M.L 2016, Chp. 186, Sec. 2 Subd. 07e Project Abstract
For the Period Ending June 30, 2019

PROJECT TITLE: Solar Energy Utilization for Minnesota Swine Farms – Phase II
PROJECT MANAGER: Lee Johnston
AFFILIATION: University of Minnesota West Central Research and Outreach Center
MAILING ADDRESS: 46352 State Hwy 329
CITY/STATE/ZIP: Morris, MN 56267
PHONE: 320-589-1711
E-MAIL: johnstlj@umn.edu
WEBSITE: https://wcroc.cfans.umn.edu/
FUNDING SOURCE: Environment and Natural Resources Trust Fund
LEGAL CITATION: M.L. 2016, Chp. 186, Sec. 2, Subd. 07e

APPROPRIATION AMOUNT: $475,000
AMOUNT SPENT: $460,772
AMOUNT REMAINING: $14,228

Sound bite of Project Outcomes and Results
Our project demonstrated that solar-generated electricity used to power a sow cooling system in a swine farrowing system can effectively improve the comfort of sows and reduce the carbon footprint of commercial pork production.

Overall Project Outcome and Results
American pork producers are trying to improve the environmental footprint of their production systems by reducing their reliance on fossil fuels. Keeping sows and pigs in their ideal temperature range during hot seasons is one way to improve animal performance and the carbon footprint of their production system. Use of solar-generated electricity is another approach for pig farmers to reduce their reliance on fossil fuels. We designed and installed a solar-powered system to cool heat-stressed sows during the farrowing and lactation periods. After installation and commissioning, we studied 84 sows and litters over two summer seasons in three contemporary groups of sows. The 20 kW solar array consistently provided enough electricity to operate the sow cooling system installed in a confinement farrowing barn. The sow cooling system studied in this project was able to significantly reduce heat stress and improve welfare of farrowing and lactating sows. Unfortunately, the reduced heat stress of sows did not support improvements in litter size at weaning or growth rate of suckling pigs. A basic economic analysis of the 20 kW solar PV system installed for this project suggested the system would breakeven after 60 years on a straight cash basis (revenues minus expenses). When tax incentives are added and fully utilized, the breakeven point is between 8 and 12 years but can depend on the utility provider in the area. A Life Cycle Assessment (LCA) of the carbon and energy footprints of the sow cooling system was completed. Because there was no increased output (number or weight of weaned pigs) as a result of the cooling system, neither the carbon footprint nor the energy footprint of the farrowing operation were improved by the cooling system. However, using electricity generated by the solar PV system did substantially reduce the carbon footprint and also significantly reduced the consumption of energy derived from fossil fuels for the swine farrowing operation. Solar-generated electricity can play an important part in reducing carbon emissions from Minnesota pork production.

Project Results Use and Dissemination
Information related to this project has been disseminated to many different audiences in a variety of formats. The target audiences for these publications include: pig farmers, engineers and builders of swine production barns, swine industry consultants, and consumers. Publications related to this project include: a video about the project (Cooling Sows and Heating Piglets with Solar Energy) and two factsheets (WCROC Farrowing Barn Heating and Cooling System and Lactating Sow Performance with Solar-Powered Cooling). Multiple conference presentations and posters were made for industry and professional audiences, and many articles were printed in

newsletters and popular press, including the West Central Research and Outreach Center Newsletter, *Land Magazine*, *Morris Star Tribune Ag Supplement*, *The Farmer Magazine*, and *Minnesota Pork Congress Magazine.* Any of these publications are available upon request from the project manager. More publications are anticipated in the future.

Environment and Natural Resources Trust Fund (ENRTF)
M.L. 2016 Work Plan – Final Report

Date of Report: September 30, 2019

Final Report

Date of Work Plan Approval: June 7, 2016

Project Completion Date: June 30, 2019

PROJECT TITLE: Solar Energy Utilization for Minnesota Swine Farms – Phase II

Project Manager: Lee Johnston

Organization: University of Minnesota West Central Research and Outreach Center

Mailing Address: 46352 State Hwy 329

City/State/Zip Code: Morris, MN 56267

Telephone Number: (320) 589-1711

Email Address: johnstlj@umn.edu

Web Address: wcroc.cfans.umn.edu

Location: Statewide

Total ENRTF Project Budget:	**ENRTF Appropriation:**	**$475,000**
	Amount Spent:	**$460,772**
	Balance:	**$14,228**

Legal Citation: M.L. 2016, Chp. 186, Sec. 2, Subd. 07e

Appropriation Language: (h) Solar Energy Utilization for Minnesota Swine Farms – Phase 2
$475,000 the second year is from the trust fund to the Board of Regents of the University of Minnesota for the West Central Research and Outreach Center in Morris to continue to develop and evaluate the utilization of solar photovoltaic systems at swine facilities to improve energy and economic performance, reduce fossil fuel usage and emissions, and optimize water usage. This appropriation is available until June 30, 2019, by which time the project must be completed and final products delivered.

I. PROJECT TITLE: Solar Energy Utilization for Minnesota Swine Farms—Phase 2

II. PROJECT STATEMENT:

This project addresses an important question facing American pork producers, namely how to lower fossil energy use and reduce the carbon and environmental footprint of swine production systems. Minnesota has been a leader in addressing competing challenges within the nexus of food, environment, and energy. Pork producers need innovative housing systems that help address environmental and energy concerns while remaining competitive in the global market for pork. Minnesota is a major pork producing state (3rd nationally). The Midwestern climate dictates considerable indoor environmental (temperature) control of production facilities to ensure efficient production and comfort of pigs and workers. This environmental control includes heating (fossil fuels) during cold conditions and cooling (electricity) during warm/hot weather for all phases of pig production. Producers are seeking solutions to their energy use challenges. Helping producers find solutions to these challenges fits well with the ten-year goal of the Univ. of MN's West Central Research and Outreach Center (WCROC). That goal is to reduce fossil energy consumption and reduce the carbon and environmental footprint of Minnesota farms. This goal was established as part of a strategic planning process that identified rising energy costs and changing market demands for low carbon footprint agricultural products as key agricultural issues in the next decade. In applying this strategic goal to the problem facing the Minnesota pork industry, the research team identified two innovative methods to cool pigs that will lower ventilation rates and thus emissions of odor, greenhouse gases, and dust in exhaust air, reduce water usage, and lower the carbon and environmental footprint of Minnesota-produced pork. The first cooling system uses liquid-cooled pads located in farrowing stalls to cool the sows while they nurse their piglets during summer. Sows will lie on the pads and heat will be transferred from their body to the liquid contained within the pad. The second cooling system will provide chilled drinking water (55 °F) to sows in a farrowing facility. Sows provided cooled water drink less water, and are physically cooled by intake of the chilled water. Water cooling will be provided by a chiller or an air-source heat pump powered by solar PV collectors mounted on the roof of the sow facility. This project complements other ongoing state- and commodity-funded projects at WCROC that are investigating clean energy agricultural production systems.

III. OVERALL PROJECT STATUS UPDATES:

Project Status as of: January 1, 2017

We are in the initial phases of this project and making good progress toward our objectives. We have identified and ordered the solar PV system; identified and ordered the cooling floor inserts; contracted with an engineering firm to develop specifications for installation of the cooling systems; and drafted a preliminary protocol that directs the study of sow performance under the cooling systems to be deployed.

Project Status as of: July 1, 2017

Report not submitted as per directions from LCCMR staff.

Project Status as of: January 1, 2018

This project is progressing nicely. We have installed the sow cooling floors and solar PV system. The cooling systems for sow floors and drinking water have been designed and installed. One group of sows have used the cooling systems in a preliminary test of the systems and data collection procedures. A second group of sows have used the systems for collection of animal and system performance data. We have shared details of this project with interested people at the Midwest Farm Energy Conference and through limited media outlets.

Project Status as of: July 1, 2018

This project is progressing as planned. We have assigned a second group of sows to use the system and have completed data collection for this second group. Summaries of data collection for this second group is underway. We will begin work on statistical analysis and interpretation of animal performance data and energy use data soon. We have shared information about this project with listeners on the Linder Farm Network (syndicated radio network based in Owatonna, MN) and subscribers to the multistate (Minnesota included) SowBridge educational series.

Project Status as of: January 1, 2019

This project is progressing as planned. We have completed data collection on three groups of sows for this experiment, one group more than originally proposed. Biological performance data has been summarized. We are in the midst of summarizing data on room conditions (temperatures, gas concentrations, humidity) and energy use within each experimental room. We have arranged for presentation of our results in several different venues in the coming months.

Amendment request as of July 19, 2019

We request extension of the date the final report is submitted from August 15 to September 30, 2019. This is being requested so we may more substantially complete and report on our dissemination outcomes, which includes publications of articles in industry and scientific journals that will occur after July 1. No funds will be spent after June 30, 2019. Amendment Approved by LCCMR 7/29/19.

Overall Project Outcomes and Results (September 30, 2019):

American pork producers are trying to improve the environmental footprint of their production systems by reducing their reliance on fossil fuels. Keeping sows and pigs in their ideal temperature range during hot seasons is one way to improve animal performance and the carbon footprint of their production system. Use of solar-generated electricity is another approach for pig farmers to reduce their reliance on fossil fuels. We designed and installed a solar-powered system to cool heat-stressed sows during the farrowing and lactation periods. After installation and commissioning, we studied 84 sows and litters over two summer seasons in three contemporary groups of sows. The 20 kW solar array consistently provided enough electricity to operate the sow cooling system installed in a confinement farrowing barn. The sow cooling system studied in this project was able to significantly reduce heat stress and improve welfare of farrowing and lactating sows. Unfortunately, the reduced heat stress of sows did not support improvements in litter size at weaning or growth rate of suckling pigs. A basic economic analysis of the 20 kW solar PV system installed for this project suggested the system would breakeven after 60 years on a straight cash basis (revenues minus expenses). When tax incentives are added and fully utilized, the breakeven point is between 8 and 12 years but can depend on the utility provider in the area. A Life Cycle Assessment (LCA) of the carbon and energy footprints of the sow cooling system was completed. Because there was no increased output (number or weight of weaned pigs) as a result of the cooling system, neither the carbon footprint nor the energy footprint of the farrowing operation were improved by the cooling system. However, using electricity generated by the solar PV system did substantially reduce the carbon footprint and also significantly reduced the consumption of energy derived from fossil fuels for the swine farrowing operation. Solar-generated electricity can play an important part in reducing carbon emissions from Minnesota pork production.

IV. PROJECT ACTIVITIES AND OUTCOMES:

ACTIVITY 1: Design, install, and evaluate a solar PV system and sow cooling pads in the farrowing facility

Description: The team will install a 20 kW solar PV collector and research the effective cooling of farrowing sows. Performance testing will be conducted over the course of Years 2 and 3. The electric energy generated from the solar PV system will be used primarily to power a water chiller / heat pump. The use of chilled water will be evaluated as a means to cool sows using water jacketed floor pads that the sows lay upon. The solar powered cooling system will be designed using a combination of internal expertise and an external engineering firm. Commercially available floor pads will be installed in a farrowing room at the WCROC facilities and be connected to the water cooling system. Evaluation of the cooling pad system will be completed to determine improvements in performance and comfort of sows and their piglets in research over 2 summers. An engineering firm will assist the project team to model and design energy-efficient cooling systems that can be retrofitted into conventional swine facilities. Most of the swine facilities located in Minnesota have standardized design and construction. Therefore, retrofit designs can be utilized extensively across the state. The intent is to use an electric powered chiller / air-source heat pump to provide chilled liquid for the cooling systems. Heat pumps, especially air-source heat pumps, can be retrofitted to existing swine facilities. Heat pumps have a coefficient of performance of 2.5 meaning for every unit of energy put into the system, 2.5 units are available for use. Therefore, heat pumps could be a novel, energy saving feature for swine facilities. Cooling systems will be utilized that can also be incorporated into existing facilities. Interface control systems will be developed to effectively manage the novel cooling systems.

In the WCROC farrowing building, the project team will use either commercially-available or custom fabricated floor pad coolers within sow farrowing stalls and heat pumps to provide the cool, circulating fluid. Farrowing stalls are challenging to maintain proper temperature as a producer wants to keep the sows cool (about 60 ^{o}F) while keeping the piglets warm and dry (about 86 ^{o}F). Pad coolers utilize plates of steel with cooling loops attached to the underside which allow liquid to circulate. The pads are placed in the sow's stall and cool liquid is pumped through the cooling loops. Pad coolers will cool the sows through direct contact as the sow will lay across the pad and allow the piglets to remain warm in a separate, adjacent area. The liquid can then return to the heat pump where there is a transfer of the heat to the exterior air. The pad cooler covers about 30 to 50% of the sow's lying area and body. The farrowing building has two rooms with each containing sixteen individual sow farrowing stalls. Within one room, each sow will be cooled with a pad cooler and heat pump(s). The other room will be operated as the Control Treatment using conventional, forced-air ventilation cooling.

The project team will begin field testing by commissioning the systems without pigs in the rooms. In months 1 through 10, the cooling pads and chiller will be ordered and installed. Following installation, the system will be commissioned over the course of two months to insure proper performance during the sow trial. The commissioning process will include:

- Calibrating and refining controls
- Measuring liquid cooling temperatures
- Modeling heat transfer performance
- Troubleshooting

Once the system and controls are fine-tuned, pigs will be added to the buildings. Testing with pigs is anticipated to begin in the second year of the project.

In the farrowing building, sows will be allotted randomly to one of the two treatments: forced air ventilation cooling (Control Treatment - Room 1) or chiller / heat pump with pad cooler (Pad Cooling Treatment - Room 2). Animal performance variables measured will include: individual sow body temperature, sow feed intake, changes in sow weight and backfat depth, piglet and litter weight gains, and number of days from farrowing (birthing) to re-breeding. Amount of feed consumed daily by each sow will be recorded. Initial and ending (weaning date) sow weights will be recorded. Body temperature and respiration rates of the sows will be measured and utilized as an indicator of heat stress experienced by the sow. Following completion of the initial testing period, the study will be replicated at least once (if appropriate weather conditions allow) with a second set of sows to increase statistical confidence. Mechanical performance measures will include electrical energy consumption including power consumed by the heat pumps and ventilation fans which will be measured along with the outdoor, room, and cooling loop (fluid) temperatures. Air temperature and quality will be important metrics so variables measured will include: room temperatures, responsiveness of cooling systems in maintaining setpoint temperatures, humidity levels, and concentrations of ammonia, hydrogen sulfide, carbon dioxide, methane, and nitrous oxide.

Outcomes will include information regarding energy savings and influences on pig performance. The information will then be used for the economic evaluation in Activity 3.

Reliability and durability of cooling systems are extremely important as equipment failure usually leads to compromised performance and in some situations could lead to death of a significant number of pigs. Swine production facilities are much harsher environments than office buildings with relatively high concentrations of dust, gases, and humidity, which increases the chances for physical damage to equipment. Typically, these undesirable components of air in the room are removed with exhaust air in a forced-air cooling system. Also, solar PV arrays may be exposed to harsher than normal conditions at a swine production facility. To characterize reliability of the solar PV and cooling systems, the project team will measure operational availability, hours of operation, energy production (solar PV), and maintenance and repair events. This information will be incorporated into an extension bulletin and be used to refine cooling system pre-designs for swine farrowing facilities (Activity 3).

Summary Budget Information for Activity 1:	**ENRTF Budget:**	**$ 272,860**
	Amount Spent:	**$ 270,516**
	Balance:	**$ 2,344**

Outcome	**Completion Date**
1. *Install solar PV collectors (20 kW) on the farrowing facility*	10/1/2016
2. *Design and install sow cooling systems including water-cooled pads for sows, heat pumps, and water delivery*	4/1/2017
3. *Field test and evaluate floor pad cooling for farrowing groups*	4/1/2019

Activity Status as of: January 1, 2017

This activity has received the most attention in the first 6 months of the project. We identified a supplier of the floor inserts that will cool the sows. The PI visited the manufacturer of the floor inserts this summer to ensure the product would work for our application. We have developed the appropriate mounting brackets that allow us to remove the existing floors from our farrowing stalls and replace them with the cooling floor inserts. Subsequently, we have ordered the flooring inserts and expect delivery in January, 2017. We established bid specifications for the solar PV system, offered those specifications to manufacturers and have selected Zenergy, LLC to supply and install the 20 kW solar PV system needed for this project. We expect installation in Spring 2017. We have also contracted with an engineering firm (AKF Engineering) to design the cooling system and controls for the system. AKF has made one site visit to begin development of the system. We have developed an initial draft of the barn protocol that will govern the conduct of the sow lactation experiment.

Activity Status as of: July 1, 2017

Report not submitted as per directions from LCCMR staff.

Activity Status as of: January 1, 2018

The floor inserts for cooling sows were received and installed early in 2017. The engineering design for the solar powered, sow cooling system was completed in the first quarter of 2017. The 20 kW solar PV system was installed using a ground mount in the spring. The entire cooling system to supply circulating cool water under sows was installed in May and June. The system was commissioned in early June. Unfortunately, only a very brief test of the system functionality (1 week) was conducted before sows had to be moved into the facility before farrowing (birthing). Sows moved into the facility on June 12 with anticipated farrowing dates of June 14 to 16. Sows remained in the facility until July 14. We planned to test the efficacy of the sow cooling system with this group of sows. However, two important factors subverted this objective. First, environmental temperatures during this period were not as hot as expected. Consequently, sows were not consistently heat stressed which prevented a true test of the cooling system. Second, there were intermittent disruptions in operation of the cooling system for a variety of reasons. Consequently, we used this sow group as a preliminary test of the cooling system and data collection systems.

