.3**

2.5 Energy in Bedding

Bedding is used in deep bedded hoop systems and allows the swine manure to be collected as a solid and also provides a comfortable laying surface for the pigs that can be used to help insulate and protect pigs from cold weather. Dry crop residues such as oat straw or corn stalks are generally used as bedding sources (Lammers et al., 2007). For this model, bedding was assumed to be from corn stalk round bales. The energy required from bedding for each finished pig was calculated by multiplying the embodied energy per kg of bedding times the average amount of bedding per finished pig, 45.4 kg (200 lbs.) (Brumm et al., 2004). This resulted in an energy use of 49.5 MJ per finished pig for bedding in the hoop system.

2.6 Manure Management Energy Use

The embodied energy of the applied manure for the hoop and confinement system was defined as a credit based on the replaced fertilizer value. Loading out and applying the manure to the field for crop utilization was included as part of the energy use for each finished pig. Different manure handling and application methods were considered for the two housing systems.

For the confinement system, the manure was assumed stored as a liquid in a pit below the slatted floor in the confinement building. Energy input into manure management was assumed only necessary at times of application using the following practices. A tractor operated unit to agitate and pump out manure from the pits along with tractors and manure tanker applicators with injector bars were used to apply the liquid swine manure. Manure was applied at a rate to meet the crop nutrient requirements of a corn-soybean rotation on a phosphorous basis (PM 1688). Swine manure nutrient densities can vary based on many factors including the amount of water added to the manure through leaking waterers, sprinkler systems, and other sources. For this model, manure densities as shown in Table 21 were used based on a survey of Iowa liquid swine manure nutrient values (Lorimor, 1998). The amount of manure applied per finished pig was approximated by dividing the total solids produced per finished pig (ASABE D384.2) by the percent solids of the manure.

Table 21. Liquid Manure Characteristics

Nitrogen (N)*	6.97	kg/1,000 liters	(58.1	lbs./1,000 gal.)
Phosphate (P_20_5)*	5.81	kg/1,000 liters	(48.4	lbs./1,000 gal.)
Potash (K_2O)*	3.51	kg/1,000 liters	(29.2	lbs./1,000 gal.)
% Solids*	6.8%			
Solids per Finished Pig**	54.5	Kg	(120	lbs.)
Total Manure per Finished Pig	800	Liters	(212	gallons)

** Lorimor, 1998*
*** ASABE D384.2*

Manure application was assumed to take place from a site with three (3) 1,000 head finishing buildings that cycle 2.6 turns of finished pigs per year. The manure produced from these three buildings required 372 hectares (929 acres) of crop ground to apply manure to meet the phosphorous needs of a two-year rotation of corn and soybeans based on a five-year average of Iowa crop yields (www.nass.usda.gov) and recommended application rates (PM1688).

Manure application was modeled using a tractor and 37,900 liter (10,000 gallon) tanker wagon with 4.6 m (15 ft.) application width with narrow point injectors at 76 cm (30 in.) spacing. A 1.6 km (2 mile) average travel distance from the swine unit to the field was modeled. The travel distance was based on assumptions of average distances to effectively reach the area of land required for application. Table 22 shows the calculated diesel use values per 1,000 liters of manure for the field operations.

Table 22. Liquid Manure Application Energy Use

Diesel Fuel Use		
Agitation	0.019	L per pig
Pump Out	0.012	L per pig
Transport Full	0.299	L per pig
Application	1.002	L per pig
Transport Empty	0.181	L per pig
Total	1.513	L per pig
Manure Production per Pig	800	L per pig
Energy per Pig	**69.6**	**MJ per pig**

Manure field application energy use for the hoop system was based on the handling and application of solid manure. The solid manure was assumed loaded out of the hoop buildings and placed into a stockpile by a tractor loader for composting and then loaded out and field applied by box spreader. Turning of the stockpile to advance the composting process was not included in the analysis. The field application rate was calculated for a corn-soybean rotation to meet the phosphorous needs of the crop for average Iowa yields (USDA-

NASS) using typical manure nutrient values for composted manure (Lammers et al., 2007) as shown in Table 23. The quantity of manure required to be hauled was based on 364 kg of bedded pack manure produced per finished pig (Richard et al., 1998). Manure from three 150 pig space hoop buildings that were cycled twice per year was used to determine the total amount of manure cleaned out from the site each year. This manure was assumed to lose 40% of its mass (Tiquia et al., 2002) while composting in the stockpile. The remaining mass of composted manure was used to calculate energy usage for field application. Field application was modeled using a 5,900 kg (6.5 ton) capacity manure spreader with an average hauling distance from the building site to the field of 0.8 km (0.5 miles).

Table 23. Hoop Manure Characteristics

Hoop System - Fresh Manure				
Nitrogen (N)	7.7	g/kg	15.4	Lb/ Ton
Phosphate (P205)	7.9	g/kg	15.8	Lb/ Ton
Potash (K2O)	9.1	g/kg	18.3	Lb/ Ton
% Solids	35.0%		700	Lb/ Ton
Deep Bedded System - Composted Manure				
Nitrogen (N)	9.8	g/kg	19.6	Lb/ Ton
Phosphate (P205)	13.6	g/kg	27.3	Lb/ Ton
Potash (K2O)	12.2	g/kg	24.3	Lb/ Ton
% Solids	51.0%		1,020	Lb/ Ton

(Lammers et al., 2007)

Diesel and oil usage for the cleanout and field application were estimated using ASAE Standard EP496.3 based on required PTO horsepower and estimated times required for the cleanout and pile formation (Duffy and Honeyman, 1998), load out, transport and application. Table 24 summarizes the diesel fuel usage and energy per pig for cleanout and manure application.

Table 24. Hoop Manure Fuel and Energy Usage

Diesel Fuel Use per Pig		
Cleanout and Pile Formation	0.90	L per pig
Load out	0.18	L per pig
Transport Full	0.04	L per pig
Application	0.52	L per pig
Transport Empty	0.03	L per pig
Total	1.67	L per pig
Energy per Pig	**77.0**	**MJ per pig**

2.7 Swine Management Energy Use

Energy use for various aspects of management and human interaction with the swine were considered in this portion of the model. Management energy use was assumed to consist solely of energy used for travel of workers to and from the swine housing site. Energy used to sustain the workers employed in the care of the pigs was not considered as part of the model. Travel of pigs to and from the housing site was considered to be outside of the model boundary and was not included in the total energy usage. Energy usage for the creation, delivery, and administration of vaccines and medical treatments was assumed to be minimal and was not considered in the model.

Worker trips to the building site were assumed to occur each day the pigs were in the building plus an additional five trips to account for veterinary and cleaning trips. Workers were assumed to travel via gasoline powered vehicle with an efficiency of 6.4 km per liter (15 miles per gallon). The hoop site was modeled as a 1.6 km (1.0 mile) round trip based on the assumption that hoop buildings are generally located on smaller operations with the worker located near the swine housing site. The confinement site was modeled as a 16 km (10 mile) round trip based on the assumption that the confinement buildings are part of a multi-site operation with a greater distance required for worker travel to and from the buildings. A building site was assumed to be three 150 head buildings for the hoop system and three 1,000 head buildings for the confinement system. Table 25 below shows the gasoline and energy usage based on these assumptions.

Table 25. Worker Trip Energy Usage per Pig

	Hoop	Confinement
Number of Trips	133	135
Number of Pigs Managed per Trip	450	3,000
Gasoline Usage per pig	0.075 L per pig	0.114 L per pig
Energy Usage per Pig	**3.2 MJ per pig**	**4.9 MJ per pig**

2.8 References

Agricultural Waste Management Field Handbook. 1992. U.S. Department of Agriculture, National Resource Conservation Service.

ASAE D384.2 March 2005. Manure Production and Characteristics. St. Joseph, Michigan; ASABE.

ASAE EP496.3. February 2006. Agricultural Machinery Management. St. Joseph, Michigan; ASABE.

Duffy, M.D., and M.S. Honeyman. 1998. Labor requirements for market swine produced in hoop structures. ASL R1685. Iowa State University Extension.

BESS Labs. Agricultural Fan Performance Data. http://bess.illinois.edu. Accessed October 1, 2009.

Brumm, M.C., J.D. Harmon, M.S. Honeyman, J.B. Kliebenstein, S.M. Lonergan, R. Morrison, and T. Richard. 2004. Hoop barns for grow-finish swine. Ames, Iowa. Midwest Plan Service.

Bureau Transportation Services. 2007. http://www.bts.gov/publications/national_transportation_statistics/html/table_04_14.html. Accessed September 9, 2009.

Edstrom. Cooling Systems for Swine. http://www.agselect.com/agselect/pdf/SwineCooling_SB6068midres.pdf. Accessed October 19, 2009.

Hammond, G., and C. Jones. 2008. Inventory of carbon and energy. Version 1.6a. Department of Mechanical Engineering, University of Bath, Bath, UK. Available at: www.bath.ac.uk/mech‐eng/sert/embodied/. Accessed October 21, 2009.

Harmon, J.D. 1996. Swine Facility Costs in Iowa. ASL 1388. Iowa State University Extension.

Hill J, E Nelson, D Tilman, S Polasky, D Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS Vol. 103 No. 30, 11206–11210.

Holden, P., R. Ewan, M. Jurgens, T. Stahly, D. Zimmerman. 1996. Life Cycle Swine Nutrition. Iowa State University. http://www.ipic.iastate.edu/LCSN/LCSNutrition.pdf. Accessed October 19, 2009.

Honeyman, M.S. and J.D. Harmon. 2003. Performance of finishing pigs in hoop structures and confinement during winter and summer. Journal of Animal Science. 81:1663-1670.

IEA. 2005. Energy Statistics Manual. International Energy Agency. http://www.iea.org/textbase/nppdf/free/2005/statistics_manual.pdf.

Lammers, P. J., M. S. Honeyman, J.D. Harmon, J.B. Kliebenstein, M.J. Helmers. 2009. Construction Resource Use of Two Different Types and Scales of Iowa Swine Production Facilities. Applied Engineering in Agriculture. Vol. 25(4):585-593.

Lammers, P.J., D.R. Stender, M.S. Honeyman. 2007. Niche Pork Production. Iowa State University.

Lorimor, J., K. Kohl. 1998. Liquid Swine Manure Nutrients. ASL-R-1596. Iowa State University Extension.

MWPS-8. 1983. Swine Housing and Equipment Handbook, Fourth edition. Ames, Iowa. Midwest Plan Service.

NREL. TMY3 Weather Data. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html#I. Accessed October 15, 2009.

Nutrient Requirements of Swine, 10th Revised edition. 1998. National Research Council. National Academy Press; Washington, D.C.

Pedersen, Soeren. 2002. Heat and Moisture Production for Pigs on Animal and House Level. ASAE Meeting Paper Number 024178.

PM 1586. Environmental Guidelines for Confinement Swine Housing. February, 1995. Iowa State University Extension.

PM 1688. A General Guide for Crop Nutrient and Lime Recommendations for Iowa. November, 2002. Iowa State University Extension.

PM 1780. Mechanical Ventilation Design Worksheet for Swine Housing. October, 1999. Iowa State University Extension.

Richard, T., J. Harmon, M. Honeyman, J. Creswell. 1998. Hoop Structure Bedding Use, Labor, Bedding Pack Temperature, Manure Nutrient Content, and Nitrogen Leaching Potential. ASL R1499. Iowa State University Extension.

Shapouri H., J. A. Duffield, M. Wang. 2003. The Energy Balance of Corn Ethanol Revisited. Transactions of the ASAE, Vol. 46(4): 959–968.

Shapouri H., J. A. Duffield, A. McAloon, M. Wang. 2004. The 2001 Net Energy Balance of Corn Ethanol. http://www.usda.gov/oce/reports/energy/index.htm. Accessed October 27, 2009.

Srivastava, A.K., C.E. Goering, R.P. Rohrbach, D.R. Buckmaster. 2006. Conveying of agricultural materials. Chapter 14 in Engineering Principles of Agricultural Machines, 2nd ed., 491-524. St. Joseph, Michigan; ASABE.

Tiquia, S.M., T.L. Richard, M.S. Honeyman. 2002. Carbon, nutrient, and mass loss during composting. Nutrient Cycling in Agroecosystems, 62: 15-24.

USDA-NASS. 2007 Ag Census. http://quickstats.nass.usda.gov. Accessed October 15, 2009.

USDA-NASS. Crop Yield Data, 5 year average 2003-2008. www.nass.usda.gov. Accessed October 15, 2009.

CHAPTER 3. SUMMARY OF RESULTS

3.1 Overview

With the energy calculated for each portion of the model, the total energy per finished pig was calculated through addition of the energy consumed from feed use, facilities, bedding, manure application and management and then subtraction of the credit for the nutrient value of the manure, as shown previously in the equations of Figure 1. The total energy consumption per finished pig was then divided by the weight gain of the pig, 104.5 kg, to produce the embodied energy per kg of gain in each finishing system. The totals were summed for each finishing system for the case of the on-farm feed mill and the off-farm feed mill. Tables 26 and 27 summarize the energy consumption values produced from the model for the on-farm and off-farm feed mill scenarios.

Table 26. Summary of Energy Use per Finished Pig with On-Farm Feed Mill

	Hoop		Confinement	
	MJ per pig	% of Inputs	MJ per pig	% of Inputs
Feed	782.2	83.9%	756.4	72.8%
Facilities	20.4	2.2%	208.3	20.0%
Bedding	49.5	5.3%	0.0	0.0%
Manure Application	77.0	8.3%	69.6	6.7%
Management	3.2	0.3%	4.9	0.5%
Subtotal	*932.2*	*100.0%*	*1039.3*	*100.0%*
Manure Energy Credit	-157.8		-233.3	
Total	**774.4**		**806.0**	
Energy per kg marketed	***7.41 MJ/kg***		***7.71 MJ/kg***	

Table 27. Summary of Energy Use per Finished Pig with Off-Farm Feed Mill

	Hoop		Confinement	
	MJ per pig	% of Inputs	MJ per pig	% of Inputs
Feed	857.9	85.1%	829.7	74.6%
Facilities	20.4	2.0%	208.3	18.7%
Bedding	49.5	4.9%	0.0	0.0%
Manure Application	77.0	7.6%	69.6	6.3%
Management	3.2	0.3%	4.9	0.4%
Subtotal	*1008.0*	*100.0%*	*1112.5*	*100.0%*
Manure Energy Credit	-157.8		-233.3	
Total	**850.1**		**879.3**	
Energy per kg marketed	***8.14 MJ/kg***		***8.41 MJ/kg***	

