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Energy and carbon inventory of Iowa swine production facilities

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ABSTRACT

This study evaluates energy and carbon use by two types of facilities—conventional confinement and hoop barn-based—within farrow-to-finish pig production systems scaled to produce 5200 and 15,600 market pigs annually in Iowa. The United States is the world's second largest producer of pork with pig production centered in the state of Iowa. Conventional confinement facilities are typical of pork industry practice in the United States and are characterized by individual gestation stalls and 1200 head grow-finish buildings with slatted concrete floors and liquid manure systems. The hoop barn-based alternative uses group pens in bedded hoop barns for gestation and finishing. Both systems use climate controlled farrowing facilities with individual farrowing crates as well as climate controlled nursery facilities. Feed is the single largest operating resource in pig production systems and feed fed to grow-finish pigs accounts for 63–65% of total energy use in raising pigs. The other stages of production are more reliant on non-renewable fuels and ignoring these stages of production misses 54–80% of the non-renewable fuel use associated with pig production. Taking into account demonstrated performance differences, hoop barn-based pig production requires 2.4% more feed and similar total energy as conventional pig production. Hoop barn-based pig production requires 63–64% less non-renewable fuel and results in 35% less emissions. There is little (<0.3%) energetic advantage to increase the scale of pig production from 5200 to 15,600 market pigs annually. Excluding the gross energy of feedstuffs fed to pigs, producing pigs in Iowa requires 7.2–8.2 MJ/kg live weight and results in emission of 1.0–1.6 kg CO_2 equivalents/kg live weight. This compares favorably with published energy assessments of pig production for European systems. Using hoop barns for grow-finish pigs and gestating sows is an effective strategy to reduce direct use of fossil fuels for pig production and may minimize global climate altering emissions.

1. Introduction

Meat production and demand is increasing throughout the world, and pork is the most widely consumed meat globally (Delgado et al., 1999; FAO, 2006). The United States is the world's second largest producer of pork (den Hartog, 2005) and has long been a leader in modern pork production. Historically the availability of fossil fuels has minimized pressure to critically consider their use in pig production. Rising energy prices, global conflicts, and recognition of the environmental impacts of using fossil fuels are increasing awareness and incentive to optimize use of these limited resources.

Multiple environmental assessments of pig production have been performed for modern European systems (Uhlin, 1998; Halberg, 1999; Zhu and van Ierland, 2004; Basset-Mens and van der Werf, 2005; Eriksson et al., 2005; Stern et al., 2005; Williams et al., 2006; Dalgaard et al., 2007; Meul et al., 2007). However there are major differences in scale of operation, diet composition, pig performance, targeted market weight, and climate between commercial pig farms in Europe and North America which limit the application of European models to evaluate US pig production systems. United States pig production is centered in Iowa (USDA, 2002b) and is a major influence on the economic and ecological condition of that region. Environmental impact of pig production is likely associated with type of facilities used and scale of production. Thus the objective of this project was to estimate energy use and resulting greenhouse gas emissions for two different types and scales of Iowa swine production facilities.

Energy use can be classified into two broad categories—embodied and operating. Embodied energy refers to the quantity of energy required to manufacture, provide, or supply a product, material, or service (Hammond and Jones, 2008). In pig production, energy used to produce facility components such as concrete, steel, plastics, and lumber are examples of embodied energy. Operating energy is the energy required for a system to function on a daily basis. The energy value of the feed directly consumed by pigs as well as liquid fuels and electricity used to modify the pig environment are examples of operating energy for pig production.

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Embodied carbon is the CO_2 and other greenhouse gases released during the production of a product (Hammond and Jones, 2008) and represents the initial global climate altering emissions associated with a product. Emissions of compounds associated with global climate change occur during fuel consumption and are often expressed in terms of CO_2 equivalents. The operating carbon of a pig production facility is simply the CO_2 equivalents released through consumption of operating energy inputs associated with pig production. Operating energy components also have embodied energy and carbon associated with their provision, but in most cases these are not included in our analysis.

2. Methods

This project considers energy inputs (embodied and operating) into a pig facility based on physical material flows. Energy used to produce facility components such as steel, plastics, and lumber are examples of embodied energy. Operating energy inputs are used directly for pig production and include feed consumed by the pigs, liquid fuels used to heat buildings and remove manure, and electricity used to ventilate and illuminate buildings. To borrow terminology from economics, operating energy can be considered analogous to variable costs—costs that are incurred (energy that is used) only if actual pig production occurs. Alternatively, embodied energy can be viewed as fixed costs—costs that are incurred (energy that is used) to create and maintain the means of production even if no pigs are produced.

Energy inputs can be used to calculate embodied carbon and emission of CO_2 equivalents. Embodied carbon is the CO_2 and other greenhouse gases released during the production of facility components (Hammond and Jones, 2008) and represent the initial CO_2 cost of building different types and scales of pig facilities. Emissions released by consumption of operating energy represent the annual addition of CO_2 equivalents resulting from raising pigs using a particular housing system. Standardized 100-year global warming potential values for emissions expressed in terms of CO_2 equivalents (IPCC, 2006, 2007; EPA, 2008) are used throughout our analysis.

Two types of facilities—conventional confinement and bedded hoop barn-based—are considered within identically scaled farrow-to-finish production systems. The conventional confinement system is typical of pork industry practice in the United States and is characterized by individual gestation stalls and 1200 head grow-finish buildings with slatted concrete floors and liquid manure systems. The hoop barn-based alternative uses group pens in bedded hoop barns for gestation and finishing. Both systems have been previously described by the authors (Lammers et al., 2009) and use climate controlled farrowing facilities with individual farrowing crates as well as climate controlled nursery facilities. Energy and carbon use is also related to volume of pig flow and so pig production systems sized to produce batches of either 400 or 1200 136-kg market pigs every 28 d, or 5200 and 15,600 136-kg market pigs annually are compared.

2.1. Embodied energy and carbon of swine production facilities

Five primary building materials are examined: concrete, steel, lumber, insulation, and thermoplastics. The mass of building materials reported by Lammers et al. (2009) for each type of pig production facility was multiplied by embodied energy and carbon data presented by Hammond and Jones (2008). Table 1 summarizes material density, embodied energy, and embodied carbon assumptions for the building materials examined.

Table 1
Density, embodied energy, and embodied carbon for building materials examined.[a]

Material	Density, g/cm^3	Embodied energy, MJ/kg	Embodied carbon, kg CO_2/kg
Concrete	2.40	0.95	0.129
Steel	8.08	24.40	1.770
Lumber	0.53	7.40	0.450
Thermoplastics	0.95	76.70	1.600
Cellulose insulation	0.03	2.12	0.000

[a] From Hammond and Jones (2008).

Another source of embodied energy and carbon of pig buildings is the diesel fuel used for earthwork associated with the construction of pig facilities. Estimated diesel fuel use for these activities have been reported by Lammers et al. (2009). The volume of diesel fuel reported by Lammers et al. (2009) was multiplied by an energy value of 38.46 MJ/L (Downs and Hansen, 1998) to estimate the energy used for earthwork. Embodied carbon from diesel fuel used for earthwork was calculated by multiplying the energy in GJ from diesel fuel associated with construction by 82.73 kg CO_2 equivalents/GJ (IPCC, 2006).

Embodied energy and carbon of pig production facilities represent one-time inputs that occur at the time of construction. To take into account the useful lifespan of different pig facilities it is appropriate to divide total embodied energy and carbon from construction by the estimated useful lifespan of a facility. Construction costs of conventional confinement facilities are often assumed to be paid over a 15-year useful lifespan. Hoop barns are often used for similar time frames, although replacement of the tarp is sometimes necessary after 10 or 12 years of use. Two different scenarios are considered for hoop barns. The first assumes that the useful lifespan of hoop barns are identical to the useful lifespan of conventional confinement facilities. The second includes additional embodied energy and carbon required to replace all tarps on hoop barns once during a 15-year useful lifespan.