From August 23 to September 22, we conducted a second trial. The cooling system worked much more reliably. To ensure heat stress of sows, we turned on furnaces in the farrowing facility to target a daytime temperature of about 85 degrees F and a nighttime temperature of about 70 degrees F. This approach ensured that sows were under consistent heat stress which enabled evaluation of the cooling system. The cooling system performed consistently with only a few minor glitches. We plan to repeat this trial and approach in spring and/or summer of 2018.

Activity Status as of: July 1, 2018

From May 29 through June 29, we conducted a third trial. The cooling system worked quite well and was much more reliable than in previous trials. Once again, we used the in-room furnaces to ensure that sows experienced heat stress so that we could effectively test the cooling potential of the system. The data collection portion of this third trial ended on June 29, 2018. In the coming weeks and months, we will summarize the animal performance, room conditions, and energy use data. After the data are summarized, we will begin preliminary statistical analysis and interpretation of the results.

Activity Status as of: January 1, 2019

From August 13 through September 7, we conducted a fourth trial of the solar-powered cooling system. The cooling system worked reliably and we used in-room heaters to ensure sows experienced heat stress during the lactation period. The artificial imposition of heat stress on sows allowed us to test the effectiveness of the cooling system. With completion of this fourth trial, we have three complete cohorts of data on which we can base our conclusions. In our original proposal, we planned to conduct this study with two groups of sows. But, we added a third group of sows so we have a more robust dataset for analysis. We have summarized data on the biological performance of the sows and are currently working on summarizing the rather large collection of raw data on energy use in the study rooms.

Final Report Summary (September 30, 2019):

Eighty-four sows and litters in three farrowing groups were studied to evaluate efficacy of the solar-powered cooling system. We consistently imposed heat stress on sows during farrowing and lactation periods to ensure an adequate test of the cooled floors. After an initial commissioning process, the floor cooling system functioned properly. Temperature of the floors that sows laid on in the Cool room were 5.7 °F cooler than similar floors in the Control (uncooled) room. Electricity use in the Cooled room was 160% to 260% of that used in the Control room. Most of this greater electricity use was attributable to operations of the heat pump, fan coil unit and pumps used to circulate cooled water through the system. The solar array produced enough electricity to meet the increased consumption of electricity in the Cooled room. The cooled floors (in combination with the cooled drinking water, see below) did alleviate a meaningful portion of heat stress experienced by sows. Rectal temperature of sows in the Cool room was significantly lower than body temperature of sows in the Control room. Furthermore, respiration rates of sows in the Cool room averaged 59 breaths per minute while sows in the Control room averaged 91 breaths per minute. Respiration rate is a very sensitive measure of heat stress in sows and would be about 30 breaths per minute when sows are housed in their most comfortable temperature range. Even though sows were more comfortable in the Cool room, there were no differences in the farrowing or postural behaviors of sows across rooms. Sows in the Cool room consumed more feed during lactation because they were more comfortable compared to sows in the Control room. However, the increased comfort and feed intake of sows in the Cool room did not improve sow or litter performance. Litter size weaned (11.2 vs. 11.4 pigs) and weight of litters at weaning (157.7 vs. 163.6 lbs) were not different statistically for Control and Cooled sows, respectively.

A comprehensive technical report has been submitted as an addendum to this final progress report. This technical report describes the conduct of the experiment and results in great detail.

ACTIVITY 2: Design, install and evaluate chilled drinking water system for pigs

Description: A second option to cool sows is to provide cool drinking water. Even though this seems to be obvious, initial testing has shown that drinking water in conventional farrowing facilities can warm up significantly and contribute to overheating animals. So chilling and recirculating the drinking water may be an effective approach to maintaining sows within their thermal neutral comfort zone. When sow body temperatures climb above the thermal neutral comfort zone, feed efficiency, reproductive performance, and litter performance can decline significantly.

In this activity, a cooling system that supplies chilled drinking water to sows will be designed by the project team and external consulting engineers. The team anticipates using the same chiller / heat pump used in Activity 1 to chill the drinking water. The system will be installed and evaluated in the farrowing building at WCROC. The system will be evaluated for its ability to provide chilled water consistently and reliably to sows over the two years of the project. Economic feasibility of the system will be determined considering costs of equipment, installation (including insulating water lines), maintenance, operation, and performance of sows. Electricity from the solar PV array will be used to power the system. Sows will be allotted randomly to one of the two treatments: conventional drinking water (Control Treatment - Room 1) or chilled drinking water (Chilled Water Treatment - Room 2). Animal performance variables measured will include: individual sow body temperature, sow feed intake, changes in sow weight and backfat depth, piglet and litter weight gains, and number of days from farrowing (birthing) to re-breeding. Amount of feed consumed daily by each sow will be recorded. Initial and ending (weaning date) sow weights will be recorded. Body temperature and respiration rates of the sows will be measured and utilized as sensitive indicators of heat stress experienced by the sow. Following completion of the initial testing period, the study will be replicated at least once (if appropriate weather conditions allow) with a second set of sows to increase statistical confidence. Water temperature of the system will be measured for both the control and chilled water treatments. Temperature of the drinking water will be measured as it enters the building, after chilling (chilled water treatment), and at various points within the farrowing room. Energy consumed in chilling the drinking water will be measured.

Summary Budget Information for Activity 2: **ENRTF Budget: $139,434**
Amount Spent: $134,689
Balance: $ 4,745

Outcome	**Completion Date**
1. *Design and install a chilled drinking water system in the sow farrowing facility*	4/1/2017
2. *Field test and evaluate the chilled drinking water system in the sow farrowing facility*	4/1/2019

Activity Status as of: January 1, 2017

Much of the work completed in Activity 1 also applies to this Activity. Selection of a solar PV supplier and engineering firm for design work applies to this activity as well. In addition, we have investigated equipment to allow remote, continuous monitoring of sow body temperatures during the sow lactation experiment.

Activity Status as of: July 1, 2017

Report not submitted as per directions from LCCMR staff.

Activity Status as of: January 1, 2018

Much of the work completed in Activity 1 also applies to this Activity. The cooling system for drinking water was designed by the same engineering firm used for Activity 1. The cooled drinking water system was installed at the same time as the cooling system for flooring. The first group of sows through the facility was used as a preliminary test as described in Activity 1. The second group of sows was used for full data collection under heat stress conditions. We used the continuous body temperature monitoring system in sows of both groups with limited success. There was not good retention of body temperature sensors in large sows.

Activity Status as of: July 1, 2018

Much of the work completed in Activity 1 also applies to this Activity. The cooled drinking water system worked reliably during the third trial of this project. Once again, we used a system to continuously measure internal body temperature of sows over selected 2-day periods as we did in the previous trial. This time, we achieved excellent retention of the sensors in sows during the first week of lactation. During the last week of lactation when suckling pigs were larger and more active, retention of the sensors was not as good; but still better than the comparable period in the last trial.

Activity Status as of: January 1, 2019

As in previous reports, much of the work described in Activity 1 also applies to this Activity. As mentioned previously, we conducted the study on a third group of sows. However, we did not use the continuous internal body temperature sensor system in sows of this last group. Because of our previous difficulties with retention of sensors, we opted not to use the continuous body temperature monitors in this last group of sows.

Final Report Summary (September 30, 2019):

As noted previously, much of the work related to Activity 2 was related closely to the work in Activity 1. The system to supply cool drinking water to sows functioned properly throughout all three farrowing groups. Temperature of drinking water ranged from 58 °F to 74 °F in the Cool room (average = 63.3 °F) and 64 °F to 106 °F in the Control room (average = 82.9 °F). This significant reduction in drinking water temperatures for sows in the Cool room is partially responsible for the increased comfort and feed intake of sows in the Cool room compared to the Control room (see Activity 1 above). However, providing cooled drinking water to sows did not have a statistically significant influence on drinking behavior of sows during the short observation periods of this experiment. We believe cool drinking water may increase drinking time of sows but we might have to observe sows for much longer periods of time (e.g. 12 to 24 hours) to detect this difference in behaviors. Providing cooled drinking water to sows may be a more practical, cost-effective approach to cooling heat-stressed sows compared with installing cooled flooring for sows.

A comprehensive technical report has been submitted as an addendum to this final progress report. This technical report describes the conduct of the experiment and results in great detail.

ACTIVITY 3: Perform economic analysis and disseminate results of system evaluations

Description: A basic cost-benefit analysis will be developed comparing the conventional and energy-optimized systems. Basic economics will be evaluated in terms of capital expense, operational and maintenance costs, pig performance, and energy savings. A closeout spreadsheet model will be developed for the farrowing treatments. The spreadsheet will include the capital and operating costs from each system and will project simple payback using performance information observed during the farrowing facility trials. A spreadsheet will be developed for swine producers so they can model their own potential return on investment for the energy-efficient cooling system retrofits. The results of the study will be transferred to swine producers through a variety of methods including presentations and tours at the Midwest Farm Energy Conference in Summer 2017 focusing on swine production facilities, development of an extension bulletin, a dedicated web page, news articles in agricultural magazines, summaries on the University of Minnesota Extension Swine webpage, peer-reviewed publications, and through presentations to swine producers at industry meetings. The information will be incorporated into an extension bulletin and be used to refine cooling system pre-designs for swine farrowing facilities.

Summary Budget Information for Activity 3:		
	ENRTF Budget:	**$62,706**
	Amount Spent:	**$ 55,567**
	Balance:	**$ 7,139**

Outcome	**Completion Date**
1. *Perform a basic economic analysis on the solar PV and sow cooling systems.*	4/1/2019
2. *Develop an extension bulletin with results as well as pre-design examples for the solar PV and sow cooling systems that producers may use as guides. The extension bulletin will be printed and placed on-line.*	4/1/2019

3. *In each of the first two years of the project, the project and preliminary results will be discussed at 3 or more producer / professional meetings. In Year 3, the team will organize three informational meetings in key swine production areas of Minnesota.*	6/1/2019

Activity Status as of: January 1, 2017

There has been no progress on this activity because we need to have the system in place and operational before there are any data to evaluate or disseminate.

Activity Status as of: July 1, 2017

Report not submitted as per directions from LCCMR staff.

Activity Status as of: January 1, 2018

There has been no progress on this activity because we need to generate sufficient data to ensure the system is working properly and that we have adequately characterized the sows' responses to the cooling systems.

Activity Status as of: July 1, 2018

As mentioned in Activity 1, we are summarizing the animal performance data and energy use data. These summaries will inform the economic analysis of the system. A University of Minnesota undergraduate student in Economics is serving as a 2018 summer intern on this project. This student is working on summarizing the economic implications of this cooling system under the direction of the project team.

Activity Status as of: January 1, 2019

The undergraduate intern hired to work on this project determined that the economic returns generated from improved performance of sows was not sufficient to cover the cost of the sow cooling system within a reasonable period of time. So, we are delving further into the economic analysis to determine the impact of the sow cooling system on energy use within the farrowing rooms. Possibly, differences in energy use elicited by the sow cooling system may improve the economic returns to the system. We are currently summarizing the energy use data so that economic calculations can be applied.

Final Report Summary (September 30, 2019):

We divided our economic analysis into two categories: 1. costs associated with installation and operation of the sow cooling systems, and 2. Costs associated with installation of the solar array. The capital costs for the sow cooling system (cool floors and cooled water) totaled $178,865 to equip 16 farrowing stalls for a cost of $11,179 per stall. If one depreciates these capital costs over a 20-year period, the annual per stall capital cost is $559 per stall. These "per stall" costs could be reduced substantially if a larger number of stalls were equipped with the cooling equipment so that the equipment costs could be spread over more stalls. The engineering design firm for the sow cooling system estimated annual operation and maintenance costs of the cooling system equipment would be about 0.5% of the equipment cost ($148,865) which amounts to $744 per year.

The 20 kW solar PV array was of sufficient size to produce electricity in excess of that needed to operate the cooling system during the hot summer months. The solar array also produced electricity during periods of the year when the sow cooling system was not needed. This excess electricity could be used other places on the farm to displace electricity purchased from the grid or sold back on the grid in certain situations. The National Renewable Energy Lab (NREL) aggregates and models solar PV costs using data from actual installations around the country and estimated operations and maintenance (O&M) costs at $13/kW/yr in 2018. A basic financial assessment of the 20 kW solar PV system installed at the WCROC was conducted. Electricity pricing and tariff fees were used from the bills submitted to the West Central Research and Outreach Center from Runestone Electric Association (REA). REA is a rural electric cooperative. Results of this economic analysis will vary significantly between rural electric cooperatives and investor owned utilities. Considering the capital costs, value of the power produced, and fees charged by the utility; the 20 kW solar PV system will breakeven after 60 years on a straight cash basis (revenues minus expenses). When tax incentives are added and fully utilized, the breakeven point is between 8 and 12 years. The tax incentives include an investment tax credit that currently is 30% in 2019 and will decline each year. The second tax advantage is accelerated depreciation which allows the system to be fully depreciated in either one year or five years. There are two key takeaway points and recommendations on financial viability of solar PV systems on farms. The first recommendation is to research the electricity pricing, incentives offered, and fees charged by the local utility. Again, these will all vary significantly across electricity utilities. The second, and perhaps most important recommendation, is to determine if available tax incentives can be fully utilized and the value completely realized by the individual or farming operation.

A Life Cycle Assessment (LCA) of the carbon and energy footprints of the sow cooling system was completed. Sow and litter performance were not improved by the sow cooling system. Consequently, there were no increases in output (number or weight of weaned pigs) of the farrowing system. Because there was no increased output as a result of the cooling system, neither the carbon footprint nor the energy footprint of the farrowing operation were improved by the cooling system. However, using electricity generated by the solar PV system did substantially reduce the carbon footprint and also significantly reduced the consumption of energy derived from fossil fuels. A complete technical report on the LCA methodology and results has been submitted as an addendum to this final report.

V. DISSEMINATION:

Description: Results of this project will be disseminated through several methods. In summer 2017, the West Central Research and Outreach Center will host the Midwest Farm Energy Conference. Attendees expect to include livestock producers, energy professionals, students and other stakeholders. At the conference, results of this project will be presented and there will be a tour of the solar energy systems at the WCROC Swine Research Unit (as long as biosecurity protocols can be met). Initial results will be discussed at three or more meetings with swine producers, swine industry professionals, or energy professionals in each of the first two years of the project. In Year Three, the project team will organize three informational meetings in key swine production areas of Minnesota. The meetings will focus on disseminating the results to swine producers and the professionals that consult with swine producers. The results will also be disseminated on-line on the WCROC website as well as the University of Minnesota Swine Extension Team website. An extension bulletin with the project results and retrofit pre-designs will be printed and provided to swine producers and other stakeholders. We also anticipate publishing results in academic journals, local and regional newspapers, and industry magazines.

Status as of: January 1, 2017

There has been no dissemination of data in the project because we are in the initial phases of developing the system. We have discussed this project with many stakeholders in related industries in numerous informal settings. A committee has been established and has met four times to plan the 2017 Midwest Farm Energy Conference (MFEC). The MFEC conference will be held June 13th and 14th. The June 14th session will include presentations about this research as well as tours.

Status as of: July 1, 2017

Report not submitted as per directions from LCCMR staff.

Status as of: January 1, 2018

The Midwest Farm Energy Conference was held at the West Central Research and Outreach Center on June 13 and 14, 2017. A tour of the farrowing facilities was included in the conference agenda. About 35 people participated in the tour. The sow cooling systems were in place and operating at the time of the conference. Sows were present in the farrowing facilities but they had not farrowed at the time of the tour. As a result of the conference tour, an article on the project appeared in *The Farmer* magazine in July, 2017. Furthermore, we wrote a short article entitled “Using sun to keep sows cool” that appeared in the August issue of the WCROC Newsletter and currently resides on the WCROC website.

Status as of: July 1, 2018

Without complete results, there was not much to share with stakeholders in the first half of 2018. Two members of the project team did a radio interview with Linda Brekke from the Linder Farm Network. The interview aired on the Linder Farm Network over the noon hour in January. The Linder Farm Network based in Owatonna, MN reaches farmers throughout Minnesota. In addition, the Project Director included information on this project as part of his presentation on the SowBridge educational series in May. SowBridge is an educational program targeted toward animal caretakers on sow farms throughout the U.S. Over the past several years, SowBridge subscribers have resided in 16 U.S. states (Minnesota included), Canada, and Ireland.

Status as of: January 1, 2019

We are working to complete analysis of results related to biological performance and energy use. With this complete summary and analysis, we can provide a complete picture of the results for pork producers and industry professionals to evaluate the utility of the solar sow cooling system. We will present our results at the 3rd Midwest Farm Energy Conference held at WCROC on July 10 and 11, 2019. In addition, we will submit an abstract for presentation at the Waste-to-Worth Conference held at the University of Minnesota (Minneapolis) in April, 2019. We also plan to present our results at the Minnesota Pork Congress (February, 2019) and at the annual meeting of the MinnKota Builders Association at a location yet to be determined (March, 2019). We will also prepare summaries for pork industry trade publications such as the National Hog Farmer magazine and a complete research paper for a peer-refereed scientific journal such as Applied Engineering in Agriculture.

Final Report Summary (September 30, 2019):

Information related to this project has been disseminated to many different audiences in a variety of formats. Below are listed the publications related to this project. Any of these publications are available upon request from the project PI. More publications are anticipated in the future.