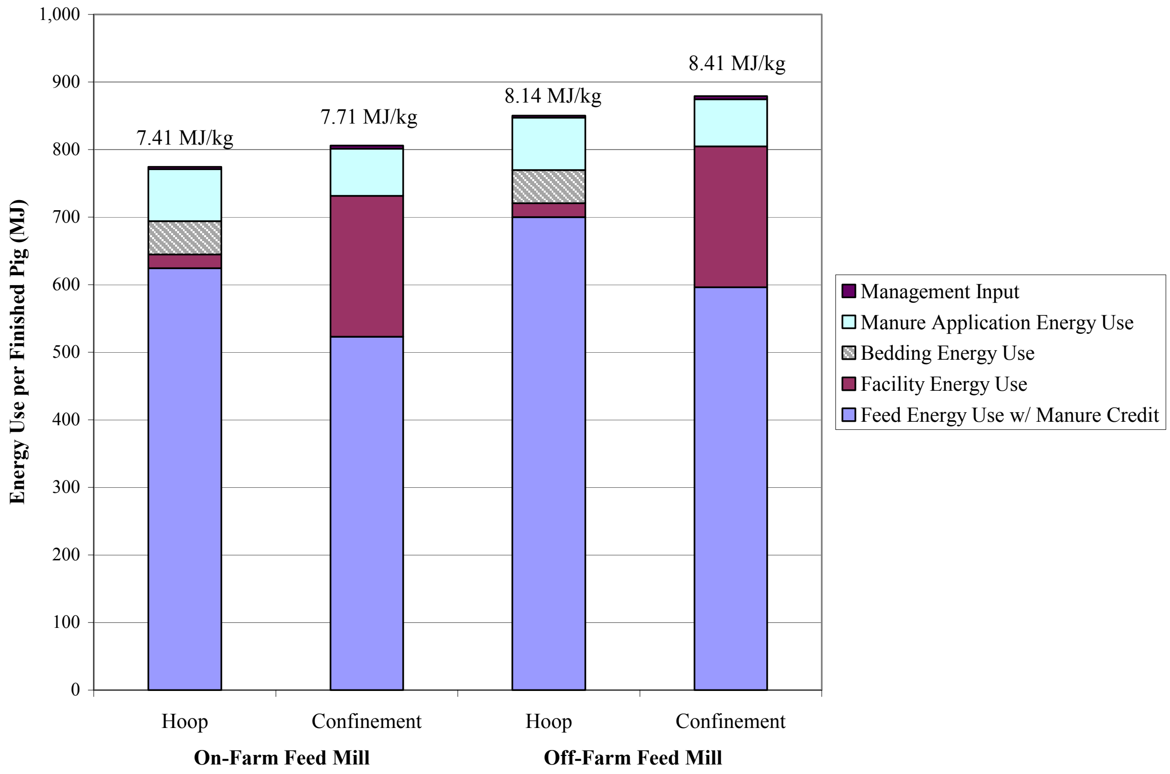

Figure 7. Energy Use per Finished Pig

The primary energy use for all cases was for the provision of feed for the finishing pigs, ranging from 72.8% to 85.1% of the overall energy consumption before consideration of the manure energy credit. The next largest area of energy consumption was facility energy use for the confinement system, requiring 1.99 MJ per kilogram of finished pig. The facility energy use consisted primarily of the energy required for heating and ventilating the building. The third largest energy consumption for the confinement system and second largest for the hoop system was for application of manure at 0.74 MJ per kg and 0.67 MJ per kg of finished pig respectively. The energy required to apply the manure was less than the energy credit for the nitrogen, phosphorous, and potassium that the applied manure would replace in synthetic fertilizers. The hoop system required 49% and the confinement system 30% of the total energy involved in the production and application of synthetic fertilizers to apply the manure with similar nutrient content. The manure energy credit provided a significant reduction in the net energy usage, reducing the energy per kilogram of finished pig by 1.51 MJ for the hoop system and 2.23 MJ for the confinement system.

3.2 Deep-Bedded Hoop Housing vs. Confinement Housing

The deep bedded hoop housing and confinement systems produced similar net energy use per kilogram of swine finished, with the hoop system using 3.9% less energy for the on-farm feed mill scenario and 3.3% less for the off-farm feed mill system. Before taking into consideration the energy credit for the value of the nutrients in the manure, the confinement system used an average of 11.0% more energy than the hoop system.

The confinement system had an advantage in feed energy use at 3.4% less than the hoop system due to the lower feed to gain ratio (Honeyman and Harmon, 2003). This is expected as more feed is generally required to maintain core body temperature of the pigs in the unheated hoop buildings than the heated confinement systems. The confinement system, however, required a significant amount of energy to provide the heating and ventilation to achieve this difference. 147 MJ per finished pig was required for heating and ventilation to achieve an average difference of 27 MJ in feed energy use.

3.3 On-Farm vs. Off-Farm Feed Mill

The on-farm feed mill provided significant reduction in energy requirements, with 9.8% and 9.1% less energy use than the off-farm feed mill for the hoop and confinement systems respectively. The difference was primarily due to the reduction in energy use for hauling corn to the feed mill and then delivering feed back to the farm, which accounted for a savings per finished pig of 83.4 MJ for the hoop system and 80.6 MJ for the confinement system. The less efficient milling system for the on-farm feed mill reduced the credit by 7.7 MJ and 7.4 MJ per finished pig for the hoop and confinement systems.

3.4 Sensitivity Analysis

The results of the model are based on input values from previous research work and assumptions of typical conditions. Variations in management and assumptions can lead to ranges of possible input values. To further understand the impact of changes to the input values, a sensitivity analysis was performed. The sensitivity analysis was performed by analyzing maximum and minimum values for a single input at a time. The resulting changes in energy use for the section and overall model were then compared.

For the energy used in providing feed for the pigs, four factors were analyzed: feed to gain ratio and embodied energy of corn, soybean meal, and supplement. These factors were analyzed for both the on-farm and off-farm feed mill scenarios. The feed to gain ratio is a measure of the efficiency of the pig in converting feed to growth. This ratio is largely influenced by genetics, ration quality, and growing conditions. Improvement of management and genetics allow for this ratio to be improved, but at a relatively slow pace compared to other factors in the management of the swine finishing system. The feed to gain ratio was analyzed for values of +/- 10% of the model values for both the hoop system and the confinement system for the on-farm and off-farm feed mill scenarios. As the feed energy is a large portion of overall energy use, changes to the quantity of feed consumed through modification of the feed to gain ratio affect the overall energy usage at nearly a 1 to 1 ratio for the range analyzed. In both the hoop and confinement systems, a 10% change in feed to gain ratio resulted in a 10% change in feed energy and a 10.1% change in the overall energy use for the hoop system and 9.4% change for the confinement system.

The other factors analyzed for their effects on feed energy use were the embodied energy values for the feed ingredients: corn, soybean meal, and supplement. All three ingredients were analyzed individually for changes of +/-50% to the embodied energy value used in the model. Whereas the feed to gain ratio is relatively slow to change, the embodied energy values for the feed ingredients can be modified significantly based on changing the cropping practices. The embodied energy value for corn is highly reliant on the commercial fertilizers and chemical pesticides used in its production (Shapouri et al., 2004). Any practices that reduce fertilizer and pesticide use while maintaining or improving yield have the potential to dramatically decrease the embodied energy of corn. Pimental et al., 2005, suggested that organic cropping practices could reduce the energy use in corn production by 30% while producing similar yields. On the other hand, dramatic reductions in yield while maintaining the same amount of inputs will greatly increase the energy per kilogram of corn.

Tables 29, 30, and 31 show the effect that changes in energy of corn, soybean meal, and supplement have on the energy requirements of swine finishing production. The 50% change in corn energy provides a 22.6% to 25.4% change in overall energy use. Changes in cropping practices for the production of soybeans can affect the embodied energy value of the soybean meal but, unlike corn, significant energy is also used in the processing of soybeans into soybean meal through crushing and oil extraction. Soybean meal provides only 23% of the total weight of feed consumed by the finished pig, but has nearly three times the embodied energy value of corn, which makes a 50% change in the embodied energy value account for a 19.7% to 22.1% change in overall energy usage. Supplements were more energy intensive than corn or soybean meal, but were required at a much lesser quantity, supplying only 3% of the total weight of the ration. Therefore, a 50% change in the embodied energy value only created a 3.5% to 4.0% change in the overall energy requirements. Energy use in feed production greatly impacts the overall energy use of producing a finished pig and changes to corn and soybean meal inputs and pig performance make significant changes to the overall energy use.

Table 28. Feed to Gain Ratio Sensitivity Analysis

Hoop System				
On-Farm Feed Mill				
		Min	Model	Max
Feed Efficiency	kg feed per kg gain	2.74	3.04	3.34
	% change	-10.0%		10.0%
Feed Energy	MJ per pig	704.0	782.2	860.4
	% change	-10.0%		10.0%
Total Energy	MJ per pig	696.2	774.4	852.6
	MJ per kg pig	6.66	7.41	8.16
	% change	-10.1%		10.1%
	Sensitivity	1.01		1.01
Off-Farm Feed Mill				
		Min	Model	Max
Feed Efficiency	kg feed per kg gain	2.74	3.04	3.34
	% change	-10.0%		10.0%
Feed Energy	MJ per pig	772.1	857.9	943.7
	% change	-10.0%		10.0%
Total Energy	MJ per pig	764.0	850.1	935.9
	MJ per kg pig	7.31	8.14	8.96
	% change	-10.1%		10.1%
	Sensitivity	1.01		1.01
Confinement System				
On-Farm Feed Mill				
		Min	Model	Max
Feed Efficiency	Kg feed per kg gain	2.65	2.94	3.23
	% change	-10.0%		10.0%
Feed Energy	MJ per pig	680.8	756.4	832.1
	% change	-10.0%		10.0%
Total Energy	MJ per pig	730.4	806.0	881.7
	MJ per kg pig	6.99	7.71	8.44
	% change	-9.4%		9.4%
	Sensitivity	0.94		0.94
Off-Farm Feed Mill				
		Min	Model	Max
Feed Efficiency	Kg feed per kg gain	2.65	2.94	3.23
	% change	-10.0%		10.0%
Feed Energy	MJ per pig	746.7	829.7	912.6
	% change	-10.0%		10.0%
Total Energy	MJ per pig	796.3	879.3	962.2
	MJ per kg pig	7.62	8.41	9.21
	% change	-9.4%		9.4%
	Sensitivity	0.94		0.94

Table 29. Corn Energy Sensitivity Analysis

Hoop System				
On-Farm Feed Mill				
		Min	Model	Max
Corn Energy	MJ per kg corn	0.81	1.61	2.42
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	591.4	782.2	972.9
	% change	-24.4%		24.4%
Total Energy	MJ per pig	583.6	774.4	965.1
	MJ per kg pig	5.58	7.41	9.24
	% change	-24.6%		24.6%
	Sensitivity	0.49		0.49
Off-Farm Feed Mill				
		Min	Model	Max
Corn Energy	MJ per kg corn	0.81	1.61	2.42
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	667.1	857.9	1048.7
	% change	-22.2%		22.2%
Total Energy	MJ per pig	659.3	850.1	1040.9
	MJ per kg pig	6.31	8.14	9.96
	% change	-22.4%		22.4%
	Sensitivity	0.45		0.45
Confinement System				
On-Farm Feed Mill				
		Min	Model	Max
Corn Energy	MJ per kg corn	0.81	1.61	2.42
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	572.0	756.4	940.9
	% change	-24.4%		24.4%
Total Energy	MJ per pig	621.6	806.0	990.5
	MJ per kg pig	5.95	7.71	9.48
	% change	-22.9%		22.9%
	Sensitivity	0.46		0.46
Off-Farm Feed Mill				
		Min	Model	Max
Corn Energy	MJ per kg corn	0.81	1.61	2.42
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	645.2	829.7	1014.2
	% change	-22.2%		22.2%
Total Energy	MJ per pig	694.8	879.3	1063.8
	MJ per kg pig	6.65	8.41	10.18
	% change	-21.0%		21.0%
	Sensitivity	0.42		0.42

Table 30. Soybean Meal Embodied Energy Sensitivity Analysis

Hoop System				
On-Farm Feed Mill				
		Min	Model	Max
Soybean Meal Embodied Energy	MJ per kg soybean meal	2.30	4.60	6.90
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	616.0	782.2	948.3
	% change	-21.2%		21.2%
Total Energy	MJ per pig	608.2	774.4	940.5
	MJ per kg pig	5.82	7.41	9.00
	% change	-21.5%		21.5%
	Sensitivity	0.43		0.43
Off-Farm Feed Mill				
		Min	Model	Max
Soybean Meal Embodied Energy	MJ per kg soybean meal	2.30	4.60	6.90
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	691.8	857.9	1024.0
	% change	-19.4%		19.4%
Total Energy	MJ per pig	684.0	850.1	1016.2
	MJ per kg	6.55	8.14	9.72
	% change	-19.5%		19.5%
	Sensitivity	0.39		0.39
Confinement System				
On-Farm Feed Mill				
		Min	Model	Max
Soybean Meal Embodied Energy	MJ per kg soybean meal	2.30	4.60	6.90
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	595.8	756.4	917.1
	% change	-21.2%		21.2%
Total Energy	MJ per pig	645.4	806.0	966.7
	MJ per kg pig	6.18	7.71	9.25
	% change	-19.9%		19.9%
	Sensitivity	0.40		0.40
Off-Farm Feed Mill				
		Min	Model	Max
Soybean Meal Embodied Energy	MJ per kg soybean meal	2.30	4.60	6.90
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	669.0	829.7	990.3
	% change	-19.4%		19.4%
Total Energy	MJ per pig	718.6	879.3	1039.9
	MJ per kg pig	6.88	8.41	9.95
	% change	-18.3%		18.3%
	Sensitivity	0.37		0.37

Table 31. Supplement Embodied Energy Sensitivity Analysis

Hoop System				
On-Farm Feed Mill				
		Min	Model	Max
Supplement Embodied Energy	MJ per kg supplement	5.25	10.49	15.74
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	736.9	782.2	827.4
	% change	-5.8%		5.8%
Total Energy	MJ per pig	729.1	774.4	819.6
	MJ per kg pig	6.98	7.41	7.84
	% change	-5.8%		5.8%
	Sensitivity	0.12		0.12
Off-Farm Feed Mill				
		Min	Model	Max
Supplement Embodied Energy	MJ per kg supplement	5.25	10.49	15.74
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	812.6	857.9	903.2
	% change	-5.3%		5.3%
Total Energy	MJ per pig	804.8	850.1	895.4
	MJ per kg pig	7.70	8.14	8.57
	% change	-5.3%		5.3%
	Sensitivity	0.11		0.11
Confinement System				
On-Farm Feed Mill				
		Min	Model	Max
Supplement Embodied Energy	MJ per kg supplement	5.25	10.49	15.74
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	712.7	756.4	800.2
	% change	-5.8%		5.8%
Total Energy	MJ per pig	762.3	806.0	849.8
	MJ per kg pig	7.29	7.71	8.13
	% change	-5.4%		5.4%
	Sensitivity	0.11		0.11
Off-Farm Feed Mill				
		Min	Model	Max
Supplement Embodied Energy	MJ per kg supplement	5.25	10.49	15.74
	% change	-50.0%		50.0%
Feed Energy	MJ per pig	785.9	829.7	873.5
	% change	-5.3%		5.3%
Total Energy	MJ per pig	835.5	879.3	923.1
	MJ per kg pig	7.99	8.41	8.83
	% change	-5.0%		5.0%
	Sensitivity	0.10		0.10

The largest non-feed energy use for the confinement system was facility energy use, specifically for the heating and ventilation of the building. The model was based on recommendations for set point temperatures for pigs in different weight ranges (PM 1586). To investigate the effects these set points have on overall energy use, the temperatures were modified up and down by 2.8 degrees Celsius (5 degrees Fahrenheit). The building heating and ventilation energy use model was run for weather data for Des Moines, a location with typical energy use for the weighted average results. Table 32 shows the resulting changes in facility and overall energy use. A 2.8 degrees Celcius reduction in temperature set points can conserve 15.3% of the heating and ventilation energy with an average savings of 3.8% for the overall energy use. The sensitivity analysis for changing temperature set points did not consider potential impacts on feed to gain ratio. As seen with the hoop and confinement housing comparison, the pigs in the hoop system required a greater amount of feed to make up for colder temperatures. The temperature settings used in the model are those listed as optimal for pig production (PM 1586, 1995). If the reduction in temperature set points increased the feed to gain ratio by 4.0%, the energy savings from lowering the set point temperatures would be negated.

