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Energy use in pig production: An examination of current Iowa Systems

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Abstract

This paper compares energy use for different pig production systems in Iowa, a leader in US swine production. Pig production systems include not only the growth and performance of the pigs, but also the supporting infrastructure of pig production. This supporting infrastructure includes swine housing, facility management, feedstuff provision, swine diets, and manure management. Six different facility type × diet formulation × cropping sequence scenarios were modeled and compared. The baseline system examined produces 15,600 pigs annually using confinement facilities and a corn-soybean cropping sequence. Diet formulations for the baseline system were corn-soybean meal diets that included the synthetic AA L-lysine and exogenous phytase. The baseline system represents the majority of current US pork production in the Upper Midwest, where most US swine are produced. This system was found to require 744.6 MJ per 136-kg market pig. An alternative system that uses bedded hoop barns for grow-finish pigs and gestating sows would require 3% less (720.8 MJ) energy per 136-kg market pig. When swine production systems were assessed, diet type and feed ingredient processing were the major influences on energy use, accounting for 61 and 79% of total energy in conventional and hoop barn-based systems, respectively. Improving feed efficiency and better matching the diet formulation with the thermal environment and genetic potential are thus key aspects of reducing energy use by pig production, particularly in a hoop barn-based system. The most energy-intensive aspect of provisioning pig feed is the production of synthetic N for crop production; thus, effectively recycling manure nutrients to cropland is another important avenue for future research. Almost 25% of energy use by a conventional farrow-to-finish pig production system is attributable to operation of the swine buildings. Developing strategies to minimize energy use for heating and ventilation of swine buildings while maintaining pig comfort and performance is a third critical area for future research. The hoop barn-based alternative uses 64% less energy to operate buildings but requires bedding and 2.4% more feed. Current Iowa pig production systems use energy differently but result in similar total energy use. Compared with 1975, current farrow-to-finish systems in Iowa require 80% less energy to produce live market pigs.

Keywords

Animal Science, Economics, energy use, hoop barn, pig production

Disciplines

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Comments

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Energy use in pig production: An examination of current Iowa systems[1]

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ABSTRACT: This paper compares energy use for different pig production systems in Iowa, a leader in US swine production. Pig production systems include not only the growth and performance of the pigs, but also the supporting infrastructure of pig production. This supporting infrastructure includes swine housing, facility management, feedstuff provision, swine diets, and manure management. Six different facility type × diet formulation × cropping sequence scenarios were modeled and compared. The baseline system examined produces 15,600 pigs annually using confinement facilities and a corn-soybean cropping sequence. Diet formulations for the baseline system were corn-soybean meal diets that included the synthetic AA L-lysine and exogenous phytase. The baseline system represents the majority of current US pork production in the Upper Midwest, where most US swine are produced. This system was found to require 744.6 MJ per 136-kg market pig. An alternative system that uses bedded hoop barns for grow-finish pigs and gestating sows would require 3% less (720.8 MJ) energy per 136-kg market pig. When swine production systems were assessed, diet type and feed ingredient processing were the major influences on energy use, accounting for 61 and 79% of total energy in conventional and hoop barn-based systems, respectively. Improving feed efficiency and better matching the diet formulation with the thermal environment and genetic potential are thus key aspects of reducing energy use by pig production, particularly in a hoop barn-based system. The most energy-intensive aspect of provisioning pig feed is the production of synthetic N for crop production; thus, effectively recycling manure nutrients to cropland is another important avenue for future research. Almost 25% of energy use by a conventional farrow-to-finish pig production system is attributable to operation of the swine buildings. Developing strategies to minimize energy use for heating and ventilation of swine buildings while maintaining pig comfort and performance is a third critical area for future research. The hoop barn-based alternative uses 64% less energy to operate buildings but requires bedding and 2.4% more feed. Current Iowa pig production systems use energy differently but result in similar total energy use. Compared with 1975, current farrow-to-finish systems in Iowa require 80% less energy to produce live market pigs.

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INTRODUCTION

Life cycle assessment (**LCA**) is a technique used to quantify and compare the environmental impacts of products or processes. Although originally applied to manufacturing processes, LCA is increasingly being applied to agriculture. Previous LCA of swine production have focused on European systems, particularly those in Denmark (Halberg, 1999; Basset-Mens and van der Werf, 2005; Eriksson et al., 2005; Williams et al., 2006; Dalgaard et al., 2007; Meul et al., 2007). The source and type of feed ingredients, feeding strategy, and physical form of diets, as well as the thermal climate conditions, size of the operation, and other management strategies, differ between pig farms in Europe and the United States. These fundamental differences between European and US swine production limit the application of European results to decision making by pig producers in the United States.

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United States swine production is centered in Iowa (USDA, 2009). Iowa is also a leader in corn and soybean production (USDA, 2009), soybean processing (Hardy, 2009), and biofuel production (National Biodiesel Board, 2008; Hardy, 2009; Renewable Fuels Association, 2010). Energy use for swine production in Iowa was last estimated as 26.2 MJ/kg of BW based on 1975 production statistics (Reid et al., 1980). A thorough examination of the carbon footprint of US swine production has been released (Thoma et al., 2011), but that report does not detail energy use for producing live pigs. Interest in energy use for all sectors of society is increasing because of rising energy prices, uncertainty about access to fossil fuel reserves, and scientific consensus about the deleterious implications of fossil fuel use for the global climate. The purpose of this paper is to examine the energy use of different combinations of facility types, crop sequences, and diet formulation strategies within pig production systems. Global warming potential associated with energy use is also estimated.

MATERIALS AND METHODS

Animal Care and Use Committee approval was not obtained for this study because no animals were used.

Our analysis builds on previous assessments of energy use to operate different types and scales of pig facilities (Lammers et al., 2010a) and swine feed production (Lammers et al., 2010b) to estimate the energy use and associated greenhouse gas emissions of entire pig production systems in Iowa. Pig production systems include not only the growth and performance of the pigs but also the supporting infrastructure of pig production. This supporting infrastructure includes swine housing, facility management, feedstuff provision, swine diets, and manure management. Six different pig production systems scaled to produce 15,600 market pigs weighing 136 kg annually were modeled. The 6 pig production systems were selected combinations of facility type, crop sequence, and diet formulation strategies that had been examined previously in isolation (Lammers et al., 2009, 2010a,b).