2.2. Operating energy of pig production facilities

Energy use for one 365-d period was modeled for each phase of pig production. This analysis examines energy use of production facilities and includes thermal environment control (heating and ventilation), pumping water, cleaning the facility between groups of pigs, lighting, consumed pig feed, bedding use, and removing manure slurry or bedding pack from the building. Assessments of operating energy are highly dependent on where the system boundary is drawn. For this analysis the boundary is the pig production facility, more explicitly the actual pig barn. Initial start-up energy for a new building can be significant, for example bringing a newly constructed nursery building or one that has been idle for an extended period of time up to an acceptable temperature in the middle of winter requires a large input of energy simply to warm the building structure. For our analysis, production is assumed to have reached steady-state; i.e. the buildings are in operation and pigs are regularly flowing through them. Two performance scenarios are considered. The first analysis assumes that feed conversion and sow reproductive performance is equal for conventional confinement and the hoop barn-based alternative. The second analysis incorporates reported performance differences for pigs and sows housed in hoop barns.

2.2.1. Thermal climate control

Thermal climate is the sum effects of air temperature, moisture, and airflow experienced by pigs (Curtis, 1983). Building characteristics and exterior temperatures as well as the number and size of pigs present affect the thermal climate of a pig barn. Mechanically ventilated pig barns commonly use liquefied petroleum (LP) gas and electricity to provide a suitable thermal environment for pigs.

Hoop barns are naturally ventilated buildings that rely on bedding and pig behavior to modify thermal environment. This section addresses energy use for mechanical control of thermal climate in pig barns. Building dimensions, thermal resistance, and pig stocking density match facilities described previously (Lammers et al., 2009).

Mason City, 43.1°N, 93.2°W, shares a latitude that is similar to six of the top 10 pig producing counties in Iowa (USDA, 2002a). In Iowa, latitude is more predictive of thermal environment than longitude and so Mason City was selected as most representative of climatic conditions experienced by pig farms in Iowa. Hourly temperature readings for a typical meteorological year for the 1961–1990 time period have been summarized for selected locations into reference tables commonly referred to as BIN data (Kjelgaard, 2001). Energy used for thermal environment control at Mason City, Iowa was modeled using annual BIN data as exterior temperature for one complete year—365 d or 8760 h.

Table 2 presents building occupancy, sensible heat production by pigs, target room temperatures, and ventilation rates used to estimate energy use for thermal control of conventional swine facilities. Farrowing, nursery, and finishing barns are emptied and cleaned between groups of pigs. This results in those buildings housing zero pigs for 1–15% of the year. When no pigs are in a given building it is assumed that heat production is zero, that ventilation is reduced to 650 $L \times min^{-1} \times building^{-1}$, and that room temperature is maintained between 10 and 32.2 °C.

The step-by-step process for calculating energy use for thermal control of swine facilities has been presented previously (Lammers, 2009). Worksheets from MidWest Plan Service publications (MWPS, 1987, 1990a,b) were combined with historic temperature data for Mason City, Iowa (Kjelgaard, 2001), and model assumptions presented in Table 2 to calculate energy used for thermal climate control of pig facilities. The difference between heat produced by pigs and the sum of heat loss from building surfaces and minimum ventilation were calculated for 8760 h (1 year) of production. If the hourly difference was negative, additional heat inputs were necessary and if the difference was positive additional cooling tactics may be required. Hourly heat input needs were summed to determine annual heat input requirements. Based on manufacturer literature and conversations with heating equipment representatives it was assumed that heating strategies would be 98% efficient. Thus annual heat input requirements were divided by 98% to estimate total energy used for heating during a typical year.

For each type of pig facility, two sets of commercially available fans with adequate capacity for a particular task—air quality or temperature modification—were selected from a third party database (BESS, 2008). Hours of operation for each set of fans were estimated for each stage of production by combining annual BIN data with pig and building characteristics. Energy use for air exchange was then calculated by multiplying the hours of operation for each fan system by reported fan efficiencies (BESS, 2008). To standardize comparisons, fan system efficiencies of 339.8 $L \times min^{-1}/W$ and 736.2 $L \times min^{-1}/W$ (12 cfm/W and 26 cfm/W) were used for air quality and temperature modification systems respectively.

The environment of the farrowing facility is a unique situation because the thermal needs of both the newborn pig and the adult sow must be addressed. Although the newborn pig has no practical upper limit for room temperature, the sow will reduce feed intake and subsequent milk production if she becomes uncomfortably warm. To address these different requirements, the room temperature of the farrowing facility is assumed to be kept at 18.3 °C with an allowable maximum of 21.1 °C. The higher temperatures necessary for young pig comfort are achieved through the use of supplemental radiant heating that does not significantly contribute to overall room temperature. For each litter of pigs farrowed it was assumed that two 175 W heat lamps are used for 48 h followed by 12 d of one 175 W heat lamp use.

2.2.2. Water

Water is essential to pig survival and growth and large quantities of water are used to clean most pig facilities. Wash water is usually heated and pressurized to assist in the cleaning process. Pumping water to a pig facility as well as heating and pressurizing wash water requires energy and is included in our analysis. Water use assumptions used to calculate required water volume are based on literature values (Fulhage and Hoehne, 2001; Thacker, 2001) and have been previously presented (Lammers, 2009). Appropriately sized well pumps were selected for the different facility sites based on water volume using MWPS guidelines (MWPS, 1987). For our analysis we assume a 0.37 kW motor with a pumping capacity of 20.8 L/min at 275.8 kPa, and a nominal efficiency of 82.5% (NEMA, 2009). Volume of water, well pump capacity, and motor efficiency were used to calculate the amount of energy needed for pumping water from the well and pressurizing water lines used for drinking water.

Most conventional confinement facilities in Iowa are cleaned using portable pressure washers and a variety of designs and specifications are commercially available. For our analysis we assume that the pressure washer will deliver 20.8 L/min at 31 MPa. The washer will be powered by a 14.9 kW electric motor with a nominal efficiency of 91.7% (NEMA, 2009). The hours of motor operation

Table 2
Building occupancy, pig size and heat production, target temperature and minimum ventilation rate assumptions for estimating energy use for thermal climate control of conventional swine facilities.

Building	Occupancy[a]		Pig body weight, kg	Sensible heat[d], kJ/pig	Room temperature[b]		Ventilation rate[c]	
	Stocked, h/yr	Empty, h/yr			Min, °C	Max, °C	Min. [e], $L \times min^{-1} \times h\,d^{-1}$	Max. [f], $L \times min^{-1} \times h\,d^{-1}$
Farrowing[g]	7447	1314	142.9	897.9	18.3	21.1	566	14,158
Nursery	7896	964	18.8	188.4	19.5	25.5	85	991
Grow-finish	8672	88	85.3	531.4	15.5	22.5	283	3398
Gestation	8760	0	157.0	598.2	12.8	21.1	396	4248

[a] Based on Lammers et al. (2009): farrowing 24 d/turn × 13 turns/yr; nursery 50 d/turn × 6.5 turns/yr; grow-finish 109 d/turn × 3.3 turns/yr; gestation continuously occupied.
[b] Based on Holden et al. (1996), Carr (1998), and Wathes and Whittemore (2006). Min and max is the temperature at which heat must be added or removed, respectively, to maintain pig comfort and performance.
[c] From MWPS (1990b).
[d] Calculated based on Pedersen (2002) and Brown-Brandl et al. (2004).
[e] Minimum ventilation rate to maintain acceptable air quality and humidity inside building.
[f] Maximum allowed ventilation rate, coupled with additional cooling strategies to reduce interior temperature of building.
[g] Lactating sows will be housed in the farrowing facility with their litter of pigs. Presented body weight and sensible heat production is for the sow only.

needed for a particular task were calculated based on water usage and flow rates. Energy used for water delivery and pressurization was calculated by combining motor size, hours of operation, and nominal efficiency. The pressure washer was assumed to have a diesel burner with capacity to raise the temperature of wash water by 60 °C at 95% efficiency. The temperature of ground water in Iowa is approximately 8 °C (USGS, 2008). It is assumed that wash water would be heated to 60 °C. Heat energy necessary to increase the temperature of the wash water by at least 52 °C was first calculated using the density and specific heat of water in combination with volume of wash water used. Energy used for heating wash water was then taken as 105% of the calculated heat energy.