Video:

Cooling Sows and Heating Piglets with Solar Energy.
https://www.youtube.com/watch?v=F8CwSZnyJq4&feature=youtu.be

Factsheets:

WCROC Farrowing Barn Heating and Cooling System. West Central Research and Outreach Center, Morris, MN. January 2019. https://z.umn.edu/4nv3

Lactating Sow Performance with Solar-Powered Cooling. West Central Research and Outreach Center, Morris, MN. September 2019. https://z.umn.edu/4nv4

Conference presentations and posters for industry and professional audiences:

Johnston, L. J. 2019. Cooling sows and heating piglets with solar energy. Midwest Farm Energy Conference, Morris, MN. July 11, 2019.

Lozinski, B. M., M. Reese, E. Buchanan, A. M. Hilbrands, K. A. Janni, E. Cortus, B. Hetchler, J. Tallaksen, Y. Li, and L. J. Johnston. 2019. Innovative solar energy utilization for Minnesota swine farms. Proceedings paper and poster for Waste-to-Worth Conference, Minneapolis, MN. April 24, 2019.

Lozinski, B., M. Reese, E. Buchanan, A. M. Hilbrands, K. A. Janni, E. Cortus, B. Hetchler, J. Tallaksen, Y. Li, and L. J. Johnston. Innovative use of solar energy to mitigate heat stress in sows. Univ. of Minnesota Department of Animal Science Showcase. St. Paul, MN. April 3, 2019.

Li, Y., M. Lou, M. Reese, E. Buchanan, and L. Johnston. 2019. Effects of cooled floor pads and cooled drinking water on behavior of lactating sows under heat stress. Midwest Section of American Society of Animal Science. Omaha, NE. March 12, 2019.

Johnston, L.J. 2019. Innovative Solar Energy Utilization for Minnesota Farms. Presented to Minnkota Builders Assoc. Mtg. Morris, MN. March 15, 2019.

Johnston, L. J. 2018. WCROC's Greening of Agriculture Project. USDA Roman L. Hruska Meat Animal Research Center, Clay Center, NE. September 6, 2018.

Johnston, L. J. and B. T. Richert. 2018. Heat Mitigation for Sows. SowBridge. May 2, 2018.

Articles in newsletters and popular press:

Johnston, L., M. Reese, E. Buchanan, Y. Li, K. Janni, E. Cortus, J. Tallaksen, and K. Sharpe. 2019. Cooling sows with solar power. West Central Research and Outreach Center Newsletter. August, 2019. https://wcroc.cfans.umn.edu/wcroc-news/cooling-sows

Johnston, L., B. Lozinski, M. Reese, E. Buchanan, Y. Li, A. Hilbrands, K. Janni, B. Hetchler, and E. Cortus. 2019. Can the sun cool sows? *Land Magazine*, Swine and U column. June 28, 2019.

Johnston, L., M. Reese, E. Buchanan, Y. Li, K. Janni, and K. Sharpe. 2018. Solar cooling of sows. *Morris Sun Tribune Ag Supplement*. March, 2018.

Morrison, L. 2017. Using the sun to keep sows cool: Morris research farm testing innovative energy practices in swine production. *The Farmer Magazine* – News Briefs. July, 2017. (Freelance article covering our project.)

Johnston, L. J. 2017. Reducing fossil fuel use in swine production – One piece at a time. MN Pork Congress. Minneapolis, MN. January 18, 2017.

VI. PROJECT BUDGET SUMMARY:

A. ENRTF Budget Overview:

Budget Category	$ Amount	Overview Explanation
Personnel:	$ 228,510	Staff to coordinate project, collect and organize data, and assist in disseminating results including: Project Coordinator at 0.4 FTE Yr 1 and 0.5 FTE Yr 2 and 3 ($97,232); 3 Student interns Yr 2 & 3 ($17,148); Junior Scientist Yr 2 ($52,137); Research Fellow 0.5 FTE Yr 1 and 0.24 FTE Yr 2 ($61,993)

Budget Category	$ Amount	Overview Explanation
Professional/Technical/Service Contracts:	$ 98,000	Contracts for engineering design and system installation including: $30,000 for engineering professional services, $35,000 for General Contracting of Cooling System installation, $20,000 for General Contracting of Solar PV installation, $3,000 for Mechanical Contractor for Energy Sensor and Meter installation, and $10,000 for Control System installation. These professional services will be bid through a RFP process following University of Minnesota purchasing policy.
Equipment/Tools/Supplies:	$ 9,000	Energy and temperature sensors for sow facilities and animals including the potential for approximately 32 electronic temperature sensors for sows, 64 water temperature sensors, 12 electrical current sensors and data loggers.
Capital Expenditures over $5,000:	$ 130,425	Chiller / air source heat pump to cool water ($50,000), 20 kW solar PV system and cooling systems for sow farrowing facilities ($60,425), Controls for sow and water cooling systems ($20,000)
Fee Title Acquisition:	$NA	
Easement Acquisition:	$NA	
Professional Services for Acquisition:	$NA	
Printing:	$ 3,600	Printing of an extension bulletin to disseminate to swine producers, their consultants, and energy professionals (300 copies @ $12 each)
Travel Expenses in MN:	$ 5,465	Travel from Saint Paul to Morris to setup experiments and to collect data (10 trips, 330 miles each, $.565/mi). Travel to regional, in-state swine producer meetings to disseminate results (At least nine total trips @ $400 each including mileage, room, and meals).
TOTAL ENRTF BUDGET:	**$ 475,000**	

Explanation of Use of Classified Staff: N/A

Explanation of Capital Expenditures Greater Than $5,000:
The University of Minnesota West Central Research and Outreach will purchase a 20 kW solar photovoltaic system ($60,425) which will produce electricity for the on-site sow farrowing facility. Energy production, availability, and other variables important to economic feasibility will be measured. In addition, the solar PV system will be used to power sow cooling systems including a chiller / heat pump. The chiller / heat pump will be installed within the sow farrowing system and produce chilled water for the sow cooling pads and chilled drinking water. The cooling system will cost approximately $50,000. The sow cooling systems will need dynamic control capabilities to measure and adjust temperature so a control system will be purchased ($20,000). Funding for installation of these components is included in the Contract budget line.

Number of Full-time Equivalents (FTE) Directly Funded with this ENRTF Appropriation:
Averages 1.2 FTE per year over three years. Cumulative FTE 3.64

Number of Full-time Equivalents (FTE) Estimated to Be Funded through Contracts with this ENRTF Appropriation: Approximately 2.4 FTE total (year 1).

B. Other Funds:

Source of Funds	$ Amount Proposed	$ Amount Spent	Use of Other Funds
Non-state			
U of MN Indirect Cost Recovery / In-kind	$123,019	$	Indirect costs associated with normal operation of the University of Minnesota will be used as in-kind cost share.
State			
	$	$	
TOTAL OTHER FUNDS:	**$123,019**	**$**	

VII. PROJECT STRATEGY:

A. Project Partners:
Dr. Lee Johnston, U of MN WCROC Director of Operations and Swine Scientist, will serve as the principle investigator and project manager. He will be responsible for all reports and deliverables. Dr. Kevin Janni (U of MN Agricultural Engineer) will be a co-investigator and provide guidance on cooling system designs and testing in the swine facilities. He will also participate in the outreach activities. Mike Reese (WCROC Renewable Energy Director) will serve as a co-investigator and assist in the design, installation, testing, and control strategies of the solar energy portions of the cooling systems. He will also assist in coordinating with other ongoing energy projects at WCROC and help disseminate results. An engineering firm will be solicited through a RFP and will provide consulting services for designing, commissioning, and control strategies. An agricultural economist (yet to be named) will assist in the economic analysis of the solar systems.

B. Project Impact and Long-term Strategy:
The WCROC has a 10-year strategic plan to reduce consumption of fossil fuel and reduce the carbon and environmental footprint within production agriculture. This proposal builds upon current projects including 2014 ENTRF funding for the solar PV system on the WCROC grow-finish swine facility, energy audit, and modeling ($500,000). Long-term funding will continue to be sought to research alternatives to fossil energy within all agricultural crop and livestock enterprises through federal, state, and stakeholder groups.

C. Funding History:

Funding Source and Use of Funds	Funding Timeframe	$ Amount
2014 ENTRF – Phase 1 – “Transitioning Minnesota Farms to Clean Energy” to audit energy consumption in conventional swine production facilities, model optimal clean energy systems, and evaluate performance	July 2014 to June 2017	$500,000
University of Minnesota College of Food, Agricultural, and Natural Resource Sciences for additional research support to develop and evaluate clean energy systems for agricultural	July 1, 2013 to June 2015	$167,061

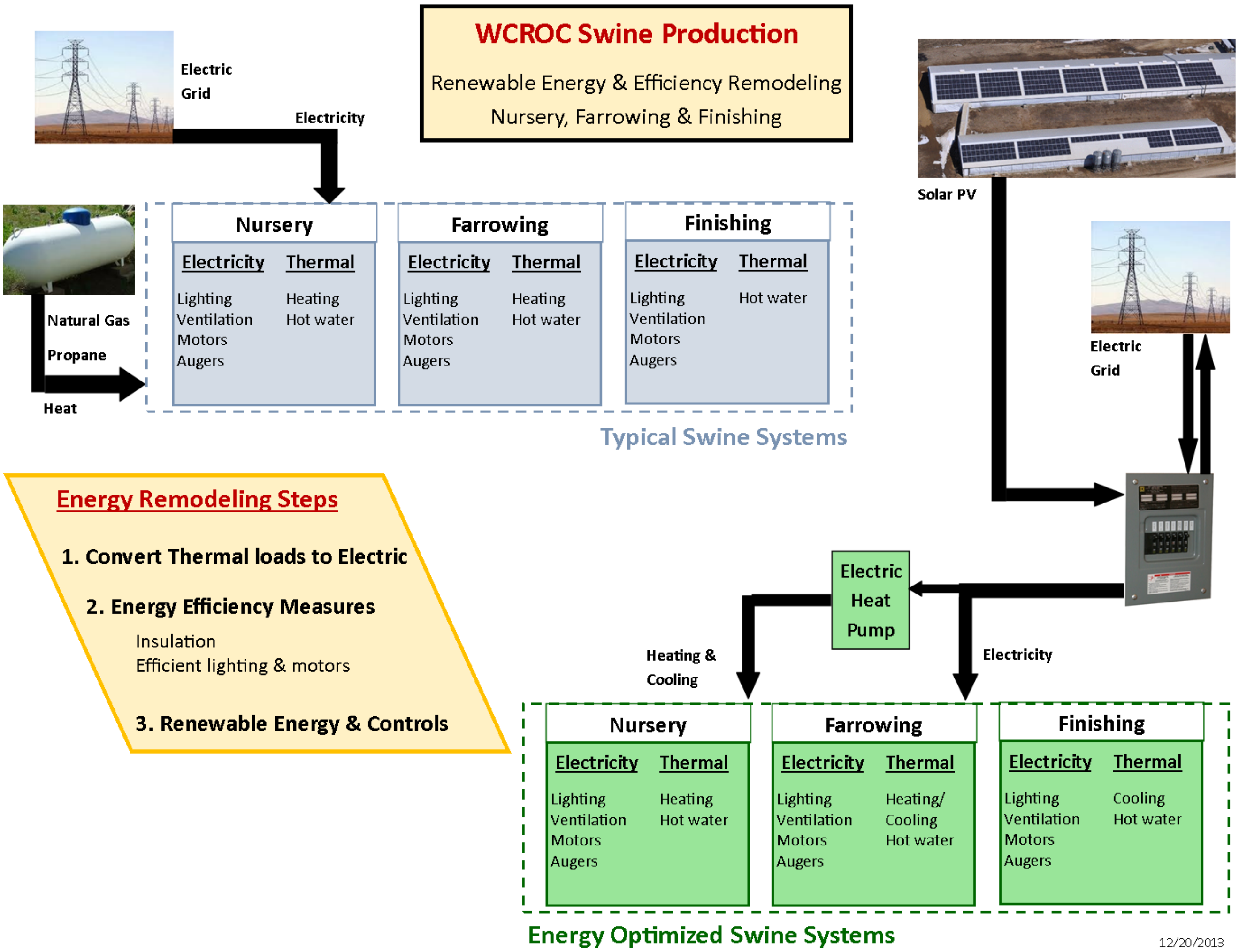
Funding Source and Use of Funds	Funding Timeframe	$ Amount
production systems including crop (feed), dairy, and swine production		
University of Minnesota Initiative for Renewable Energy and the Environment – Establishment of baseline energy consumption of dairy and crop / feed production systems	Through January 2016	$350,000

VIII. FEE TITLE ACQUISITION/CONSERVATION EASEMENT/RESTORATION REQUIREMENTS: Not applicable

IX. VISUAL COMPONENT or MAP(S):

Environmental and Natural Resources Trust Fund
2016 Visual Graphics
Project Title: Solar Energy Utilization for Minnesota Swine Farms—Phase 2

Graphics 1. Schematic representation of the energy-optimized WCROC swine facilities



The project team has received past funding from the Environment and Natural Resources Trust Fund to audit energy consumption and install a 27 kW solar photo voltaic system for the WCROC swine facilities. Funding is being requested from LCCMR in this proposal to install a second 20 kW solar photo voltaic system. These two solar electric generation systems will provide electricity for their respective buildings. The primary purpose of this proposal is to develop effective uses for the solar power generated on swine farms. So therefore, additional funding is being requested to evaluate and optimize the local use of the solar energy on Minnesota swine farms by installing electric heating and cooling systems within the facilities. Using novel solar electric-powered heating and cooling systems will enable the increased utilization of locally-produced renewable energy and have the added potential to lower ventilation rates and thus emissions of odor, greenhouse gases, and dust in exhaust air, reduce water usage, and lower the carbon footprint of Minnesota-produced pork.

X. RESEARCH ADDENDUM: The following addenda are included with this report:

1. Factsheet: WCROC Farrowing Barn Heating and Cooling System
2. Factsheet: Lactating Sow Performance with Solar-Powered Cooling
3. Technical report: Effects of a Solar Cooling System on Sow Performance
4. Technical report: Life Cycle Assessment of Cooling Sows Using Solar Electricity

XI. REPORTING REQUIREMENTS:

Periodic work plan status update reports will be submitted no later than January 1, 2017; July 1, 2017; January 1, 2018; July 1, 2018; and January 1, 2019. A final report and associated products will be submitted between June 30 and September 30, 2019.

Project Length and Completion Date: 3 Years, June 30, 2019
Date of Report: September 30, 2019

ENVIRONMENT AND NATURAL RESOURCES TRUST FUND BUDGET	Activity 1 Budget	$ Spent as of 6/30/19	Activity 1 Balance	Activity 2 Budget	$ Spent as of 6/30/19	Activity 2 Balance	Activity 3 Budget	$ Spent as of 6/30/19	Activity 3 Balance	TOTAL BUDGET	FINAL TOTAL BALANCE
BUDGET ITEM	*Install/ evaluate solar PV & sow cooling*			*Install/ evaluate chilled sow drinking water*			*Perform economic analysis & outreach*				
Personnel (Wages and Benefits)	**$86,502**	$86,502	$0	**$86,502**	$86,502	$0	$55,506	$53,023	$2,483	$228,510	$2,484
Eric Buchanan, Project Coordinator: $97,232 (.4 FTE Yr 1, .5 FTE Yrs 2 & 3) 72.6 % Salary and 27.4% Fringe Rate											
Junior Scientist, Technician for data collection, system testing: $52,137 (1 FTE Yr 2) 72.6 % Salary and 27.4% Fringe Rate											
Brian Hetchler, Research Fellow, Facilility data collection and testing: $61,993 (.5 FTE Yr 1, .24 FTE Yr 2) 72.6% salary and 27.4% Fringe Rate											
Undergrad Student Interns to evaluate Clean Energy Technology for MN Swine Farms as well as help with Economic Analysis: $17,148 (2 summer interns in Yr 2 & 1 summer intern in Yr 3) 100 % Salary and 0% Fringe Rate											
Professional/Technical/Service Contracts											
AKF Engineering (or equivalent firm) - Professional design and commissioning engineering services. AKF Engineering is working on past phases. Contracts will be bid /awarded based on U of MN purchasing policy.	**$22,000**	$21,824	$176	**$8,000**	$6,611	$1,389				$30,000	$1,564
General Contractor TBD - Installation of Cooling Systems. Contracts will be bid /awarded based on U of MN purchasing policy.	**$20,000**	$20,000	$0	**$15,000**	$12,094	$2,906				$35,000	$2,906
General Contractor TBD - Installation of Solar PV Systems Contracts will be bid /awarded based on U of MN purchasing policy.	**$20,000**	$20,000	$0							$20,000	$0
Mechanical Contractor TBD - Installation of energy and temp meters / sensors. Contracts will be bid /awarded based on U of MN purchasing policy.	**$1,500**	$1,500	$0	**$1,500**	$1,500	$0				$3,000	$0
Mechanical Contractor TBD - Installation of control systems in swine facilities. Contracts will be bid /awarded based on U of MN purchasing policy.	**$7,000**	$5,620	$1,380	**$3,000**	$3,000	$0				$10,000	$1,380
Equipment/Tools/Supplies											
Sensors and Meters - For measurement of energy consumption and temperature in swine facilities and in animals (temperature only).	**$4,500**	$4,500	$0	**$4,500**	$4,050	$450				$9,000	$450
Capital Expenditures Over $5,000											
Chillers / Air Source Heat Pump(s) and Cooling Pads for Swine Farrowing Facility	**$38,000**	$37,457	$543	**$12,000**	$12,000	$0				$50,000	$543
20 kW Solar Photovoltaic System for Swine Farrowing Facility	**$60,425**	$60,178	$247							$60,425	$247
Controls for Pad and Chilled Water Cooling Systems	**$12,000**	$12,000	$0	**$8,000**	$8,000	$0				$20,000	$0
Fee Title Acquisition											
Easement Acquisition											
Professional Services for Acquisition											
Printing											
Printing of outreach materials / extension bulletin for swine producers and energy / swine facility professionals (engineers, etc) - 300 @ $12 ea							$3,600	$978	$2,622	$3,600	$2,622
Travel expenses in Minnesota											
Ten trips by Janni / Hetchler from St. Paul to Morris (330 miles @ $.565 /mi	**$933**	$933	$0	**$932**	$932	$0				$1,865	$0
In-state travel by project team to regional outreach events and meetings (At least 3 events per year)							$3,600	$1,567	$2,033	$3,600	$2,033
Other											
									$0	$0	$0
COLUMN TOTAL	**$272,860**	**$270,516**	**$2,344**	**$139,434**	**$134,689**	**$4,745**	**$62,706**	**$55,567**	**$7,139**	**$475,000**	**$14,228**

Life Cycle Assessment of Cooling Sows Using Solar Electricity

Joel Tallaksen

West Central Research and Outreach Center

University of Minnesota

Version 1.0

2016-2019

Table of Contents

Funding Acknowledgment

RARF- funding from the Rapid Agricultural Response Fund was used to carry out this LCA analysis for LCCMR funded water heating and cooling as well as further RARF research with electric piglet heating.