For each of the 6 pig production systems, multiple submodels were run in series to characterize and sum the energy use for constructing and operating different types of pig barns; crop cultivation and processing of feed ingredients; and returning manure nutrients back to cropland. Although several commercially available LCA packages exist, our Iowa-focused submodels were developed using Microsoft Excel (Microsoft Corporation, Redmond, WA) as described in Lammers (2009). Underlying assumptions regarding pig growth, performance, and nutrient cycling were adjusted as appropriate for each scenario. For each facility type × diet formulation × crop sequence scenario examined, energy use and the associated 100-yr global warming potential, as well as land area required, were totaled from submodel results. Because the outputs of the modeled pig production systems were 136-kg market pigs, results are reported per 136-kg market pig produced.

Process analysis methodology was used to calculate direct and indirect energy inputs based on physical material flows (Jones, 1989). Similar to previous assessments (Meul et al., 2007), a cradle-to-gate approach that included embodied energy one step before the farm gate was used. For example, the energy used to synthesize L-lysine and the exogenous enzyme phytase are included, but the energy required to build the equipment and facility necessary for manufacturing these diet components is not considered. Similarly, for the crop production submodel, the diesel fuel used by a tractor for field operations was considered, but the energy required to manufacture the tractor itself was not. Consistent with process analysis methods, we did not include human labor inputs or solar energy captured by plants through photosynthesis (Jones, 1989). Global warming potential was estimated based on energy use for each pig production system using standard emission factors for each fuel type [Intergovernmental Panel on Climate Change (**IPCC**), 2006; US Environmental Protection Agency, 2008; Energy Information Administration-US Department of Energy, 2009]. The present study focuses on energy use and reports only the greenhouse gas emissions directly associated with energy use within a pig production system. Emissions resulting from manure management and enteric fermentation are thus excluded from this analysis.

Pig Herd

The current analysis examines farrow-to-finish pig herds sized to produce 15,600 market pigs weighing 136 kg annually. As described previously by Lammers et al. (2009), a baseline sow population sufficient to produce batches of 1,200 market pigs every 28 d was modeled using PigCHAMP reproduction performance records and USDA survey data (USDA, 2007; PigCHAMP, 2008). Sow reproductive performance is influenced by housing conditions (Lammers et al., 2007). Lammers et al. (2007) demonstrated that sows housed in group pens with feeding stalls in bedded hoop barns gave birth to 7% more live pigs than sows gestated in individual stalls and that preweaning mortality was not influenced by gestation housing. Thus, systems housing sows in group pens within bedded hoop barns were assumed to require a 7% smaller sow herd than systems using conventional housing in this analysis. Mortality rates for growing pigs were assumed to be equal for both types of housing examined based on the report of Honeyman and Harmon (2003). The modeled herd size and pig flow parameters have been detailed previously (Lammers et al., 2009) and are summarized here as Table 1.

Modeled feed consumption by growing pigs was calculated based on feed intake and nutrient content of the control diets in a previous wean-to-finish feeding trial (Lammers et al., 2008b). Appropriate feed intake ad-

Table 1. Swine herd assumptions[1]

Parameter	Housing and management	
	Conventional[2]	Hoop barn-based[3]
Supporting breeding herd, sows and gilts	790	735
Weaned pigs per litter,[4] pigs	9.2	9.9
Litters weaned per sow, litters/yr	2.3	2.3
Farrowing rate, % (litters born/sows mated)	77.6	77.6
Sow herd replacement rate, %	60.0	60.0
Nursery mortality rate, %	2.9	2.9
Grow-finish mortality rate, %	3.9	3.9
Pig age at weaning, d	21	21
Maximum pig age at market, d	180	180

[1]Based on USDA (2007) and PigCHAMP (2008) data unless otherwise noted.

[2]Pigs housed in mechanically ventilated buildings with liquid manure handling for all production phases.

[3]Grow-finish pigs and gestating sows housed in bedded hoop barns, with conventional farrowing and nursery facilities used for those production phases.

[4]Lammers et al. (2007).

justments for different diet formulations were made, as detailed by Lammers et al. (2010b). In these analyses, feed consumption included not only the feed directly consumed by the pig, but also feed losses attributable to storage, waste from feeders, and growing pig mortality. Pig growth performance is affected by housing conditions (Honeyman and Harmon, 2003), and the current model takes those differences into consideration. Table 2 summarizes feed consumption parameters included in the current analysis.

Facilities

Previous examinations of the construction (Lammers et al., 2009) and operation (Lammers et al., 2010a) of farrow-to-finish swine systems were combined to estimate energy and greenhouse gas emissions associated with different types of pig facilities. Conventional farrow-to-finish swine facilities in Iowa are mechanically ventilated buildings with liquid manure handling systems. Pigs are born in farrowing crates and at weaning are moved to a heated nursery facility. As the pigs grow, they are often moved from nursery facilities to larger grow-finish buildings. Grow-finish buildings typically house 1,200 animals in pens of 30 to 60 animals. The entire floor space is slatted concrete. Gestation occurs in buildings similar to grow-finish barns, except that pens are replaced with individual gestation stalls. Conventional housing for swine in Iowa and a hoop barn-based alternative have been detailed and examined previously (Lammers et al., 2009, 2010a). The hoop barn-based system uses farrowing and nursery facilities similar to those of the conventional system, but grow-finish pigs and gestating sows are housed in bedded hoop barns. Hoop barns in Iowa are 21.9 × 9.1 m Quonset-shaped structures, which have been described previously (Honeyman et al., 2001; Brumm et al., 2004; Harmon et al., 2004). Hoop barn sidewalls are approximately 1.5 m high and consist of wooden posts and lumber. Tubular steel arches are attached to the posts, forming a hooped roof. A UV light-resistant, high-density polyethylene tarp is pulled over the arches

Table 2. Modeled feed disappearance associated with production of one 136-kg market pig fed complex corn-soybean meal diets[1]

Diet	BW, kg	Feed disappearance, kg	
		Conventional[2]	Hoop barn-based[3]
Phase 1	5 to 12	10.2	10.2
Phase 2	12 to 23	16.8	16.8
Phase 3	23 to 45	57.8	58.9
Phase 4	45 to 78	92.3	95.3
Phase 5	78 to 136	181.4	187.4
Gestation	157	37.0	37.0
Lactation	143	15.6	15.6
Total		411.1	421.2

[1]Corn-soybean meal diets that include synthetic AA and exogenous phytase. Adapted from Lammers et al. (2010a,b).

