Life Cycle Assessment of Cooling Sows Using Solar Electricity

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Disclaimer

All data, models, and predictions contained in this report are solely works of the authors. Neither the University of Minnesota nor the funding agency(ies) have reviewed these statements for accuracy or completeness. For comments or questions, please contact the author.

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1 Introduction

The farrowing phase of pork production uses a great deal of energy. Much of the energy is used for keeping piglets warm, as they grow most productively at around 95°F (35°C) in the first days of life. However, the much larger sows need to be kept comfortably cool 60-65°F (15-18°C) for best performance (feed consumption, lactation, and weight maintenance). Because both piglets and sows are in close proximity, it is challenging to provide ideal conditions for both swine growth stages at the same time. Typically, priority is given to piglets whose mortality and productivity are more sensitive to temperature. This leaves sows prone to heat stress, especially in Minnesota summers. Farrowing facilities are typically only cooled with ventilation fans blowing outside air into the building. Since swine don't sweat, they release excess heat by panting. This extra exertion increases their bodies' energy use at the same time their appetites are suppressed due to being hot. Therefore, heat stressed sows lose more weight while lactating than non-stressed sows. In some situations, they will produce less milk for the growing piglets and piglet health can be compromised.

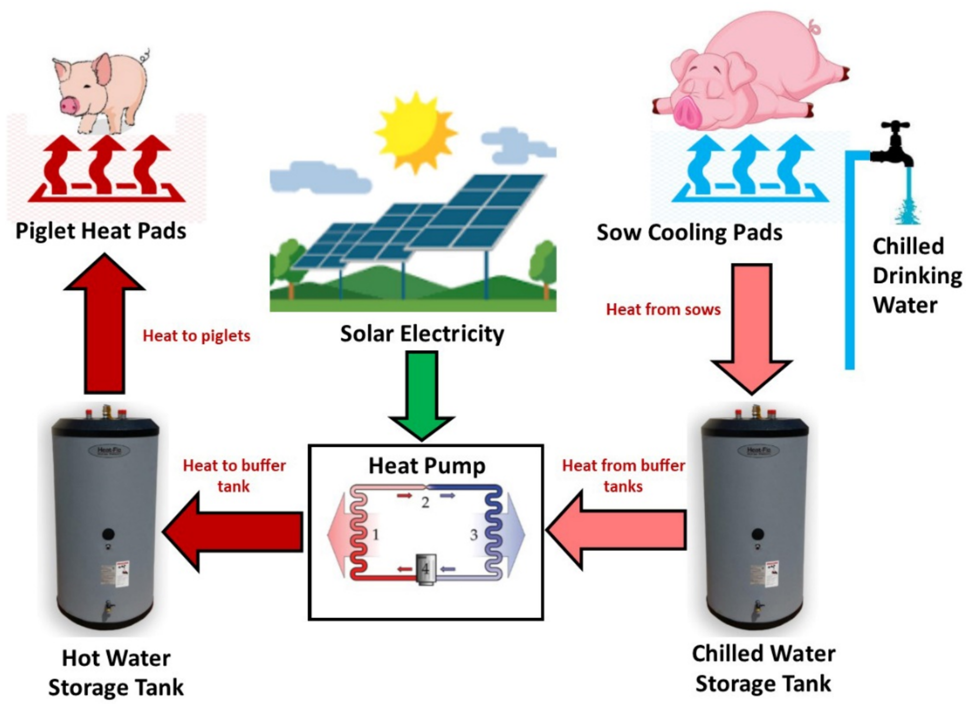

Figure 1. Schematic of Swine Farrowing Heating and Cooling System. The simplified diagram of the heating and cooling system shows how heat collected from the sows via the hydronic mats under the sow and is transferred to piglets via the electric heat pump, which uses solar electricity.

The University of Minnesota, West Central Research and Outreach Center (WCROC) swine production and renewable energy teams designed a joint research project to examine a renewably-based strategy that uses solar electric panels to cool sows and warm piglets. The heart of the system is a commercial heat pump that transfers heat energy from one tank of water to another. In this case, water from one tank is used to cool sows and the heat energy sent to another tank to warm piglets. Thermal exchange pads or mats under the animals use cool or warm water from the storage tanks to cool or warm the sows or piglets, respectively. In addition, cooled drinking water was provided to the sows using the same heat exchange technology. The hydronic (water-based) swine thermal pads are a relatively new technology in the U.S. that is unproven from economic and environmental aspects. As part of an innovative research project, WCROC designed and installed farrowing stalls that included cooling and heating pads for the animals. The research covered several aspects of the system, including behavior, physiology, productivity, energy use, economics, and environmental impacts.

Because funding for different aspects of the projects (sow cooling vs. piglet heating) were from different sources, the results are being reported separately. The work reported here documents the life cycle assessment (LCA) of sow cooling aspects and focuses on the environmental impact differences between the standard ventilation cooling system and the hydronic cooling system powered by renewable energy during heat stressed periods.