LCCMR-The development of the swine sow cooling and piglet heating equipment with water heating/cooling mats in this project was supported by The Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative - Citizen Commission on Minnesota Resources (LCCMR) Project #: LCCMR-2016-07e. The Trust Fund is a permanent fund constitutionally established by the citizens of Minnesota to assist in the protection, conservation, preservation, and enhancement of the state's air, water, land, fish, wildlife, and other natural resources. Currently 40% of net Minnesota State Lottery proceeds are dedicated to growing the Trust Fund and ensuring future benefits for Minnesota's environment and natural resources.

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.

LCA Subsection Author:

Dr. Joel Tallaksen, Research Scientist, University of Minnesota

Cover Images: Top left-WCROC staff, Bottom right- David Hansen, University of Minnesota

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.

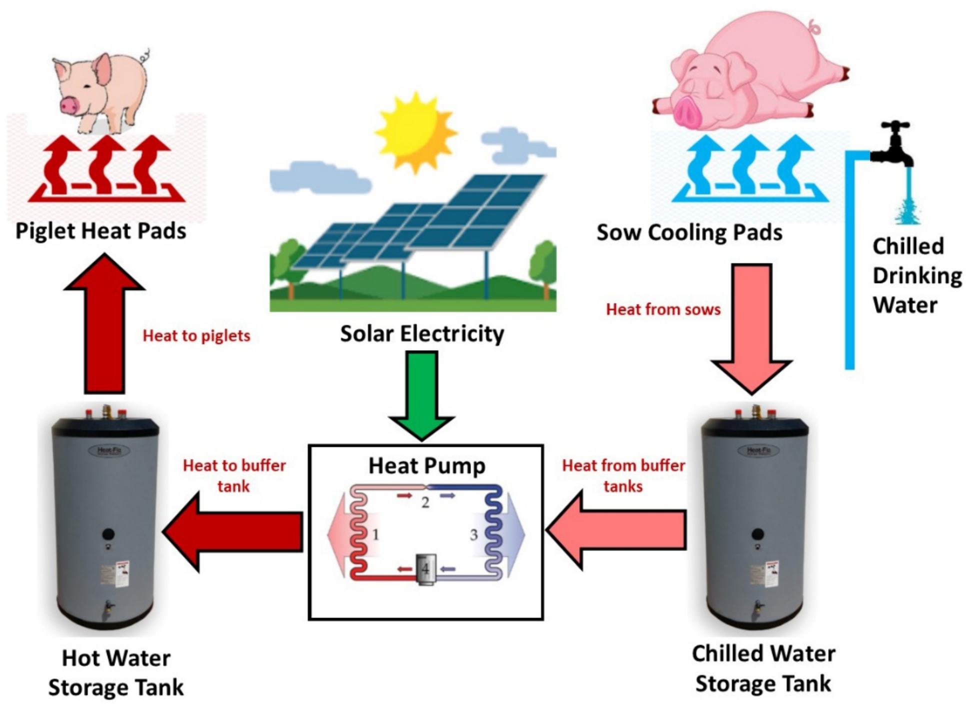


Figure 1. Schematic of Swine Farrowing Heating and Cooling System. The simplified diagram of the heating and cooling system shows how heat collected from the sows via the hydronic mats under the sow and is transferred to piglets via the electric heat pump, which uses solar electricity.

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.

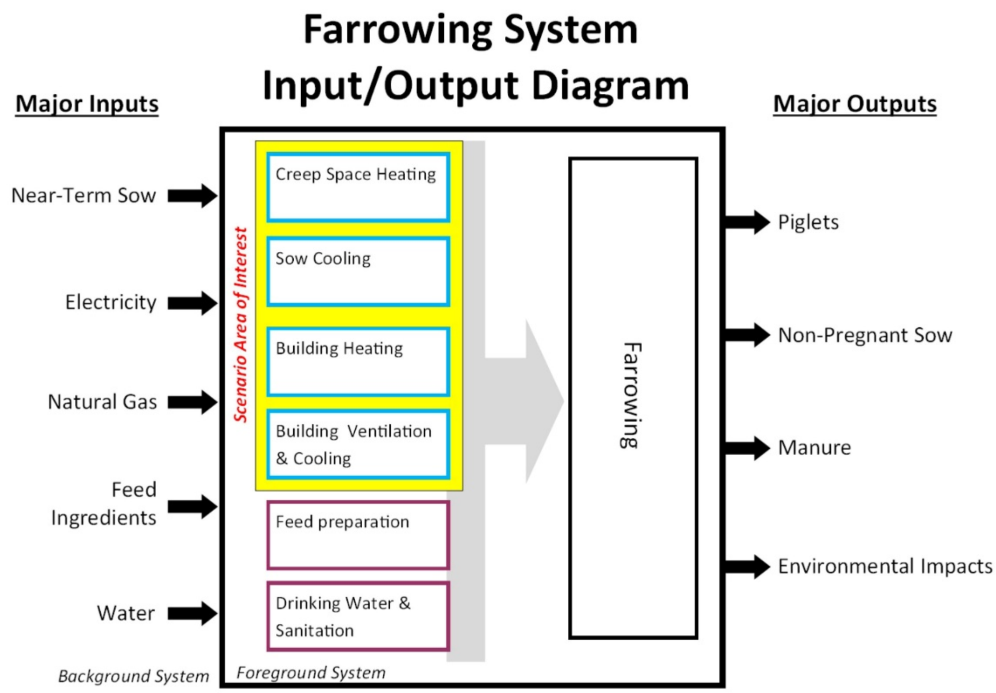


Figure 2. Farrowing System Diagram. The diagram shows the foreground system being analyzed, with the specific areas of interest highlighted in yellow. The background system includes the feed ingredients, energy inputs, and other items needed to support operations in the farrowing system.

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.

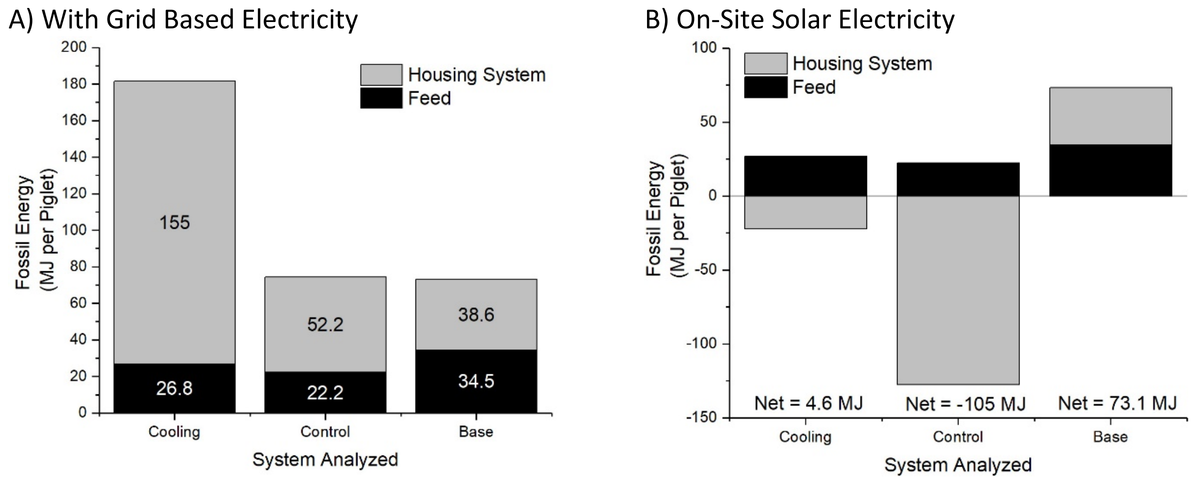


Figure 3. Fossil Energy Use in Sow Farrowing Scenarios. Data shows fossil energy use for the scenarios analyzed. A) Fossil energy use when the farrowing system is operated on grid-based electricity. B) Farrowing system fossil energy use with solar power and a fossil energy credit for excess electricity 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.

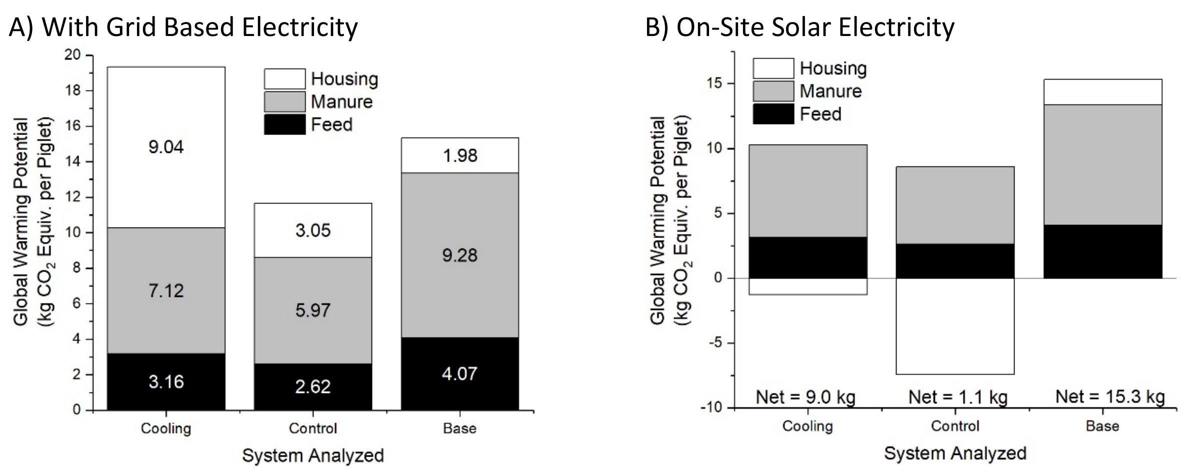


Figure 4. Global Warming Potential Emissions in Cooled Sow Farrowing Systems. The negative value of housing for the control system indicates credit for renewable energy leaving the system after factoring swine cooling system energy consumption. The WCROC base system is included only for comparison and 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.

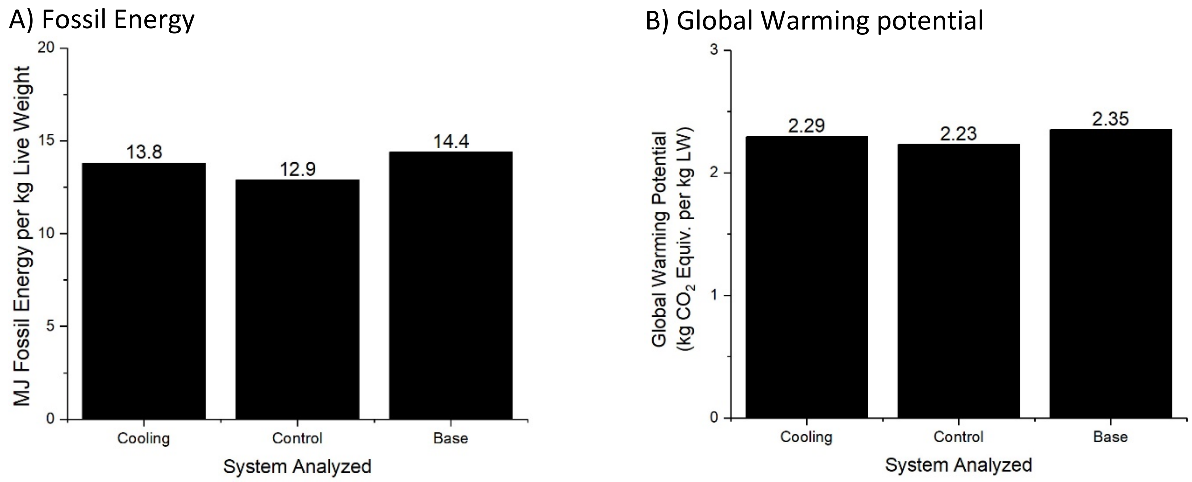


Figure 5. Effects of Farrowing Cooling Scenarios on Overall Environmental Impacts for Full Swine Production Systems. Environmental impacts for market weight animals in the full system are expressed per kg of live weight pork leaving the farm.

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.

6 References for Main Text and Supplement

ASABE. (2005). *Manure Production and Characteristics*. Retrieved from ASABE: https://elibrary.asabe.org/abstract.asp?aid=32018&t=2&redir=&redirType=

Blonk. (2017). *Agri-Footprint 3.0 - Part 2 - Description of data*. Retrieved from Gouda, Netherlands: http://www.agri-footprint.com/wp-content/uploads/2017/07/Agri-Footprint-3.0-Part-2-Description-of-data-31-05-2017.pdf

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., . . . Spielmann, M. (2005). The ecoinvent Database: Overview and Methodological Framework (7 pp). *The International Journal of Life Cycle Assessment, 10*(1), 3-9. doi:http://doi.org/10.1065/lca2004.10.181.1

Frischknecht, R., Jungluth, N., Althaus, H.-J., Bauer, C., Doka, G., Dones, R., . . . Nemecek, T. (2007). *Implementation of Life Cycle Impact Assessment Methods.* Retrieved from Swiss Centre for LCI: http://esu-services.ch/fileadmin/download/publicLCI/03_LCIA-Implementation.pdf

IPCC. (2006). *Ch. 10 Emissions from Manure and Livestock*. In Vol. 4 Agriculture, Forestry and Other Land Use. E. H.S., B. L., M. K., N. T., & T. K. (Eds.), *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (pp. 10.11-10.87). Retrieved from http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_10_Ch10_Livestock.pdf

IPCC. (2013). *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Marinussen, M., & Kool, A. (2010). *Environmental impacts of synthetic amino acid production*. Retrieved from Netherlands:

Mosnier, E., van der Werf, H. M. G., Boissy, J., & Dourmad, J. Y. (2011). Evaluation of the environmental implications of the incorporation of feed-use amino acids in the manufacturing of pig and broiler feeds using Life Cycle Assessment. *animal, 5*(12), 1972-1983. doi:10.1017/S1751731111001078

NREL. (2012). U.S. Life Cycle Inventory Database. Retrieved 11/1/17 https://www.nrel.gov/lci/

Sandefur, H., Burek, J., Matlock, M., Thoma, G., & Boles, E. (2015). *Development of Life Cycle Inventory Data for U.S. Swine Production Scenarios: Dataset Documentation and User's Guide, Version 2*. Retrieved from: http://dx.doi.org/10.15482/USDA.ADC/1337872

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 HCl		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

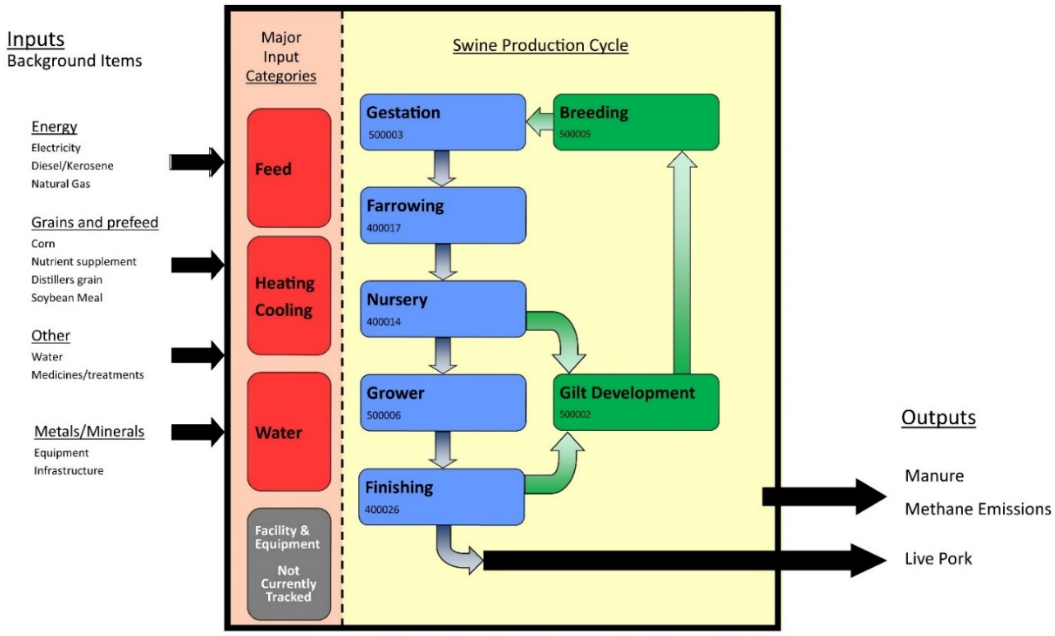


Figure A1. LCA Overview and Boundaries for the Swine Production System. The schematic shows the foreground and background components of the full swine systems as used in section 3.2. Items within the foreground system boundaries (peach and yellow areas) are considered the main focus of the study. Items 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.