[2]Pigs housed in mechanically ventilated buildings with liquid manure handling for all production phases.

[3]Grow-finish pigs and gestating sows housed in bedded hoop barns, with conventional farrowing and nursery facilities used for those production phases. Increased grow-finish feed disappearance based on Honeyman and Harmon (2003).

and fastened to the sidewalls. The floor is solid, usually concrete, with raised areas for eating and drinking. The rest of the floor is bedded with cornstalks or other plant materials. Buildings for grow-finish pigs are typically managed as a single pen with 180 to 200 animals per pen (Honeyman et al., 2001; Brumm et al., 2004). Gestating sows in hoop barns are often managed in group pens with individual feeding stalls (Harmon et al., 2004; Lammers et al., 2007, 2008a). Our analysis assumed the useful life of the conventional buildings was 15 yr. The useful life of the hoop barns was also 15 yr, but we included replacement of the tarp once within the useful life.

Diet Formulation

Seven reference diets were the basis for calculating NE and nutrient intake associated with production of one 136-kg market pig, as described previously by Lammers et al. (2010b). These included diets for gestating and lactating sows and 5 growing pig diets (Lammers et al., 2010b). For this analysis, 3 sets of phased diets described previously were considered (Lammers et al., 2010b). The first diet type was a corn-soybean meal (**SBM**) diet typically fed in Iowa. The second type (oat-SBM) was similar to the first except that it included oats. The third diet type (coproducts) was a corn-SBM diet that included the biofuel coproducts dried distillers grains with solubles (**DDGS**) and crude glycerin. The coproduct set of diets was formulated to include 25 and 40% DDGS for growing pigs and sows, respectively, and 10% crude glycerin for growing pigs. These inclusion rates correspond to recommended maximal inclusion rates for biofuel coproducts in swine diets (Honeyman et al., 2007; Kerr et al., 2007). The 3 diet types were selected to examine historic conditions (corn-SBM), an increased crop diversity scenario (oat-SBM), and a maximum use of biofuel coproducts for pig production scenario (coproducts).

One of 2 general formulation strategies, "simple" and "complex," was paired with each diet type in this analysis. The simple diets provided adequate standardized ileal digestible lysine and available P through traditional feedstuffs, primarily corn, SBM, and monocalcium P. The complex diets included the synthetic AA L-lysine, thereby reducing the total CP content of the diets fed to pigs. Additionally, complex diets included the exogenous enzyme phytase, which allowed reduction of total P in the diets compared with formulations of the simple diets (Lammers et al., 2010b). For this analysis, the corn-SBM and coproduct diet types were paired with the complex formulation strategy, and the oat-SBM diet type was paired with the simple formulation strategy. Thus, 3 sets of phased diets were considered: complex corn-SBM, simple oat-SBM, and complex coproducts.

Crop Sequence × Diet Type

Two crop sequence scenarios described previously (Lammers et al., 2010b) were considered; they are a corn-soybean sequence and a corn-soybean-corn-oat underseeded with leguminous cover crop sequence. The longer crop sequence was coupled with the simple oat-SBM diet type, and the corn-soybean sequence was partnered with the complex corn-SBM and coproduct diet types. Our previous model of crop production assumed that 100% of crop nutrients would be delivered by synthetic fertilizers and through the crop sequence itself (Lammers et al., 2010b). For this assessment of Iowa pig production systems, the crop production model included application of manure nutrients and subsequent reduced synthetic fertilizer use. Excretion of N and P from pigs fed different diets was estimated and corrected for losses during storage and application. Modeled crop production inputs and yields have been summarized and are presented as Table 3.

Feed Provision

Once grown, crops are generally processed before being fed to pigs. Energy use associated with the provi-

Table 3. Modeled crop production inputs and yields[1]

	Corn-soybean sequence		Corn-soybean-corn-oat sequence[2]		
Item	Corn	Soybean	Corn	Soybean	Oat
Crop					
Limestone, kg/m^2	0.5	0.5	0.5	0.5	0.5
Anhydrous ammonia,[3] g/m^2	23.2	0	20.8	0	9.7
Diammonium phosphate,[3] g/m^2	18.7	11.2	18.7	11.6	12.0
Muriate of potash, g/m^2	11.2	15.7	11.2	16.2	22.4
Herbicide, mg of active ingredient/m^2	252.8	138.1	252.8	138.1	0
Seed production,[4] kg/m^2	1.26	0.38	1.26	0.39	0.43
Stover or straw, kg/m^2	1.04	0	1.04	0	0.21

[1]Based on Lammers (2009). Initial conditions assumed 100% of crop fertility was supplied by synthetic sources.

[2]Corn-soybean-corn-oat underseeded with leguminous cover crop.

[3]Modeled application rates of anhydrous ammonia and diammonium phosphate reduced based on estimated delivery of crop nutrients by swine manure from pigs managed under different production scenarios.

[4]Seed production reported at storage moisture of 15.5, 13.0, and 14.0% for corn, soybeans, and oats, respectively.

sion of 13 swine feedstuffs has been reported previously (Lammers et al., 2010b). Although far from a comprehensive list of every possible swine feed ingredient, the feedstuffs presented by Lammers et al. (2010b) include L-lysine, phytase, and all other ingredients used in the modeled diets. The energy required to grind, mix, and deliver complete pig feed to pig farms in Iowa was also estimated (Lammers et al., 2010b). This information was combined with the crop production submodel to estimate total energy use and associated greenhouse gas emissions related to pig feed in the current analysis.