Table 32. Facility Set Point Temperature Sensitivity Analysis

Confinement System				
		Min	Model	Max
Min. Set Point Temperature	degrees Celsius	-2.8°	--	+2.8°
Heating Energy	MJ per pig	61.6	94.3	137.1
	% change	-34.7%		45.4%
Ventilation Energy	MJ per pig	53.1	52.2	51.0
	% change	1.8%		-2.3%
Facility Energy	MJ per pig	176.5	208.3	249.9
	% change	-15.3%		20.0%
On-Farm Feed Mill				
Total Energy	MJ per pig	774.2	806.0	847.6
	MJ per kg pig	7.41	7.71	8.11
	% change	-3.9%		5.2%
Off-Farm Feed Mill				
Total Energy	MJ per pig	847.5	879.3	920.9
	MJ per kg pig	8.11	8.41	8.81
	% change	-3.6%		4.7%

Bedding has a large impact on the non-feed energy use for the hoop system. Two factors directly affecting the energy use are the amount of bedding used per pig and the mechanical efficiency with which the bedding is harvested. Bedding use was varied by +/-50%, which resulted in a nearly 50% change in energy requirement for bedding but only resulted in an average of 3.2% change in overall energy use as shown in Table 33.

Table 33. Bedding Quantity Sensitivity Analysis

Hoop System				
		Min	Model	Max
Bedding per Pig	kg corn stalks	45.43	90.9	136.30
	% change	-50.0%		50.0%
Bedding Energy	MJ per pig	25.0	49.5	73.9
	% change	-49.6%		49.3%
On-Farm Feed Mill				
Total Energy	MJ per pig	749.9	774.4	798.8
	MJ per kg pig	7.18	7.41	7.64
	% change	-3.2%		3.2%
	Sensitivity	0.06		0.06
Off-Farm Feed Mill				
Total Energy	MJ per pig	825.6	850.1	874.5
	MJ per kg pig	7.90	8.14	8.37
	% change	-2.9%		2.9%
	Sensitivity	0.06		0.06

The mechanical efficiency with which corn stalk bales were baled, collected, transferred, and deposited was varied by +/- 25%. When the mechanical efficiency was reduced by 25%, the energy required for bedding increased 16.8% and the overall energy increased an average of 1.1%. With the mechanical efficiency improved by 25%, the energy required for bedding decreased 8.6% and the overall energy decreased an average of 0.6%. While having relatively minor influence in the overall energy use per finished pig, changes to the bedding use and mechanical efficiency can lead to significant changes in the bedding energy use for the hoop system.

Table 34. Bedding Mechanical Efficiency Sensitivity Analysis

Hoop System				
		Min	Model	Max
Mechanical Efficiency	%	75%	100%	125%
	% change	-25.0%		25.0%
Bedding Energy	MJ per pig	57.8	49.5	45.2
	% change	16.8%		-8.6%
On-Farm Feed Mill				
Total Energy	MJ per pig	782.7	774.4	770.1
	MJ per kg pig	7.49	7.41	7.37
	% change	1.1%		-0.6%
	Sensitivity	-0.04		-0.02
Off-Farm Feed Mill				
Total Energy	MJ per pig	858.5	850.1	845.9
	MJ per kg pig	8.21	8.14	8.09
	% change	1.0%		-0.5%
	Sensitivity	-0.04		-0.02

Manure application accounts for 8 to 10% of the net energy use for the swine finishing systems. A key factor in the energy usage was the distance traveled by the manure applicator from the swine site to the field. For the model, average distances to reach areas of contiguous crop land for application from swine sites located on the edge of the crop land were assumed. Swine finishing sites located more centrally on the crop land could reduce the average travel distance. Contrarily, more dispersed crop land could increase the average travel distance. A sensitivity analysis was run for the hoop and confinement systems for one-half the and twice the travel distance assumed in the model. For the hoop system, the distances traveled were less than the confinement system as the area of land required for manure application was smaller. The sensitivity analysis reflects this as the decrease in travel distance resulted in only a 2.3% change in manure application energy use and the increase resulted in 4.5% increase in manure application energy use. These changes had only a minor affect on the overall energy use. For the confinement system, where travel distances were greater, the changes had a more significant effect. With the distance reduced by half, nearly 16% of the manure application energy use was saved. With the travel distance doubled, a nearly 32% increase in manure application energy use was modeled. These changes resulted in average changes of -1.3% and 2.6% to the overall energy use. Strategies to minimize manure hauling distance can result in significant changes to the manure application energy use and the overall energy use per finished pig.

Table 35. Manure Transfer Distance Sensitivity Analysis

Hoop System				
		Min	Model	Max
Travel Distance	km	0.4	0.8	1.6
	% change	-50.0%		100.0%
Manure Application Energy	MJ per pig	75.2	77.0	80.4
	% change	-2.3%		4.5%
On-Farm Feed Mill				
Total Energy	MJ per pig	772.6	774.4	777.8
	MJ per kg pig	7.39	7.41	7.44
	% change	-0.2%		0.4%
	Sensitivity	0.00		0.00
Off-Farm Feed Mill				
Total Energy	MJ per pig	848.4	850.1	853.6
	MJ per kg pig	8.12	8.14	8.17
	% change	-0.2%		0.4%
	Sensitivity	0.00		0.00
Confinement System				
		Min	Model	Max
Travel Distance	km	1.6	3.2	6.4
	% change	-50.0%		100.0%
Manure Application Energy	MJ per pig	58.6	69.6	91.7
	% change	-15.9%		31.7%
On-Farm Feed Mill				
Total Energy	MJ per pig	795.0	806.0	828.1
	MJ per kg pig	7.61	7.71	7.92
	% change	-1.4%		2.7%
	Sensitivity	0.03		0.03
Off-Farm Feed Mill				
Total Energy	MJ per pig	868.2	879.3	901.3
	MJ per kg pig	8.31	8.41	8.62
	% change	-1.3%		2.5%
	Sensitivity	0.03		0.03

3.5 References

Honeyman, M.S. and J.D. Harmon. 2003. Performance of finishing pigs in hoop structures and confinement during winter and summer. Journal of Animal Science. 81:1663-1670.

Pimentel, D., Hepperly, P., Hanson, J., Seidel, R., and Douds, D. 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience 55(7): 573-582.

PM 1586. Environmental Guidelines for Confinement Swine Housing. February, 1995. Iowa State University Extension.

Shapouri H., J. A. Duffield, A. McAloon, M. Wang. 2004. The 2001 Net Energy Balance of Corn Ethanol. http://www.usda.gov/oce/reports/energy/index.htm. Accessed October 27, 2009.

CHAPTER 4. CONCLUSIONS

4.1 Review of Results

The net non-solar energy used per kilogram of finished pig is similar between the hoop and confinement systems with the hoop system consuming on average 3.6% less than the confinement system. Average non-feed energy use per finished pig is significantly less in the hoop system, 150 MJ, than in the confinement system, 283 MJ. The modeled hoop system consumes more feed, per the feed to gain ratios of Honeyman and Harmon, 2003, which results in an average of 27 MJ more energy used for feed per finished pig. The hoop system also displaces 76 MJ per finished pig less in synthetic fertilizer inputs due to losses of nutrients from manure. If the hoop system handled manure in a manner to match the nutrient losses of the confinement system, the overall energy use could be reduced to 6.69 MJ per kilogram of finished pig, nearly 13% less energy than the confinement system. On-farm feed mills save an average of 9.5% over off-farm feed mills. The reduction in energy used to haul corn to market and feed back to the farm outweighs the reduced efficiencies of smaller scale feed processing equipment.

Energy savings for the feed in the confinement system can partly be attributed to the energy used for heating and ventilation, 147 MJ per pig. The bedding in the hoop system serves the purpose of both providing a medium to handle the manure as a solid bedded pack and also helps the pigs modify their environment to maintain thermal comfort. If energy for providing extra feed and bedding for the hoop system, 76 MJ per pig, is considered as equivalent to providing heating and mechanical ventilation for the confinement system, 71 MJ per pig is saved through the use of the hoop system. Development of pigs that are able to perform comparably at lower minimum temperatures in the confinement system can reduce the heating and ventilation energy requirements significantly, but the system still requires a relatively large amount of energy for heating and ventilation to produce a minimal gain in feed efficiency.

Lammers, 2009, evaluated energy use for two prototype farrow-to-finish systems. The system utilizing hoop buildings for finishing and gestation pigs was reported to require 940 MJ per finished pig of non-solar energy. The system using confinement buildings for all phases of the swine system was reported to require 967 MJ per finished pig. The finished pig size assumed in the Lammers model was 136 kg (300 lbs.), larger than the size considered in this model. The energy per kilogram of finished pig is reported by Lammers as 6.9 MJ/kg and 7.1 MJ per kg for the hoop and confinement farrow-to-finish systems respectively. These values are less than the 7.4 MJ/kg and 7.7 MJ/kg values found in this model for the on-farm feed mill scenario for the finishing system only. The differences result from different assumptions on pig growth rate, feed efficiency, and embodied energy values for corn and soybean meal. Lammers also reported less energy required for bedding harvest and manure application for the hoop system. The energy use for facility operation of the confinement system was greater in this study than in Lammers. Lammers used average weather bin data for Mason City to estimate average heating and ventilation energy use while this study used a time series evaluation with a weighted average from 39 locations of typical meteorological year (TMY3) data. While there are differences in approaches and results between this study and Lammers, 2009, both studies draw similar conclusions that hoop systems require less overall energy than confinement systems and require significantly less energy for non-feed related operations.

4.2 Opportunities for Energy Savings

Many factors determine a swine finishing system’s long term viability. Reliance on non-solar energy sources is a potential downfall of current swine finishing systems. Opportunities for reduction of non-solar energy use for the hoop and confinement systems are analyzed below.

As seen in the sensitivity analysis, the largest impact to overall energy usage is through modification of energy used for feed. Improvement of the feed to gain ratio, thereby reducing the amount of feed consumed, is the most direct method of reducing overall energy use. Biological and practical limits affect the speed and amount feed efficiency can be improved. Improvements in genetics and optimization of growing environment and rations to improve the feed to gain ratio will benefit overall energy use over time. Other avenues must be pursued, as well, for more dramatic reductions in energy use. To this end, reduction of energy requirements to provide feedstuffs for the pig ration are the next most effective method of reducing overall energy use. A large portion of the energy requirements for corn and soybean production are from the use of synthetic fertilizers and chemical pesticides that have high embodied energy values due to there derivation from fossil fuels. Continued improvement in yields through plant breeding and limited application of fertilizers and pesticides through precision agriculture has the potential to reduce the energy per unit mass of conventional corn and soybean cropping systems. However these systems still rely on fossil fuels. The most direct route to reducing the energy required for cropping systems is through development of management systems that minimize or eliminate the need for energy intensive fertilizers, pesticides, and fuels while maintaining similar yields. Utilization of extended crop rotations and low external input systems provide an opportunity to significantly reduce fossil fuel inputs in production of corn and soybeans (Liebman, 2008). If the energy use for both corn and soybean meal can be reduced by 50% through the use of management changes in crop production, the total energy requirement can be reduced to 4.0 to 5.1 MJ per kilogram of finished pig.

Another approach to reduction of feed energy use is replacement of corn, soybean meal, and supplements with less energy intensive feeds. Small grains, such as oats, barley, rye, triticale, and wheat, can be incorporated at levels up to 95% of the finishing pigs diet (PM 1994). Small grains also fit into extended crop rotations that are an integral part of energy reduction in low external input cropping practices. Small grains also fit well into systems utilizing on-farm feed mills, as no extensive processing is required to use the grains in feed. Small grains contain more protein and a higher percentage of lysine, an essential and generally limiting amino acid, than corn, but are also less energy dense than corn and contain less protein per unit weight than soybean meal. Incorporation of small grains into the pig ration therefore replaces both a portion of the corn and a portion of the soybean meal. Using a low inclusion rate of 25% of triticale or wheat into the finisher ration per PM 1994, 14% of the corn and 11% of the soybean meal is displaced. If triticale or wheat is assumed to have an embodied energy of 0.50 MJ per kilogram (Cruse, 2009) and produce similar pig performance, the net energy per finished pig would be reduced by 68 MJ from the model values. If the triticale or wheat is incorporated into the ration with low external input cropping practices and on-farm feed mill with the hoop system, the energy per weight of finished pig could be reduced down to as low as 3.5 MJ per kilogram. Development of integrated low external input cropping and swine systems offers a promising opportunity for reducing energy use in swine finishing systems.

Conservation of manure nutrients in both hoop and confinement systems allows the displacement of synthetic fertilizers in the cropping practices, which serves as a sizable energy credit to the swine finishing system. Both the hoop and confinement systems are imperfect in maintaining nutrients in the stored manure. Improvements through advances in technology and management have the potential to improve the energy balance of the entire system. While conserving more nutrients in the manure requires the manure to be spread over a larger area of ground to match the nutrient needs of the crop, the energy required to apply the manure is significantly less than the energy saved from displacement of synthetic fertilizers. For the confinement system where manure is stored as a slurry in a pit below slatted floors, the primary loss of nutrients is through volatilization of gases, mainly affecting nitrogen through volatilization of ammonia. Management of rations to include protein and essential amino acids in the rations to support optimal growth but not excrete excess nitrogen can limit the potential for losses from the manure (Powers et al., 2007) as well as optimize the amount of soybean meal included in the diet. Another potential nutrient loss from liquid swine manure is leaching of nutrients after the manure is field applied. The use of biological and chemical additives has the potential to stabilize nutrients in forms that are less likely to be volatilized or leached away prior to being utilized by the crops (Heber et al., 2000, Miller et al., 1986, Powers et al., 2009). Conservation of the remaining 25% of nitrogen and 5% of phosphate and potash in the liquid manure would result in an additional credit of 68.5 MJ per finished pig, with 66.8 MJ of the savings attributed to conservation of nitrogen.

Manure from the hoop system has even greater room for improvement in maintaining nutrients. Primary losses are from volatilization of ammonia and leaching of nutrients while stockpiled (Tiquia et al., 2002). Manure can be field applied directly from the hoop, but requires crop land to be available to spread the manure after each finishing cycle and also poses the risk of increased loss of nutrients through volatilization, leaching, and runoff if the manure is not incorporated into the soil directly after application. The composting process that occurs while in the bedded pack and while stockpiled helps stabilize nutrients in forms less apt to volatilize or be leached away. Part of the reason for nutrient losses in the bedded pack manure of the hoop system may be due to a less than optimum carbon to nitrogen (C:N) ratio, allowing nutrients to volatilize and leach out of the stockpile while composting. Tiquia et al., 2002, reported bedded pack manure exiting the hoop with a C:N ratio of 11 to 1. If additional bedding was added to bring the bedded pack C:N ratio to 25 to 1, a more optimal range for composting, energy would be required to provide the added bedding, but the savings in kept nutrients in the manure could outweigh this added energy use. If an additional 36.3 kilograms (80 lbs.) of bedding would bring the C:N ratio to 25 to 1, an additional 19.4 MJ per pig would be required to provide the bedding. If this improved C:N ratio reduced the losses of nitrogen to 25% from 50% and phosphate and potash to 5% from 30%, an additional 75.5 MJ would be saved in synthetic fertilizers not applied to crop land. This is close to a 400% return on energy investment for the added bedding. Minimizing nutrient losses to the environment increases the energy efficiency of the swine production system and advancements in manure management are an essential part of any strategy to improve overall system energy use.