2.2.3. Illumination

Adequate illumination is essential for conscientious stockmanship and electric lighting of mechanically ventilated facilities is common. Compact fluorescent lights with an efficiency of 68 lm/W were modeled in this analysis. Energy use for illumination in conventional confinement facilities was calculated using ASAE recommendations for pig facilities (ASAE, 2005). It was assumed that 100% of the floor area in the confinement facility would be illuminated and that hours of operation would match ASAE recommendations (ASAE, 2005) Hoop barns use some electric lights, but typically only 33–50% of the barn is illuminated. Natural lighting also allows reduction in the hours electrical lights are needed. Energy used for illuminating 50% of the total floor area was calculated for hoop barns. It was also assumed that hours of illumination in hoop barns would be 50% of ASAE recommendations because of natural lighting (ASAE, 2005).

2.2.4. Feed

Feed is typically the largest expense in farrow-to-finish pig operations and the amount of energy associated with feed is also very large. Operating energy in our analysis is the energy directly consumed by pigs as feed and the energy required for the system to function on a daily basis. With that in mind, the gross energy (GE) of the feed presented to pigs and the energy used to move feed from on-site storage to feeders are clearly energy components that fall within our system boundary.

It is estimated that producing one 136.0 kg market pig under typical Iowa conditions requires 411.1 kg of feed (Lammers et al., 2010). Approximately 13% of the feed attributed to producing 1 market pig is devoted to sow nutrition—37.0 kg during gestation and 15.6 kg during lactation (Lammers et al., 2010). The individual growing pig consumes 51.0 kg during the nursery stage, and 307.5 kg during the grow-finish phase (Lammers et al., 2010). On average the GE of pig feed fed from farrow-to-finish is 16.0 MJ/kg (Sauvant et al., 2004; Lammers et al., 2010). Total feed energy consumed was calculated by multiplying feed use per market pig sold by GE value of feed by the total number of market pigs sold in a particular system.

Commercially available feed augers were selected to move feed from bulk storage bins to pig feeders. The size of electric motors used for feed delivery in a particular facility was determined based on auger and feed characteristics (APS, 2008). All electrical motors used for feed delivery were assumed to have a nominal efficiency of 82.5% (NEMA, 2009). Hours of operation for feed auger motors were calculated using manufacturer capacity estimates (APS, 2008). Hours of operation, motor size, and nominal efficiency were combined to calculated energy used for feed delivery.

The energy required to provide swine diets in Iowa is dependent upon crop sequence, diet formulation strategy, and feed ingredient choice (Lammers et al., 2010). Feed production falls outside of our defined system boundary. However because feed is the major component of pig production systems, our analysis includes the embodied energy and resultant carbon emissions associated with feed provision. Based on Lammers et al. (2010) it is estimated that each kg of feed requires 2.0 MJ of production energy.

2.2.5. Bedding

Hoop barns for pigs require bedding to effectively operate. Large round bales of cornstalks are the most commonly used bedding for gestation and grow-finish pigs in Iowa. A single bale weighs approximately 544 kg and occupies approximately 2.8 m^2 of area. In Iowa, bedding is baled following corn harvest in October–November and stored for use throughout the year. Usually only bedding that will be exposed to heavy spring and summer rains is stored under shelter (Harmon et al., 2004). Thus for our analysis we assume storage space in hoop barns adequate for 50% of the required bedding for a particular system. Each finishing pig sold will require approximately 91 kg of bedding (Brumm et al., 2004). Each gestation space will require approximately 730 kg of bedding annually (Harmon et al., 2004). The GE of corn stover ranges between 16.7 and 20.9 MJ/kg dry matter (Pordesimo et al., 2005). We assume that baled cornstalks are 85% dry matter, thus the GE value of cornstalk bedding used in this analysis is 14.2 MJ/kg of cornstalk bedding. The energy needed to bale and deliver cornstalks to the hoop barn site is assumed to be 53.4 kJ/kg of bedding (Lammers et al., 2010).

2.2.6. Manure handling

Energy required to remove manure from the production facility is included in this analysis. It was assumed that liquid slurry was agitated and pumped from the storage pits annually. It was assumed that the pump/agitator would require 41 kW and would have a capacity of 7500 L/min when agitating and 6500 L/min when pumping slurry from a 2.4 m deep pit. Liquid manure volume was calculated using reference excretion data for different body weights of pigs (ISU, 2003). Water used to clean pig barns ultimately is removed from the building as manure slurry. The volume of wash water for each barn was calculated based on Fulhage and Hoehne (2001). Total manure slurry volume was calculated by combining the volumes of manure and wash water and used to estimate annual energy use for agitating and pumping liquid slurry. A representative tractor-driven slurry pump was selected based on manufacturer literature and interviews with technical support staff. For this analysis we assumed a slurry pump with a capacity of 6500 L/min when pumping and 7500 L/min when agitating. An appropriately sized diesel tractor was selected to power the slurry agitator using the Nebraska Tractor Test Laboratory database (NTTL, 2008). The tractor identified has an expected fuel efficiency of 16.42 L/h operation while agitating and pumping liquid manure (NTTL, 2008). Calculated hours of operation were multiplied by fuel use per hour to estimate total fuel use for agitating and pumping liquid manure slurry. Energy used for liquid manure handling was calculated by multiplying the volume of diesel fuel used by an energy value of 38.46 MJ/L (Downs and Hansen, 1998).

Bedded hoop barns are cleaned between groups of pigs using a tractor with mechanical front-wheel drive and a front-end loader. For our analysis we assume that the bedding pack is moved from the hoop barn to a compost site within 300 m of the hoop barns. The model assumes the bedding pack in hoop barns for gestating sows is removed twice annually. Hoop barns for grow-finish pigs are typically cleaned out and re-bedded between each group of pigs and that is what our model assumes. Based on our experience a 21.9 × 9.1 m bedded hoop barn can be cleaned and re-bedded in 2 h if the removed bedding is stored on site. Tractors used to clean hoop barns typically have mechanical front-wheel drive and a power take-off that delivers a maximum power of 48–63 kW. When cleaning a hoop barn, maximum tractor power is not required for the entire time, thus to calculate fuel use, reported fuel consumption for an appropriately sized tractor operating at 83% of maximum power (16.42 L/h) was used (NTTL, 2008).

2.2.7. Demonstrated performance differences

The efficacy of converting feed into pork is affected by housing conditions. Because feed is by far the largest source of operating energy it is important to consider feed use by pigs raised in different types of facilities. In a 3-year study in Iowa, Honeyman and Harmon (2003) compared growth and performance of grow-finish pigs housed in bedded hoop barns and conventional confinement. During summer (June–October) gain-to-feed was not different for the two systems but during winter (December–April) pigs housed in deep bedded hoop barns required 8.2% more feed per unit of gain (Honeyman and Harmon, 2003). Based on historic climate data for Iowa, it is estimated that for approximately 40% of the year (146 d) temperatures are sufficiently cold ($\leqslant$7 °C) to require more feed per unit of gain in bedded hoop barns compared to conventional systems (Kjelgaard, 2001; ISU, 2008). During other days of the year feed consumption is identical for pigs housed in bedded hoop barns and conventional finishing buildings. Feed use for grow-finish pigs in hoop barns was calculated to be 103.3% of conventional grow-finish feed use or 317.6 kg/market pig. Because identical farrowing and nursery facilities are used by both systems, feed consumption by lactating sows and nursery pigs in the hoop-based system is identical to the conventional system or 15.6 and 51.0 kg of feed per market pig, respectively.

Annual feed use for gestating sows housed in hoop barns was assumed to be 7% more than feed use by gestating sows in conventional confinement facilities (Lammers et al., 2008). Reproductive performance of group housed sows in hoop barns is equal to sows housed in individual gestation stalls and for some measures may be improved (Lammers et al., 2007). Sows housed in hoop barns for gestation gave birth to 7.5% more live pigs per litter and had equal pre-wean mortality rates as sows house in individual gestation stalls (Lammers et al., 2007). Gestating sow feed consumption per litter in bedded hoop barns was estimated as 107% of gestating sow feed use in the conventional system, but 7.5% more pigs per litter are assumed to be marketed from sows gestated in hoop buildings. Taking into consideration these performance differences, gestation feed per market pig sold from the hoop barn-based system is equal to or slightly less than gestation feed per market pig sold from the conventional system. We assume feed that gestation feed per market pig sold for both systems is 37.0 kg. Each market pig in the conventional system was attributed 411.1 kg of feed. Taking into account demonstrated performance differences (Honeyman and Harmon, 2003; Lammers et al., 2007), farrow-to-finish swine farms using bedded hoop barns for gestating sows and grow-finish pigs require approximately 2.4% more feed annually than conventional systems or 421.2 kg per market pig.