2 Methods

Testing of the sow cooling system was conducted at the WCROC research farm. Three scenarios were tested that used the same feed and water supplies. Near-term gestating sows were randomly chosen for the control or cooling treatments. Three cohorts of sows were studied, although one replicate examined electric heat mats rather than heat lamps. The scenarios used to analyze the environmental impacts were:

- **Control system under heat stress:** This scenario uses electric heat lamps for piglets as is typical of most farrowing facilities. No cooling for sows is included other than wall and pit fans used to bring outside air into the room and wall mounted indoor circulation fans.
- **Cooling system under heat stress:** This scenario specifically examines hydronic cooling of sows using pads under the sows and chilled drinking water, in addition to fans. The piglets are heated via pads using the hot water produced from the heat extracted when cooling the sows.
- **Long-term baseline (for WCROC farrowing facility):** This scenario examines the WCROC farrowing facility using baseline energy inputs and swine production over multiple years as established in previous research. It includes both summer and winter inputs and outputs. Piglet heating was via heat lamps and no additional means, beyond fans, were used to cool sows.

The main question considered was, ‘How does integrating the novel solar-based cooling/heating systems into farrowing operations impact the fossil energy use and greenhouse gas emissions per piglet weaned?’ Life cycle assessment methodology was employed to answer this question using the data provided by monitoring systems and equipment at the WCROC swine research facilities.

2.1 Life Cycle Assessment

The LCA for this study was an attributional LCA focused on the farrowing system (Fig. 2). It examined the system from production of feed until weaning (cradle-to-wean). The functional unit selected for the farrowing analysis was piglet production as determined by the number of piglets weaned. The central focus of the LCA process of the farrowing system was one litter (sows and piglets). The impacts of the scenarios were also analyzed for the complete cradle-to-farm gate market weight swine production system as a comparison (Supplement Figure A1). The full system analysis used 1 kg of live weight market hog as the functional unit. The analysis did not include infrastructure associated with energy production or that for the heating and cooling equipment examined.

The LCA work done for this project was conducted using ISO 14000 standard methodology as a general guide. SimaPro (9.0) software was used for modeling swine systems and calculating results. Background databases used in conjunction with the SimaPro work included: Ecoinvent (Frischknecht *et al.*, 2005), US LCI (NREL, 2012), and Agri-footprint (Blonk, 2017). For global warming calculations (GWP), GWP 100a (IPCC, 2013) method was used to calculate impacts. Fossil energy impacts were calculated using the CED 1.08 method (Frischknecht *et al.*, 2007) with the addition of United States-based fossil energy sources.

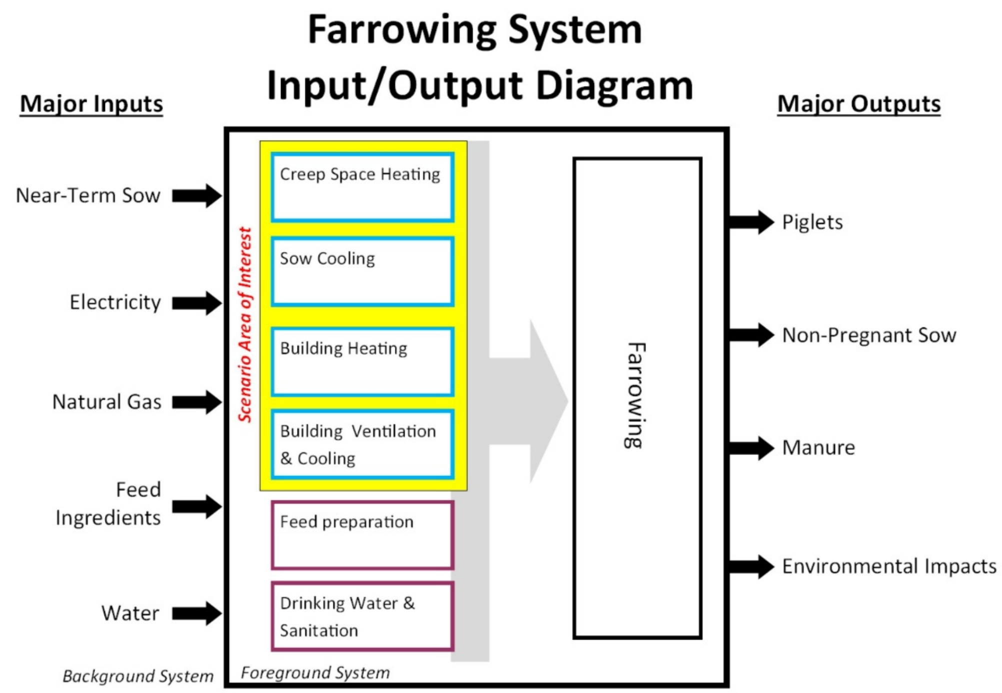

Figure 2. Farrowing System Diagram. The diagram shows the foreground system being analyzed, with the specific areas of interest highlighted in yellow. The background system includes the feed ingredients, energy inputs, and other items needed to support operations in the farrowing system.

2.1.1 Foreground System Items

Life cycle assessment often divides the system of interest into two areas of study, the foreground system and the background system. The foreground system typically describes the model's area of focus and where there a is desire to develop a deeper understanding of process environmental impacts and how making process changes influences those impacts. In this LCA work, the foreground system includes the activities directly related to farrowing and lactation. This primarily includes heating and cooling, manure management and emissions, and feed systems.

2.1.2 Background System Items

The background system refers to items that are generally upstream of the system of interest and not in the control of those managing the foreground system. For this project, these are the items under the heading "Major Inputs" on the left side of Fig. 2. In this case, activities such as production of gestating animals, crop production, electricity generation/transmission, and natural gas extraction/delivery were included in the background system.