4.3 Suggestions for Future Work

This work analyzes a portion of the overall production system that is required to produce market pigs from the farm. Further analysis of breeding, gestation, farrowing, and nursery operations would enable further understanding of the energy requirements to produce the pig that enters the finishing systems modeled in this work. A variety of systems could be analyzed for these operations from pasture-based to confinement systems.

This work utilizes modeling of fuel consumption for field operations such as bedding collection and manure application. Fuel and electricity use for heating and ventilation of the confinement building was also modeled. The fuel and electricity consumption for these items was modeled in place of utilizing representative data from producers as there was no data found that accurately defined fuel and electricity use for swine finishing systems. Surveys of Iowa producers to confirm actual fuel and electricity use values for swine systems is recommended for future work to better define these energy values.

As this work focused solely on finishing systems located in Iowa, further work to analyze energy usage in other swine producing areas would allow a fuller picture of the nation's energy usage for swine production as well as the effects of different management systems and climactic conditions of different regions on energy consumption.

Systems analysis allows for identification of opportunities for energy savings within the systems as well as objective comparison of energy usage between systems. Systems analysis of all facets of food production is work that will aid the world in making decisions to meet the needs of a growing population from a diminishing fossil fuel energy supply.

4.4 Conclusions

Future scarcity of non-solar energy sources will require a hard look at how we use energy. Development of swine production systems that minimize energy use will be essential to ensuring pork remains a viable source of food for society. Traditionally, pigs were kept as part of a diverse farming operation to utilize grain along with scraps and wastes of other farm products not suitable for human consumption to produce an energy-dense meat. Advances in pig production systems, genetics, and ration formulation have greatly improved pig performance. Crop yields of corn and soybeans have also increased dramatically from the times of traditional pig production systems. These advances have also required significant amounts of non-solar energy through the use of fossil fuels to heat and ventilate hog confinement buildings and to produce synthetic fertilizers and pesticides for corn and soybean production. Alternatives to the current systems are needed to reduce reliance on fossil-fuels in swine production systems. Deep bedded hoop systems provide a viable alternative to reduce the energy use in pork finishing systems while eliminating the energy required to heat and ventilate the pig's living space. Low external input cropping systems can reduce the overall energy required to produce feedstuffs for the pigs. Even further improvement of energy use in these alternative systems and development of novel energy efficient production systems will likely be required in a future where fossil fuels are increasingly scarce.

4.5 References

Heber, A.J., J.Q. Ni, T.T. Lim, C.A. Diehl, A.L. Sutton, R.K. Duggirala, B.L. Haymore, D.T. Kelly, V.I. Adamchuk. 2000. Effect of a Manure Additive on Ammonia Emission from Swine Finishing Buildings. Transactions of the ASAE, Vol 43(6):1895-1902.

Lammers, P.J. 2009. Energy and nutrient cycling in pig production systems. Ph.D. thesis. Iowa State University.

Liebman, M., L.R. Gibson, D.N. Sundberg, A.H. Heggenstaller, P.R. Westerman, C.A. Chase, R.G. Hartzler, F.D. Menalled, A.S. Davis, P.M. Dixon. 2008. Agronomic and Economic Performance Characteristics of Conventional and Low-External-Input Cropping Systems in the Central Corn Belt. Agronomy Journal 100: 600-610.

Miller, E.R., D.D. Jones, D.M. Huber, A.L. Sutton. 1986. Technique and Equipment for Nitrification Inhibitor Addition to Liquid Swine Manure. Applied Engineering in Agriculture Vol. 2: 186-189, 192.

PM 1994. Sullivan, Z., M.S. Honeyman, L.R. Gibson, J. McGuire, M. Nelson. 2005. Feeding Small Grain to Swine. Iowa State University Extension.

Powers, W. J., S. B. Zamzow, and B. J. Kerr. 2007. Reduced crude protein effects on aerial emissions from swine. Appl. Engng in Agric. 23(4): 539-546.

Powers, W.J., A.C. Fogiel. 2009. Impact of Amendments on Air Emissions from Stored Animal Manures. ASABE Meeting Paper No. 096123.

APPENDIX A. SWINE ENERGY USE MODEL CALCULATIONS

Included in this appendix are the equations and data used to calculate average energy use per finished pig for the hoop and confinement swine finishing systems.

Inherent Energies

High Heating Value						
Diesel Fuel	54.16	MJ/kg	45.71	MJ/liter	0.844	kg/liter
Gasoline	58.51	MJ/kg	43.34	MJ/liter	0.741	kg/liter
Oil	52.60	MJ/kg	46.29	MJ/liter	0.880	kg/liter
LP Gas	50.64	MJ/kg	26.44	MJ/liter	0.522	kg/liter
Electricity	8.99	MJ/kWh				
Corn	1.61	MJ/kg				
Soybean Meal	4.60	MJ/kg				
Supplement	10.49	MJ/kg				
Nitrogen Fertilizer	56.86	MJ/kg				
Phosphorous Fertilizer	6.96	MJ/kg				
Potassium Fertilizer	9.28	MJ/kg				
Lime Fertilizer	1.29	MJ/kg				

Pig Data

	Hoop		Confinement	
Entry Weight	35	lbs	35	lbs
	15.9	kg	15.9	kg
Exit Weight	265	lbs	265	lbs
	120.4	kg	120.4	kg
Weight Change	230.0	lbs	230.0	lbs
	104.5	kg	104.5	kg
Average Daily Gain[1]	1.80	lbs/day	1.77	lbs/day
	0.82	kg/day	0.80	kg/day
Days in System	128	Days	130	days

1 - Honeyman and Harmon, 2003

Summary of Energy Use

Feed Energy Use

	Hoop		Confinement	
Energy of Feed Inputs				
Corn	237.0	kg per pig	229.2	kg per pig
	381.5	MJ per pig	369.0	MJ per pig
Soybean Meal	72.2	kg per pig	69.9	kg per pig
	332.2	MJ per pig	321.3	MJ per pig
Supplement	8.6	kg per pig	8.3	kg per pig
	90.5	MJ per pig	87.6	MJ per pig
Total	317.8	Kg per pig	307.4	Kg per pig
	804.3	***MJ per pig***	***777.8***	***MJ per pig***
Energy for Processing, Mixing, and Hauling with On-Farm Feed Mill				
	2.389	kWh/pig	2.311	kWh/pig
	0.647	L diesel/pig	0.625	L diesel/pig
	0.002	L oil/pig	0.002	L oil/pig
	51.1	**MJ/pig**	**49.5**	**MJ/pig**
Credit for transport of Corn from Corn Energy Value				
Energy Credit	-73.2	MJ/pig	-70.8	MJ/pig
Net Energy with On-Farm Feed Mill	**-22.1**	**MJ/pig**	**-21.4**	**MJ/pig**
Energy for Processing, Mixing, and Hauling with Off-Farm Feed Mill				
	1.537	kWh/pig	1.487	kWh/pig
	0.868	L diesel/pig	0.839	L diesel/pig
	0.003	L oil/pig	0.003	L oil/pig
	53.6	**MJ/pig**	**51.9**	**MJ/pig**
Total Energy from feed per pig				
On-Farm Feed Mill	***782.2***	***MJ per pig***	***756.4***	***MJ per pig***
Off-Farm Feed Mill	***857.9***	***MJ per pig***	***829.7***	***MJ per pig***

Summary of Energy Use (continued)

Facility Energy Use

		Hoop		Confinement	
Electricity					
	Ventilation Fans	0.00	kWh per pig	5.80	kWh per pig
	Lighting	0.30	kWh per pig	0.05	kWh per pig
	Well Pump	0.31	kWh per pig	0.65	kWh per pig
	Power Washing	0.00	kWh per pig	2.57	kWh per pig
	Feed Delivery Auger	0.04	kWh per pig	0.19	kWh per pig
	Site Electricity Use	0.65	kWh per pig	9.27	kWh per pig
	Electrical Energy Use	**5.8**	**MJ per pig**	**83.3**	**MJ per pig**
LP Gas					
	Heaters	0	L LP per pig	3.57	L LP per pig
		0.0	**MJ per pig**	**94.3**	**MJ per pig**
Facility Construction inherent energy		**14.5**	**MJ per pig**	**30.6**	**MJ per pig**
	Total Facility Energy Use	***20.4***	***MJ per pig***	***208.3***	***MJ per pig***

Bedding Energy Use

	Hoop		Confinement	
Bedding Baling, Transport, and Deposition	1.07	L Diesel/pig	0.0	L Diesel/pig
	0.02	L Oil/pig	0.0	Liters Oil
Bedding Energy Use	***49.5***	***MJ per pig***	***0.0***	***MJ per pig***

Manure Application Energy Use

	Hoop		Confinement	
Liquid Manure Application	0.0	L Diesel/pig	1.5	L Diesel/pig
	0.0	L Oil/pig	0.0	L Oil/pig
Solid Manure Application	1.67	L Diesel/pig	0.0	L Diesel/pig
	0.01	L Oil/pig	0.0	L Oil/pig
Manure Application Energy Use	***77.0***	***MJ per pig***	***69.6***	***MJ per pig***

Management Input

	Hoop		Confinement	
Personnel Travel	0.07	L Gasoline/pig	0.11	L Gasoline/pig
Management Energy Use	***3.2***	***MJ per pig***	***4.9***	***MJ per pig***

Manure Energy Credit

	Hoop		Confinement	
Manure Energy Credit	***157.8***	***MJ per pig***	***233.3***	***MJ per pig***

Summary of Energy Use (continued)

Total Energy Use per Pig Produced - On Farm Feed Mill

	Hoop		Confinement	
Feed Energy Use	782.2	MJ per pig	756.4	MJ per pig
Facility Energy Use	20.4	MJ per pig	208.3	MJ per pig
Bedding Energy Use	49.5	MJ per pig	0.0	MJ per pig
Manure Application Energy Use	77.0	MJ per pig	69.6	MJ per pig
Management Input	3.2	MJ per pig	4.9	MJ per pig
Subtotal	932.2	MJ per pig	1039.3	MJ per pig
Manure Energy Credit	-157.8	MJ per pig	-233.3	MJ per pig
Total	**774.4**	**MJ per pig**	**806.0**	**MJ per pig**
Energy per kg marketed	**7.41**	**MJ/kg**	**7.71**	**MJ/kg**

Total Energy Use per Pig Produced - Off Farm Feed Mill

	Hoop		Confinement	
Feed Energy Use	857.9	MJ per pig	829.7	MJ per pig
Facility Energy Use	20.4	MJ per pig	208.3	MJ per pig
Bedding Energy Use	49.5	MJ per pig	0.0	MJ per pig
Manure Application Energy Use	77.0	MJ per pig	69.6	MJ per pig
Management Input	3.2	MJ per pig	4.9	MJ per pig
Subtotal	1008.0	MJ per pig	1112.5	MJ per pig
Manure Energy Credit	-157.8	MJ per pig	-233.3	MJ per pig
Total	**850.1**	**MJ per pig**	**879.3**	**MJ per pig**
Energy per kg marketed	**8.14**	**MJ/kg**	**8.41**	**MJ/kg**

Feed Use

Ration – Honeyman and Harmon, 2003

Ingredient,kg per 100 kg	Phase				
Stage	1	2	3	4	5
Corn	61.7	67	73.2	77.4	81.6
Soybean meal,dehulled	35	30	24	20	16
Supplement	3.3	3	2.8	2.6	2.4
Supplement Components					
Dicalcium Phosphate	1.70	1.40	1.10	0.90	0.75
Calcium Carbonate	0.80	0.80	0.90	0.90	0.90
Salt	0.42	0.41	0.40	0.40	0.35
Trace Mineral & Vitamins	0.38	0.39	0.40	0.40	0.40

Stage	1	2	3	4	5
Pig Start Weight lb	35	64	97	139	189
Pig End Weight lb	64	97	139	189	265
Pig Start Weight kg	16	29	44	63	86
Pig End Weight kg	29	44	63	86	120
Corn	61.7%	67.0%	73.2%	77.4%	81.6%
Soybean Meal	35.0%	30.0%	24.0%	20.0%	16.0%
Supplement	3.3%	3.0%	2.8%	2.6%	2.4%

Weighted Average % Corn	74.6%
Weighted Average % SBM	22.7%
Weighted Average % Suppl.	2.7%

Hoop

Feed/Gain Ratio	3.04	(includes runts/culls)(Honeyman & Harmon, 2003)		
Total Pig Weight Gain	230.0	lbs	104.5	kg
Feed Use Total	699.2	lbs	317.8	kg
Corn Use Total	521.3	lbs	237.0	kg
SBM Use Total	158.9	lbs	72.2	kg
Supplement Use Total	19.0	lbs	8.6	kg

Confinement

Feed/Gain Ratio	2.94	(includes runts/culls)(Honeyman & Harmon, 2003)		
Total Pig Weight Gain	230.0	lbs	104.5	kg
Feed Use Total	676.2	lbs	307.4	kg
Corn Use Total	504.2	lbs	229.2	kg
SBM Use Total	153.7	lbs	69.9	kg
Supplement Use Total	18.4	lbs	8.3	kg

On-Farm Feed Mill

Calculations based on Chapter 14 - Conveying of Agricultural Materials –
Engineering Principles of Ag Machines

#	Function	Equipment
1	Corn Delivery to Storage	100 ft. Grain Leg
2	SBM Delivery to Storage	30 ft. long 6" Screw Auger
3	Supplement Deliver to Storage	30 ft. long 6" Screw Auger
4	Corn Milling	5 hp Hammer Mill (www.carterday.com)
5	Ground Corn Transfer to Mixer	10 ft./30 ft.4" Horizontal/Vertical Screw Auger
6	SBM Transfer to Mixer	15 ft. long 4" Screw Auger
7	Supplement Transfer to Mixer	15 ft. long 4" Screw Auger
8	Mixing of Feed	3,000 lb. 10 hp Mixer (www.hcdavis.com)
9	Transfer of Feed to Delivery Wagon	30 ft. long 8" Screw Auger

	Energy usage per 1,000 kg of Feed		
1	Corn Delivery to Storage	0.0819	kWh
2	SBM Delivery to Storage	0.0051	kWh
3	Supplement Deliver to Storage	0.0006	kWh
4	Corn Milling	5.7528	kWh
5	Ground Corn Transfer to Mixer	0.0315	kWh
6	SBM Transfer to Mixer	0.0019	kWh
7	Supplement Transfer to Mixer	0.0002	kWh
8	Mixing of Feed	1.6283	kWh
9	Transfer of Feed to Delivery Wagon	0.0161	kWh
	Total	7.52	kWh
	Feed Hauling and Delivery	2.03	L diesel fuel
	Total Energy Use	160.9	MJ

Feed use per pig	Hoop	317.8	kg
	Confinement	307.4	kg

Total Energy Input per finished Pig			
	Hoop	2.39	kWh
		0.65	liter diesel
		1.89E-03	liter oil
	Confinement	2.31	kWh
		0.63	liter diesel
		1.83E-03	liter oil

On Farm Feed Mill (continued)