Originally it was assumed that prolificacy and sow inventory would be identical for the two systems (Lammers et al., 2009). Taking into consideration the demonstrated differences in prolificacy, fewer sows are needed in the hoop barn-based system. A hoop barn-based production system with 7.5% greater sow prolificacy compared to conventional confinement sows would require 45 vs. 48 and 130 vs. 140 farrowing crates to produce 5200 and 15,600 market pigs. Similarly gestation spaces required for the hoop systems is 288 (eight hoop barns) and 838 (23 hoop barns) vs. 310 and 900 individual gestation stalls. Because fewer hoop barns were needed for gestating sows in the second analysis, bedding use and energy required to remove bedding and manure pack was adjusted accordingly. Energy use for heat lamps in the farrowing facility was also reduced to match the number of sows in farrowing crates for the hoop barn-based system. Modeled energy use for ventilation and heating of the farrowing barn in the hoop barn-based system was either less than or equal to the conventional system. Because the reduction in modeled energy use for ventilation and heating was very small, no adjustments were made for these parameters.

2.3. Energy type and greenhouse gas emission

Energy comes from several fuels. Operating energy for mechanical control of the thermal environment, water, lights, feed, bedding, and manure handling was calculated and then divided by fuel type. Emissions of three greenhouse gases—CO_2, CH_4, and N_2O—were estimated based on fuel type (IPCC, 2006; EPA, 2008). Standardized global warming potentials for the three gases of interest (IPCC, 2007) were used to calculate emission of CO_2 equivalents or operating carbon by fuel type. Operating energy and carbon were then totaled for each system considered.

Two fuel categories are considered in this analysis: renewable and non-renewable. It is generally accepted that non-renewable fuels require long periods of time to form and that reserves are being used faster than the rate of formation. Alternatively renewable fuels are fuels that are consumed at rates similar to their rate of regeneration. In our analysis there are three types of non-renewable fuel: electricity, LP gas, and diesel. Electricity is not inherently non-renewable, for example electrical generation using wind turbines is growing in Iowa and is generally considered a renewable source of electricity. However, more than 75% of electricity in Iowa is produced by burning coal (EIA-DOE, 2009) and coal is indisputably a non-renewable fuel. Similarly there has been rapid growth in production and use of biodiesel—monoalkyl esters derived from vegetable oils or animal fats rather than petroleum. Biodiesel is typically considered a renewable fuel, but the majority of diesel used in Iowa is petroleum based which is non-renewable. In this analysis the category renewable fuel refers exclusively to sources of energy that can be regenerated annually. Feed and bedding are produced from annual crops in Iowa and are the two types of renewable of fuel included in our analysis.

2.3.1. Non-renewable fuels

In this analysis electricity is used for pumping water, air exchange, moving feed from storage to feeders, illumination, auxiliary heat lamps in the farrowing barn, and similar activities. Domestic electricity generation emission factors are available for Iowa (EPA, 2008). It is calculated that 229.32 kg of CO_2 equivalents are released for every GJ of electrical energy used (IPCC, 2006, 2007; EPA, 2008).

Liquefied petroleum (LP) gas is commonly used to heat pig facilities in Iowa. In our analysis, energy used for heating pig facilities will originate from LP gas. It is calculated that 63.52 kg of CO_2 equivalents are released for every GJ of energy that originates from liquefied petroleum gas (IPCC, 2006, 2007).

Diesel fuel is a common source of mobile energy on Iowa farms. Energy used for handling bedding and manure and heating wash water is assumed to originate from diesel fuel. It is calculated that 82.73 kg of CO_2 equivalents are released for every GJ of energy that originates from diesel fuel (IPCC, 2006, 2007).

A combination of diesel fuel, LP gas, and electricity is used to provide pig diets (Lammers et al., 2010). Based on Lammers et al. (2010) we estimate that each kg of feed provided to pigs results in release of 0.14 kg CO_2 equivalents. Thus 57.55 kg of CO_2 equivalents is associated with providing nutrition for each 136-kg market pig in conventional Iowa systems.

2.3.2. Renewable fuels

Most feed and all bedding material comes from annual plants and are considered renewable fuels in this analysis. The GE of feed and bedding delivered to pigs is the potential renewable energy consumption of a given facility. Because feed and bedding originate from annual plants, no net CO_2 emissions are associated with these forms of energy in this analysis.

Renewable fuels are further divided between energy that is directly consumed (feed) and energy that is recycled (bedding). Swine feed is consumed by pigs and converted to meat and other tissue. Metabolism is not 100% efficient and some of the energy delivered as feed is lost in manure, urine, and gaseous emissions. The GE of feed eaten by pigs is irretrievably transformed and so it is truly consumed energy. Alternatively, cornstalks used for bedding are not significantly altered in form. Pigs use bedding for lounging, dunging, and controlling their thermal climate. Little bedding is eaten by pigs and so the mass of bedding that enters a hoop barn is later removed with additional mass (and energy) from urine and feces. Generation of energy from combustion of corn stalks in Iowa is very small and most corn stalks are simply returned to the soil following harvest. Cornstalks used for bedding are also ultimately returned to cropland, and so any energy found in cornstalk bedding is not consumed but rather recycled back to cropland after a short ($\leqslant$1 yr) delay. Because the boundary of this analysis is drawn around the pig production facility, implications of this delayed return of cornstalks to cropland as well as delivering crop nutrients as pig manure and subsequently reducing synthetic fertilizer application are beyond the scope of this paper.

2.3.3. Other emissions

Swine production systems transform non-renewable and renewable streams of energy into meat and other tissue. The efficiency of this conversion is not 100%. The consumed energy that is lost as feces, urine, or through enteric fermentation is assumed to be associated with feed intake. Livestock production results in emission of CH_4 from enteric fermentation and CH_4 and N_2O emissions associated with manure management. Our analysis incorporates assumptions specified by IPCC (2006) to estimate emissions of CO_2 equivalents from enteric fermentation and manure management. Under the assumption of equal feed intake the only differences in other emissions between conventional and hoop barn-based systems results from manure management. When production differences are incorporated enteric fermentation from pigs raised in hoop barn-based systems is modeled to increase linearly with feed consumption.

3. Results

3.1. Annual embodied energy and carbon during useful life of facilities

Table 3 presents annual embodied energy and carbon of all buildings under a 15-year useful lifespan scenario. Each year, the conventional confinement system scaled to produce 15,600 market pigs annually is allotted 87.0 MJ and 6.7 kg embodied energy and carbon respectively. This is 18% less investment energy compared to the smaller conventional system but is still $\geqslant$20% more embodied energy and carbon compared to the similarly scaled hoop barn-based system. In all cases increasing from 5200 market pigs/yr to 15,600 market pigs/year reduces embodied energy and carbon investments. Adding replacement tarps into the analysis increases the embodied energy and carbon of the hoop barn-based system slightly. The overall advantage of hoop barn-based facilities sized to produce 15,600 market pigs annually is maintained in spite of this increase. Hoop barn-based facilities sized to produce 5200 market pigs annually require greater embodied energy, but less embodied carbon per market pig than conventional confinement facilities sized to produce 15,600 market pigs. The conventional confinement facility sized to produce 5200 pigs annually requires the most embodied energy and carbon per market pig of all facility types examined.

3.2. Operating energy of pig facilities

The estimated annual energy use per pig space for thermal environment control of different phases and scales of conventional confinement facilities located near Mason City Iowa is presented as Table 4. Providing adequate heat accounts for 86–97% of the estimated energy use for thermal environment control in pig barns. Increasing from 5200 to 15,600 market pigs annually reduces energy use per pig space by 5–8% for most production phases.