Effects of a Solar Cooling System on Sow Performance

Lee Johnston, Mike Reese, Eric Buchanan, Yuzhi Li, and Adrienne Hilbrands
West Central Research and Outreach Center, Morris

Kevin Janni, Brian Hetchler, and Erin Cortus
Biosystems and Biological Engineering, St. Paul

University of Minnesota

Version 2.0

2016-2019

Table of Contents

Funding Acknowledgment

RARF- funding from the Rapid Agricultural Response Fund was used to carry out this LCA analysis for LCCMR funded water heating and cooling as well as further RARF research with electric piglet heating.

LCCMR-The development of the swine sow cooling and piglet heating equipment with water heat/cool mats in this project was supported by The Minnesota Environment and Natural Resources Trust Fund as recommended by the Legislative - Citizen Commission on Minnesota Resources (LCCMR) Project #: LCCMR-2016-07e

The Trust Fund is a permanent fund constitutionally established by the citizens of Minnesota to assist in the protection, conservation, preservation, and enhancement of the state's air, water, land, fish, wildlife, and other natural resources. Currently 40% of net Minnesota State Lottery proceeds are dedicated to growing the Trust Fund and ensuring future benefits for Minnesota's environment and natural resources.

Disclaimer

1 Introduction

Global climate change is predicted to make our climate hotter with a greater frequency of extreme weather events compared with 50 years ago. This increased temperature will increase the severity and frequency of heat stress events for swine produced in Minnesota. Heat stress of pigs reduces their growth and reproductive performance and compromises their welfare (Ross et al., 2015) leading to decreased efficiency of pork production systems. This decreased efficiency leads to an increase in resources (e.g. feed, water, fuel, electricity) required to produce a pound of edible pork which negatively affects the carbon footprint of pork production.

Minnesota's northern climate does not protect pigs from heat stress. Most pig barns are designed and built to protect pigs against cold temperatures during the long Minnesota winters with less consideration for cooling needed during the short but hot Minnesota summers. All classes of pigs are susceptible to heat stress during summer but sows are particularly sensitive around the time of farrowing and during lactation. Mortality rate of sows typically increases during summer on commercial sow farms in the Upper Midwest region (Deen and Xue, 1999) compared with other times of the year. Consequently, installation and operation of an effective cooling system for sows might improve sow performance and welfare and simultaneously enhance the carbon footprint of commercial pork production systems during summer heat stress periods.

Currently, there are several approaches to cooling sows in the farrowing stage of production such as increased ventilation rates, evaporative cooling pads, drip coolers, snout coolers, and altered diet formulations. Each approach provides some degree of cooling sows but each has drawbacks. Our intent in this project was to investigate a different approach to cooling sows that was powered by renewable energy. Our hypothesis was that sows cooled by a solar-powered system would be more comfortable and productive during heat stress than uncooled sows and this would improve the carbon footprint of the farrowing operation.

2 Methods

2.1 Facilities and equipment

2.1.1 Farrowing barn design

A mechanically-ventilated, confinement farrowing barn with two identical, mirror image rooms was used for this experiment. This farrowing barn was located at the West Central Research and Outreach Center in Morris, MN. Ventilation was provided by a combination of wall and pit fans controlled by thermostats in each room. Supplemental heat was provided by one natural gas fired heater located in each room. Each farrowing room was equipped with 16 farrowing stalls (5 ft x 7 ft) that confined sows in the center portion with piglet creep areas on both sides of the sow. Each farrowing stall was fitted with a stainless steel, deep bowl feeder for sows, a nipple drinker for sows, and one nipple drinker for piglets. Perforated flooring under the sow was made of cast iron while flooring under piglets was plastic-coated woven wire. Piglet creep areas were provided with supplemental heat. Farrowing stalls were situated above an anaerobic manure collection pit that was 8 ft. deep.

One room was designated as the Control room which was provided with no supplemental cooling for sows. The Cool room was identical to the Control room except cooling pads were installed in floors beneath sows were connected to a cooling loop.

2.1.2 Floor cooling pads

A cast iron pad manufactured by Nooyens Corporation (Netherlands) was placed in the front portion of the floor under each sow in the Cool room (Figure 1). Underneath this flooring pad, a serpentine tubing is attached that allows cool water to circulate which cools the floor surface sows lie on. The same flooring pads were installed in each farrowing stall in the Control room but the underfloor tubing was not connected to any cooling system.

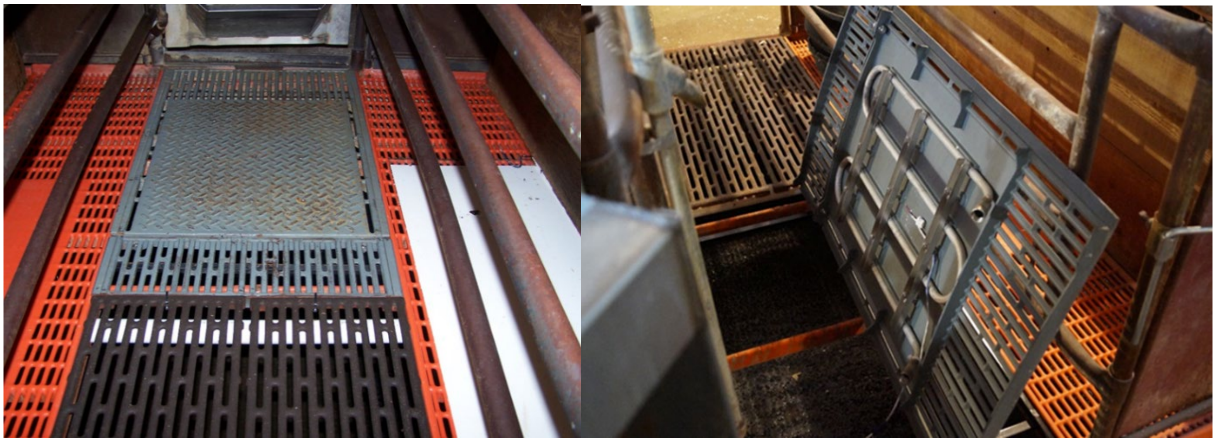


Figure 1. Flooring pad installed in the front portion of the sow's farrowing stall (left) and the cooling loop attached beneath the flooring (right).

Water contained in a closed loop is cooled to about 65 °F using a liquid-to-liquid heat pump (Carrier Corp., Indianapolis, IN; Model GW024). Pumps circulate cooled water to each farrowing stall in a parallel loop so that each stall receives cool water at a similar temperature. Sows lying on the cooled floor transfer heat from their body to the floor and this heat is transferred to the cool water circulating in the loop. The warmed water that exits the flooring is returned to the heat pump where it is cooled and circulated back to the flooring inserts in a closed loop system. A buffer tank is included in the cooling system to serve as a cool water reservoir to ensure consistent delivery of cool water to all 16 farrowing stalls in the Cool room. If the heat extraction capacity of the heat pump is overwhelmed, a fan coil unit included in the system extracts excess heat and exhausts it outside the barn. As part of a supplemental project, the heat extracted from the sow cooling loop was moved to a separate, independent system that circulated heated water through pads located in the piglet creep area. Further discussion of the piglet heating project is beyond the scope of this report. A complete schematic drawing of the sow cooling and piglet heating system is displayed in Figure 2.

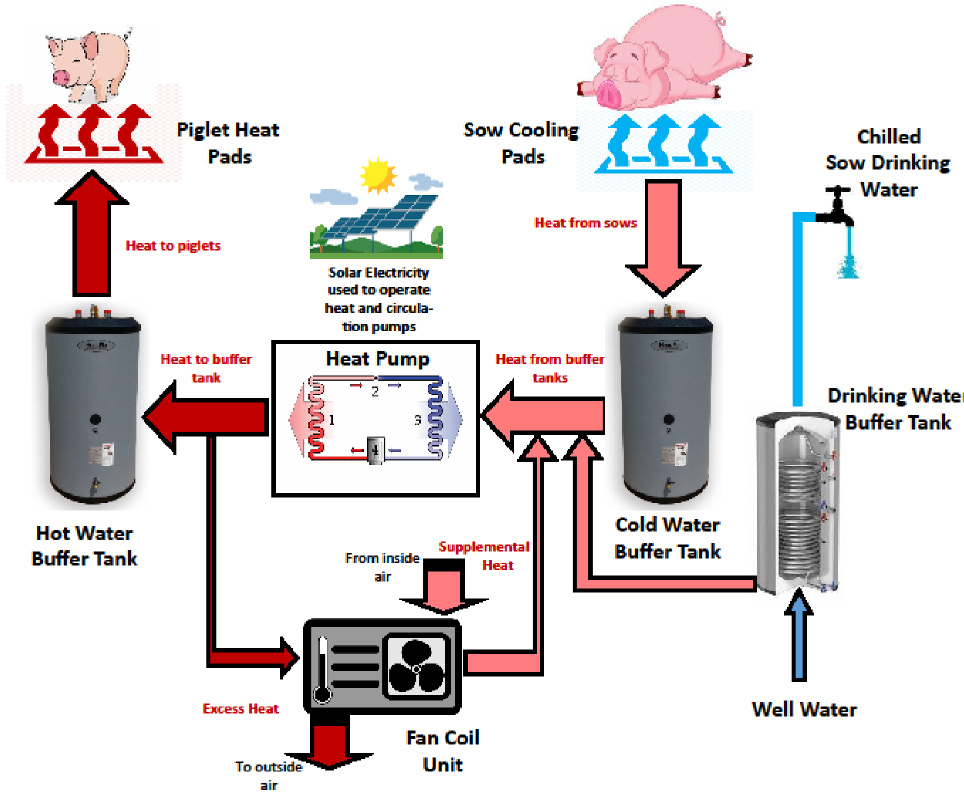


Figure 2. Schematic representation of the sow cooling and piglet heating system used in this experiment.

The entire cooling system is powered by a 20 kW solar array (Figure 3) installed outside the barn. The solar array consisted of 60 solar photovoltaic panels (Heilene USA, Mount Iron, MN; Model 72P320) and 2 power inverters (SolarEdge Technologies Inc, Fremont, CA; Model SE9KUS).

Figure 3. Solar panels (20 kW) installed at the WCROC used to power the sow cooling system

2.1.3 Cooled drinking water

In the Cool room, cool water (55 to 60 °F) was supplied to the sow's nipple drinker in each farrowing stall. Cool water was circulated continuously to each nipple drinker through insulated supply lines to ensure each time a sow drank, it was cool water. Water was cooled by the heat pump described above.

2.2 Animals and management

Eighty four, mixed parity, crossbred maternal-line sows were used to evaluate the efficacy of the solar-powered cooling system. Parity of sows ranged from 0 to 9. Sows farrowed in three contemporary groups from June to August of 2017 and 2018. Sows were assigned randomly within parity to Control or Cool rooms when they were moved into farrowing rooms on about day 109 of gestation (5 days before expected farrowing date). During commissioning and testing of the cooling system (June, 2017), cooler than expected weather did not provide consistent heat stress of sows. Without consistent heat stress conditions, we could not adequately evaluate efficacy of the cooling system. So, during three subsequent farrowing groups included in the data for this project, we imposed consistent heat stress on sows. Heaters and ventilation fans were set to a target temperature of 85 °F during daytime (9:00 am to 7:00 pm) and 75 °F at night (7:00 pm to 9:00 am). Heaters and ventilation fans were set to ensure desired room temperatures were achieved while maintaining acceptable air quality. Heat stress conditions were imposed in both Control and Cool rooms so that the cooling system could be properly evaluated. Sows were exposed to heat stress conditions upon entry to the farrowing rooms. The cooling system in the Cool room was also operational beginning the day sows entered the farrowing room until pigs were weaned.

Sows were provided ad libitum access to water throughout the study. A standard corn-soybean meal based lactation diet was offered at 5 pounds per head daily from entry to the farrowing room until the sow farrowed. After farrowing, feed allowance for sows was increased steadily until day 4 postpartum at which time sows were allowed ad libitum access to feed. Sows farrowed naturally without induction. Within 24 hours of birth, piglets were processed which included docking tails, clipping needle teeth, ear tagging for individual piglet identification, injecting supplemental iron, and castration of male piglets.

Litter size was equalized within farrowing room as much as possible by cross-fostering pigs within 24 hours of birth. Litters were weaned at about 21 days of age and sows were moved to a single barn for mating. Manipulation of room temperatures and operation of cooling systems ceased on weaning day.

2.3 Data collected

2.3.1 Cooling system performance

The water flow rate and temperatures entering and leaving every flow loop within the sow cooling and chilled drinking water systems were measured by sensors (Badger Meter, Milwaukee, WI; Model 380 CS/HS) installed in system piping. Data from these sensors were recorded by a supervisory and control system (Johnson Controls Inc., Milwaukee, WI; Model JACE FX30). Thermocouples were connected to the underside of three flooring pads in both the Control and Cool rooms to measure temperature of the flooring pads. In addition, two Novus RNT-WM 0-10V sensors were placed at pig level within each room to measure temperature and humidity. Data were recorded from the day sows entered the farrowing room until the day of weaning.

Concentrations of carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4), and nitrous oxide (N_2O) were monitored and recorded every hour throughout the study period in each room. Concentrations of these gases provide a qualitative measure of ventilation adequacy.

2.3.2 Electricity use and solar array performance

Electrical current sensors (Magnelab, Longmont, CO; Model SCT 0400) were installed on most electrical circuits including wall and pit ventilation fans, lights, and heaters. Data from these sensors were averaged and recorded every 10 minutes with a Campbell Scientific CR800 data logger. Another data logger (eGauge, Boulder, CO; Model EG3000) with a total of 9 AC current sensors was installed to monitor electricity consumption by the sow cooling system including heat pump, fan coil unit, and circulation pumps. In addition, three AC current sensors were used to measure the total electricity consumed by the entire barn. Electricity produced by the solar array was monitored at the array power inverters and stored on a server provided by the inverter company and accessed via an internet connection.

2.3.3 Sow and litter performance

Parity, farrowing date, and weaning date were recorded for each sow. Sows were weighed at entry to the farrowing room, within 24 hours after farrowing, and at weaning. Backfat depth and loineye area at the 10^{th} and last rib were recorded using real-time ultrasonography on day 109 of gestation and at weaning. Voluntary feed intake of sows was recorded on a weekly basis. Respiration rate and rectal body temperature of sows was recorded on the day before farrowing, within 24 hours after farrowing and weekly throughout the lactation period. Days from weaning to expression of estrus were recorded.

Litter size at farrowing (total born, live born, stillborns, and mummies) and weaning was recorded. Individual pigs were weighed at birth and at weaning. Records of piglet deaths included date of death, weight of piglet at death, and the suspected cause of death.

2.3.4 Sow behavior

Behavior of sows in Group 1 and Group 2 was recorded using video cameras (tru-Vision High Definition TVI Bullet, Built-in IR, Interlogix, Costa Mesa, CA) mounted over 8 farrowing stalls in each room. Sows and litters were video-recorded 24 hours daily beginning the day before farrowing through the first week of lactation. Additionally, video-recording occurred one day (24 hours) per week throughout lactation and the day before weaning. Videotapes were transcribed using continuous observation for farrowing behavior and drinking behavior, and using the scan sampling method for postures. For farrowing behavior, total duration of farrowing started from delivery of the first piglet until the last piglet, and intervals between delivery of piglets were registered. Drinking behavior and postures were registered for day 1, day 3, day 7, day 14 and day 21 after farrowing. For drinking behavior, number of drinking bouts and duration of each drinking bout were registered for 2 hours between 3 and 5 pm when sows were least disturbed by routine management and room temperature was at the highest point during the day. For postures, sows were scanned at 5-min intervals for 24 hours on each of the five days. At each scan, postures of standing, lying laterally (on side), lying ventrally (on belly), or sitting of each sow was recorded, and time budgets for each posture for sows were calculated (Martin and Bateson, 1993).

2.4 Statistical analysis of data

Data collected to characterize environmental conditions in the farrowing rooms, performance of the cooling system, and electricity use and production for each farrowing group are expressed as raw means over time. Within each farrowing group, there was only one cooled room and one control room so replication of treatments was achieved over successive farrowing groups. By presenting these data as raw means, one can understand the repeatability of environmental conditions which allows a more complete understanding of the sow and litter responses.

Data for sow and litter responses were analyzed using the Glimmix procedure of SAS (SAS Institute, Cary, NC) with room treatment as a fixed effect and contemporary farrowing group as a random effect. For sow traits that were measured repeatedly (body weight, backfat depth, feed intake, rectal temperature, respiration rate, postures, and drinking behavior), a repeated measures analysis was used that included the fixed effects of room treatment, time, and their interaction with farrowing group as a random effect. Behavioral data were analyzed using the Glimmix procedure with Poisson distribution with room treatment, day (sow postures and drinking behavior) and their interaction as fixed effects. For analysis of farrowing behavior, total litter size was used as a co-variate. Sow and litter were considered the experimental unit in the analysis of animal performance and behavioral responses.