Credit for removal of transport from Farm to Local Eleavator

Assume Tractor with two 300-bushel wagons

PTO Power Required for Hauling

Wagon + Corn Weight	36600	lbs	
Slip	0.08	Assumed firm surface (D497.5)	
Bn	55	Assumed firm surface (EP496.3)	
rho (motion resistance)	0.064		D497.5 - 3.2.1.2
Draft, D = MR =	2,327	lbs	
Drawbar Power, Pdb =	49.6	hp	EP496.3 - 4.1.1.1.3
Tractive Efficiency =	0.72	Firm Surface, 2WD	
PTO Power =	68.9	hp	
Fuel Type	Diesel		
Rated Engine Horsepower	150.0	hp	
Maximum PTO Horsepower	125.0	hp	
PTO Horsepower - Transport Full	75.0	hp	
PTO Horsepower - Transport Empty	25.0	hp	
Travel Distance	5	miles	
Avg Travel Speed	8	miles per hour	
Avg Time per Trip	0.625	hours = Distance / Avg Speed	
Energy Credit	0.08	MJ per kg corn	

Credit for Transport of Corn from Local Elevator to Centralized Feed Mill

Energy used to transport corn from local elevator to ethanol plant	0.23	MJ per kg corn
	(Shapouri et al., 2004)	
Total Credit per weight of corn	*0.31*	*MJ per kg corn*

	Hoop		Confinement	
Corn used per pig	237.0	kg	229.2	kg
Total Credit	*73.25*	*MJ*	*70.84*	*MJ*

Off-Farm Feed Mill

Calculations based on Chapter 14 - Conveying of Agricultural Materials – Engineering Principles of Ag Machines

#	Function	Equipment
1	Corn Delivery to Storage	140 ft. Grain Leg
2	SBM Delivery to Storage	140 ft. Grain Leg
3	Supplement Deliver to Storage	140 ft. Grain Leg
4	Corn Milling	100 hp Hammer Mill (www.carterday.com)
5	Mixing of Feed	12,000 lb. 75 hp Mixer (www.hcdavis.com)

Energy usage per 1,000 kg of Feed

1	Corn Delivery to Storage	0.1050	kWh
2	SBM Delivery to Storage	0.0320	kWh
3	Supplement Deliver to Storage	0.0038	kWh
4	Corn Milling	3.7879	kWh
5	Mixing of Feed	0.9084	kWh
	Total	4.84	kWh
	Feed Hauling and Delivery	2.72	L diesel fuel
	Total Energy Use	168.7	MJ

Feed use per pig	Hoop	317.8	kg
	Confinement	307.4	kg

Total Energy Input per finished Pig

Hoop	1.54	kWh
	0.87	liter diesel
	2.60E-03	liter oil
Confinement	1.49	kWh
	0.84	liter diesel
	2.52E-03	liter oil

Facility Energy

Heating and Ventilation Energy Requirements

Energy Use per Pig Space from Heating and Ventilation Analysis

Weighted Average from weather station data and county pig numbers

Weighted Average - Gallons LP per pig space	2.45
Weighted Average - Fan kWh per pig space	15.08
Turns per year	2.6

Energy Use for Heating and Ventilation per Finished Pig

(=Energy Use/Turns per Year)

Heating propane per Pig	0.94	gallons LPG
	3.57	liters LPG
Ventilation Electricity	5.80	kWh

Lighting Energy Requirements

	Hoop		Confinement		
Lighting Wattages per area					
	0.8	W/sf	0.2	W/sf	MWPS-8
	8.61	W/sq m	2.15	W/sq m	
	(Assumes fluorescent for confinement and incandescent for hoop)				
Area per pig	12	sq ft	8	sq ft.	Honeyman & Harmon, 2003
	1.11	sq m	0.74	sq m	
Wattage per pig	9.6	W	1.6	W	
Usage	90	days/year	90	days/year	
	1	hour/day	1	hour/day	
	90	hours/year	90	Hours/year	
Total kWh per pig per year					
	0.864	kWh	0.144	kWh	
Average kWh per pig per day (Total kWh per year/365)					
	0.00237	kWh/day	0.00039	kWh/day	
Days per pig in building					
	127.1	days	126.0	Days	Honeyman & Harmon, 2003
Average kWh per pig	**0.30**	**kWh**	**0.05**	**kWh**	
	1,083	**kJ**	**179**	**kJ**	

Facility Energy (continued)

Water Energy Requirements

Pig Drinking Water Use per Pig

	Hoop		Confinement		
Water/Feed Intake	2.5		2.5		1998 Swine NRC
Total Feed Intake	317.8	kg	307.4		
Total Water Intake	794.5	kg	768.4	kg	
% Wastage	5.0%		5.0%		
Wasted Water	39.7	kg	38.4	kg	
Total Drinking Water	834.3	kg	806.8	kg	
	1835.4	lbs	1775.0	lbs	
	220.3	gallons	213.1	gallons	
Average Daily Use	1.19	L/day	1.19	L/day	
	0.32	gal/day	0.32	gal/day	

Pig Cooling Water

	Hoop	Confinement		
Spray Cooling Water Usage per Pig				
		0.045	gpm	MWPS-8
		2.7	gal/hour	
		22.5	lbs/hour	
		10.2	kg/hour	
Cooling Threshold Temperature		80	deg F	ISU PM1586
		26.7	deg C	
Hours above Threshold Temperature		699	hours	
Albright, Environmental Control for Animals and Plants, Appendix 6-2 for Des Moines, IA				
Water Cycle On-Time		20%	http://www.agselect.com	
Total Cooling Water Use per pig		1,429	kg	
Average Usage of Cooling Systems in Iowa		61%		ISU ASL 1388
	(Assumes drip 5% and Tunnel 11% use comprimable water amounts)			
Average Iowa Cooling Water Use per Pig		871.7	kg	

Facility Energy (continued)

Water Energy Requirements (continued)

Power Washing Water per Pig

	Hoop	Confinement	
Average Water Use Per Pig		80	kg
Average Time Per Pig		1.8	minutes
Warm Water Usage Ratio		0.85	
Assumed Temperature Water Change		40	deg F
		22.2	deg C
Assumed Heating Efficiency		0.75	
Power Washing Heat Energy - Average Use		8,436	kJ
		2.34	kWh
Power washing pumping			
Washing Pressure		1000	psi
		6894.8	kPa
Feed Pressure		50	psi
		344.7	kPa
Change in Pressure		6550.0	kPa

= Pressure (kPa) * Total Water (kg)/ (Motor Eff*Pump Eff *1000 J/kJ* Specific Gravity)

Energy Use		831.7	kJ
		0.23	kWh

Assume 0.9 motor eff, 0.7 pump eff.

Total Water Use per Pig

	Hoop		Confinement	
Drinking	834.3	Kg	806.8	kg
Cooling			871.7	kg
Power Washing			80	kg
Total	834.3	kg	1758.6	kg

Assume pumped from groundwater well, 150' deep, using 40/60 psi pressure system

Motor Efficiency	0.9	
Pump Efficiency	0.7	
Average system pressure	50	psi
	344.7	kPa
Assumed Well Depth	150	ft water
	448.3	kPa
Assumed Pipe Pressure Loss	15	ft water
	44.8	kPa
Total Pressure against Pump	837.9	kPa

= Pressure (kPa) * Total Water (kg)/ (Motor Eff*Pump Eff *1000 J/kJ* Specific Gravity)

Well Pump Energy Use				
	1109.6	**kJ**	**2338.9**	**kJ**
	0.31	**kWh**	**0.65**	**kWh**
Power Washing Energy Use			**9,268**	**kJ**
			2.57	**kWh**

Facility Energy (continued)

Feed Delivery Energy Requirements

Assume 3.5 inch flex auger system

Typical System Specs				
Motor Size	1	hp	746	Watts
Auger Length	150	feet	45.7	M
Feed Rate	50	lb/min	0.38	kg/s
Assumed motor efficiency	0.85		0.85	
Estimated Unit Feed Conveyance Energy Use			50.7	J/kg-m

	Hoop		Confinement	
Total Feed per Pig	317.8	kg	307.4	Kg
Average Length of Auger				
	9.1	m	45.0	M

Hoop: 1/2 building width + 15 feet
Confinement: 1/2 Building Width + 1/2 Building Length + 15 feet

Feed Delivery Energy Use per Pig				
	147	**kJ**	**701**	**kJ**
	0.04	**kWh**	**0.19**	**kWh**

Bedding Energy Use

Assume all corn stalk large round bales

Number of Pig Spaces	450		
Pigs Produced Per Year per Pig Space	2		
Pigs Produced Per Year	900	head	
Bedding Required Per Pig Space Per Year	400	lbs/pig space	Brumm et al., 2004
Bedding Required per pig produced	200	lbs/head	
	90.9	kg/head	
Total Bedding Per Year	90	tons	
Corn Stalk Yield Per Acre	2	tons per acre	
Required Field Area	45	acres	
Bale Size	700	lbs	
Number of Bales Required	258	bales	

Chopper/Gathering Rake

PTO power required	20.0	hp	
Avg. Field Speed	6	mph	
Field Efficiency	75%		from ASAE D497.5
Total Tractor and Implement Weight	8500	lbs	
Draft	552	lbs	10% slip, firm soils
Drawbar Power Req'd	8.8	hp	= Draft * speed / 375
Electric, Hydraulic, Misc PTO power	5	hp	
Total equivalent PTO Power Required	37.8	hp	ASAE EP496, Section 4.2
Effective implement width	10	ft	4 rows of corn stalks
Field Capacity	5.5	acre/hour	ASAE EP496, Section 5.2
Required Hours - Chopper/Rake	8.3	hours	
Max Tractor PTO Power	75.0	hp	
Rated Engine Power	90.0	Hp	

Large Round Baler PTO Power Requirements

No Load PTO power	3.4	Hp	ASAE D497.5, EP496
PTO power per material feed rate	2.2	Hp-h/ton	Fixed chamber baler
Baler Capacity	15	ton/hour	
PTO power required	36.4	Hp	
Avg. Field Speed	4	mph	
Field Efficiency	65%		ASAE D497.5
Total Tractor and Baler Weight	9350	Lbs	
Draft	607	Lbs	10% slip, firm soils
Drawbar Power Req'd	6.5	Hp	= Draft * speed / 375
Electric, Hydraulic, Misc PTO power	5	Hp	
Total equivalent PTO Power Required	50.8	Hp	ASAE EP496, Section 4.2
Effective baler width	10	Ft	4 rows of corn stalks

Bedding Energy Use (continued)

Field Capacity	3.2	acre/hour	ASAE EP496, Section 5.2
Required Hours - Baling	14.3	hours	
Max Tractor PTO Power	75.0	Hp	
Rated Engine Power	90.0	Hp	

Transport PTO power requirements
*Assume loaded on bale wagon and by loader/tractor, transferred, and unloaded

Bale Wagon Capacity	11	bales
No. of loads required	24	
Loading Efficiency	20	bales/hour
Loading Time	12.9	hours
Unloading Efficiency	40	bales/hour
Unloading Time	6.5	hours
Avg. Transport Distance	0.5	miles
Avg. Transport Speed	8	mph
Avg. Transport Time	0.0625	hours
Total Transport Time Full	1.5	hours
Total Transport Time Empty	1.5	hours
Loading/Unloading Max Tractor PTO Power	65	Hp
Loading/Unloading Rated Engine Power	80	Hp
Transport Max Tractor PTO Power	65	Hp
Transport Rated Engine Power	80	Hp

Deposition in hoop

Rate of work	10	bales per hour
Time Required	25.8	hours

*Assume same horsepowers as loading/unloading tractor

	Diesel (liter)	Oil (liter)	Energy (MJ)
	per 1000 kg of corn stalks		
Chopping/Raking	1.42	0.01	65
Baling	2.84	0.10	135
Loading/Unloading	2.87	0.02	132
Transport	0.78	0.01	36
Deposition in Hoop	3.83	0.03	176
Total	11.74	0.17	544

Solid Manure Application Energy Use

Deep Bedded System - Fresh Manure

Nitrogen (N)	15.4	lb/ Ton	7.7	g/kg
Phosphate (P205)	15.8	lb/ Ton	7.9	g/kg
Potash (K2O)	18.3	lb/ Ton	9.1	g/kg
% Solids	700.0	lb/ Ton	35.0%	
Reference	Lammers et al., 2007. Niche Pork Production			

Deep Bedded System - Composted Manure

Nitrogen (N)	19.6	lb/ Ton	9.8	g/kg
Phosphate (P205)	27.3	lb/ Ton	13.6	g/kg
Potash (K2O)	24.3	lb/ Ton	12.2	g/kg
% Solids	1020.0	lb/ Ton	51.0%	
Reference	Lammers et al., 2007. Niche Pork Production			

Assume typical site with three buildings, 150 pigs per building

No of Buildings	3	
No. of pigs per building	150	
Turns per year	2	
Total finished pigs per year	900	pigs
	(no. bldgs x no. pigs per bldg x turns per year)	
Manure Solids + Bedding production (average from ASL-1499)		
Total Wean to Finish	800	lbs per finished pig (35 lbs to 265 lbs)
	363.5	kg
Total Manure Production per Site	360	tons per site per year
Mass Loss from Composting	40%	Tiquia et al., 2002
Total Composted Manure per Site	216	tons per site per year = Total Manure * (1-Mass Loss,%)
Total Manure Nutrients (based on average values)		
Nitrogen (N)	7,056	lbs
Phosphate (P205)	9,810	lbs
Potash (K2O)	8,756	lbs

Solid Manure Application Energy Use (continued)

***Assume corn-soybean rotation

Iowa Average Yield

Corn	152.4	bu/acre	5 year average 2003-2008
Soybeans	50.0	bu/acre	www.nass.usda.gov

Crop uptake (based on PM1688 for P & K and assuming optimum soil levels)

Corn	N*	1.20	lb/bushel	x yield =	132.9	lb/acre
	P2O5	0.37	lb/bushel	x yield =	55.9	lb/acre
	K2O	0.30	lb/bushel	x yield =	45.7	lb/acre
	*(Includes one lb per bushel credit from soybeans up to 50 lbs)					
Soybeans	N	0.00	lb/bushel	x yield =	0.0	lb/acre
	P2O5	0.80	lb/bushel	x yield =	40.0	lb/acre
	K2O	1.50	lb/bushel	x yield =	75.0	lb/acre

Combined Two-Year Nutrient requirements per acre

N	132.9	lb/acre
P2O5	95.9	lb/acre
K2O	120.7	lb/acre

Required land area for application of nutrients
(Total nutrient in manure / nutrient per acre requirement)
***Assumed manure applied to bean stubble every other year.