Thermal control of farrowing facilities requires at least 225% more energy per pig space than any other production facility. This is not unexpected but highlights the importance of including all phases of pig growth in assessments of pig production. Farrowing buildings must be kept at higher temperatures than other buildings to meet the thermal needs of young pigs. Farrowing buildings also have less density of pig spaces than other building types. Conventional confinement gestation facilities are estimated to use more energy per pig space than nursery and grow-finish facilities but less than farrowing barns. Providing heat is the major use of energy for thermal control of conventional pig facilities for all production phases in Iowa. As growing pigs increase in size, less energy is used for heating buildings and more is used for ventilation. Approximately 96–97% of the energy use for thermal control of farrowing barns is associated with providing heat. Alternatively, 86% of the energy use for thermal control of grow-finish buildings results from providing heat.

Table 5 details the operating energy for different types and scales of pig production facilities by fuel type and activity when feed conversion and reproductive performance are identical for the two systems. Liquefied petroleum gas for heating pig barns is the single largest non-renewable energy input for conventional

Table 3
Annual allotment of embodied energy and carbon for 15-year useful lifespan of different pig production systems by scale and facility type.[a]

System	Embodied energy, MJ/market pig	Embodied carbon, kg/market pig
5200 Market pigs/year		
Conventional	102.8	7.6
Hoop barn-based	92.3	6.2
Hoop barn-based, replace tarps once	94.5	6.3
15,600 Market pigs/year		
Conventional	87.0	6.7
Hoop barn-based	70.9	5.4
Hoop barn-based, replace tarps once	72.6	5.5

[a] As described by Lammers et al. (2009).

Table 4
Annual energy use per pig space for thermal environment control of different phases and scales of conventional confinement facilities in Mason City, Iowa.[a]

Barn	Scale, market pig/yr	Pig spaces	Ventilation, MJ/space	Heat, MJ/space	Auxiliary heat, MJ/space	Total, MJ/space
Farrowing	5200	48	114.6	1433.3	2737.5	4285.4
Nursery	5200	880	16.0	246.0	0	262.0
Grow-finish	5200	1600	37.5	230.0	0	267.5
Gestation	5200	310	144.2	1175.5	0	1319.7
Farrowing	15,600	140	188.6	1378.6	2737.5	4304.7
Nursery	15,600	2600	15.4	226.4	0	241.8
Grow-finish	15,600	4800	35.0	210.5	0	245.5
Gestation	15,600	900	144.4	1112.6	0	1257.0

[a] Mason City, 43.1°N, 93.2°W.

Table 5
Operating energy of different systems and scales of pig facilities by fuel type and activity.[a]

System	Conventional		Hoop barn-based	
Market pigs per year[b]	5200	15,600	5200	15,600
Non-renewable energy, MJ/market pig				
Electricity				
Ventilation	26.9	26.6	5.3	5.1
Auxiliary heat	25.3	24.6	25.3	24.6
Water delivery	2.6	2.5	2.6	2.5
Pressure washing	3.4	3.2	0.9	0.7
Illumination	6.5	5.8	3.8	3.7
Feed delivery	2.7	1.0	0.2	0.3
Liquefied petroleum gas				
Building heat	109.5	103.5	21.1	20.3
Diesel fuel				
Heating wash water	16.8	15.9	4.6	4.4
Manure handling	3.0	2.9	11.2	10.9
Total non-renewable energy	196.7	186.0	75.0	72.5
Renewable energy, MJ/market pig				
Feed	6534.4	6534.4	6534.4	6534.4
Bedding into barn	0	0	1910.2	1890.2
Bedding removed from barn			(1910.2)	(1890.2)
Net renewable energy	6534.4	6534.4	6534.4	6534.4
Total energy, MJ/market pig	6731.1	6720.4	6609.4	6606.9

[a] Feed conversion and reproductive performance identical for both systems.
[b] 136-kg finished weight.

systems. The hoop barn-based system uses 80% less energy as liquefied petroleum gas compared to conventional systems. Hoop barns do not use mechanical systems to provide heat, but use bedding packs. Removal of bedding packs with a front-end loader occurs between every group of grow-finish pigs, or 3.3 times annually in our analysis. Liquid manure storage pits typical of conventional systems are usually designed to store manure slurry for a year. Our analysis assumes liquid manure pits are pumped annually. This results in more time, and ultimately more diesel fuel use for removing bedding packs in the hoop barn-based system as compared to pumping liquid manure in the conventional system.

The hoop barn-based systems uses 73–74% less energy for ventilation, pressure washing, illumination, feed delivery, and heating of wash water compared to identically scaled conventional facilities. Despite using nearly four times more energy for manure handling, the hoop barn-based systems uses 61–62% less total non-renewable energy to produce market pigs than the conventional system. On a per pig basis, the hoop barn-based system producing 15,600 market pigs annually uses the least non-renewable energy. The hoop barn system producing 5200 market pigs annually uses 40% of the non-renewable energy that the conventional system scaled to produce 15,600 market pigs annually requires. The conventional system producing 5200 market pigs annually requires the most non-renewable energy per market pig. Increasing the number of pigs marketed reduces the non-renewable energy used by 5% in the conventional system and by 3% in the hoop barn-based system.

The amount of renewable energy—feed and bedding—used to operate pig facilities dwarfs the non-renewable energy inputs. Energy in feed is by far the largest single contributor to operating energy in all pig production systems examined. No bedding is used in conventional facilities, but bedding is a critical component of managing pigs in hoop barns. Our analysis assumes 100% of energy present in bedding entering hoop barns is returned when hoop barns are cleaned out. The hoop barn-based system uses similar amounts (2% less) of total energy as the conventional system. This is because of the overwhelming impact of feed energy to the overall energy consumption total.

Increasing pig production by threefold barely changes total energy use per pig (0.04–0.2%) in both systems. Once again the influence of renewable energy, particularly feed on the total energy budget of pig production is responsible for the similarity between systems producing 5200 market pigs and systems scaled to produce 15,600 market pigs annually. From a total operating energy consumption per market pig produced standpoint, there is little if any inherent energetic advantage in increasing the scale of pig production.

3.2.1. Operating energy by phase of pig production

Table 6 presents type of fuel inputs for operating facilities for different phases of production. Because the farrowing and nursery facilities are operated the same way under hoop barn-based and conventional confinement systems, the operating energy for farrowing and nursery facilities are identical at a given level of production. Approximately 66% of the non-renewable energy used in farrowing facilities is electricity, primarily because of heat lamps. Liquefied petroleum gas accounts for 56–58% of the non-renewable energy use in nursery buildings. In conventional grow-finish and gestation buildings liquefied petroleum gas is the largest non-renewable energy source. As expected diesel fuel use mirrors manure production—grow-finish pigs produce the most manure of any phase of production and use the most diesel fuel of all phases. Other than diesel fuel to clean out bedding packs, there is very little non-renewable energy used in hoop barns for grow-finish pigs and gestating sows. A large portion (⩾63%) of non-renewable energy use in conventional confinement facilities for grow-finish pigs and gestating sow is used to heat buildings.