2.2 The Swine Production System

Field testing of the swine cooling system was conducted at the WCROC swine farrowing facility. The facility has two identical farrowing rooms accommodating 16 sows. One of the rooms was equipped with sow cooling equipment. About thirty-two sows were assigned randomly to one of the two rooms during each test run. Performance data was collected during the 21 to 28 day farrowing and lactation period. Sow and piglet productivity data was collected during the study by repeated measurement of sows and piglets for mortality, body weight, physiological reactions, feed consumption, and behavior. A primary issue for this LCA work was the survival of piglets. However, performance variables such as body weight and feed use were also examined. Sow body temperature was analyzed (during cooling study). Environmental measurements were recorded in different locations throughout the facility. These measures included: air temperatures, moisture levels, surface temperatures, and humidity.

2.3 Data Collection

A number of different data sources were used in this study. Priority was given to data generated by WCROC staff from work done on the WCROC swine production research systems. Much of the data collected is included in other sections of the final project report, as reported by other subject matter experts. However, summary data important for LCA efforts is included in Table 1. Some LCA related information was outside the ability or scope of staff to collect and, therefore, was found in databases or literature. This was primarily background data for items brought into the swine feed and the crop production systems.

Table 1. Main Variables Used in Farrowing LCA Analysis. Key variables for LCA analysis are summarized in the table, including animal productivity data, allocation, energy use, and manure impacts. Note that rather than directly changing daily manure emissions based on feed intake and resulting manure production, the number of 'manure management days' was proportionally changed to indirectly account for feed use differences.

	Base WCROC system			Control System			Cooling System		
Farrowing System	**#**	**Unit**	**Alloc.**	**#**	**Unit**	**Alloc.**	**#**	**Unit**	**Alloc.**
Weened piglets	11	p	84.2%	11.24		13.8%	11.37	p	85.8%
Open Sow	0.75	p		0.75	p		0.75	p	
Sow Morality	0	kg		0	kg		0	kg	
Culled Sow (kg)	62.5	kg	15.8%	54.58	kg	86.2%	57.13	kg	14.3%
Materials/fuels Inputs									
Swine Lactation Mix (kg) per Sow	225.4	kg		144.7	kg		177.5	kg	
Days of Housing System Use	35	day		35	day		35	day	
Manure Management (Days)	35	day		22.47	day		27.25	day	
Swine, Full Gestation Sow	1	p		1	p		1	p	
Housing System									
Electricity (kWh) per day	1.02	kWh		1.65	kWh		4.98	kWh	
Natural Gas (M^3) per day	0.0635	m3		0	m3		0	m3	
Manure Manage (Days)	35			22.47			27.25		
Methane per day	1.084	kg		1.084	kg		1.084	kg	
N_2O direct per day	0.267	g		0.267	g		0.267	g	
N_2O indirect per day	0.334	g		0.334	g		0.334	g	

2.4 Feed Systems

The lactation feed mix (Supplement Table A1) used for this LCA analysis of farrowing systems and mixes for other production stages (Supplement Table A2 and A3) are based on feed guidelines from the US Center for Pork Excellence, as applied at WCROC. The majority of each mix is corn (energy source), plus dried distillers grains with solubles and/or soybean meal (protein and fat source). A number of other nutrients and minerals are required at low levels to make a complete diet.

2.5 Energy Sources

Swine production uses a number of different energy types; electricity and propane/natural gas are the most common. Electricity is the largest energy demand in the warm summer months.

Solar electricity production was monitored over the course of the three-year study; however, only data obtained during the periods when the cooling system was being tested were used in this study. This data was generated exclusively during warmer months with more sunlight, when the cooling system would most likely be in use. Average production was 91 kWh per day. When divided by the number of farrowing stalls (16), this yielded 5.7 kWh per sow space.

Electricity consumption in farrowing rooms was tracked and averaged over three replicates of the cooling trials (Table 2). Tracking was done using power metering and logging equipment, and liquid flow meters in conjunction with temperature sensors to track energy going into and within the hydronic cooling/heating systems. For this study, the primary heating fuels, propane and natural gas, were not tracked during the heat stress periods as heating would not typically be used during summer heat-stress events.

Table 2. Electricity Use Summary Data. The final daily average electricity use per sow space is calculated using the average daily electricity use from three replicates.

	Control Room		Cooling Room	
Group 1	35.3	kWh/day	93.0	kWh/day
Group 2	19.7	kWh/day	71.5	kWh/day
Group 3	24.3	kWh/day	74.4	kWh/day
Average Per Room	26.4	kWh/day	79.6	kWh/day
Sow Spaces	16.0		16.0	
Per Sow Space Per day	1.65	kWh/day	4.98	kWh/day

The solar electricity modeled in the study did not include emissions or impacts for the manufacturing of the solar equipment used in the solar cooling and heating project. Therefore, this energy would be considered burden free, without GWP or fossil energy implications. For comparisons with grid energy, data from the 2011 Minnesota electricity generation mix was used in conjunction with electricity emissions for different generation methods (i.e. nuclear, coal-based, wind…). The GWP emissions from the 2011 Minnesota electrical grid were 600 g CO_2 equiv. per kWh and fossil energy resources consumed were 21 MJ per kWh.