Nutrient Excretion from Pigs

Nitrogen excretion was estimated based on results of a previously reported grow-finish feeding study (Canh et al., 1998). Pigs were fed diets containing 12.5 to 16.5% CP for 9 wk, with total collection of urine and feces (Canh et al., 1998). We estimated, based on the results of that study, that for pigs fed diets typical of the Midwest region of the United States, N excretion could be calculated by the following equation:

N excretion by the growing pig:

$$N_{ex} = 0.1369 \times CP_{in} - 15.154, \quad [1]$$

where N_{ex} is N excretion (g/pig) and CP_{in} is CP intake (g/pig).

Phosphorus excretion was estimated based on the results of 2 studies examining phytase in nursery (Veum and Ellersieck, 2008) and finishing (Veum et al., 2006) pigs. Both studies examined the efficacy of exogenous phytase by comparing P retention in pigs fed graded amounts of exogenous phytase in diets formulated to be low in available P (Veum et al., 2006; Veum and Ellersieck, 2008). Both studies included a positive control diet that was adequate in available P by inclusion of inorganic P sources (Veum et al., 2006; Veum and Ellersieck, 2008). The intake and excretion of P fed in the negative and positive control diets in previous studies (Veum et al., 2006; Veum and Ellersieck, 2008) were the basis for the following equation used to predict P excretion by pigs in our assessment:

P excretion by pigs:

$$P_{ex} = 0.79 \times P_{in} - 1.0593, \quad [2]$$

where P_{ex} is the total P excreted (g/pig) and P_{in} is the total P intake (g/pig).

Formulation strategy and ingredient choice affect the energy density of diets fed to pigs, and pigs consume feed based on the energy density of the diet. Total feed intake for each diet formulation was estimated based on NE intake (Lammers et al., 2010b) and was used to calculate intake of CP and total P. Thermal conditions can influence feed intake. It has been demonstrated that growing pigs housed in hoop barns require 8% more feed during the cold winter months than do growing pigs housed in confinement but that performance during the warm summer months is similar (Honeyman and Harmon, 2003). Thus, in this analysis, grow-finish pigs housed in hoop barns were assumed to consume more feed during the cold months than grow-finish pigs housed in conventional confinement. Lammers et al. (2007) also demonstrated that sows housed in group pens with feeding stalls in bedded hoop barns gave birth to 7% more live pigs than did sows gestated in individual stalls, and that preweaning mortality was not influenced by gestation housing. In this analysis, systems housing sows in group pens within bedded hoop barns were assumed to require a 7% smaller sow herd, and thus less sow feed per weaned piglet, than systems using conventional housing. Taking into account previously demonstrated performance differences for grow-finish pigs and sows housed in bedded hoop barns (Honeyman and Harmon, 2003; Lammers et al., 2007, 2008a), we assumed that for the hoop barn-based systems, total life-cycle feed consumption for a given diet formulation would be 2.4% more than total feed consumption for the same diet in the conventional system (Lammers et al., 2010a).

Because not all feed consumed is utilized by the pig, it is necessary to estimate relative differences in fecal mass when comparing different dietary strategies. Pigs fed complex corn-SBM diets were assumed to produce waste at rates found in tables used for developing manure management plans (Iowa State University, 2003). For other diet formulations, for every 1% increase in feed intake over the baseline corn-SBM scenario, a 1% increase in waste volume was assumed.

Manure Nutrient Losses During Storage and Application

Loss of N from pig manure during storage and application is a major concern in pig production systems (Iowa State University, 2003; IPCC, 2006; Wathes and Whittemore, 2006). Nitrogen losses from different types of manure storage systems vary greatly (Arogo et al., 2003; Nicks et al., 2004; Phillippe et al., 2006, 2007). Previous examinations of N loss from swine manure storage units have focused on liquid manure systems or deep litter systems that use sawdust. Tiquia et al. (2002) examined the characteristics of cornstalk bedding packs in hoop barns with swine. Using a mass balance approach, they reported N losses of 35 to 45% (Tiquia et al., 2002). European researchers have reported N losses of 28% from deep-litter pens when using straw (Nicks et al., 2004). Others have reported losses of up to 75% from deep-litter pens using straw bedding (Phillippe et al., 2006). No published studies have specifically examined N loss from liquid manure stored in deep pits compared with N loss from bedded hoop barns. For our analysis, we assumed N losses of 25% from liquid manure storage and 50% from bedded hoop barns (IPCC, 2006).

Liquid manure is often injected directly into cropland. Our model assumed injection of liquid manure and that 98% of the N remaining in the stored slurry was delivered and made available to crops in the year of application (Iowa State University, 2003). Thus, for every 100 kg of N excreted by pigs and handled as liquid manure, our analysis assumed 73.5 kg was ultimately available to crops, with 25 kg of N lost during storage and 1.5 kg lost during application.

Manure and bedding from hoop barns is often composted before application. The ratios of C to N in the composting material, moisture content, and frequency of turning have all been shown to influence a reduction of material mass, total losses of N, and type of N emission from composting pig manure (Huang et al., 2001, 2004; Tiquia et al., 2002). Our analysis assumed passive composting, no turning of compost material, and that a 40% reduction in material mass would occur (Tiquia et al., 2002). Our analysis assumed that the 50% N loss reported included all N loss during storage and composting (IPCC, 2006). The analysis also assumed 0% loss of N from stable compost that was applied and incorporated into crop fields and that 60% of the delivered N was available to plants during the year of application, with the remaining 40% available to plants in the following year (Shaffer, 2001). Thus, for every 100 kg of N excreted by pigs housed in bedded hoop barns, our analysis assumed that 50 kg of N was available to crops over a 2-yr period.