3 Results and Discussion

This experiment was designed to test the efficacy of a renewably-powered cooling system to mitigate the negative effects of heat stress on lactating sows. A valid evaluation of the cooling system demanded sows be consistently heat stressed. Consequently, this experiment was designed to be conducted during summer when heat stress typically occurs. The cooling system and solar array were installed and operational in time for the first group of sows to farrow in mid-June, 2017. Unfortunately, environmental conditions were rather cool such that sows experienced only transient heat stress. Additionally, we experienced a variety of glitches in the cooling system that resulted in intermittent operation during the first farrowing group. Because of these problems, data from this first group of sows were not included in the final dataset. These experiences with the first group of sows allowed us to fine-tune the cooling system for consistent operation in subsequent farrowing groups. And, we learned that we could not rely on the ambient environment to provide consistent heat stress conditions for sows. In subsequent farrowing groups, we imposed a consistent heat stress on all sows by setting the natural gas-fired heater to supplement heat when needed to maintain a room temperature of about

85 °F during daytime (9:00 am to 7:00 pm) and 75 °F during nighttime (7:00 pm to 9:00 am). This artificial control of room temperatures allowed us to adequately test the efficacy of the cooling system.

3.1 Farrowing room conditions

Room temperatures remained above 75 °F throughout the entire experiment and oscillated between 75 and 85 °F throughout most of the experiment (Figure 4). Temperatures were very consistent between Control and Cool rooms. These data confirm that target room temperatures were achieved as dictated by the experimental design and that sows were consistently heat stressed. Black et al. (1993) suggested that lactating sows experience heat stress when environmental temperatures rise above about 64 to 72 °F. Efficacy of the sow cooling system could be properly tested since sows were consistently heat stressed. Humidity readings in each room ranged from 43 to 77% and were consistent between Control and Cool rooms (Figure 5).

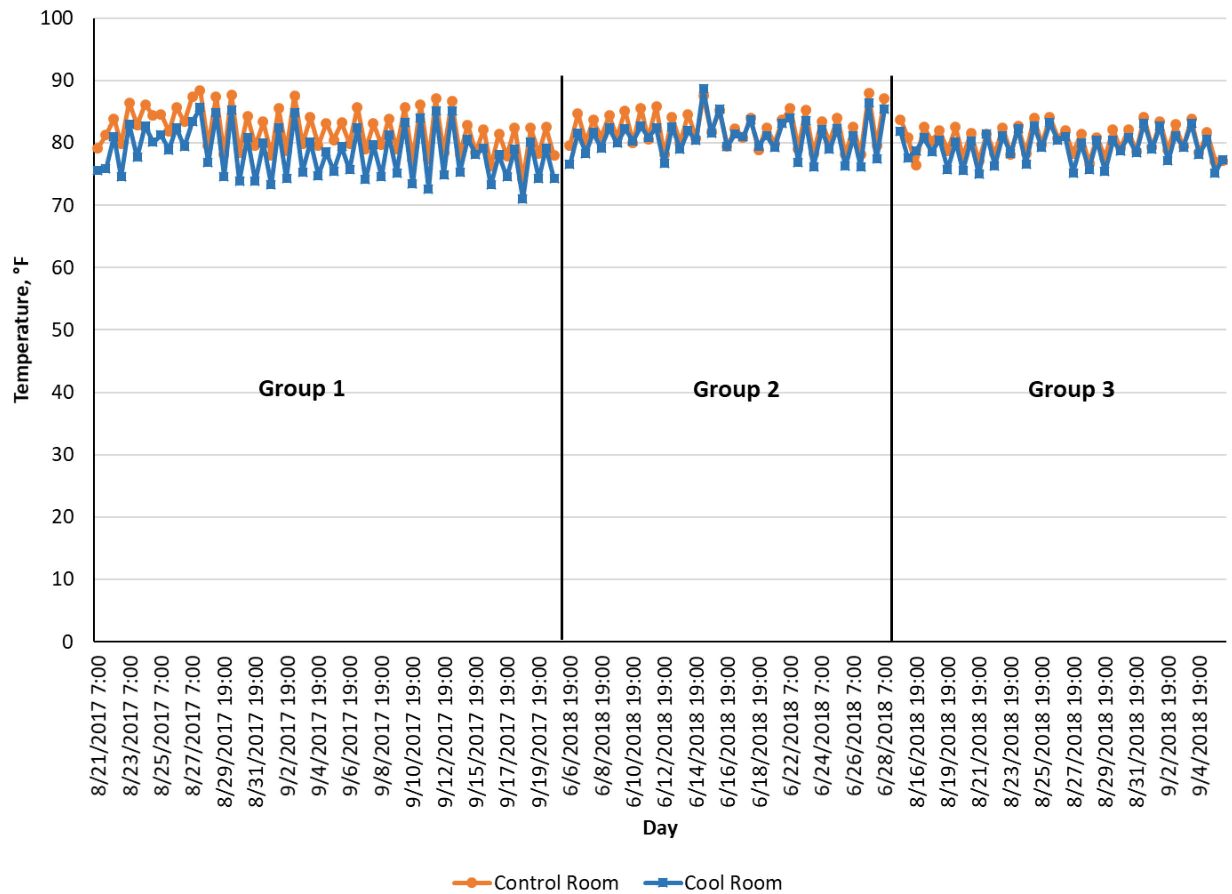


Figure 4. Temperatures recorded in farrowing rooms averaged over 12-hour periods (7:00 am to 7:00 pm) each day of all three farrowing groups.

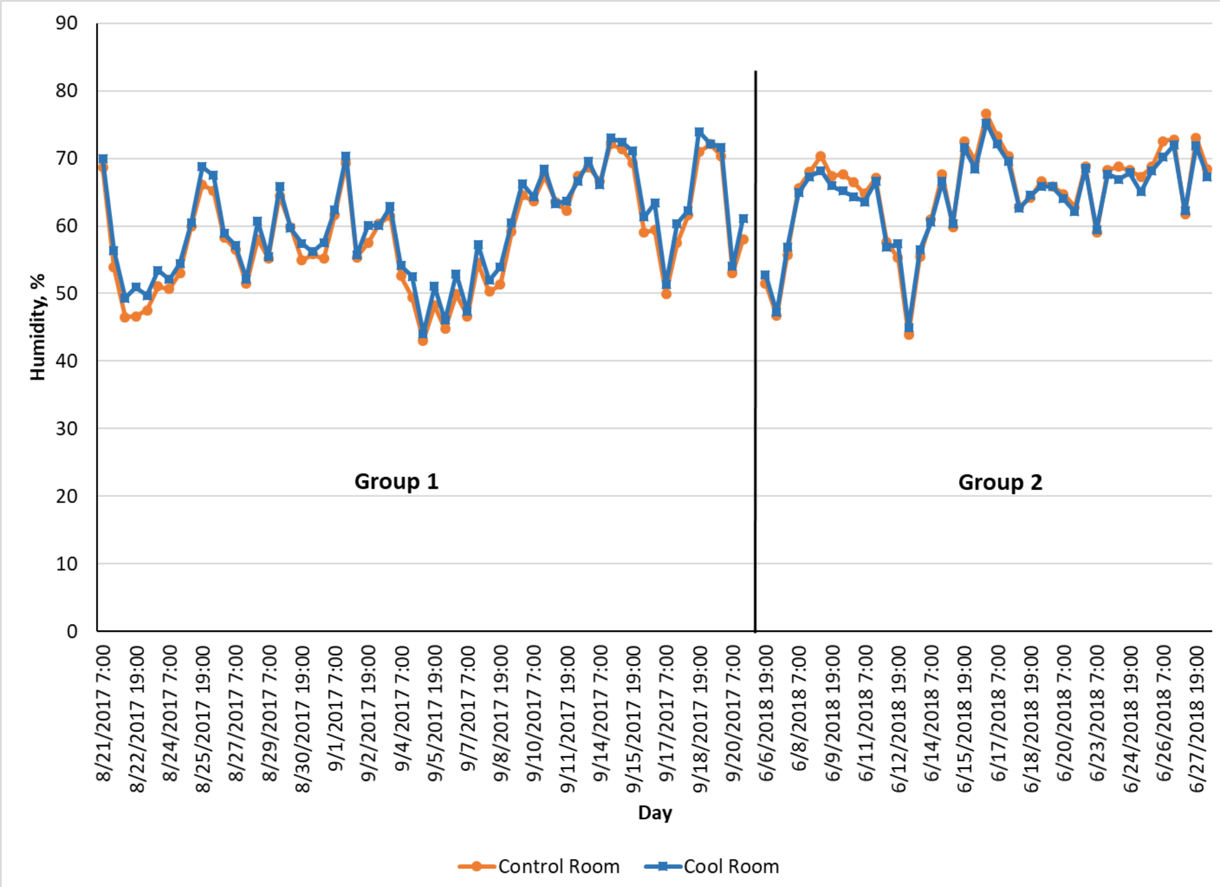


Figure 5. Humidity recorded in farrowing rooms averaged over 12-hour periods (7:00 am to 7:00 pm) each day in two farrowing groups.

Equipment to sample room air and analyze gas concentrations was available for Groups 1 and 2. Gas concentrations for Group 3 were not determined. We were unable to directly measure ventilation rates within each farrowing room. However, carbon dioxide concentration in the farrowing rooms were measured as an indirect indicator of ventilation rates. The concentration of carbon dioxide in ambient air is about 400 ppm (NOAA, 2019). Carbon dioxide is exhaled by pigs housed in the farrowing rooms which increases the concentration of carbon dioxide within the room compared with ambient air. Inadequate ventilation rates result in extreme increases in carbon dioxide concentrations within the room. A carbon dioxide concentration in excess of 5,000 ppm is indicative of ventilation rates that are too low (MWPS, 1990). Carbon dioxide concentrations were similar between Control and Cool rooms and were well below the critical threshold of 5,000 ppm (Figure 6). These data indicate that rooms were ventilated similarly and adequate quantities of air fresh ambient air were introduced to each room throughout the experiment.

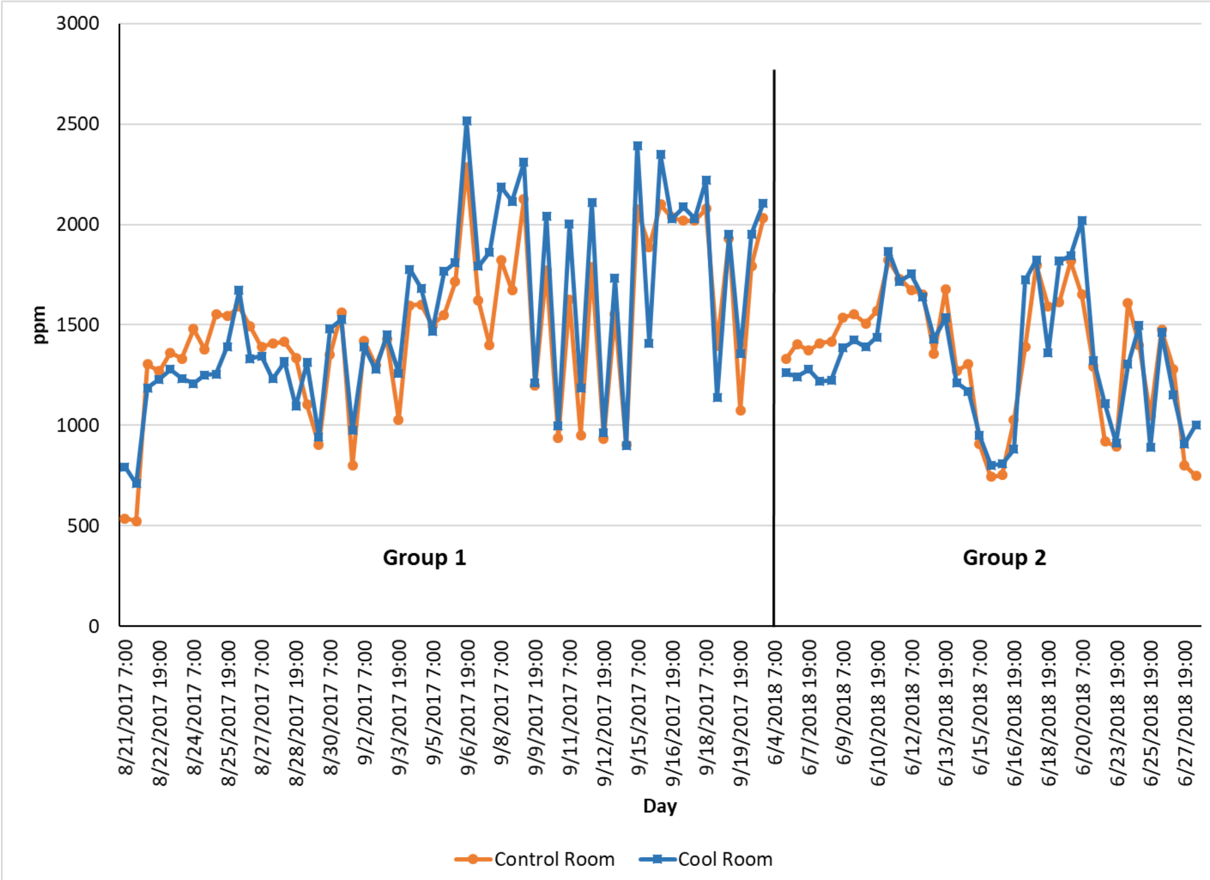


Figure 6. Carbon dioxide concentration in farrowing rooms averaged over 12-hour intervals (7:00 am to 7:00 pm) for each day of farrowing groups one and two

Ammonia concentrations of air in farrowing rooms indicate the adequacy of manure management systems employed. Elevated ammonia concentrations suggest excessive accumulation of manure in the pigs' airspace. Ammonia concentrations were consistently below 8 ppm in both rooms throughout Group 1 (Figure 7). About a week after the start of Group 2, ammonia concentration spiked above 25 ppm in the Cool room during one 12-hour period but returned to baseline concentrations in the next 12-hour period. Through the latter portion of Group 2, ammonia concentrations in the Cool room were higher than in the Control room. A clear explanation for this rise in ammonia concentrations in the Cool room is not readily apparent. With the exception of one 12-hour period, ammonia concentrations were well within accepted ranges and remained well below the critical threshold of 25 ppm outlined by the National Pork Board in the Pork Quality Assurance Plus program (National Pork Board, 2019).

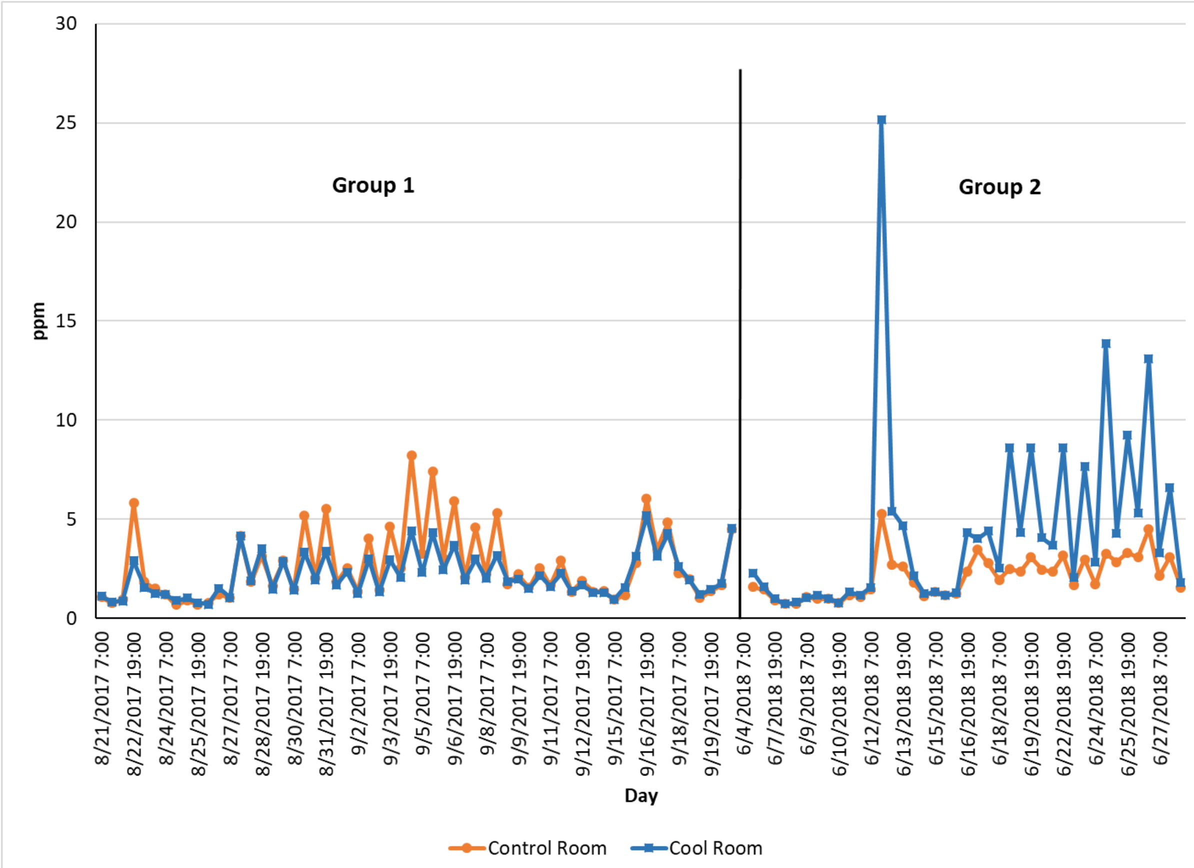


Figure 7. Ammonia concentrations in farrowing room air averaged over 12-hour periods (7:00 am to 7:00 pm) for each day of farrowing groups one and two

3.2 Cooling system performance

Temperatures from the underside of three flooring pads below the sows in both the Control and Cool rooms were averaged over 12 hours (Figure 8). In both studies, measured temperatures of the flooring pads in the Cool room were lower than the pads in the Control room. The differences in flooring pad temperatures in the Cool room and the Control room were larger in Group 2. It is noted that the Control room pads were warmer than the room temperature indicating the sows were heating the pads as they laid on them.