As expected renewable energy use is highest in the grow-finish phase because of the large quantities of feed that is consumed by pigs in this phase. In hoop barns, 21% of renewable energy input in the grow-finish phase is bedding. Gestating sows are limit fed and in gestation hoop barns 50% of total renewable energy input is bedding. Conventional systems do not use bedding and so feed

Table 6
Energy inputs for different phases of pig production by system and scale of facilities.[a]

	Non-renewable energy, MJ/market pig[b]				Renewable energy, MJ/market pig[b]		
	Electricity	LP gas	Diesel	Total	Feed	Bedding	Total
Conventional confinement; 5200 market pigs annually							
Farrowing	29.5	12.2	2.5	44.2	248.0	0	248.0
Nursery	4.0	8.9	2.5	15.4	820.8	0	820.8
Grow-finish	21.7	56.9	12.1	90.7	4875.2	0	4875.2
Gestation	12.2	31.5	2.7	46.4	590.4	0	590.4
Conventional confinement; 15,600 market pigs annually							
Farrowing	28.7	12.2	2.5	43.4	248.0	0	248.0
Nursery	3.9	8.1	2.4	14.4	820.8	0	820.8
Grow-finish	19.5	54.5	11.3	85.3	4875.2	0	4875.2
Gestation	11.6	28.7	2.6	42.9	590.4	0	590.4
Hoop barn-based; 5200 market pigs annually							
Farrowing	29.5	12.2	2.5	44.2	248.0	0	248.0
Nursery	4.0	8.9	2.5	15.4	820.8	0	820.8
Grow-finish	2.2	0	6.4	8.6	4875.2	1292.2	6167.4
Gestation	2.4	0	4.4	6.8	590.4	618.0	1208.4
Hoop barn-based; 15,600 market pigs annually							
Farrowing	28.7	12.2	2.5	43.4	248.0	0	248.0
Nursery	3.9	8.1	2.4	14.4	820.8	0	820.8
Grow-finish	2.0	0	6.4	8.4	4875.2	1292.2	6167.4
Gestation	2.3	0	4.0	6.3	590.4	598.0	1188.4

[a] Feed conversion and reproductive performance identical for both systems.
[b] 136-kg finished weight.

accounts for 100% of renewable energy in those systems. The grow-finish phase of pig production is the most energetically intensive, however the other phases cannot be entirely ignored. Approximately 30% of the non-renewable energy use occurs in the farrowing and nursery stages of production and gestation buildings account for 23% of total non-renewable energy use in conventional systems. In hoop barn-based systems farrowing and nursery phases account for 59% and 20% of non-renewable energy use, respectively. Gestation accounts for only 9% of non-renewable energy consumption in hoop barn-based pig production. Regardless of system, focusing only on the grow-finish phase ignores large amounts of non-renewable energy use that may be important to consider when estimating greenhouse gas emissions associated with pig production.

3.3. Greenhouse gas emissions associated with operating pig facilities

Greenhouse gas emissions from operation of pig production facilities are presented as Table 7. Because feed and bedding originate from annual plants, no net CO_2 emissions are associated with these forms of energy in this analysis. Our analysis does include emissions resulting from enteric fermentation and manure storage. The vast majority of emissions associated with pig production result from enteric fermentation and manure storage and most of these emissions are associated with the grow-finish stage of production. Both of our modeled systems used identical farrowing and nursery facilities and so emissions from those phases are not different for conventional and hoop barn-based systems. Although loss of N_2O–N is greater from bedded systems than from liquid manure storage, 2–3 times more CH_4 is generated by conventional liquid manure storage systems compared to solid storage systems (IPCC, 2006). With enteric fermentation identical for the two systems the end result is that manure management in conventional systems results in 70% more greenhouse gas as compared to manure management in hoop barn-based systems. Producing 15,600 market pigs annually using hoop barn-based facilities results in emission of 85.73 kg of CO_2 equivalents per market pig. Producing only 5200 market pigs annually using hoop barn-based facilities increases the greenhouse gas emissions per market pig sold by 1% to an average of 86.61 kg CO_2 per market pig. Producing market pigs in conventional confinement facilities requires greater use of electricity, liquefied petroleum gas, and diesel fuel. This in combination with reported CH_4 production by liquid manure systems (IPCC, 2006) translates into larger greenhouse gas emissions from operation of those facilities (150–153 kg CO_2 per market pig). Increasing the number of market pigs produced from 5200 to 15,600 results in 1.6% less greenhouse gas emissions per market pig sold from conventional confinement facilities. However using conventional confinement facilities to produce 15,600 market pigs annually results in 74% more greenhouse gas emissions per market pig sold compared to producing 5200 market pigs annually using hoop barn-based facilities.

Feed and manure management account for ⩾85% of all greenhouse gas emissions associated with operation of pig facilities. However the other aspects of modern pig production facilities, particularly when comparing different systems should not be entirely ignored. Greenhouse gas emissions associated with heating, ventilating, cleaning, and illuminating conventional pig production systems is twice that of comparable hoop barn-based systems. Although proportionally a small percentage of total emissions, these differences between systems are notable.

Table 7
Greenhouse gas emissions from operation of different phases of pig production by system and scale of facilities.[a]

	Electricity, kg CO_2/market pig[c]	LP gas, kg CO_2/market pig	Diesel, kg CO_2/market pig	Metabolism and manure[b], kg CO_2/market pig	Total, kg CO_2/market pig
Conventional confinement; 5200 market pigs annually					
Farrowing	6.76	0.77	0.21	4.90	12.64
Nursery	0.92	0.57	0.21	16.24	17.94
Grow-finish	4.98	3.61	1.00	96.16	105.75
Gestation	2.80	2.00	0.22	11.60	16.62
Total	15.46	6.95	1.64	128.90	152.95
Conventional confinement; 15,600 market pigs annually					
Farrowing	6.58	0.77	0.21	4.86	12.42
Nursery	0.89	0.51	0.20	16.10	17.70
Grow-finish	4.47	3.46	0.93	95.34	104.20
Gestation	2.66	1.82	0.22	11.50	16.20
Total	14.60	6.56	1.56	127.80	150.52
Hoop barn-based; 5200 market pigs annually					
Farrowing	6.76	0.77	0.21	4.90	12.64
Nursery	0.92	0.57	0.21	16.24	17.94
Grow-finish	0.50	0	0.53	48.27	49.30
Gestation	0.55	0	0.36	5.82	6.73
Total	8.73	1.34	1.31	75.23	86.61
Hoop barn-based; 15,600 market pigs annually					
Farrowing	6.58	0.77	0.21	4.86	12.42
Nursery	0.89	0.51	0.20	16.10	17.70
Grow-finish	0.46	0	0.53	47.97	48.96
Gestation	0.53	0	0.33	5.79	6.65
Total	8.46	1.28	1.27	74.72	85.73

[a] Feed conversion and reproductive performance identical for both systems.
[b] Enteric fermentation and emissions from manure storage (IPCC, 2006) allocated to production phase based on modeled feed consumption.
[c] 136-kg finished weight.

3.4. Energy and carbon associated with provision of feed

Cultivation and processing of feed ingredients into pig feed falls outside of our pre-defined system boundary. The energy and carbon associated with pig feed is influenced by crop sequence, ingredient choice, and diet formulation strategy (Lammers et al., 2010). A comparison of multiple approaches to feeding pigs is beyond the scope of this paper. However feed plays a dominating role in pig production and so we have included simplified estimates of energy and carbon associated with pig feed and bedding by production phase for the hoop barn-based system as Table 8. In this scenario feed conversion and reproductive performance is equal to conventional confinement systems. Just under 75% of the energy required to provide feed for one 136-kg market pig in Iowa is attributed to

Table 8
Energy and carbon associated with provision of feed and bedding by phase for hoop barn-based pig production.[a]

Phase	Feed[b]		Bedding	
	MJ/market pig	kg CO_2/market pig	MJ/market pig	kg CO_2/market pig
Farrowing	31.2	2.2	0	0
Nursery	102.0	7.1	0	0
Grow-finish	615.0	43.1	4.9	0.4
Gestation	74.0	5.2	2.2	0.2
Total	822.2	57.6	7.1	0.6

[a] Complex corn–soybean meal diets that include synthetic amino acids and exogenous phytase phase-fed to growing pigs. Crops grown in corn–soybean sequence with all crop nutrients being provided by synthetic inputs (Lammers et al., 2010).
[b] Feed conversion and reproductive performance equal for hoop barn-based and conventional systems (411.1 kg feed/136-kg market pig).

the grow-finish phase of production. Although the grow-finish phase is the largest consumer of feed, the other phases of production account for a significant portion of energy use and greenhouse gas emissions. Nearly 70% of the energy associated with providing bedding to pigs housed in hoop barns is attributed to the grow-finish stage. In the conventional confinement system, no bedding is used and so no energy or carbon associated with bedding occurs in those systems.