Phosphorus does not volatilize, and under typical manure storage and handling scenarios, most of the excreted P is delivered to crop fields (Fulhage and Hoehne, 2001). Our analysis assumed that 100% of the excreted P was delivered to crop fields and was available for plant growth in the year of application. We also assumed that the cropland had a P index of 2 to 5, which would allow N-based manure management but prohibit application of P to exceed 200% of the P removal rates of the planned crop (USDA-Natural Resources Conservation Service, 2001; Iowa Department of Natural Resources, 2006).

Land Application of Manure Slurry or Compost

Our model assumed swine manure was returned to cropland that was used to grow crops fed to pigs. Application rates of swine manure were based on nutrient removal rates by the crops, with application rates of synthetic fertilizers reduced accordingly (Sawyer et al., 2002; Iowa State University, 2003). Concentrations of nutrients in swine manure slurry or compost were calculated for liquid manure systems and bedded hoop barns. For liquid pig manure, the masses of N and P after taking into account storage and application losses were divided by the calculated slurry volume. Energy for transporting and injecting liquid pig manure into cropland has been reported as 20.8 kJ/L (Wiens et al., 2008), and we assumed identical energy requirements for our model. Application rate of slurry was calculated based on manure slurry nutrient concentration and nutrient removal rates by crops.

For swine manure compost, the masses of N and P after taking into account losses during composing were divided by the mass of the finished compost. Application rate was calculated based on nutrient concentration of the compost and nutrient removal rates by crops. It was assumed, based on discussions with commercial haulers operating in Iowa, that compost would be loaded onto a trailer with a capacity of 22,000 kg and hauled an average of 3.2 km, with a fuel efficiency of 3 km/L. The energy density of diesel fuel was assumed to be 38.46 MJ/L (Downs and Hansen, 1998). Thus, transportation energy costs of delivering compost to cropland were calculated as 1.9 kJ/kg. Energy use for spreading and incorporating the compost was estimated based on reported diesel fuel use for field operations (Downs and Hansen, 1998; Hanna, 2001).

Use of diesel fuel for transporting, injecting, or spreading liquid swine manure or compost results in the emission of greenhouse gases. The 100-yr global warming potential of diesel fuel consumption was reported as 82.73 g of CO_2 equivalents/MJ of energy as diesel fuel (IPCC, 2006). Diesel fuel consumption for manure handling was totaled and used to calculate greenhouse gas emissions associated with energy use for manure handling for each diet × housing comparison.

Useful Energy Balance

Not all grains, oilseeds, and biomass produced within a given crop sequence are necessarily consumed by pigs. Crop products not consumed by pigs within the system boundaries were exported from the farm. All cropping scenarios were designed to provide adequate feed grain. As needed, SBM was imported to the farm. Imports and exports of crop products were totaled for each facility type × diet formulation × crop sequence scenario considered. Net energy best represents the biologically useful energy present in a given mass of feedstuff. The masses of imported and exported feedstuffs were multiplied by the NE value of each feedstuff for growing pigs (Sauvant et al., 2004) to determine the import and export of energy as crop products.

Although pigs are not generally produced or consumed as a primary source of energy, consideration of the NE present in the live pig is appropriate for this analysis. Approximately 60% of the body of market pigs fed ad libitum is water (Whittemore and Kyriazakis, 2006). The NE value of meat and bone meal is a conservative measure of the useful energy present in pigs. For our analysis, we estimated that the NE exported as the pig body was equal to the water-free mass of the body of the pig multiplied by 7.5 MJ/kg, or the NE of meat and bone meal on a DM basis, as reported by Sauvant et al. (2004).

RESULTS AND DISCUSSION

Table 4 presents the baseline scenario for pig production in Iowa. In the baseline scenario, each 136-kg market pig was estimated to require 744.6 MJ of energy, which resulted in emission of 65.0 kg of CO_2 equivalents. Forty-eight percent of the total energy use was due to the cultivation of crops. Approximately 60% of total energy use could be attributed to feed provision, cultivation of crops, and processing of feed. Almost 25% of the total energy use associated with producing pigs in the conventional system resulted from operating the mechanically ventilated buildings. It is interesting that 35% of the total 100-yr global warming potential associated with conventional pig production systems resulted from operating the buildings. Although relatively small, the energy inputs and resulting global warming potential of simply constructing conventional pig production systems were not insignificant. The baseline scenario assumed a corn-soybean cropping sequence and resulted in export of 20.5 kg of SBM and 17.2 kg of soybean oil per market pig sold. The total cropland area needed to produce feed grown on farm was 537 m^2 per market pig or a total of 837.7 ha for the 15,600 pig system.

Table 5 details 2 alternative crop sequence and diet type scenarios for the conventional confinement system. The simple oat-SBM diet formulation did not include L-lysine or exogenous phytase and required 34% more energy for processing feed ingredients compared with the baseline scenario presented in Table 4. This was mainly due to the high energy cost of producing monocalcium phosphate, which was the primary source of available P in the simple formulation strategy but was reduced dramatically in the complex approach through the addition of exogenous phytase (Lammers et al., 2010b). Energy used for the cultivation of crops was only 2% more for the simple oat-SBM option compared with the baseline complex corn-SBM approach. Including synthetic AA increased the processing energy required to manufacture pig diets and decreased the CP content of the feed. This ultimately reduced N excretion by the pig and subsequent delivery of N to crops. Removing synthetic AA from diets should increase N excretion, increasing N delivery to fields, and may reduce the need for synthetic N fertilizers. However, feeding diets with greater CP did not sufficiently reduce application of synthetic N to be energetically favorable in the conventional system examined.

Cultivation energy for the complex coproduct diet formulation was less than in any other scenario; however, the processing energy was 5 to 8 times greater. This is because of the way DDGS and crude glycerin were assessed. Our analysis assumed DDGS and crude glycerin were imported to the farm, and cultivation of the corn and soybeans required to produce those biofuel coproducts was attributed to the processing energy of those feed ingredients. The different crop sequence × diet formulations resulted in differing amounts of crop surpluses. The baseline complex corn-SBM scenario assumed a corn-soybean sequence and resulted in export of 20.5 kg of SBM and 17.2 kg of soybean oil per market pig, respectively. The simple oat-SBM scenario assumed a corn-soybean-corn-oat sequence and resulted in export of 50.5 kg of corn grain and 10.4 kg of soybean oil per market pig, but also required importing 28.3 kg of SBM per market pig. The complex coproduct scenario within a corn-soybean sequence resulted in export of 15.7 kg of SBM. Because all soybean oil produced on farm was refined to biodiesel and crude glycerin, no soybean oil was exported from the complex coproduct scenario.