N	53	acres
P	102	acres
K	73	acres

Apply based on controlling nutrient: P 102 acres

Application Rate (Total Weight Manure / Number of Required Acres)

2.1 tons per acre

Solid Manure Application Energy Use (continued)

Assume loadout of manure by tractor loader to comost pile, no compost turning, loadout of compost to solids spreader and application by Tractor and Spreader

Cleanout and Compost Pile Formation		
Fuel Type	Diesel	
Rated Engine Horsepower	100.0	hp
Maximum PTO Horsepower	80.0	hp
PTO Horsepower - Required	40.0	hp
Cleanout efficiency	0.06	hours per pig (ASL R1685)
Cleanout time	54	hours = Total Pigs Finished x Cleanout Efficiency
Loadout		
Assume same tractor loader as cleanout		
PTO Horsepower - Required	40.0	hp
Loadout efficiency	20	tons/hour
Loadout time	10.8	hours = Total Composted Manure / Loadout Efficiency
Transfer and Application		
Spreader Size	6.50	tons
Number of Loads	34	
Application Area	3.1	acres per load = Application Rate / Spreader Size
Fuel Type	Diesel	
Rated Engine Horsepower	100.0	hp
Maximum PTO Horsepower	90.0	hp
PTO Horsepower - Transport Full	50.0	hp
PTO Horsepower - Application	75.0	hp (Kuhn Knight)
PTO Horsepower - Transport Empty	30.0	hp
PTO Power Required for Hauling		
Full Manure Spreader Weight	23,000	lbs
Slip	0.08	Assumed firm surface (D497.5)
Bn	55	Assumed firm surface (EP496.3)
rho (motion resistance)	0.064	D497.5 - 3.2.1.2
Draft, D = MR =	1,462	lbs
Drawbar Power, Pdb =	31.2	hp EP496.3 - 4.1.1.1.3
Tractive Efficiency =	0.72	2WD, firm surface, EP496.3
PTO Power =	43.3	hp
Travel Distance	0.5	miles
Avg Travel Speed	8	miles per hour
Avg Time per Trip	0.063	hours = Distance / Avg Speed
Total One-way Travel Time	2.1	hours = Number of Loads * Avg Time Per Trip
Applicion Width	15	ft
Applicator Field Speed	4	miles per hour
Application Field Efficiency	70%	
Application Time	0.60	hours = Application Area / [Applicator Width * Field Speed * Field Efficiency / 8.25]
Total Application Time	20.6	hours = Application Time * Number of Loads

Solid Manure Application Energy Use (continued)

Diesel Fuel Use per Pig

Cleanout and Compost Pile Formation	0.90	L
Loadout	0.18	L
Transport Full	0.04	L
Application	0.52	L
Transport Empty	0.03	L
Total	1.67	L
Energy per Pig	77.0	MJ

Liquid Manure Application Energy Use

Manure Nutrient Densities - Swine Finisher - Deep Concrete Pit

Nitrogen (N)	58.1	lb/ 1000 gal
Phosphate (P205)	48.4	lb/ 1000 gal
Potash (K2O)	29.2	lb/ 1000 gal
% Solids	6.8%	
Reference	Lorimor, 98	

Assume typical site with three buildings, 1000 pigs per building

No of Buildings	3	
No. of pigs per building	1000	
Turns per year	2.6	
Total finished pigs per year	7800	pigs
		(no. bldgs x no. pigs per bldg x turns per year)

Manure Solids production (from ASABE D384.2)

Total Grow to Finish	120	lbs per finished pig (35 lbs to 265 lbs)
Total Manure Solids Production	936,000	lbs solids per site per year
Total Manure Production	13,764,706	lbs per site per year (lbs solids / avg % solids)
	1,652,426	gallons per site per year (lbs manure / 8.33)
	1,765	lbs per finished pig
	212	gallons per finished pig

Total Manure Nutrients (based on average values)

Nitrogen (N)	96,006	lbs
Phosphate (P205)	79,977	lbs
Potash (K2O)	48,251	lbs

***Assume corn-soybean rotation

Iowa Average Yield

Corn	152.4	bu/acre	5 year average 2003-2008
Soybeans	50.0	bu/acre	www.nass.usda.gov

Crop uptake (based on PM1688 for P & K and assuming optimum soil levels)

Corn	N*	1.20	lb/bushel	x yield =	132.9	lb/acre
	P2O5	0.37	lb/bushel	x yield =	55.9	lb/acre
	K2O	0.30	lb/bushel	x yield =	45.7	lb/acre
	*-(Includes one lb per bushel credit from soybeans up to 50 lbs)					
Soybeans	N	0.00	lb/bushel	x yield =	0.0	lb/acre
	P2O5	0.80	lb/bushel	x yield =	40.0	lb/acre
	K2O	1.50	lb/bushel	x yield =	75.0	lb/acre

Combined Two-Year Nutrient requirements per acre

N	132.9	lb/acre
P2O5	95.9	lb/acre
K2O	120.7	lb/acre

Liquid Manure Application Energy Use (continued)

Required land area for application of nutrients
(Total nutrient in manure / nutrient per acre requirement)
***Assumed manure applied to bean stubble every other year.

N	723	acres	289	hectares
P	834	acres	334	hectares
K	400	acres	160	hectares

Apply based on controlling nutrient: P 834 acres 334 hectares

Application Rate (Total volume manure / number of required acres)
1,981 gallons per acre

Assume application of manure by Tractor and Tanker

Agitation/Pumping

Fuel Type	Diesel	
Rated Engine Horsepower	150.0	hp
Maximum PTO Horsepower	120.0	hp
PTO Horsepower - Agitation	100.0	hp
PTO Horsepower - Pumping	110.0	hp
Agitation Time	5	hours
Pump Out Rate	2,000	gallons per minute
Time per Load	5	minutes = Tanker Size / Pump Out Rate
Pumping Efficiency:	80%	
Total Pumping Time:	17.29	hours = Time per Load * Number of Loads / (60 * Pumping Efficiency)

Transfer and Application

Tanker Size	10,000	gallons	
Number of Loads	166		
Application Area	5.0	acres per load	
Tractor Info			
PTO Power Required for Hauling Full			
Full Manure Tanker Weight	103,300	lbs	
Slip	0.08	Assumed firm surface (D497.5)	
Bn	55	Assumed firm surface (EP496.3)	
rho (motion resistance)	0.064		D497.5 - 3.2.1.2
Draft, D = MR =	6,567	lbs	
Drawbar Power, Pdb =	175.1	hp	EP496.3 - 4.1.1.1.3
Tractive Efficiency =	0.77	4WD, firm surface, EP496.3	
PTO Power =	227.4	hp	

Liquid Manure Application Energy Use (continued)

Transfer and Application (continued)

PTO Power Required for Hauling Empty

Empty Manure Tanker Weight	20,000	lbs
Slip	0.08	Assumed firm surface (D497.5)
Bn	55	Assumed firm surface (EP496.3)
rho (motion resistance)	0.064	
Draft, D = MR =	1,272	lbs
S =	20	mph
Drawbar Power, Pdb =	67.8	hp
Tractive Efficiency =	0.77	4WD, firm surface, EP496.3
PTO Power =	88.1	hp
Fuel Type	Diesel	
Rated Engine Horsepower	300.0	hp
Maximum PTO Horsepower	250.0	hp
PTO Horsepower - Transport Full	230.0	hp
PTO Horsepower - Application	170.0	hp
PTO Horsepower - Transport Empty	100.0	hp
Travel Distance	2	miles
Avg Travel Speed	10	miles per hour
Avg Time per Trip	0.200	hours = Distance / Avg Speed
Total One-way Travel Time	33.2	hours = Number of Loads * Avg Time Per Trip

PTO Power Required for Field Application

Average Manure Tanker Weight	61,650	lbs
Slip	0.1	Assumed firm surface (D497.5)
Bn	55	Assumed firm surface (EP496.3)
rho (motion resistance)	0.065	
S =	10	mile/hr
Rsc =	7,232	lbs
Draft, D = MR + Rsc =	11,235	lbs
Drawbar Power, Pdb =	119.8	hp
Tractive Efficiency =	0.77	4WD, firm surface, EP496.3
PTO pump =	12.6	hp
Total PTO Power =	168.3	hp

Injector Draft (ASAE D497.5)

A =	129	Assumed narrow point injector
B =	0	
C =	2.7	
F1 =	1	Assumed fine textured soils
W =	6	no. of tools (30 inch spacing for 15 ft toolbar)
T =	7	in. (assumed)
S =	4	mile/hr
D = Rsc =	7,232	lbs

Liquid Manure Application Energy Use (continued)

PTO requirement for agitation/application pump

Flow Rate = 500 gpm

Pressure = 50 ft TDH

Pump Efficiency = 50%

PTO Power = 12.6 hp

Applicator Width 15 ft

Applicator Field Speed 4 miles per hour

Application Field Efficiency 80%

Application Time 0.87 hours = Application Area / [Applicator Width * Field Speed * Field Efficiency / 8.25]

Total Application Time 144.0 hours = Application Time * Number of Loads

Diesel Fuel Use per 1,000 L of Manure

Agitation	0.024	L
Pump Out	0.015	L
Transport Full	0.374	L
Application	1.252	L
Transport Empty	0.226	L
Total	1.891	L
Manure Production per Pig	800	L
Energy per Pig	69.6	MJ

Management Energy Use

Travel of Workers to Site

Fuel Efficiency	15.0	miles per gallon
	6.4	km per liter

One-way travel distance to Site			
	miles	0.5	5.0
	km	0.8	8.0
Fuel Usage - Round Trip			
	gallons	0.07	0.67
	liters	0.25	2.52

Number of Pigs Checked per Trip

Hoop	450
Confinement	3000

Number of Trips per group of pigs - assumed to be one trip per day + 5 trips

Hoop	133
Confinement	135

Fuel Usage - Per Pig Produced

Hoop	gallons	0.020	
	liters	0.075	
Confinement	gallons		0.030
	liters		0.114

Appendix A References

Agricultural Waste Management Field Handbook. 1992. U.S. Department of Agriculture, National Resource Conservation Service.

ASAE D384.2 March 2005. Manure Production and Characteristics. St. Joseph, Michigan; ASABE.

ASAE EP496.3. February 2006. Agricultural Machinery Management. St. Joseph, Michigan; ASABE.

Brumm, M.C., J.D. Harmon, M.S. Honeyman, J.B. Kliebenstein, S.M. Lonergan, R. Morrison, and T. Richard. Hoop barns for grow-finish swine. Ames, Iowa. Midwest Plan Service.

Bureau Transportation Services. 2007. http://www.bts.gov/publications/national_transportation_statistics/html/table_04_14.html. Accessed September 9, 2009.

Duffy, M.D., and M.S. Honeyman. 1998. Labor requirements for market swine produced in hoop structures. ASL R1685. Iowa State University Extension.

Edstrom. Cooling Systems for Swine. http://www.agselect.com/agselect/pdf/SwineCooling_SB6068midres.pdf. Accessed October 19, 2009.

Hammond, G., and C. Jones. 2008. Inventory of carbon and energy. Version 1.6a. Department of Mechanical Engineering, University of Bath, Bath, UK. Available at: www.bath.ac.uk/mech‐eng/sert/embodied/. Accessed October 21, 2009.

Harmon, J.D. 1996. Swine Facility Costs in Iowa. ASL 1388. Iowa State University Extension.

Hill J, E Nelson, D Tilman, S Polasky, D Tiffany. 2006. Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. PNAS Vol. 103 No. 30, 11206–11210.

Holden, P., R. Ewan, M. Jurgens, T. Stahly, D. Zimmerman. 1996. Life Cycle Swine Nutrition. Iowa State University. http://www.ipic.iastate.edu/LCSN/LCSNutrition.pdf. Accessed October 19, 2009.

Honeyman, M.S. and J.D. Harmon. 2003. Performance of finishing pigs in hoop structures and confinement during winter and summer. Journal of Animal Science. 81:1663-1670.

IEA. 2005. Energy Statistics Manual. International Energy Agency. http://www.iea.org/textbase/nppdf/free/2005/statistics_manual.pdf.

Lammers, P. J., M. S. Honeyman, J.D. Harmon, J.B. Kliebenstein, M.J. Helmers. 2009. Construction Resource Use of Two Different Types and Scales of Iowa Swine Production Facilities. Applied Engineering in Agriculture. Vol. 25(4):585-593.

Lammers, P.J., D.R. Stender, M.S. Honeyman. 2007. Niche Pork Production. Iowa State University.

Lorimor, J., K. Kohl. 1998. Liquid Swine Manure Nutrients. ASL-R-1596. Iowa State University Extension.

MWPS-8. 1983. Swine Housing and Equipment Handbook, Fourth edition. Ames, Iowa. Midwest Plan Service.

Nutrient Requirements of Swine, 10th Revised edition. 1998. National Research Council. National Academy Press; Washington, D.C.

PM 1688. A General Guide for Crop Nutrient and Lime Recommendations for Iowa. November, 2002. Iowa State University Extension.

Richard, T., J. Harmon, M. Honeyman, J. Creswell. 1998. Hoop Structure Bedding Use, Labor, Bedding Pack Temperature, Manure Nutrient Content, and Nitrogen Leaching Potential. ASL R1499. Iowa State University Extension.

Shapouri H., J. A. Duffield, M. Wang. 2003. The Energy Balance of Corn Ethanol Revisited. Transactions of the ASAE, Vol. 46(4): 959–968.

Shapouri H., J. A. Duffield, A. McAloon, M. Wang. 2004. The 2001 Net Energy Balance of Corn Ethanol. http://www.usda.gov/oce/reports/energy/index.htm. Accessed October 27, 2009.

Srivastava, A.K., C.E. Goering, R.P. Rohrbach, D.R. Buckmaster. 2006. Conveying of agricultural materials. Chapter 14 in Engineering Principles of Agricultural Machines, 2nd ed., 491-524. St. Joseph, Michigan; ASABE.

Tiquia, S.M., T.L. Richard, M.S. Honeyman. 2002. Carbon, nutrient, and mass loss during composting. Nutrient Cycling in Agroecosystems, 62: 15-24.

USDA-NASS. Crop Yield Data, 5 year average 2003-2008. www.nass.usda.gov. Accessed October 15, 2009.

APPENDIX B. SWINE CONFINEMENT BUILDING HEATING AND VENTILATION ENERGY USE CALCULATIONS

Included in this appendix are the equations and data sources used to calculate average heating and ventilation energy use for the swine confinement finishing building. The following is information on the assumed swine production information, building construction, and location.

Swine Finisher Assumed Conditions

No of pigs	1,000	hd			
Beginning Weight	35	lbs	15.91	kg	
End Weight	265	lbs	120.45	kg	
Average daily growth	1.77	lbs/day	0.80	kg/day	(Honeyman, 2003)
Avg Time to grow out	130	days			
Average Mortality	2.0%				
Finishing cycles per year	2.6				
Cycle Length	140	days			
Average rest period	3	days			
Entrance date	Solved for 1 through 365 [julian day]				

	Cycle Date	No Pigs
Entrance	1	1000
Mortality Loss	65	980
1st Loadout	123	653
2nd Loadout	130	326
3rd Loadout	137	0

Building Construction R-Values

	R-value (sq m - deg C / W)
Endwall Construction	
Sidewall Curtain, 5'-0" High	0.11
8" Concrete Wall, 3'-0" High	0.04
Interior Air Film	0.11
Total	0.29
Sidewall Construction	
Sidewall Curtain, 5'-0" High	0.11
8" Concrete Wall, 3'-0" High	0.04
Interior Air Film	0.11
Total	0.29
Ceiling Construction	
Interior Air Film	0.11
Insulation-8.5" Blown-in	4.68
Insulation-3.5" Blown-in	1.54
Wood 2x4 Framing	0.15
Steel Liner	0.00
Interior Air Film	0.11
Total	6.59
Slatted Floor Construction	
Interior Air Film	0.11
Concrete	0.08
Interior Air Film	0.11
Total	0.30
Roof and Endwall Peak Construction	
Ribbed Metal Roofing	0.00
Interior Air Film	0.11
Total	0.14

Note: Exterior air film accounted for in sol-air temperature calculation.