2.6 Manure Management System

Although not an important component of energy in these systems, manure management is an important part of the greenhouse gas emissions during pork production. Microorganisms break down manure into methane, nitrous oxides, and carbon dioxide, all of which are greenhouse gases. Therefore, manure emissions are calculated for the scenarios in this LCA based on standardized formulas developed by ASABE (ASABE, 2005) and IPCC (IPCC, 2006). Rather than directly changing daily manure emissions based on daily feed intake and resulting manure production, the total number of 'manure management days' was proportionally changed to indirectly account for total feed use differences.

2.7 Allocation

Economic allocation of impacts was used during the farrowing stage to divide the impacts of the system between the piglet output and the culled sow output (Supplement Table A4). Valuation of piglets was $40 per weaned pig and culled sow meat was valued at $1.32 per kg ($.60 per pound). Allocation for each scenario was calculated using the specific number of piglets and sow weights from each scenario.

2.8 Analysis of the Full Swine Production System

Modeling examining the complete swine production system used previous research at WCROC. The system encompassed a cradle-to-farm gate analysis of swine production that included the farrowing operation as well as all other areas needed to produce market animals.

2.9 Sensitivity Analysis of Input and Output Variable

Sensitivity analysis was performed on both major output variables (number of weened pigs produced and sow weight) along with important input variables (feed and energy). A 20% increase and decrease over the control system was used in testing the sensitivity of the control scenario to changes.

3 Results

In the productivity data collected, significant variations were observed in only a few select measurements. Specifically, sow weight change and feed consumption during farrowing were significantly impacted. A number of other variables showed trends towards increased productivity in the cooled system. However, they were not statistically different between scenarios and the correlation was fairly weak. Using the productivity, feed intake, and energy data from the three replicates (Table 1) of the study, the life cycle impacts were calculated.

3.1 Farrowing LCA Results

3.1.1 Fossil Energy Consumption

The solar-based sow cooling system used considerably more electricity than the control system (Table 2) or the base long term WCROC system (data not shown). If operated exclusively on grid-based electricity (Fig. 3A), substantially more fossil energy depletion would occur in the cooling scenario compared with the control scenario. However, the onsite solar electricity production examined in this study (5.7 kWh/sow space per day) more than eliminated the need for grid-based power in housing systems in both the cooling and control scenarios. This excess electricity was used elsewhere on the WCROC farm and credit for the avoided power that would have been purchased from the grid was applied to the farrowing scenarios studied.

In the control system, 4.0 kWh per sow space per day of over-production and the related environmental impacts were credited back to the farrowing system. In the cooling system, over-production was 0.71 kWh per sow space per day. The net impact on fossil energy use when crediting this electricity over-production can be seen in Fig. 3B. The control system had net negative fossil fuel consumption (-105 MJ per piglet) due to the credits for over-production of renewable electricity. Though the cooling scenario had slightly positive fossil energy consumption (4.6 MJ per piglet), this is still relatively low compared to that of the base WCROC value of 73.1 MJ per piglet.

An interesting observation in this data is the reduction of fossil energy use in feed production for the heat-stressed systems (control and cooling) compared with the base model system. Though somewhat difficult to see in these graphs, animals in the base system (non-stressed) consumed more feed and, consequently, required more energy for feed production (Fig. 3A and3B). While this feed related impact reduction does improve the environmental aspects of the farrowing system, it indicates that the animals are experiencing heat-stress and is not desirable from an animal welfare perspective.

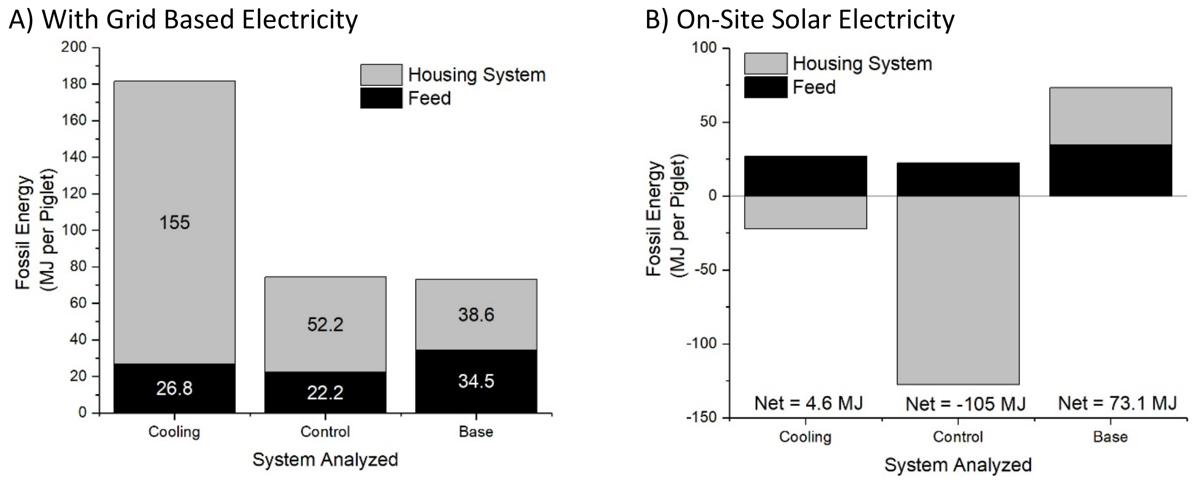

Figure 3. Fossil Energy Use in Sow Farrowing Scenarios. Data shows fossil energy use for the scenarios analyzed. A) Fossil energy use when the farrowing system is operated on grid-based electricity. B) Farrowing system fossil energy use with solar power and a fossil energy credit for excess electricity exported from the farrowing system to other uses on the farm. The WCROC base system is included only for comparison and does not use solar electricity.