A hoop barn-based pig production system requires less energy for operation of facilities, but also requires more feed (Lammers et al., 2010a). Because swine manure slurry from conventional facilities and swine manure compost from hoop barns have different release rates of crop available nutrients, different cropping sequences may be more effective in a hoop barn-based system than in the conventional system. Table 6 details 3 diet formulations × cropping sequence scenarios for farrow-to-finish swine production using hoop barns for gestation and grow-finish. Feeding pigs housed in hoop barns a complex corn-SBM diet from a corn-soybean

Table 4. Assessment of nonsolar energy and resultant 100-yr global warming potential (GWP) associated with farrow-to-finish pig production in a typical system for Iowa[1]

Item	Nonsolar energy, MJ/pig	100-yr GWP,[2] kg of CO_2 equivalents/pig
Facility construction	87.0	6.7
Facility operation	186.0	22.8
Cultivation of crops	354.1	26.8
Processing of feed	102.4	7.4
Manure application	15.1	1.3
Total	744.6	65.0

[1]Conventional confinement facilities scaled to produce 15,600 market pigs weighing 136 kg annually. Pigs are fed a corn-soybean meal diet that includes synthetic AA and exogenous phytase (complex system). Requires 537 m^2 cropland/market pig managed in a corn-soybean sequence and results in surplus production of soybeans equivalent to 20.5 kg of soybean meal and 17.2 kg of soybean oil.

[2]The 100-yr GWP directly associated with energy use. Emissions resulting from manure management and enteric fermentation are excluded from this analysis.

Table 5. Alternative crop sequences and diet formulation strategies for Iowa swine farrow-to-finish production systems using conventional confinement scaled to produce 15,600 market pigs weighing 136 kg annually

Item	Corn-soybean-corn-oat sequence,[1] oat-soybean meal diet,[2] simple formulation strategy[3]		Corn-soybean sequence, coproduct diet,[2] complex formulation strategy[3]	
	Nonsolar energy, MJ/pig	100-yr GWP,[4] kg of CO_2 equivalents/pig	Nonsolar energy, MJ/pig	100-yr GWP,[4] kg of CO_2 equivalents/pig
Building construction	87.0	6.7	87.0	6.7
Building operation	186.0	22.8	186.0	22.8
Cultivation of crops	362.0	27.6	55.0	5.6
Processing of feed[5]	137.5	12.0	778.6	24.9
Manure application	16.3	1.3	16.8	1.4
Total	788.8	70.4	1,123.4	61.4
System characteristic	(m^2/pig)			
On-farm feed production area	630.0		320.6	
Off-farm feed production area[6]	94.1		10,300.2	
System characteristic	(kg/pig)			
Imported soybean meal	28.3		0	
Surplus corn grain	50.5		0	
Surplus soybean meal[7]	0		15.7	
Surplus soybean oil[7]	10.4		0	
Oat straw production	33.1		0	

[1]Corn-soybean-corn-oat underseeded with leguminous cover crop.

[2]Oat-soybean meal = corn-soybean meal diet that includes <16% oats; coproducts = maximal amounts of biofuel coproducts.

[3]Simple = no synthetic AA or exogenous phytase; complex = includes synthetic AA and exogenous phytase.

[4]The 100-year global warming potential (GWP) directly associated with energy use. Emissions resulting from manure management and enteric fermentation are excluded from this analysis.

[5]Processing of feed includes energy required to cultivate crops processed into biofuels and coproducts less the NE of feedstuffs not fed to pigs and the GE of the biofuel produced (Lammers et al., 2010b).

[6]Assumes crops grown in a corn-soybean sequence.

[7]Assumes surplus soybeans are converted to soybean meal and soybean oil.

sequence required 720.8 MJ of energy and resulted in emission of 58.3 kg of CO_2 equivalents per market pig sold. This was 3.2% less than the energy associated with the same diet × crop sequence when pigs were housed in conventional confinement. The hoop barn-based system also resulted in 10.3% less 100-yr global warming potential compared with the conventional system. Approximately 25% of the energy used to produce pigs in conventional systems was devoted to heating and ventilating the buildings. This created a more ideal thermal environment that enabled pigs housed in conventional systems to consume less feed per unit of BW gain and less feed overall. Alternatively, about 9% of the energy used to produce pigs in the hoop barn-based system was devoted to heating and ventilating the buildings. Existing hoop barn-based systems require more energy for cultivating and processing feedstuffs than do conventional systems. The increase in energy used for producing feed did not outweigh the energy savings gained by avoiding operation of conventional grow-finish and gestation barns. The hoop barn-based systems examined ultimately required 3.2% less energy and created 10.3% less 100-yr global warming potential compared with the system using conventional confinement facilities.

Less energy is associated with manure handling from hoop barn-based systems than conventional facilities. Injecting liquid pig manure using an umbilical cord system requires 20.8 kJ/L (Wiens et al., 2008). Loading, hauling, and surface spreading the same amount of N as finished swine manure compost requires approximately 66% less nonsolar energy. The major advantage of the conventional system is its ability to retain excreted N and deliver it to cropland in a highly available form. In conventional systems, it was assumed that 25% of excreted N was lost during storage; in the hoop barn-based system, N losses of 50% were assumed. The conventional system thus returned more N to cropland per pig produced, thereby displacing a greater amount of energy-intensive synthetic N.