3.5. Incorporating demonstrated performance differences

Table 9 presents performance adjusted operating energy and associated greenhouse gas emissions of different pig production systems and scales by fuel type and activity. With 7.5% more pigs per sow in the hoop barn-based system, fewer sows must be maintained in gestation and fewer litters need to be farrowed. This results in reductions in the amount of electricity used for heat lamps in the farrowing facility and in diesel fuel used for cleaning out hoop barns for gestating sows. Under this analysis, hoop barn-based pig production uses 63–64% less non-renewable energy than conventional systems.

Grow-finish pigs housed in bedded hoop barns require 3.3% more feed per unit of gain, this translates into the 2.4% increase in renewable energy as feed for the entire pig herd presented for hoop barn-based pig production in Table 9. Similarly provisional energy also increases by 2.4%. Because of increased feed consumption during the grow-finish phase of production, systems using hoop barns for gestation and grow-finish at the two scales examined require similar amounts (⩽1% more) of total operating energy/market pig as the conventional systems.

Incorporating improved sow reproduction reduces non-renewable energy use for hoop barn-based pig production and reduces total emission of greenhouse gases. Despite increases in emissions associated with providing feed and bedding total emissions are 35% less per pig for the hoop barn-based system. This is due to the differences in emissions from manure management systems. Although bedded systems lose more nitrogen than liquid systems, liquid systems produce considerably more methane (IPCC, 2006). When the combined 100-year global warming potential of all gases from manure management are considered the bedding system results in less CO_2 release (IPCC, 2006, 2007) The optimal system for producing pigs in terms of minimizing greenhouse gas emissions is the hoop barn-based system scaled to sell 15,600 market pigs annually (139.4 kg CO_2/market pig). The conventional system scaled to produce 5200 market pigs annually uses the most non-renewable energy of any system examined and consequently emits the most greenhouse gas per market pig sold (218.2 kg CO_2/market pig).

Table 9
Performance adjusted[a] energy and associated greenhouse gas emissions of different pig production systems and scales by fuel type and activity.

System	Conventional		Hoop barn-based	
Market pigs per year[b]	5200	15,600	5200	15,600
Embodied energy, MJ/market pig				
Building construction	102.8	87.0	94.5	72.6
Feed provision	822.2	822.2	841.9	841.9
Bedding provision	0	0	7.1	7.1
Total embodied energy	925.0	909.2	943.5	921.6
Non-renewable energy, MJ/market pig				
Electricity				
Ventilation	26.9	26.6	5.3	5.1
Auxiliary heat	25.3	24.6	23.7	19.8
Water delivery	2.6	2.5	2.6	2.4
Pressure washing	3.4	3.2	0.9	0.9
Illumination	6.5	5.8	3.8	3.7
Feed delivery	2.7	1.0	0.2	0.3
Liquefied petroleum gas				
Building heat	109.5	103.5	21.1	20.3
Diesel fuel				
Heating wash water	16.8	15.9	4.6	4.4
Manure handling	3.0	2.9	10.6	10.5
Total non-renewable energy	196.7	186.0	72.8	67.4
Renewable energy, MJ/market pig				
Feed	6534.4	6534.4	6691.2	6691.2
Bedding into barn	0	0	1866.3	1849.0
Bedding removed from barn			(1866.3)	(1849.0)
Net renewable energy	6534.4	6534.4	6691.2	6691.2
Total energy, MJ/market pig	7656.1	7629.6	7707.5	7680.2
Greenhouse gas emissions, kg CO_2/market pig				
Building construction	7.6	6.7	6.3	5.5
Electricity	15.5	14.6	8.4	7.4
LP gas	7.0	6.6	1.3	1.3
Diesel	1.6	1.6	1.3	1.2
Feed and bedding provision	57.6	57.6	59.0	59.0
Enteric fermentation	13.6	13.5	13.8	13.7
Manure management	115.3	114.3	51.6	51.3
Total emissions, kg CO_2/market pig	218.2	214.9	141.7	139.4

[a] Grow-finish pigs housed in hoop barns consume 3.3% more feed and sow herd reduced by 7% in hoop barn-based system to account for reproductive performance differences.
[b] 136-kg finished weight.

4. Discussion and conclusion

Producing pigs using hoop barns for grow-finish and gestation requires less embodied energy and carbon than using conventional confinement facilities. Hoop barn-based pig production requires similar quantities of total operating energy compared to conventional facilities but results in less greenhouse gas emissions per market pig. There is little (<0.3%) energetic advantage to increasing the scale of pig production from 5200 to 15,600 market pigs annually. Hoop barn-based production scaled to produce 5200 market pigs annually requires similar amounts of embodied energy and less embodied carbon compared to conventional confinement facilities scaled to produce 15,600 market pigs annually. Using hoop barns for grow-finish and gestation requires less non-renewable energy and results in lower emissions of greenhouse gas.

This analysis demonstrates that hoop barns for pigs have several energetic and environmental advantages over conventional confinement facilities. Operating energy use and the thermal environment regime of a particular pig facility will depend on climate conditions. The conditions assumed in this analysis are typical of historic averages for Iowa, the leader in United States pig production. This model is representative of the environment where the majority of pigs in the United States are raised. Producing one 136-kg market pig in Iowa requires 7656–7708 MJ or 56.3–56.6 MJ/kg live weight. This includes energy present (48.0–49.2 MJ/kg live pig weight) in feed that could be diverted to other uses. However it must be noted that energy present as feed was calculated as gross energy. Humans and other animals are not capable of utilizing 100% of gross energy in typical feedstuffs. If gross energy of feed is excluded, producing pigs in conventional US facilities requires 8.1 MJ/kg live weight and results in equivalent emissions of 1.6 kg CO_2. Alternatively the hoop barn-based system requires 7.2 MJ/kg live weight and results in equivalent emissions of 1.0 kg CO_2/kg live weight.

Eriksson et al. (2005) report energy use of 5.3–6.8 MJ/kg live weight for pig production in Denmark, however their analysis focused exclusively on feed provision and the grow-finish phase of production. Energy use for all aspects of pig production in the US is considerably less than energy required by European systems

(Uhlin, 1998; Halberg, 1999; Zhu and van Ierland, 2004; Basset-Mens and van der Werf, 2005; Stern et al., 2005; Williams et al., 2006; Dalgaard et al., 2007; Meul et al., 2007). This indicates a need to use caution when using life cycle assessments of livestock production performed under country or region specific conditions to generate continental or global estimates of the environmental impact of livestock. Our work demonstrates that building and operating pig barns accounts for 14–27% of the total energy use associated with pig production with key differences between conventional and hoop barn-based production systems.

Hoop barn-based pig production is more dependent on operating energy from feed and bedding than conventional confinement production. Alternatively conventional confinement facilities rely more on non-renewable fossil fuels to modify pig environment. Hoop barns for grow-finish pigs and gestating sows have been successfully demonstrated and performance of pigs in these facilities are similar to pigs in conventional confinement (Honeyman and Harmon, 2003; Lammers et al., 2007). Historically the availability of fossil fuels has minimized pressure to critically consider all uses of energy in pig production. Rising energy prices, global conflicts, and recognition of the environmental impacts of using fossil fuels are increasing awareness and incentive to optimize use of these limited resources. Using hoop barns for grow-finish pigs and gestating sows is an effective strategy to reduce direct use of fossil fuels for pork production and may minimize global climate altering emissions.

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References

APS, 2008. AP Flex-Flo™ Systems. Automated Production Systems, Assumption, IL. <http://www.automatedproduction.com/english/swine/delivery/flexflo.htm> (accessed 28.05.09).

ASAE, 2005. EP344.3 lighting systems for agricultural facilities. In: ASABE (Ed.), ASABE Standards. American Society of Agricultural and Biological Engineers, St. Joseph, MI, pp. 686–697.

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

BESS, 2008. Agricultural Ventilation Fans, Performance and Efficiencies. University of Illinois, Department of Agricultural and Biological Engineering, Bioenvironmental and Structural Systems Laboratory.

Brown-Brandl, T.M., Nienaber, J.A., Xin, H., Gates, R.S., 2004. A literature review of swine heat production. Transactions of the ASAE 47, 259–270.

Brumm, M.C., Harmon, J.D., Honeyman, M.S., Kliebenstein, J.B., Lonergan, S.M., Morrison, R., Richard, T., 2004. Hoop Barns for Grow-finish Swine. AED 44. MidWest Plan Service, Ames, IA.