3.1.2 Greenhouse Gas Emissions

The greenhouse gas emissions for this system were impacted in three main areas: manure, feed, and housing. The primary impacts for the changes in the cooling and control scenarios examined were in the housing system. When tested with grid electricity (Fig. 4A), the cooling scenario emitted significantly more GWP emissions than the control system and more than the previously documented base system scenario.

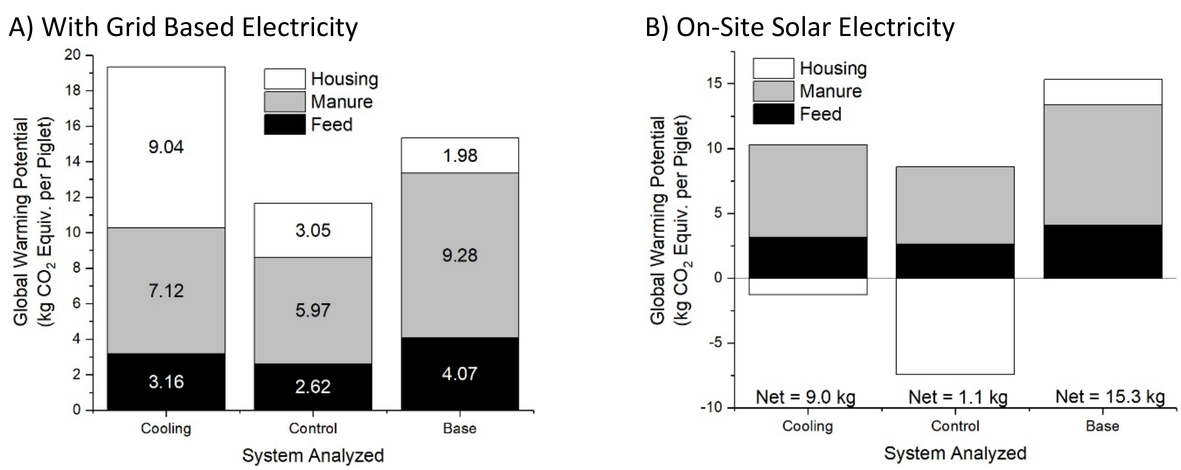

Figure 4. Global Warming Potential Emissions in Cooled Sow Farrowing Systems. The negative value of housing for the control system indicates credit for renewable energy leaving the system after factoring swine cooling system energy consumption. The WCROC base system is included only for comparison and does not use solar electricity.

As was done above for fossil energy depletion calculations, an emissions credit is given for over-production of electricity in the control and cooling scenarios (Fig. 4B). The result is that net GWP emissions are considerably lower for both the cooling (9.0 kg CO_2 Equiv. per piglet) and control systems (1.1 kg CO_2 Equiv. per piglet) when using solar electricity, as compared to the non-solar base system (15.3 kg CO_2 Equiv. per piglet). The emissions credit for the control system almost lowers the total emissions from the farrowing system to zero. However, the cooling scenario system used much of the electricity generated by the solar panels, thus a smaller amount of emissions credit was applied to farrowing cooling system emissions.

Greenhouse gas emissions as measured by GWP are typically most impacted by feed and manure components, which can be seen in the results for the base system (Fig. 4). The heat stress depressed feed consumption and consequently manure excretion. This impacted the amount of both emissions related to feed production and the emissions from the manure breakdown. The reduction in feed consumption due to heat stress was most noticeable in the control scenario, which had the lowest manure and feed related GWP emissions.

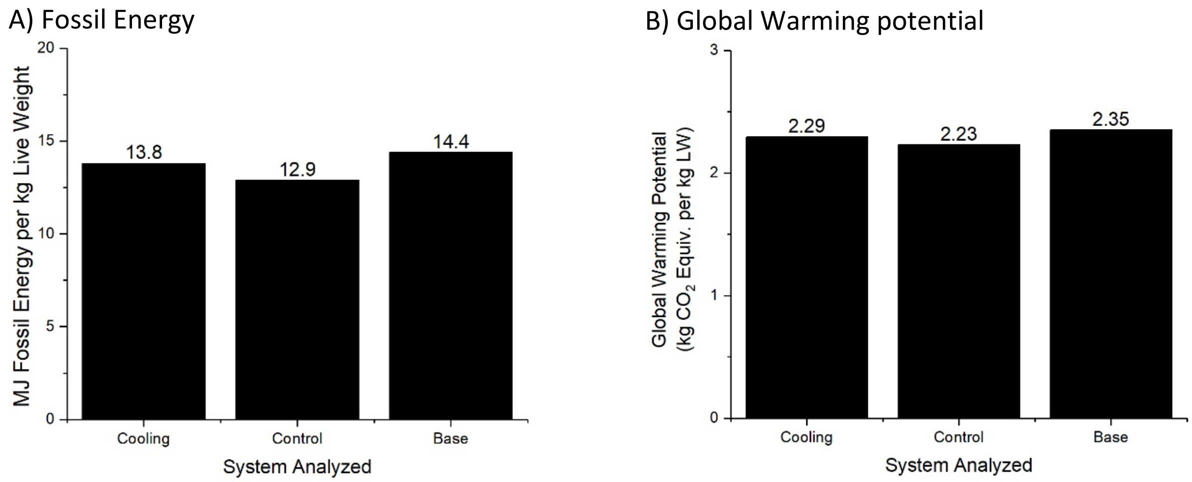

Figure 5. Effects of Farrowing Cooling Scenarios on Overall Environmental Impacts for Full Swine Production Systems. Environmental impacts for market weight animals in the full system are expressed per kg of live weight pork leaving the farm.