Previously, we reported an energy use of 1,095.2 and 989.0 MJ/market pig for conventional confinement and hoop barn-based systems, respectively (Lammers et al., 2010a). In that comparison, the hoop barn-based system required 10% less energy than one using conventional confinement facilities. However, that analysis did not include the return of pig manure to cropland and resulting reductions in synthetic crop nutrient application. When pig manure was returned to cropland, energy use for pig production decreased by 27 to 32%

Table 6. Assessment of nonsolar energy and the resultant 100-yr global warming potential (GWP) associated with Iowa farrow-to-finish pig production systems using bedded hoop barns for gestating sows and grow-finish pigs[1]

Item	Corn-soybean sequence, corn-soybean meal diet,[2] complex formulation strategy[3]		Corn-soybean-corn-oat sequence,[4] oat-soybean meal diet,[2] simple formulation strategy[3]		Corn-soybean sequence, coproduct diet,[2] complex formulation strategy[3]	
	Nonsolar energy, MJ/pig	100-yr GWP,[5] kg of CO_2 equivalents/pig	Nonsolar energy, MJ/pig	100-yr GWP,[5] kg of CO_2 equivalents/pig	Nonsolar energy, MJ/pig	100-yr GWP,[5] kg of CO_2 equivalents/pig
Facility construction	72.6	5.5	72.6	5.5	72.6	5.5
Facility operation	67.4	9.9	67.4	9.9	67.4	9.9
Cultivation of crops	464.3	34.4	475.3	35.3	177.2	13.9
Processing of feed[6]	105.5	7.6	141.6	12.3	801.9	25.6
Manure application	4.1	0.3	4.4	0.4	4.6	0.4
Harvesting bedding	6.9	0.6	6.9	0.6	6.9	0.6
Total	720.8	58.3	768.2	64.0	1,130.6	55.9
System characteristic	(m^2/pig)					
On-farm feed production area	553.0		648.8		330.0	
Off-farm production area[7]	0		96.9		10,609.0	
System characteristic	(kg/pig)					
Imported soybean meal	0		29.2		0	
Surplus corn grain	0		52.0		0	
Surplus soybean meal[8]	21.1		0		16.2	
Surplus soybean oil[8]	17.7		17.2		0	
Oat straw production	0		34.1		0	

[1]Scaled to produce 15,600 market pigs weighing 136 kg annually.

[2]Oat-soybean meal = corn-soybean meal diet that includes <16% oats; coproducts = maximal amounts of biofuel coproducts.

[3]Simple = no synthetic AA of exogenous phytase; complex = includes synthetic AA and exogenous phytase.

[4]Corn-soybean-corn-oat underseeded with leguminous cover crop.

[5]The 100-year GWP directly associated with energy use. Emissions resulting from manure management and enteric fermentation are excluded from this analysis.

[6]Processing of feed includes energy required to cultivate crops processed into biofuels and coproducts less the NE of feedstuffs not fed to pigs and the GE of the biofuel produced (Lammers et al., 2010b).

[7]Assumes crops grown in the corn-soybean sequence.

[8]Assumes surplus soybeans are converted to soybean meal and soybean oil.

because of the reduced application of synthetic fertilizers. Because of assumptions regarding N losses from liquid and solid manure storage systems, the relative difference between hoop barn-based and conventional facilities narrowed to the 3.2% reported in the current study.

A simple oat-SBM diet produced in a corn-soybean-corn-oat cropping sequence required 8 to 9% more energy than a complex corn-SBM diet produced in a corn-soybean cropping sequence. This difference was present in both the conventional and hoop barn-based housing systems. Feeding a simple oat-SBM diet was not energetically favorable in either housing system examined. Our analysis demonstrated that regardless of the facility type, it was not energetically preferable to include oats underseeded with alfalfa in a crop sequence intended exclusively to feed pigs. Our results also demonstrated that increasing both the CP and total P contents of swine diets with the intent of reducing the application of synthetic fertilizers to crops was not energetically advantageous. It should be noted that our analysis considered only 2 crop sequences and 3 diet strategies. It is possible that other combinations of crop sequence and diet formulation may produce different results.

It was anticipated that the more complex crop sequence would require less energy for cultivation of crops per pig than would the simpler corn-soybean sequence because of enhanced nutrient cycling. This may indeed be the case if ruminant animals are present to utilize forages produced by perennial legumes. Our current analysis examined only pig production systems and, as such, could not capture some of the energetic benefits of more complex farming systems that include both ruminant and nonruminant animals as well as both perennial and annual crops. Producing swine feed from feedstuffs produced by crop sequences more complex than the typical corn-soybean sequence may require less energy per kilogram of feedstuff. However, the key measure to consider is not energy use per kilogram of feedstuff, but rather energy use per megajoule of NE for pig production generated. Given the limited ability of the pig to utilize cellulosic components of plant material, a corn-soybean crop sequence may be difficult to replace in the Midwest region of the United States. More complex crop sequences may offer soil conservation, biodiversity, and water quality-related benefits, but in order for these crop sequences to be fully utilized, a mix of ruminant and nonruminant animals must be included in the system.

The complex coproduct diet strategy required the most energy input in both conventional confinement and hoop barn-based systems. In terms of energy use per market pig produced, feeding biofuel coproducts to pigs may not be the optimal use of those resources. However, comparative pricing of various feed ingredients at different locations may make feeding biofuel coproducts economical for individual producers. This illustrates how existing markets may not necessarily reward energetic efficiency: although feeding pigs may not be the best use of biofuel coproducts from an energy use standpoint, the economics of feeding DDGS to pigs in many locations is sometimes favorable.

It should be noted that the demonstrated advantages hoop barn-based systems have over conventional confinement facilities in terms of reduced energy use and resultant greenhouse gas emissions are not uniform for all crop sequences and diet formulation strategies. It is not entirely clear why this is the case. However, it suggests that the optimal crop sequence and diet formulation for 1 housing system may not be ideal for another. The current study demonstrated that a corn-soybean crop sequence in conjunction with corn-SBM diets that included synthetic AA and exogenous phytase required the least energy and thus produced less 100-yr global warming potential for both housing options. However, this analysis considered only 3 crop sequence × diet formulation strategies and was far from exhaustive.