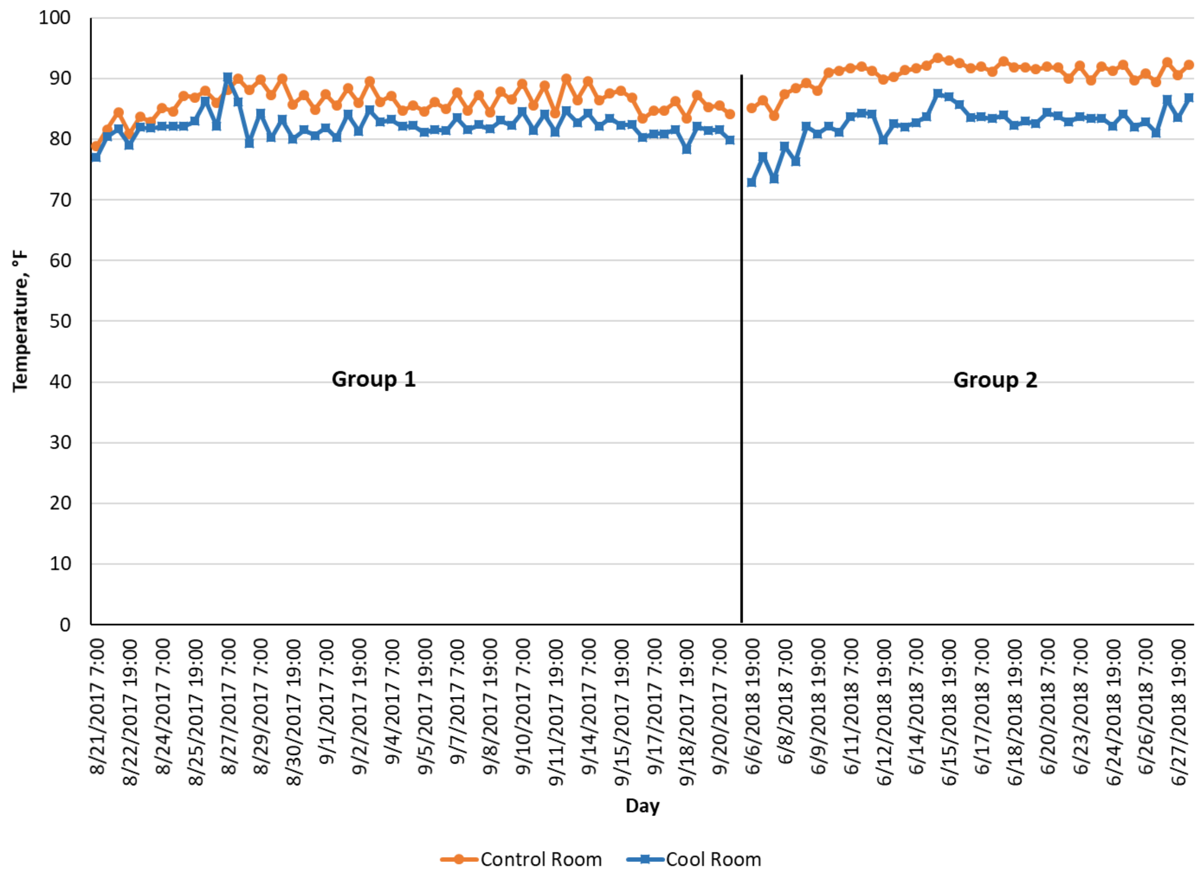


Figure 8. Temperature of flooring pads in Cool and Control rooms averaged over 12-hour periods (7:00 am to 7:00 pm) for each day of farrowing groups one and two.

Temperatures of the cooled drinking water were consistently lower in the Cool room compared with the Control room (Figure 9). Temperature of drinking water ranged from 58 °F to 74 °F in the Cool room (average = 63.3 °F) and 64 °F to 106 °F in the Control room (average = 82.9 °F). Jeon et al. (2006) reported that decreasing temperature of drinking water for heat-stressed lactating sows from 72 °F to 59 °F increased voluntary feed intake of sows by 40%. So, cool temperature of drinking water in the Cool room likely encouraged increased feed intake of sows in the Cool room compared with the Control room (see below).

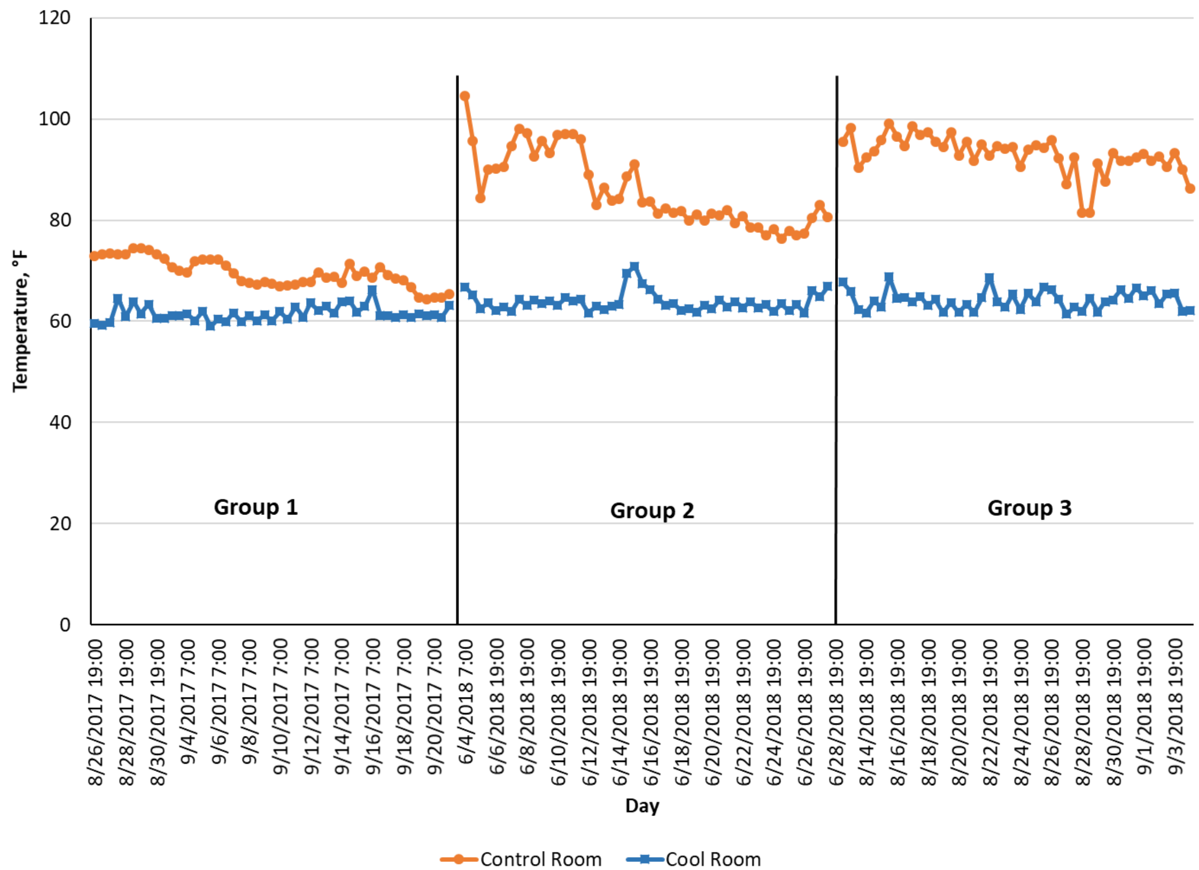


Figure 9. Temperature of drinking water in Control and Cool rooms averaged over 12-hour periods (7:00 am to 7:00 pm) each day for all three farrowing groups.

3.3 Electricity use and solar array performance

Electricity consumed in the Cool room was consistently higher than that consumed in the Control room. For each farrowing group, electricity use in the Cool room was 160% to 260% higher than electricity use in the Control room (Figures 10, 11, and 12). The higher electricity use in the Cool room can be attributed to operation of the heat pump, the fan coil unit and the continuous operation of pumps used to circulate cool water in the floor pads and nipple drinkers. These three components represented between 61 and 87% of the total electricity used in the Cool room on a daily basis. Interestingly, the solar array generated sufficient electricity to meet the higher electrical usage in the Cool room for farrowing groups one and two.

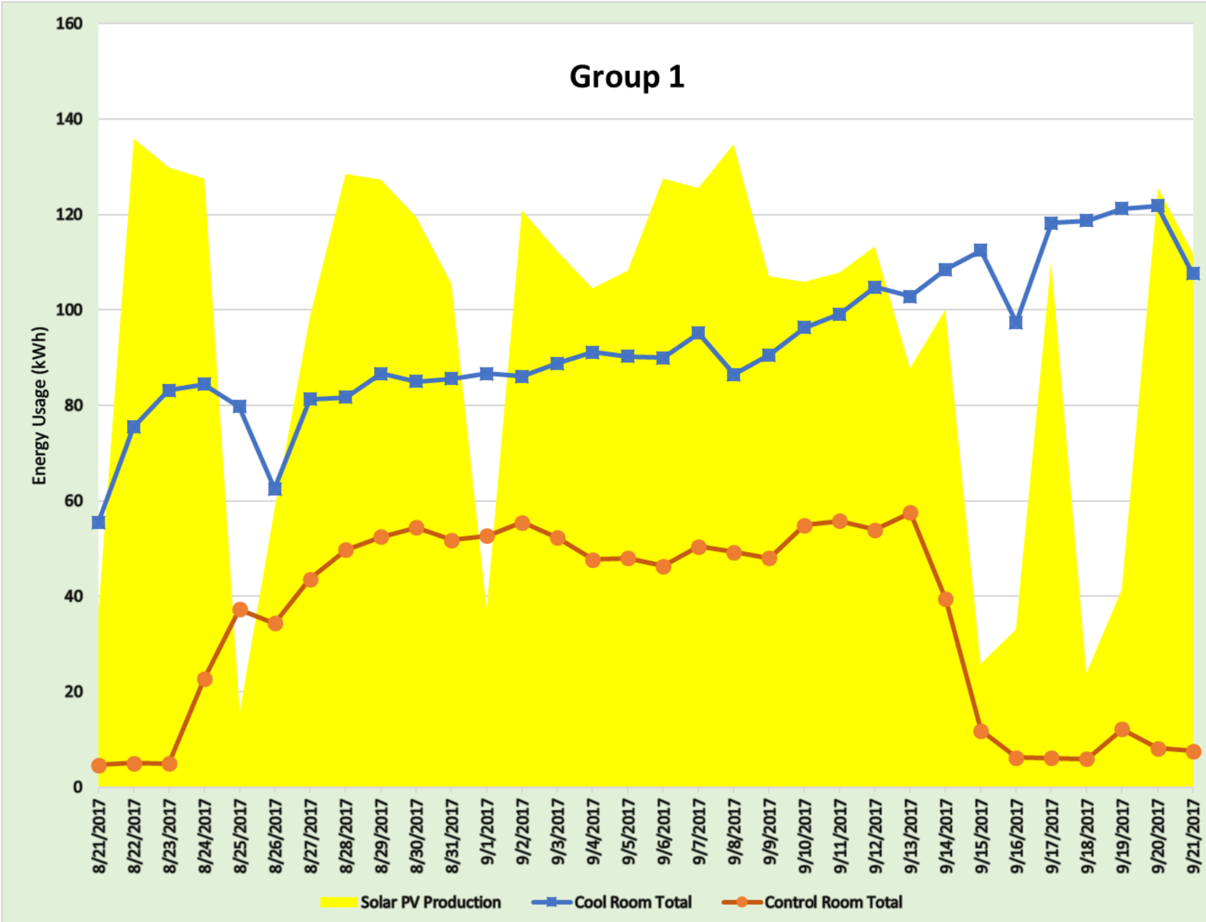


Figure 10. Electricity used in Control and Cool rooms and solar PV electricity produced for the first farrowing group. Average daily use of electricity in the Control and Cool rooms was 35.3 and 93.0 kWh, respectively. Average daily solar electricity production was 95.3 kWh.

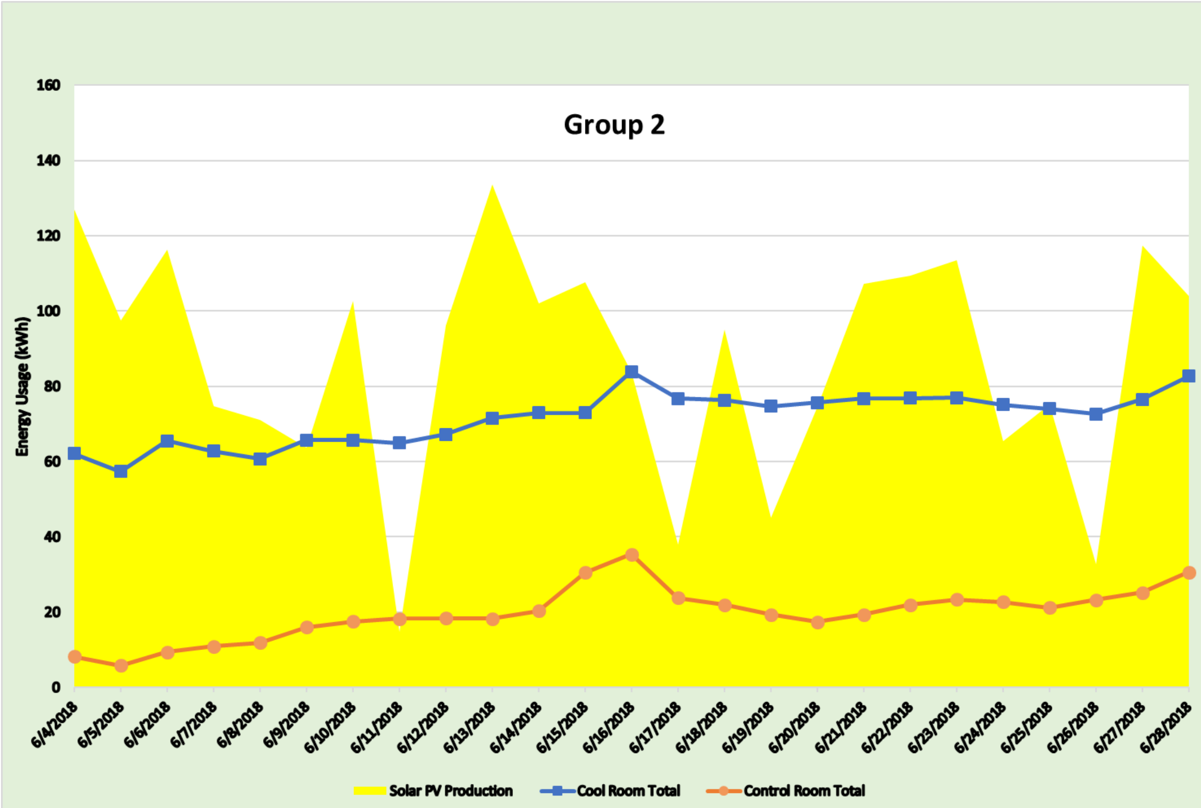


Figure 11. Electricity used in Control and Cool rooms and solar PV electricity produced for the second farrowing group. Average daily use of electricity in the Control and Cool rooms was 19.7 and 71.5 kWh, respectively. Average daily solar electricity production was 86.7 kWh.