3.2 Impacts of Farrowing System Changes on the Full Production System

To understand the broader impact that the farrowing cooling system would have on the full swine production system, the cooling and control scenarios were tested in an LCA model of the full swine production system (farrow-to-finish). For both fossil energy and GWP, the control scenario had less environmental impacts (Fig. 5A & 5B) than the base WCROC production system. As farrowing is a shorter component of the production process with less overall impacts, the differences in environmental impacts between scenarios were relatively modest when considering the full system. The majority of environmental impacts for market hogs is in the grow-finish phase of production.

3.3 Sensitivity Analysis

Sensitivity analysis was used to determine how changes in important input and output variables could alter the overall impacts observed (Table 3). The two major inputs (feed consumption and energy inputs) and outputs (number of piglets produced and culled sow meat) from the farrowing system were tested for impacts.

For output variables, the number of piglets had a considerable impact on the final result. A 20% change in the number of piglets resulted in a roughly 20% change in both global warming potential and fossil energy consumption. Whereas, the change in weight of the sows had much less impact. This is somewhat expected as most of the environmental impacts are economically allocated to the piglets leaving the system rather than the small portion of sows sold for meat.

Table 3. Sensitivity Analysis Results. Variations in major inputs and outputs to the farrowing system were tested in the modeled scenarios to see how much a ±20% change in each would impact the overall environmental results. The resulting changes are shown along with the relative percentage of change in parenthesis. The control for the sensitivity analysis was the control scenario data.

Outputs			GWP (kg CO_2 Equiv.)				
Item	Absolute Change		20% Less Productive		Control	20% More Productive	
Piglet #	± 2.25	Piglets	32.8	(20.8%)	27.2	23.2	(-17.2%)
Sow Weight	± 43.66	kg	27.9	(2.9%)	27.2	26.4	(-2.8%)
					MJ		
Piglet #	± 2.25	Piglets	25.8	(20.8%)	21.3	18.2	(-17.2%)
Sow Weight	± 43.66	kg	22.0	(2.9%)	21.3	20.8	(-2.7%)
Inputs			GWP (kg CO_2 Equiv.)				
Item	Absolute Change		20% Less Inputs		Control	20% More Inputs	
Feed Consumption	± 28.94	kg	26.6	(-1.9%)	27.2	27.7	(1.9%)
(Feed w/manure)			25.5	(-6.3%)	27.2	28.9	(5.9)
Electricity Use	± 0.33	kWh/day	26.6	(-2.3%)	27.2	27.7	(2.1%)
					MJ		
Feed Consumption	± 28.94	Kg	25.8	(-20.8%)	21.3	16.9	(17.2%)
Electricity Use	± 0.33	kWh/day	31.7	(-49.2%)	21.3	10.8	(32.7%)

Overall, the amount of feed consumed did not change GWP impacts considerably. This was examined in terms of changing the feed consumption values, plus a separate assessment of changing feed consumption along with the resulting manure volumes. Use of electricity also had a relatively limited impact on GWP in the sensitivity analysis. Both feed and electricity use had more impacts on the overall fossil energy consumed. The fossil energy impacts were particularly sensitive to electricity use. This is likely because the credits for overproduction in the system mean that a reduction of electricity use both lowers fossil energy consumption and increases the amounts of credits for over-production.

4 Discussion

Typically, in evaluating new systems that are designed to limit environmental impacts, three major factors are considered; productivity changes, environmental impacts, and costs. The overall goal of this project was to test whether a renewable sow cooling system could increase sow productivity while maintaining or improving environmental impacts. Based on the results, it appears that the cooling system in its current form does not sufficiently improve productivity (see main report). Therefore, the current cooling system does not appear to be beneficial to swine producers.

The LCA portion of the project asked the additional question of whether the cooling system with integrated solar could result in net zero or better GWP and fossil energy impacts. Based on the LCA results, the integrated solar was able to reduce both GWP and fossil energy impacts considerably. However, the lowest impacts were in the control system, which integrated solar for electricity for existing building energy needs and provided fossil energy and GWP credits for energy leaving the system. This supports the overall notion that renewable energy sources such as solar have a role in reducing the environmental impacts of conventional pork production.

While the findings of this study don’t rule out the objective of increasing productivity by cooling sows in heat stressed conditions using renewable energy, the current cooling system is not able to effectively meet that goal. Although discussed in other portions of the final project report, the costs associated with the system are high and would require a certain level of return to justify farmer investment.

4.1 Areas for Enhanced Research

While conducting this study, areas were noted where the existing experimental system or methodologies could be improved in future studies with more data or different types of data. A short summary of some of these topics is below.

4.1.1 Technoeconomic Assessment

The lack of productivity benefits made it clear in this case that the cooling system examined would not be economically viable for commercial swine systems. However, a technoeconomic assessment would be appropriate to examine the level of productivity benefits needed to make the cooling technology cost effective. This information can then be combined with LCA data for making a final determination of whether the system meets the combined cost, productivity, and environmental goals.