Building Dimensions

Building Width	40	ft	12.19	m
Building Length	225	ft	68.58	m
Wall Height	8	ft	2.44	m
Pit Depth	10	ft	3.05	m
Roof Slope	4	/12	18.43	degrees
Ridge Direction from N-S	0 and 90 degrees			
Roof Peak Height above wall	6.67	ft	2.03	m

Building Construction Areas & U-Values

(U-Value = 1 / R-Value)

End Wall Construction

Wall Area	29.73	sq m
Average U-value	3.85	W/sq m - deg C

End Wall Peak Construction

Peak Area	12.39	sq m
Average U-value	9.31	W/sq m - deg C

Side Wall Construction

Wall Area	167.23	sq m
Average U-value	3.85	W/sq m - deg C

Ceiling

Ceiling Area	836.13	sq m
Average U-value	0.15	W/sq m - deg C

Roof

Roof area (one side)	440.68	sq m
Average U-value	9.31	W/sq m - deg C

Slatted Floor

Floor Area	836.13	sq m
Average U value	3.34	W/sq m - deg C

Room Volume	2038.81	cu m
Attic Volume	849.51	cu m

Building Surface Angles and Radiation Characteristics

	Surface Tilt, Σ	Surface Azimuth, ψ		Surface Absorptivity, α	Surface Emissivity, ε
		N-S*	E-W*		
Sidewall 1	90°	-90°	0°	0.3	0.9
Sidewall 2	90°	90°	180°	0.3	0.9
Endwall 1	90°	0°	90°	0.3	0.9
Endwall 2	90°	180°	270°	0.3	0.9
Roof 1	18.43°	-90°	0°	0.3	0.9
Roof 2	18.43°	90°	180°	0.3	0.9

** Building ridge orientation.*

Weather Data

The weather data used for the model was typical meteorological year (TMY3) data from NREL. Weather data for each hour in the year is provided in sequential order based on weather data for each month from a specific year that reflects the statistical average of weather from the period of 1976 to 2005. Weather data for the dry bulb temperature, relative humidity, atmospheric pressure, solar radiation, and sky cover were used. The field number in the TMY3 dataset and the variables used in the following equations for this data is as follows.

Date, d: TMY3 Field 1 [MM/DD/YYYY] – Converted to julian day [1 to 365]

Time, t: TMY3 Field 2 [HH:MM] – Converted to hour of day [0 to 23]

Direct Normal Irradiance E_{DN}: TMY3 Field 8 [Watt-hour per square meter]

> *TMY3 Definition:* The a*mount of solar radiation (modeled) received in a collimated beam on a surface normal to the sun during the 60-minute period ending at the timestamp.*

Total Sky Cover, Ω: TMY3 Field 26 [Tenths of sky cover, 0 to 10]

> *TMY3 Definition: Amount of sky dome covered by clouds or obscuring phenomena at the time indicated.*

Dry Bulb Temperature, T_{db}: TMY3 Field 32 [degrees C]

Relative Humidity, RH: TMY3 Field 38 [%]

Atmospheric Pressure, P_{atm}: TMY3 Field 41 [Millibar] – Converted to Pascals

Solar Incident Angles

The following equations and variables were used in determination of the incident angle of solar radiation as part of the solution for the sol air temperature at each building surface at each time step.

Day of year, d: Julian day of year, 1 to 365

Hour of day, t: Hour of day from 0 (midnight) to 23 for local standard time

Longitude, LON: Angle from Prime Meridian [degrees]

Latitude, LAT: Angle from Equator [degrees]

Solar Declination, δ: Angle of sun relative to plane of equator [degrees]

$$\delta = \frac{360}{2\,\pi}\left\{0.0069180 - 0.399912 \times COS\left[\frac{2\pi(d-1)}{365}\right]\right\} + 0.070257 \times SIN\left[\frac{2\pi(d-1)}{365}\right]$$
$$- 0.006758 \times COS\left[2 \times \frac{2\pi(d-1)}{365}\right] + 0.000907 \times SIN\left[2 \times \frac{2\pi(d-1)}{365}\right]$$
$$- 0.002697 \times COS\left[3 \times \frac{2\pi(d-1)}{365}\right] + 0.00148 \times SIN\left[3 \times \frac{2\pi(d-1)}{365}\right]$$

(http://en.wikipedia.org/wiki/Declination)

Equation of Time, ET: Difference between Apparent Solar Time and Mean Solar Time [minutes]

$$ET = 9.87 \times SIN\left[2 \times \frac{2\pi(d-81)}{364}\right] - 7.53 \times COS\left[\frac{2\pi(d-81)}{364}\right] - 1.5 \times SIN\left[\frac{2\pi(d-81)}{364}\right]$$

(http://en.wikipedia.org/wiki/Equation_of_time)

Local Standard Time Meridian, LSM: Angle from Prime Meridian for location's time zone [degrees]

LSM = 90 degrees, Central Time Zone (UTC-6)

Solar Incident Angles (continued)

Apparent Solar Time, AST: Hour angle of the sun for the location [hours]

$$AST = t + \frac{ET}{60} + \frac{(LSM - LON)}{15}$$

(2005 ASHRAE, Chapter 30, Table 14)

Hour Angle, H: Hour angle of the sun location [degrees].

$$H = 15 \times (AST - 12)$$

(2005 ASHRAE, Chapter 30, Table 14)

Solar Altitude, β: Angle of sun above or below the horizon [degrees]

$$\beta = SIN^{-1}\left[COS(LAT) \times COS(\delta) \times COS(H) + SIN(LAT) \times SIN(\delta)\right]$$

(2005 ASHRAE, Chapter 30, Table 14)

Solar Azimuth, Φ: Angle of sun from South on ground surface plane [degrees]

$$\phi = COS^{-1}\left[\frac{SIN(\beta) \times SIN(LAT) - SIN(\delta)}{COS(\beta) \times COS(LAT)}\right]$$

(2005 ASHRAE, Chapter 30, Table 14)

Surface Tilt, Σ: Angle of building surface from horizontal [degrees] (See table for values used for each building surface.)

Surface Azimuth, Ψ: Angle of building surface from South; South = 0 degrees, West = 90 degrees, East = -90 degrees [degrees] (See table for values used for each building surface for the North-South and East-West building ridge orientation cases)

Solar Incident Angles (continued)

Incident Angle, Θ: Incident angle of solar radiation with each building surface.

Calculated for each building surface at each time step [degrees]

$$\Theta = COS^{-1}\left[COS(\beta)\times COS(\phi-\psi)\times SIN(\Sigma)+SIN(\beta)\times COS(\Sigma)\right]$$

(2005 ASHRAE, Chapter 30, Table 14)

Sol-Air Temperatures

The incident angle of solar radiation for each building surface in combination with the weather data from the TMY3 weather data were used to calculate the sol-air temperature at each time step. The sol-air temperature is the equivalent temperature of the outer building surface to account for solar heat gain and radiant losses to the environment. The sol-air temperature was calculated using the following equation and data.

$$T_{sa} = T_{db} + \left[\frac{\alpha \times E_{DN} \times COS(\Theta) - 6 \times \varepsilon \times (10 - \Omega)}{h_o} \right]$$

(Adapted from 2005 ASHRAE, Chapter 30, Eqation 30)

T_{sa} : Sol-Air Temperature [degrees Celcius]

T_{db} : Ambient Dry Bulb Temperature from TMY3 data [degrees Celcius]

α: Surface Absorptivity [unit less]

E_{DN}: Direct Normal Irradiance from TMY3 data [Watt-hour per square meter]

Θ: Surface Incident Angle [degrees] (For $\Theta > 90$ degrees, $E_{DN} \cdot COS(\Theta) = 0$)

ε: Surface Emissivity [unit less]

Ω: Total Sky Cover from TMY3 data [0 to 10]

h_o: Coefficient of heat transfer for long-wave radiation and convection at outer surface [Watts per square meter per degree Celcius]

NOTE: Per 2005 ASHRAE Chater 30, h_o was set equal to 17 $W/(m^2\text{-}^\circ C)$. Further refinement of the model to include effects of wind would require incorporating a valid relationship between h_o and wind speed and direction. No suitable relationships were found in previous research that would allow a straightforward approach to include the effects of wind in the model, and therefore the h_o value was set as constant per the ASHRAE Fundamentals recommended value.

Building Heat Gain/Loss

The sol-air temperatures and building characteristics were used to determine the heat gain or loss through the building surfaces using the following equations.

$$
\begin{aligned}
&Q_{Bldg}(t) = (T_{Endwall1} - T_i) \times U_{Endwall1} \times A_{Endwall1} + (T_{Endwall2} - T_i) \times U_{Endwall2} \times A_{Endwall2} \\
&(T_{Sidewall1} - T_i) \times U_{Sidewall1} \times A_{Sidewall1} + (T_{Sidewall2} - T_i) \times U_{Sidewall2} \times A_{Sidewall2} \\
&(T_{Attic} - T_i) \times U_{Ceiling} \times A_{Ceiling} + (T_{Pit} - T_i) \times U_{Floor} \times A_{Floor}
\end{aligned}
$$

$Q_{Bldg}(t)$: Building heat gain or loss through the building envelope for the hour at time step t [W-h].

U: Building heat transfer coefficient at each surface [Watt per square meter per degrees Celcius].

A: Area of building surface [square meters].

T_i: Interior air temperature of building [degrees Celcius].

$T_{Endwall1}$, $T_{Endwall2}$, $T_{Sidewall1}$, $T_{Sidewall2}$: Sol-air temperature at building surface at time step t [degrees Celcius].

T_{pit}: Temperature of manure pit air [degrees Celcius]. T_{pit} was assumed to equal the interior air temperature air as the interior air is continuously drawn through the slatted floor into the manure pit by the pit fans. The effects of heat loss through the pit foundation and the insulation factor of manure pit level as well as any potential heat generation from microbial activity in the manure were ignored.

Building Heat Gain/Loss (continued)

T_{Attic}: Attic air temperature at time step t [degrees Celcius]. Attic air temperature was calculated using a heat balance at each step per the following equations.

$$
\begin{aligned}
&T_{Attic} = \frac{X}{Y} \\
&where: \\
&X = \left(T_{Roof1} + T_{Roof2}\right) \times U_{Roof} \times A_{Roof} + \left(T_{Endwall1} + T_{Endwall2}\right) \times U_{Endpeak} \times A_{Endpeak} \\
&+ T_i \times U_{Ceiling} \times A_{Ceiling} + T_{db} \times v_{Attic} \times 1006 \\
&Y = 2 \times U_{Roof} \times A_{Roof} + 2 \times U_{Endpeak} \times A_{Endpeak} + U_{Ceiling} \times A_{Ceiling} + v_{Attic} \times 1006
\end{aligned}
$$

T_{Roof1}, T_{Roof2}: Roof sol-air temperature at time step t [degrees Celcius].

v_{Attic}: Ventilation rate of attic at time step t - 1 [kg_{air} per second]. Ventilation rate was determined as shown in the following section.

Ventilation Heat Gain/Loss and Energy Use

The ventilation rate of the building was determined at each time step based on a management assumed to be typical for Iowa confinement housing systems. The interior, exterior, and attic temperatures were then used to determine heat gain or loss from ventilation. Fan efficiencies were then used to determine electrical usage for the ventilation fans.

Ventilation management was assumed to take place in three different scenarios while pigs were present; minimum ventilation, natural ventilation, and tunnel ventilation. A fourth scenario, empty, was used when no pigs were in the building. The choice of the ventilation scenario was evaluated at each time step based on the exterior ambient dry bulb temperature and the size of pigs in the building. If the ambient air temperature was below the minimum ventilation set point, minimum ventilation was selected and ventilation rates were set to maintain the interior temperature and maintain a minimum ventilation rate. Supplemental heating loads were also determined at each time step to maintain the interior temperature.

If the exterior ambient temperature was above the tunnel ventilation set point, ventilation rates were calculated between a minimum and maximum tunnel ventilation rate to maintain the interior temperature at a specified offset above the exterior temperature. If the exterior ambient temperature fell between the minimum set point and tunnel set point, natural ventilation was assumed. The pit fans were assumed to maintain a minimum ventilation rate and the interior temperature was assumed to be equal to the exterior temperature. The following table defines set point temperatures and minimum ventilation rates for different pig weights (PM 1586, PM 1780).

Pig Weight (kg)	Minimum Ventilation Rate (cu. m per s)	Min Ventilation Set Point Temperature (deg. C)	Tunnel Ventilation Set Point Temperature (deg. C)
15.9	1.42	25.0	28.9
26.4	1.42	21.1	27.8
36.8	3.30	18.9	26.7
47.3	3.30	16.7	26.7
57.7	3.30	14.4	26.7
68.2	4.72	13.3	26.7
78.6	4.72	13.3	26.7
89.1	4.72	12.2	26.7
99.5	4.72	12.2	26.7
110.0	4.72	11.1	26.7
120.5	4.72	11.1	26.7

Ventilation Management Settings

Under the minimum ventilation scenario, pit fans were assumed to provide a minimum ventilation rate for the building to maintain air quality and suitable humidity levels. Air was assumed to be primarily brought through the ceiling through adjustable ceiling air inlets. Leakage of 15 percent of the airflow through the curtain side walls was also assumed in the ventilation heat gain/loss calculations. The assumption was made that the ceiling air inlets and pit fan operation were adjusted by the manager of the building at the different pig growth stages to adjust the minimum ventilation rate to the recommended levels. Gas fired heaters located in the building were assumed to maintain the interior temperature at the minimum ventilation set point. If during the minimum ventilation scenario, pig heat gain exceeded the losses from the building and ventilation, supplemental minimum ventilation was assumed to be provided through an end wall fan to maintain the interior temperature. Minimum ventilation rates were calculated as follows.

$v(t) = Maximum(v_{temperature}, v_{min}) < vmaxCW$

v_{min}: User set minimum building ventilation rate for the size range of pigs at each time step t [cubic meter per second].

v_{maxCW}: User set maximum building ventilation rate for cold weather minimum ventilation scenario [cubic meter per second].

$v_{temperature}$: Ventilation rate to maintain interior set point temperature at time step t [cubic meter per second]. Calculated per the following equation

$$v_{temperature} = \frac{V_i \times (Q_{Bldg} + Q_{Pig})}{1006 \times (T_{db} - T_i)}$$

V_i: Specific volume of interior air at time step t [cubic meter per kg of air]. Calculated per the following equation.

$$V_i = \frac{R_a}{P_{atm}} \times (T_i + 273.15) \times \frac{(1 + 1.0678 \times W)}{(1 + W)}$$

R_a: Gas Constant [287.055].

P_{atm}: Atmospheric pressure at time step t [Pascals]. From TMY3 data.

W: Humidity ratio [kg of water to kg of air]. Set at 0.010 for this equation.

Q_{Pig}: Sensible heat production from pigs in building [W].

Q_{Bldg}: Building heat gain or loss [W].

T_{db}: Exterior dry bulb temperature [degrees Celcius].

T_i: Interior dry bulb temperature [degrees Celcius].

During the natural ventilation scenario, sufficient ventilation from external wind and air currents were assumed to provide sufficient ventilation to maintain air quality in the building and maintain the interior temperature at suitable levels. As the interior temperature does not affect the energy usage for ventilation or heating during natural ventilation periods, the interior temperature was set equal to the exterior temperature under this scenario. The pit fans were assumed to run continuously at their maximum level during natural ventilation periods to maintain air quality and minimize escape of manure gases from the pit into the pig space.

Pig Heat Production

Sensible heat production from the pigs housed in the building was calculated based on number of pigs, average pig weight, and interior temperature. Total heat production was calculated per Pederson, 2002, using the following equation.

$$Q_{Pig-Total} = n \times \left\{5.09 \times m^{0.75} + \left[1-\left(0.47+0.003 \times m\right)\right] \times \left(v-1\right) \times 5.09 \times m^{0.75}\right\}$$
$$\times \left[1 + 0.00004 \times \left(20 - T_i\right)^3\right]$$

$Q_{Pig-Total}$: Total heat production from pigs in building [W].

n: Number of pigs in building.

m: Pig live weight [kg]

v: Level of feeding as a multiple of maintenance. Assumed constant of 3 per Pederson, 2002.