Carr, J., 1998. Garth Pig Stockmanship Standards. 5MEnterprises Ltd., Sheffield, UK.

Curtis, S.E., 1983. Control and integration of thermoregulatory processes. In: Curtis, S.E. (Ed.), Environmental Management in Animal Agriculture. Iowa State University Press, Ames, pp. 59–70 (Chapter 6).

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

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S., Courbois, C., 1999. Livestock to 2020: The Next Food Revolution. International Food Policy Research Institute/Food and Agriculture Organization of the United Nations/International Livestock Research Institute (IFPRI/FAO/ILRI), Washington, DC.

den Hartog, L.A., 2005. Global perspectives on integrated pork production. In: Proc. of London Swine Conference: Production at the Leading Edge, London, ON, Canada, pp. 97–103.

Downs, H.W., Hansen, R.W., 1998. Estimating Farm Fuel Requirements No. 5.006. Colorado State University Extension, Fort Collins. <www.cde.state.co.us/artemis/ucsu20/ucsu2062250061998internet.pdf> (accessed 28.05.09).

EIA-DOE, 2009. State Energy Profiles: Iowa. Energy Information Administration, Washington, DC. <http://tonto.eia.doe.gov/state/state_energy_profiles.cfm?sid=IA> (accessed 28.05.09).

EPA, 2008. eGRID Subregion GHG Output Emission Rates for Year 2005. Washington, DC. <http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html> (accessed 28.05.09).

Eriksson, I.S., Elmquist, H., Stern, S., Nybrant, T., 2005. Environmental systems analysis of pig production: the impact of feed choice. International Journal of Life Cycle Assessment 10, 143–154.

FAO, 2006. World Agriculture: Towards 2030/2050, Interim Report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fulhage, C., Hoehne, J., 2001. Lesson 21: Sizing Manure Storage, Typical Nutrient Characteristics. Livestock and Poultry Environment Stewardship Curriculum. MidWest Plan Service, Ames, IA.

Halberg, N., 1999. Indicators of resource use and environmental impact for use in a decision aid for Danish livestock farms. Agriculture, Ecosystems and Environment 76, 17–30.

Hammond, G., Jones, C., 2008. Inventory of Carbon and Energy. Version 1.6a. Department of Mechanical Engineering, University of Bath, Bath, UK. <www.bath.ac.uk/mech-eng/sert/embodied/> (accessed 28.05.09).

Harmon, J.D., Honeyman, M.S., Kliebenstein, J.B., Richard, T., Zulovich, J.M., 2004. Hoop Barns for Gestating Swine. AED 44. MidWest Plan Service, Ames, IA.

Holden, P., Ewan, R., Jurgens, M., Stahly, T., Zimmerman, D., 1996. Life Cycle Swine Nutrition. PM-489. Iowa State Univ. Extension, Ames.

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

IPCC, 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Kamiyamaguchi, Japan. <http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html> (accessed 28.05.09).

IPCC, 2007. Climate Change 2007: The Physical Science Basis. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

ISU, 2003. Managing Manure Nutrients for Crop Production. PM 1811. Iowa State University Extension, Ames.

ISU, 2008. Iowa Ag Climate Network. Iowa State University, Ames. <http://mesonet.agron.iastate.edu/agclimate/index.phtml> (accessed 28.05.09).

Kjelgaard, M.J., 2001. Engineering Weather Data. McGraw-Hill, New York, NY.

Lammers, P.J., 2009. Energy and Nutrient Cycling in Swine Production Systems. PhD Diss, Iowa State University, Ames.

Lammers, P.J., Honeyman, M.S., Mabry, J.W., Harmon, J.D., 2007. Performance of gestating sows in bedded hoop barns and confinement stalls. Journal of Animal Science 85, 1311–1317.

Lammers, P.J., Honeyman, M.S., Kliebenstein, J.B., Harmon, J.D., 2008. Impact of gestation housing system on weaned pig production cost. Applied Engineering in Agriculture 24, 245–249.

Lammers, P.J., Honeyman, M.S., Harmon, J.D., Kliebenstein, J.B., Helmers, M.J., 2009. Construction resource use of two different types and scales of Iowa swine production facilities. Applied Engineering in Agriculture 25, 585–593.

Lammers, P.J., Kenealy, M.D., Kliebenstein, J.B., Harmon, J.D., Helmers, M.J., Honeyman, M.S., 2010. Nonsolar energy use and one-hundred-year global warming potential of Iowa swine feedstuffs and feeding strategies. Journal of Animal Science 88, 1204–1212.

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

MWPS, 1987. Structures and Environment Handbook, 11th revised ed. MidWest Plan Service, Ames, IA.

MWPS, 1990a. Heating, Cooling, and Tempering Air for Livestock Housing, first ed. MidWest Plan Service, Ames, IA.

MWPS, 1990b. Mechanical Ventilation Systems for Livestock Housing, first ed. MidWest Plan Service, Ames, IA.

NEMA, 2009. NEMA Premium Motors. Washington DC. <http://www.nema.org/gov/energy/efficiency/premium/> (accessed 28.05.09).

NTTL, 2008. Tractor Test Reports. University of Nebraska Tractor Test Laboratory, Lincoln. <http://tractortestlab.unl.edu/testreports.htm> (accessed 28.05.09).

Pedersen, S., 2002. Heat and moisture production for pigs on animal and house level. Paper no. 024178. In: ASAE Annual International Meeting; CIGR XVth World Congress, Chicago, IL.

Pordesimo, L.O., Hames, B.R., Sokhansanj, S., Edens, W.C., 2005. Variation in corn stover composition and energy content with crop maturity. Biomass and Bioenergy 28, 366–374.

Sauvant, D., Perez, J.M., Tran, G. (Eds.), 2004. Tables of Composition and Nutrition Value of Feed Materials: Pigs, Poultry, Cattle, Sheep, Goats, Rabbits, Horses, Fish, second ed. Wageningen Academic Publishers, Wageningen, NL.

Stern, S., Sonnesson, U., Gunnarsson, S., Öborn, I., Kumm, K.-I., Nybrant, T., 2005. Sustainable development of food production: a case study on scenarios for pig production. Ambio 34, 402–407.

Thacker, P.A., 2001. Water in swine nutrition. In: Lewis, A.J., Southern, L.L. (Eds.), Swine Nutrition. CRC Press, Boca Raton, FL (Chapter 17).

Uhlin, H.-E., 1998. Why energy productivity is increasing: an I–O analysis of Swedish agriculture. Agricultural Systems 56, 443–465.

USDA, 2002a. Iowa State and County Data. 2002 Census of Agriculture. USDA – National Agricultural Statistics Service, Washington, DC. <http://www.agcensus.usda.gov/Publications/2002/Census_by_State/Iowa/index.asp> (accessed 20.01.09).

USDA, 2002b. Table 12. Hogs and Pigs – Inventory and Sales: 2002 and 1997. 2002 Census of Agriculture. USDA – National Agricultural Statistics Service, Washington, DC. <http://www.agcensus.usda.gov/Publications/2002/Volume_1,_Chapter_2_US_State_Level/index.asp> (accessed 28.05.09).

USGS, 2008. USGS Ground Water Level Annual Statistics for Iowa. United States Geological Survey, Reston, VA. <http://waterdata.usgs.gov/ia/nwis/annual?> (accessed 28.05.09).

Wathes, C., Whittemore, C.T., 2006. Environmental management of pigs. In: Kyriazakis, I., Whittemore, C.T. (Eds.), Whittemore's Science and Practice of Pig Production. Blackwell Publishing, Oxford, UK., pp. 533–592 (Chapter 17).

Williams, A.G., Audsley, E., Sandars, D.L., 2006. Determining the Environmental Burdens and Resource Use in the Production of Agricultural and Horticultural Commodities. Main Report. Defra Research Project ISO205. Cranfield University, Silsoe, UK.

Zhu, X., van Ierland, E.C., 2004. Protein chains and environmental pressures: a comparison of pork and novel protein foods. Environmental Sciences 1, 254–276.