4.1.2 Heating and Cooling System

The heating and cooling system design is complex, with heat exchangers, pumps, and a compressor that are continually operating to keep the cooling surfaces and drinking water at the proper temperature. There was the potential for the heating components in the system to increase the overall temperature of the swine farrowing rooms due to heat being emitted by the piping and fixtures related to the heating/cooling system. Similarly, the cooling system also had losses in piping and other areas. As a first of its kind system, there were several areas where improvements may be possible in the future to provide more insulation and reduce energy use. These improvements may be able to both improve energy efficiency and increase animal comfort.

4.1.3 Infrastructure Impacts

Because of the exploratory nature of the project, it was decided not to include infrastructure impacts in the LCA analysis. Factors such as the use of metals, refrigerants, and plastics in the heating and solar-based cooling system would likely have increased the environmental impacts for the cooling scenario. However, there is the potential that this would be offset by the longer lifespan of equipment being used versus the use of heat lamps for warming piglets. With a better understanding of the lifespan of the equipment and materials used, it may be possible to include some of this data in future work.

4.1.4 Allocation

Early in the project, selection of the functional unit was discussed. At that time, it was hoped that there would be significant improvement in a number of output productivity measures (piglet number, piglet weight, sow weight, sow health). As the measured differences in outputs between scenarios appeared to be fairly limited, it was decided to use a straightforward weaned piglet number per litter as the functional unit for farrowing system productivity. Given a larger data set exhibiting significant differences in additional productivity measures, a more complex productivity output measure could be employed to more completely incorporate sow factors into the productivity measure.

5 Summary Conclusions

- The current renewably powered cooling system was not able to effectively improve productivity of sows and litters. Enhancements in cooling system efficiency both in terms of energy use and animal productivity are needed to meet these goals.
- The solar electricity associated with this production system was able to greatly improve the environmental impacts of piglet production in the control scenario. With fossil energy use well below net zero (-105 MJ per piglet) and global warming potential slightly above net zero (1.1 kg

CO_2 Equiv. per piglet), solar production is a viable means of reducing impacts. This compares to the long-term WCROC baseline fossil energy depletion of 73.1 MJ and GWP of 15.3 kg CO_2 equiv. Per piglet.

- The added energy demanded by the cooling system greatly reduced the positive environmental impacts of solar panels for pork production, with impacts of 4.6 MJ of fossil energy consumption and 9 kg of CO_2 equiv. per piglet.

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7 Appendix: Supplemental Data

The following tables contains additional information that may be informative to those interested in LCA methodology or the particular data used in calculation.

7.1 Feed Systems

The lactation feed mix below presents the amount of each ingredient in the 2000-unit ratio of feed produced (kgs or lbs). The primary ingredients for the mix are corn (energy) and soymeal (protein).

Table A1. Lactation Feed Mix Ingredients.

Output Products	Quantity	
Swine Ration, Lactation Mix	2000	kg
Input Materials/fuels	**Quantity**	
Corn Grain	1415	kg
Soymeal	485	kg
Soy Oil	20	kg
L-lysine	0.9	kg
Monocalcium Phosphate 21%	31.2	kg
Limestone	24.7	kg
Salt	10	kg
Swine Vitamin Premix	5	kg
Swine Trace Mineral	3	kg
DDGS	0	kg
Other Activities/Processing	**Quantity**	
Grain Milling	2000	kg

Table A2. Niche Feed Mixes This table contains a representative feed mix for a niche system. Data is based on weights of ingredients used to make roughly 2000 units of feed.

	Gestation	Lactation	Nursery				Grow Finish				
Sub-Phase			Phase 1	Phase 2	Phase 3	Phase 4	Phase 1	Phase 2	Phase 3	Phase 4	Phase 4+
Beginning body weight, kg			4.4	5.4	7.3	12.2	22.0	44.0	66.0	88.0	110.0
Assumed daily intake, kg	2.05	6.94	0.17	0.27	0.54	1.08	1.52	1.95	2.30	2.59	2.59
Corn	1547	1415	684	772	1100	1295	1235	1362	1462	1542	1362
Soybean meal, 47.5% CP	353	485	300	400	530	610	670	550	455	385	506
L-lysine HCI		0.9	3.2	3.4	5.6	7.4	7.8	7.0	6.4	5.8	5.8
L-threonine			0.8	1.6	2.4	2.8	2.8	2.2	2.0	1.6	1.6
DL-methionine			3.2	3.8	3	2.8	2.2	1.4	1.2	0.6	0.6
Soy oil	20	20	80.6	73	20	20	20	20	20	20	20
Monocalcium phosphate	32.9	31.2	6.2	10.2	12.6	18.6	14.6	11.2	8.6	6.2	6.2
Limestone	26.4	24.7	10	8.6	21.8	24.8	25.4	24.4	23.8	23.4	23.4
Salt	10	10	5	6	6	7	6.0	6.0	6.0	6.0	6.0
Phytase 600					1.6	1.6	1.6	1.6	1.6	1.6	1.6
Zinc oxide			8.4	8.4	5.6						
Whey, dried			625	500	200						
Plasma proteins, spray-dried			130	60							
Fish meal, menhaden			135	125	58						
Blood cells, spray-dried				20	20						
Paylean® 9 g											1
NSNG grow-finish vitamin premix	5	5	5	5	5	5	5.0	5.0	4.0	4.0	4.0
NSNG trace mineral premix	3	3	3	3	3	3	2.6	2.6	2.0	2.0	2.0

Table A3. Global warming potential (GWP) and fossil energy depletion (cumulative energy demand [CED]) for feed ingredients per kg of ingredient.