T_i: Interior air temperature of building [degrees Celcius].

To determine the sensible portion of the total heat production for use in the building heat balance the following formulas were used per Pederson, 1999.

$$Q_{Pig-Sensible} = r \times Q_{Pig-Total}$$
$$r = {}^{I_{Sensble}}\!/_{I_{Total}}$$
$$I_{Total} = 1000 + 12 \times \left(20 - T_i\right)$$
$$I_{Sensible} = I_{Total} \times 0.62 - 0.000000115 \times T_i^6$$

$Q_{Pig-Sensible}$: Sensible heat production from pigs in building [W].

r: Ratio of sensible to total heat production of pigs.

I_{Total}: Relative total heat production of pigs [W]. (Pederson, 1999)

$I_{Sensible}$: Relative sensible heat production of pigs [W]. (Pederson, 1999)

Building Heat Balance

The building heat balance was calculated at each step to maintain the interior set point. The building heat gain or loss, ventilation heat gain or loss, and pig total sensible heat production were summed at each time step. If the sum of these values was a net loss and the ventilation scenario was Minimum, the heating requirement for that hour time step was set equal to the loss to maintain the interior temperature at the set point. The total heating requirement was then calculated by taking the sum of heating requirements for each time step.

Electricity used by the heater blower was also included in the model using the following data and equations.

Heating Electrical Input

Assumed LP direct fire gas burner located in building
Heaters assumed to be 225,000 BTUh and 1,000 cfm

Heater capacity =	225,000	BTUh =	65.9	kW

Heater run time [h] = Total Heater Output [kWh] / Heater Capacity [kW]

Blower Efficiency	10	cfm/watt	0.0047	cms/watt
Blower Rate	1000	cfm	0.4719	cms

Heater Electrical Usage [kWh] = Blower rate [cms] / Blower Efficiency [cms/watt] / 1000 * Heater Run Time [h]

Final Energy Use Values

The final energy use values for heating and ventilation of the swine confinement building were calculated by performing iterations for pig entry date from 1 to 365 for each of the two ridge orientations of North-South and East-West. The total values were then averaged to provide representative energy use values for heating and ventilation. The following tables identify average values for each weather station and the counties, pig numbers, and associated weather station used in the weighted average.

Weather Station Ventilation Results

Weather Station	Hours Min. Ventil- ation	% Min. Ventil- ation	Hours Natural Ventil- ation	% Natural Ventil- ation	Hours Tunnel Ventil- ation	% Tunnel Ventil- ation	Hours Empty Ventil- ation	% Empty Ventil- ation	Heater Run Time hours
Algona	5,787	66.1%	2,348	26.8%	433	4.9%	192	2.2%	962
Atlantic	5,594	63.9%	2,435	27.8%	539	6.2%	192	2.2%	920
Boone	5,752	65.7%	2,257	25.8%	559	6.4%	192	2.2%	807
Burlington	5,007	57.2%	2,541	29.0%	1,020	11.6%	192	2.2%	795
Carroll	5,665	64.7%	2,291	26.2%	612	7.0%	192	2.2%	1,080
Cedar Rapids	5,666	64.7%	2,488	28.4%	414	4.7%	192	2.2%	1,310
Chariton	5,374	61.3%	2,422	27.6%	772	8.8%	192	2.2%	680
Charles City	5,871	67.0%	2,277	26.0%	420	4.8%	192	2.2%	925
Clarinda	5,186	59.2%	2,498	28.5%	884	10.1%	192	2.2%	811
Clinton	5,603	64.0%	2,352	26.9%	612	7.0%	192	2.2%	996
Council Bluffs	5,443	62.1%	2,563	29.3%	561	6.4%	192	2.2%	659
Creston	5,381	61.4%	2,608	29.8%	579	6.6%	192	2.2%	784
Decorah	5,430	62.0%	2,569	29.3%	570	6.5%	192	2.2%	673
Denison	5,484	62.6%	2,343	26.7%	741	8.5%	192	2.2%	922
Des Moines	5,365	61.2%	2,443	27.9%	760	8.7%	192	2.2%	983
Dubuque	5,959	68.0%	2,344	26.8%	265	3.0%	192	2.2%	1,220
Estherville	6,030	68.8%	2,167	24.7%	371	4.2%	192	2.2%	1,952
Fair Field	5,402	61.7%	2,419	27.6%	747	8.5%	192	2.2%	789
Fort Dodge	5,703	65.1%	2,312	26.4%	553	6.3%	192	2.2%	1,141
Fort Madison	5,216	59.5%	2,640	30.1%	712	8.1%	192	2.2%	404
Keokuk	5,020	57.3%	2,774	31.7%	774	8.8%	192	2.2%	623
Knoxville	5,172	59.0%	2,644	30.2%	752	8.6%	192	2.2%	740
LeMars	5,298	60.5%	2,698	30.8%	572	6.5%	192	2.2%	847
Mason City	5,924	67.6%	2,185	24.9%	459	5.2%	192	2.2%	1,631
Monticello	5,611	64.1%	2,501	28.6%	456	5.2%	192	2.2%	1,201

Weather Station Ventilation Results (continued)

Weather Station	Hours Min. Ventil-ation	% Min. Ventil-ation	Hours Natural Ventil-ation	% Natural Ventil-ation	Hours Tunnel Ventil-ation	% Tunnel Ventil-ation	Hours Empty Ventil-ation	% Empty Ventil-ation	Heater Run Time hours
Muscatine	5,304	60.5%	2,576	29.4%	688	7.9%	192	2.2%	832
Newton	5,564	63.5%	2,537	29.0%	467	5.3%	192	2.2%	859
Oelwein	5,778	66.0%	2,433	27.8%	357	4.1%	192	2.2%	755
Orange City	5,764	65.8%	2,253	25.7%	551	6.3%	192	2.2%	886
Ottumwa	5,627	64.2%	2,374	27.1%	567	6.5%	192	2.2%	1,195
Red Oak	5,326	60.8%	2,331	26.6%	911	10.4%	192	2.2%	777
Sheldon	5,922	67.6%	2,137	24.4%	509	5.8%	192	2.2%	919
Shenandoah	5,320	60.7%	2,436	27.8%	813	9.3%	192	2.2%	847
Sioux City	5,566	63.5%	2,307	26.3%	695	7.9%	192	2.2%	1,095
Spencer	6,040	69.0%	2,125	24.3%	403	4.6%	192	2.2%	1,725
Storm Lake	5,727	65.4%	2,340	26.7%	501	5.7%	192	2.2%	1,013
Washington	5,569	63.6%	2,385	27.2%	614	7.0%	192	2.2%	723
Waterloo	5,733	65.5%	2,197	25.1%	637	7.3%	192	2.2%	1,252
Webster City	5,518	63.0%	2,274	26.0%	776	8.9%	192	2.2%	783
Max	6,040	69.0%	2,774	31.7%	1,020	11.6%	192	2.2%	1,952
Min	5,007	57.2%	2,125	24.3%	265	3.0%	192	2.2%	404
Average	5,556	63.4%	2,406	27.5%	606	6.9%	192	2.2%	962
Std Dev	266	3.0%	158	1.8%	167	1.9%	0	0.0%	306

Weather Station Energy Use Results

Weather Station	Gal. LP per Pig Space	Heater Electric Use kWh	Min. Ventil-ation Energy Use kWh	Natural Ventil-ation Energy Use kWh	Tunnel Ventil-ation Energy Use kWh	Total Vent. Energy per pig space kWh/ pig space
Algona	2.36	96	10,549	4,187	204	15.04
Atlantic	2.26	92	10,633	4,040	234	15.00
Boone	1.98	81	10,606	4,234	236	15.16
Burlington	1.95	80	11,033	3,874	331	15.32
Carroll	2.65	108	10,583	4,147	283	15.12
Cedar Rapids	3.22	131	10,753	4,332	202	15.42
Chariton	1.67	68	10,756	4,098	264	15.19
Charles City	2.27	93	10,575	4,507	190	15.36
Clarinda	1.99	81	10,836	3,767	288	14.97
Clinton	2.45	100	10,847	3,697	231	14.87
Council Bluffs	1.62	66	10,617	4,494	240	15.42
Creston	1.92	78	10,636	4,121	275	15.11
Decorah	1.65	67	10,693	4,098	243	15.10
Denison	2.27	92	10,644	3,948	293	14.98
Des Moines	2.41	98	10,835	3,805	300	15.04
Dubuque	3.00	122	10,582	4,003	158	14.87
Estherville	4.79	195	10,474	3,945	177	14.79
Fair Field	1.94	79	10,834	4,090	269	15.27
Fort Dodge	2.80	114	10,606	3,940	231	14.89
Fort Madison	0.99	40	10,892	4,300	272	15.50
Keokuk	1.53	62	10,968	3,995	286	15.31
Knoxville	1.82	74	10,859	3,956	267	15.16
LeMars	2.08	85	10,674	3,962	294	15.01
Mason City	4.01	163	10,552	4,011	195	14.92

Weather Station Energy Use Results (continued)

Weather Station	Gal. LP per Pig Space	Heater Electric Use kWh	Min. Ventil-ation Energy Use kWh	Natural Ventil-ation Energy Use kWh	Tunnel Ventil-ation Energy Use kWh	Total Vent. Energy per pig space kWh/ pig space
Monticello	2.95	120	10,737	4,109	182	15.15
Muscatine	2.04	83	10,950	3,724	264	15.02
Newton	2.11	86	10,702	4,520	190	15.50
Oelwein	1.85	75	10,583	4,553	164	15.38
Orange City	2.18	89	10,510	4,224	256	15.08
Ottumwa	2.94	120	10,775	4,451	205	15.55
Red Oak	1.91	78	10,776	4,083	317	15.25
Sheldon	2.26	92	10,451	4,510	220	15.27
Shenandoah	2.08	85	10,812	3,750	281	14.93
Sioux City	2.69	110	10,697	3,972	259	15.04
Spencer	4.24	172	10,477	4,075	180	14.90
Storm Lake	2.49	101	10,471	4,076	222	14.87
Washington	1.78	72	10,809	4,254	221	15.36
Waterloo	3.08	125	10,759	3,870	279	15.03
Webster City	1.92	78	10,701	4,177	322	15.28
Max	4.79	195	11,033	4,553	331	15.55
Min	0.99	40	10,451	3,697	158	14.79
Average	2.36	96	10,699	4,100	244	15.14
Std Dev	0.75	31	147	232	46	0.20

County Pig Numbers and Weather Stations

County	No. of Pigs	Weather Station
SIOUX	1,094,268	Orange City
HARDIN	875,386	Webster City
PLYMOUTH	765,318	LeMars
KOSSUTH	747,370	Algona
FRANKLIN	599,768	Mason City
WASHINGTON	593,631	Washington
WRIGHT	576,113	Webster City
LYON	561,045	Sheldon
CARROLL	529,108	Carroll
PALO ALTO	528,486	Algona
O BRIEN	477,181	Sheldon
SAC	474,104	Storm Lake
HAMILTON	466,691	Webster City
OSCEOLA	451,961	Sheldon
BUENA VISTA	445,321	Storm Lake
CRAWFORD	345,434	Denison
BUTLER	340,877	Waterloo
DELAWARE	337,066	Monticello
CALHOUN	306,224	Fort Dodge
HANCOCK	285,163	Algona
AUDUBON	281,883	Atlantic
MITCHELL	275,550	Mason City
BUCHANAN	271,198	Oelwein
MAHASKA	264,176	Knoxville
FAYETTE	255,138	Oelwein
CHEROKEE	246,170	Storm Lake
GRUNDY	232,942	Waterloo
JASPER	228,492	Newton
HOWARD	224,101	Decorah
POCAHONTAS	222,118	Storm Lake
CHICKASAW	219,213	Charles City
CLAY	215,294	Spencer
DUBUQUE	199,665	Dubuque
KEOKUK	187,682	Washington
CLAYTON	182,309	Oelwein
JOHNSON	177,012	Cedar Rapids
WEBSTER	163,750	Fort Dodge
EMMET	163,749	Estherville
CEDAR	160,784	Cedar Rapids
FLOYD	157,739	Charles City
BLACK HAWK	151,440	Waterloo
LOUISA	151,300	Muscatine
MARSHALL	140,135	Newton
WINNEBAGO	137,985	Mason City
LINN	137,523	Cedar Rapids
CERRO GORDO	131,481	Mason City
SHELBY	128,046	Denison
BREMER	122,934	Waterloo
SCOTT	120,704	Muscatine
TAMA	118,772	Waterloo
IDA	118,646	Storm Lake
GREENE	112,703	Carroll
JONES	112,106	Monticello
IOWA	109,602	Cedar Rapids
HUMBOLDT	109,388	Fort Dodge
GUTHRIE	103,144	Atlantic
UNION	102,871	Creston
WINNESHIEK	102,163	Decorah
HENRY	95,935	Washington
ALLAMAKEE	87,017	Decorah
VAN BUREN	85,130	Fair Field
RINGGOLD	83,070	Creston
WOODBURY	83,003	Sioux City
CLINTON	81,541	Clinton
DAVIS	80,786	Ottumwa
TAYLOR	80,463	Clarinda
BENTON	79,933	Cedar Rapids
CASS	67,985	Atlantic
STORY	66,515	Boone
POTTAWATTAMIE	64,746	Council Bluffs
JEFFERSON	63,623	Fair Field
MUSCATINE	61,384	Muscatine
BOONE	61,266	Boone
DALLAS	58,775	Des Moines
LEE	54,795	Fort Madison
ADAMS	53,304	Creston

County Pig Numbers and Weather Stations (continued)

County	No. of Pigs	Weather Station
JACKSON	51,558	Dubuque
POWESHIEK	51,416	Newton
WAPELLO	45,383	Ottumwa
DES MOINES	42,846	Burlington
DICKINSON	37,838	Estherville
HARRISON	36,404	Denison
MADISON	35,675	Des Moines
MARION	34,662	Knoxville
WORTH	34,291	Mason City
MONONA	31,655	Denison
WARREN	31,041	Des Moines
POLK	30,223	Des Moines
DECATUR	23,527	Creston
PAGE	16,643	Clarinda
ADAIR	16,033	Creston
MONROE	14,333	Ottumwa
LUCAS	14,318	Knoxville
FREMONT	8,174	Shenandoah
MONTGOMERY	7,823	Red Oak
APPANOOSE	1,817	Ottumwa
MILLS	1,461	Red Oak
CLARKE	(D)	
WAYNE	(D)	
TOTAL	19,216,815	

(Pig Numbers from USDA-NASS 2007 Ag Census)

Appendix B References

ASHRAE 2005. Fundamentals Handbook. American Society of Heating, Refrigerating, and Air Conditioning Engineers. Atlanta, GA.

BESS Labs. Agricultural Fan Performance Data. http://bess.illinois.edu. Accessed October 1, 2009.

NREL. TMY3 Weather Data. http://rredc.nrel.gov/solar/old_data/nsrdb/1991-2005/tmy3/by_state_and_city.html#I. Accessed October 15, 2009.

Pedersen, Soeren. 2002. Heat and Moisture Production for Pigs on Animal and House Level. ASAE Meeting Paper Number 024178.

PM 1586. Environmental Guidelines for Confinement Swine Housing. February, 1995. Iowa State University Extension.

PM 1780. Mechanical Ventilation Design Worksheet for Swine Housing. October, 1999. Iowa State University Extension.

USDA-NASS. 2007 Ag Census. http://quickstats.nass.usda.gov. Accessed October 15, 2009.