Useful Energy Balance

Table 7 summarizes total energy flows for the 2 housing systems under a corn-soybean cropping sequence and complex corn-SBM diet strategy. Previously, we presented the GE of feed consumed by pigs in the 2 housing systems (Lammers et al., 2010a). Gross energy is a poor measure of the biologically useful energy in feedstuffs; thus, for the current analysis, we included NE of feed consumed as an energy input into our system. We also accounted for the export of NE as surplus crops and as pig carcasses. Although our earlier analysis (Lammers et al. 2010a) did not include the nutrient value of pig manure, the current study does. Because pigs housed in hoop barns for grow-finish require more feed than pigs housed in conventional confinement, the total energy needed for hoop barn-based production systems was 1.5% greater than the total energy needed for the conventional confinement system. Each pig produced in the system using hoop barn facilities required 3,981.3 MJ/animal, or 29.3 MJ/kg of BW. Alternatively, housing pigs in conventional facilities required 3,922.5 MJ/animal, or 28.8 MJ/kg of BW.

Energy present in feedstuffs represents both nonrenewable energy inputs and solar energy harvested by the plants through photosynthesis. In our analysis, the energy associated with the cultivation of crops and processing of feed represented the quantified energy inputs into feed production. Thus, the difference between the NE consumed as feed and the energy associated with the cultivation of crops and feed processing represented the solar energy harvested by plants or photosynthetic energy. Photosynthetic energy inputs into pig production systems dwarf all other energy inputs.

The total energy use for the current pig production systems was 28.8 MJ/kg of BW produced. This energy consumption resulted in production of at least 477.9 g of CO_2 equivalents/kg of BW. A hoop barn-based production system reduced greenhouse gas emissions by 10% (428.7 g of CO_2 equivalents/kg of BW) but required

Table 7. Useful energy balance for 2 Iowa pig production systems[1]

Item	Conventional confinement	Hoop barn-based	Conventional: hoop barn
Nonsolar input energy			
Facility construction, MJ/pig	87.0	72.6	1.20
Facility operation, MJ/pig	201.1	78.4	2.57
Cultivation of crops, MJ/pig	354.1	464.3	0.76
Processing of feed, MJ/pig	102.4	105.5	0.97
NE consumed as feed,[2] MJ/pig	4,270.7	4,373.2	0.98
NE exported as crops,[3] MJ/pig	−684.8	−704.7	0.97
NE exported as pig body,[4] MJ/pig	−408.0	−408.0	1.00
Total energy balance,[5] MJ/pig	3,922.5	3,981.3	0.99

[1]Farrow-to-finish systems scaled to produce 15,600 market pigs weighing 136 kg annually, corn-soybean meal crop sequence, and complex corn-soybean meal diets fed in phase. Negative numbers represent energy available for export from the system.

[2]Based on Lammers et al. (2010b).

[3]Calculated as mass of net crop exports (surpluses − imports) presented in Tables 1 to 3, multiplied by NE of feedstuffs as presented by Sauvant et al. (2004).

[4]Calculated as 54.4 kg of DM/market pig (Whittemore and Kyriazakis, 2006) multiplied by 7.5 MJ/kg of DM (Sauvant et al., 2004).

[5]Calculated as total energy inputs − NE exported as crops and pig body.

1.7% more total energy (29.3 MJ/kg of BW). Hoop barn-based systems required less energy to heat and ventilate buildings and thus created less greenhouse gas emission. However, pigs raised in hoop barn-based systems required more feed for thermal regulation; thus, hoop barns required more total energy to operate than conventional confinement facilities.

There are 3 promising approaches to reducing energy use by pig production systems, based on results of this project. The first is reducing energy use in the operation of conventional confinement systems. The use of naturally ventilated buildings and zone temperature control within facilities are available technologies that should be considered and further refined. Second, our analysis assumed identical diets would be fed to pigs housed in conventional confinement facilities and hoop barns. Diets for pigs could be formulated to take into consideration the thermal environment of the pig facility. Hoop barns are a relatively new technology and little research regarding the nutritional needs and optimal genetics of pigs housed in hoop barns has been completed. As the hoop barn-based system is more widely explored and adopted, it is reasonable to expect that the feed conversion differences between the 2 systems will narrow. Finally, increasing the delivery of excreted N and other nutrients to cropland is of critical importance. Approximately 50% of energy associated with pig production was due to crop cultivation. More than 50% of the energy associated with crop cultivation was due to the provision of synthetic fertilizers (Lammers, 2009). It is widely recognized that pig manure is a valuable nutrient resource; however, with reported manure-N losses from storage and application approaching 50%, there is clearly room for improvement in this area.

Current reports from Europe of energy use for pig production range from 5.3 to 23.5 MJ/kg of BW (Basset-Mens and van der Werf, 2005; Eriksson et al., 2005; Williams et al., 2006). Previous analyses have been conducted in Europe and have considered crop production and feed processing scenarios different from those we have presented. Others have not included facility operation, focusing exclusively on feeding strategies. With more than 35% of total energy use required to produce a pig resulting from facility construction and operation, reports that do not include this aspect of pig production are incomplete. Energy use for the Upper Midwest region of the United States was last estimated as 26.2 MJ/kg of BW based on 1975 production statistics (Reid et al., 1980). This estimate does not include the energy present in the feedstuffs consumed by the pigs (Reid et al., 1980).

The present study demonstrates that raising pigs in conventional systems operating in Iowa uses 5.5 MJ of energy/kg of BW. An alternative system using hoop barns for grow-finish pigs and gestating sows uses slightly less energy or 5.3 MJ/kg of BW. If we include the NE of feed consumed by pigs and consider the NE exported as the pig carcass and surplus crop products, the conventional system requires 28.8 MJ/kg of BW and a system using hoop barns for gestation and grow-finish requires 29.3 MJ/kg of BW. Energy use by conventional pig production systems in the Midwest region of the United States results in production of 65.0 kg of CO_2 equivalents per market animal (477.9 g/kg of BW). A system that uses hoop barns for grow-finish pigs and gestating sows may reduce the 100-year global warming potential by 10% (58.3 kg of CO_2 equivalents/animal or 428.7 g/kg of BW).

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