Ingredient	GWP (kg CO_2 Equiv.)	CED (MJ Fossil Energy)	Source database or reference
Corn	0.2099	2.09	WCROC data in preparation
Soybeans	0.2323	1.591	WCROC data in preparation
Soybean meal, 47.5% CP	0.1916	1.597	WCROC data in preparation
Soy oil	1.082	8.8087	WCROC data in preparation
Choice white grease	0.6531	10.1	Ecoinvent 2.2 (Frischknecht *et al.*, 2005)
Limestone	0.216	3.9	Ecoinvent 2.2 (Frischknecht *et al.*, 2005)
DL-methionine	5.493	127.4	Marinussen and Kool (2010)
L-lysine HCl	8.04	107.6	Marinussen and Kool (2010)
L-threonine	16.98	284.6	Marinussen and Kool (2010)
Monocalcium phosphate	1.202	18.4	Mosnier *et al.* (2011)
Phytase 600	1.9	26	Mosnier *et al.* (2011)
Whey, dried	1.01	35.6	Agrifootprint (Blonk, 2017)
Zinc oxide	2.832	43.71	Ecoinvent 2.2 (Frischknecht *et al.*, 2005)
Plasma proteins, spray-dried	2.417	20.15	Agrifootprint (Blonk, 2017)
Fish meal, menhaden	0.8887	15.92	Agrifootprint (Blonk, 2017)
Paylean®	0.904	44	Based on Sandefur *et al.* (2015)

7.2 Allocation Details

Table A4. Economic Allocation Calculations The economic allocation for each of the scenarios is calculated below using the value of 0.60$ per pound for culled meat and $40 per piglet for weaned piglet. replacement rate of 25%

BASE	250	kg sow weight									
	62.5	kg culled per litter									% Allocation
	sow	62.5	kg	137	lbs	$	0.60	$ per lb	$	82.67	15.8%
	Piglet	11	Units			$	40.00	$ per pig	$	440.00	84.2%
CONTROL	218.3	kg sow weight									
	54.58	kg culled per litter									% Allocation
	sow	54.58	kg	120	lbs	$	0.60	$ per lb	$	72.19	13.8%
	Piglet	11.24	Units			$	40.00	$ per pig	$	449.60	86.2%
COOLING	228.53	kg sow weight									
	57.14	kg culled per litter									% Allocation
	sow	57.14	kg	125	lbs	$	0.60	$ per lb	$	75.57	14.3%
	Piglet	11.37	units			$	40.00	$ per pig	$	454.80	85.8%

7.3 Full Swine Production System

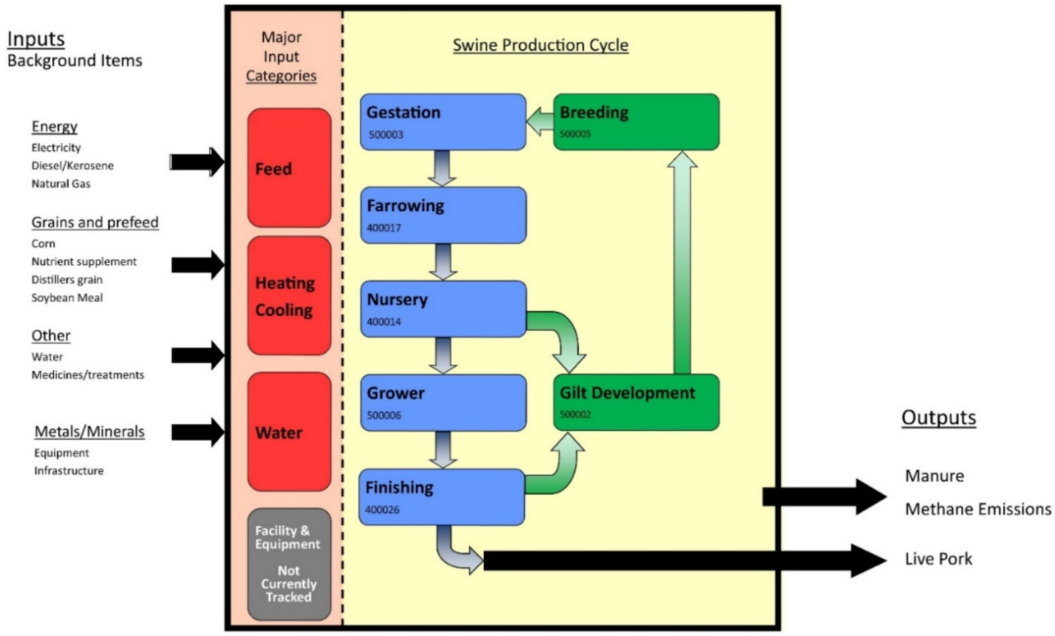

Figure A1. LCA Overview and Boundaries for the Swine Production System. The schematic shows the foreground and background components of the full swine systems as used in section 3.2. Items within the foreground system boundaries (peach and yellow areas) are considered the main focus of the study. Items in the background system (outside the black boundary lines) are items that are considered secondary and can't be varied as part of the main system.