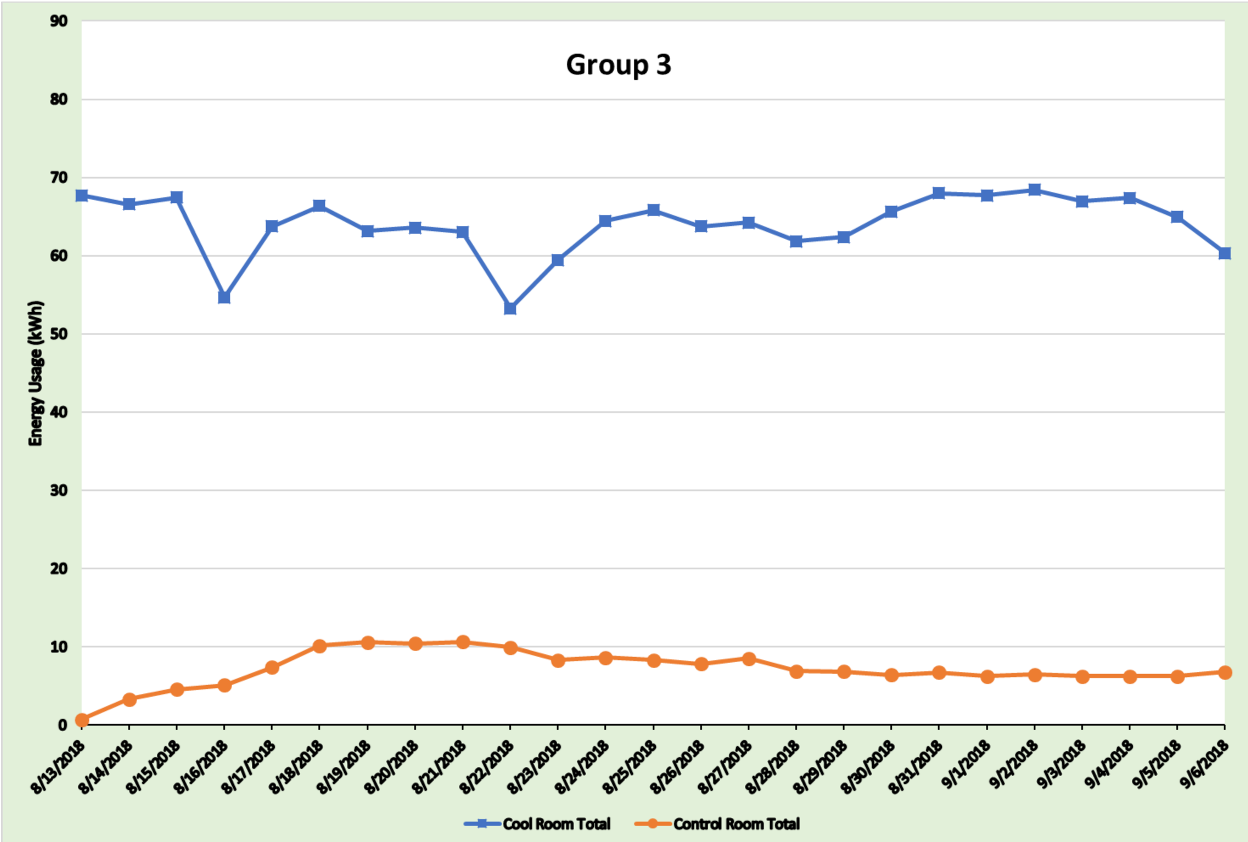


Figure 12. Electricity used in Control and Cool rooms for the third farrowing group. Average daily use of electricity in the Control and Cool rooms was 24.3 and 74.4 kWh, respectively. Average daily solar electricity production was not recorded due to a failure of the monitoring equipment.

3.4 Sow and litter performance

Average parity of sows assigned to Control and Cool treatments was not different as expected in this experiment (Table 1). Similarly, body weight of sows was not different statistically when sows entered the farrowing room at the start of the experiment or at any point in the experiment. Body weight of sows declined ($P < 0.001$) over time as the sows lost weight during the farrowing process and as lactation progressed. When considering total body weight loss during lactation, sows housed in the Cool room lost less weight ($P < 0.05$) than sows housed in the Control room. Other measures of sow body condition, backfat depth and loin muscle area, were not influenced by the sow cooling system (Table 1). Throughout farrowing and lactation, sows lost a significant amount of backfat depth and loin muscle area but the magnitude of these losses were similar for sows in the Cool and Control rooms. Lactation length and days from weaning to estrus were similar for sows housed in the Control and Cool rooms.

Table 1. Effect of solar-powered cooling system on sow performance

Trait	Control room	Cool Room	SE[a]	Significant effects
No. of sows	41	43	--	--
Parity of sows	2.93	3.00	0.29	NS[b]
Sow weight, lb:				
Day 109 of gestation	592.8	575.3		
24 h post farrowing	537.9	526.6	12.43	Time (<0.001)
Weaning	490.5	495.2		
Sow wt. loss in lactation, lb	47.3	31.4	7.61	Room (<0.05)
Sow backfat depth, in.:				
Day 109 of gestation	1.25	1.20	0.113	Time (<0.001)
Weaning	0.90	0.94		
Sow loin muscle area, in^2:				
Day 109 of gestation	8.04	7.93	0.175	Time (<0.001)
Weaning	7.11	7.16		
Lactation length, days	21.9	21.8	2.39	NS
Days to estrus	4.42	4.40	0.24	NS

[a]Standard error.
[b]Not significant.

The reduction in body weight loss for sows housed in the Cool room likely resulted from the higher voluntary feed intake of Cool sows compared to Control sows (Figure 13). Averaged over the entire lactation period, daily feed intake of sows housed in the Cool room was 11.56 lb compared with 9.87 lb for Control sows. Admittedly, feed intake of sows in the Cool room was lower than desired suggesting that these sows still experienced some degree of heat stress but the magnitude was significantly less than for sows housed in the Control room. This is supported by the significantly lower rectal temperatures of sows housed in the Cool room compared with those housed in the Control room (Figure 14). Rectal temperatures were recorded in the early afternoon when heat stress conditions were at the highest point during the day. At this time, rectal temperature of Cool sows was about 0.5 °F lower than that of Control sows. Likewise, respiration rate of sows in the Cool room was lower ($P < 0.001$) than sows housed in the Control room (Figure 15). Respiration rate of Cool sows averaged 59 breaths/min over the entire experimental period compared with Control sows that respired at a rate of 91 breaths/min over the same time period. Increased respiration rates are a reliable early indicator of heat stress in pigs (Nienaber and Hahn, 2007). While the Cool sows were noticeably more comfortable than Control sows, their respiration rate was still higher than the expected 30 breaths/min for sows housed in thermal neutral conditions (Johnston et al., 1999). Sows housed in thermal neutral conditions are most comfortable as they are neither heat stressed nor cold stressed.

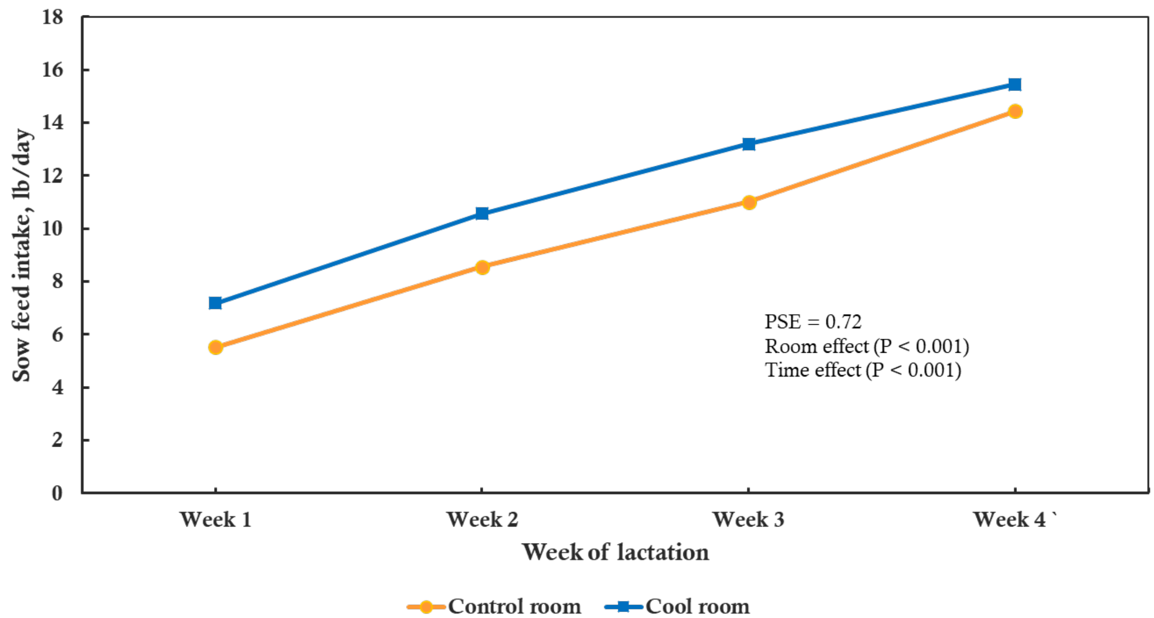


Figure 13. Effect of solar-powered sow cooling on voluntary feed intake of sows after farrowing.

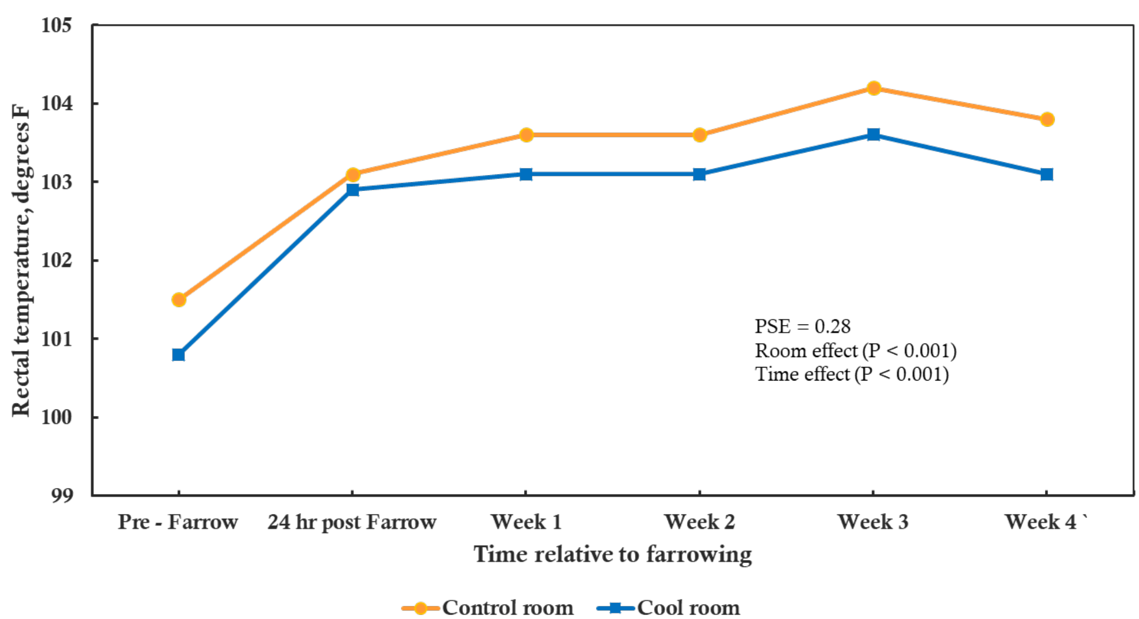


Figure 14. Effect of solar-powered sow cooling on rectal temperatures of sows before and after farrowing.

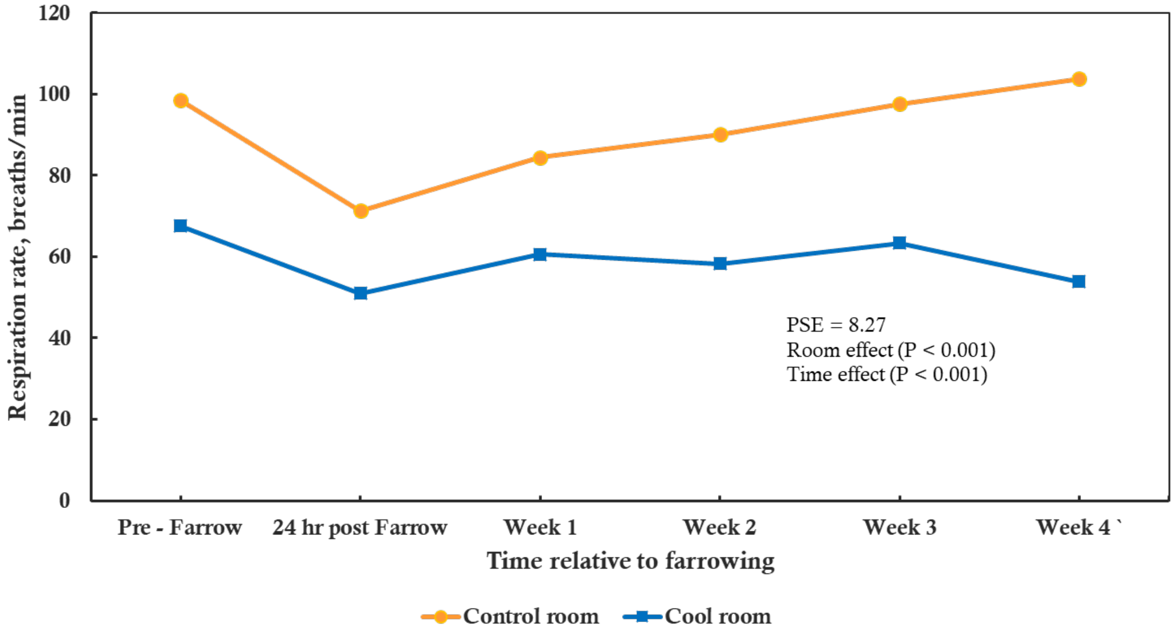


Figure 15. Effect of solar-powered sow cooling on respiration rates of sows before and after farrowing.

Despite the reduced heat stress and increased comfort of sows housed in the Cool room, we detected no improvements in litter performance for sows housed in the Cool room compared to contemporary sows housed in the Control room (Table 2). Total litter size at farrowing was not expected to be influenced by the sow cooling treatment because this trait was determined well before the cooling treatment was imposed. However, one could speculate that cooling heat stressed sows might increase comfort of sows during farrowing and speed the farrowing process which might reduce the number of stillborn pigs and increase number of live born pigs at farrowing. However, we detected no evidence for an improvement in litter size at farrowing or at weaning as a result of the sow cooling system. Similarly, there were no significant improvements in litter weight or average piglet weight at weaning as a result of reducing the magnitude of heat stress through use of cooled floor pads and drinking water.

Table 2. Effect of solar-powered sow cooling system on litter performance

Trait	Control room	Cool room	SE[a]	Significant effects
Litter size:				
Total pigs born	14.44	14.86	0.57	NS[b]
Pigs born live	13.07	13.30	0.58	NS
Stillborn pigs	1.38	1.53	0.48	NS
Mummies	0.20	0.39	0.13	NS
Weaning	11.23	11.39	0.38	NS
Litter weight, lb:				
Total birth	46.41	45.39	1.33	NS
Live birth	42.70	41.62	2.30	NS
Weaning	157.7	163.6	22.55	NS
Piglet weight, lb:				
Avg. live birth wt.	3.34	3.24	0.14	NS
Avg. wean wt.	13.99	14.55	1.90	NS

[a]Standard error.
[b]Not significant.

Behavior data (Table 3) indicate that sows in the Cool room spent similar amount of time farrowing a litter. On average, sows required about 4.5 hours (271 and 261 min in the Cool and Control room, respectively) to farrow a litter. Likewise, birth-intervals were similar for sows housed in the Cool and Control rooms. Farrowing is a labor-intensive act for sows. Although the cooling treatment reduced rectal temperature and respiration rate, it did not affect farrowing behavior. Consequently, the cooling treatment did not affect the number of stillborn piglets as mentioned above.

The Cooling treatment did not affect drinking behavior or postures of sows. We hypothesized that if sows prefer cool drinking water under heat stress, sows in the Cool room may spend more time drinking the water (to drink more) than sows in the Control room. We noticed that sows in the Cool room had 0.6 more drinking bouts in the 2-hour observation period compared with sows housed in the Control room but this difference was not statistically significant. Sows in the Cool room tended ($P = 0.10$) to spend more time drinking than sows in the Control room (48 vs. 35 sec, respectively) during the observation period. Due to the time constraints for data collection, we could not collect drinking behavior data for longer than 2 hours on the observation days in this study. We speculate if we had observed drinking behavior for 24 hours each day, the total daily drinking time would have been longer for sows in the Cool room than in the Control room, which would support our hypothesis.

During the farrowing and lactation period, sows spent 77% of their time lying laterally (on their shoulder), 11% lying ventrally, 7% standing, and 3% sitting. There was no difference in each posture for sows between the Cool and Control rooms. All these data indicate that in general, the Cooling treatment did not change behaviors of sows during farrowing and lactation. In other words, the improved sow comfort was not reflected in sow behavior. This could be attributed to many factors, such as large variation in the sow behaviors measured, the small sample size of sows involved in behavioral data collection, and short data collection periods (such as for drinking behavior). In addition, sow behavior during farrowing and lactation may be more affected by factors other than cooled floors and cooled drinking water, such as the intensive labor during farrowing, recovery from the fatigue of farrowing, and nursing instincts.

Table 3. Effect of solar-powered cooling system on sow behavior

Trait	Control room	Cool room	SE[a]	Significant effects
No. of sows	15	15		
Parity of sows	2.3	2.4		
Total piglet born, piglets/litter	14.0	15.4	1.01	NS[b]
Farrowing behavior:				
Total duration, min	260.8	270.9	25.70	NS
Birth-interval, min	17.4	18.0	2.09	NS
Drinking behavior:				
Frequency of drinking, bouts/2h	2.8	3.4	0.43	NS
Avg. duration of drinking, sec/bout	9.7	10.7	0.98	NS
Total drinking time, sec/2h	34.7	47.5	6.10	NS
Postures (Time budget), %:				
Lying laterally	77.5	77.0	0.91	NS
Lying ventrally	11.1	11.5	0.65	NS
Standing	6.9	7.2	0.38	NS
Sitting	2.8	3.1	0.23	NS

[a]Standard error.
[b]Not significant.

4 Basic Economic Analysis

A rudimentary economic analysis of the solar powered sow cooling system is displayed in Table 4. Capital costs for the system can be divided into costs for the system installed in the farrowing room and costs for the solar PV array used to power the cooling system. Capital costs for the cooling system (floor pads and drinking water) totaled $178,865 to retrofit and equip 16 farrowing stalls for a cost of $11,179 per stall. If one depreciates these capital costs over a 20 year period, the annual per stall capital cost is $559 per stall. These "per stall" costs could be reduced substantially if a larger number of stalls were equipped with the cooling equipment so that the equipment costs could be spread over more stalls. The engineering design firm for the sow cooling system estimated annual operation and maintenance costs of the cooling system equipment would be about 0.5% of the equipment cost.

The 20 kW solar PV array was of sufficient size to produce electricity in excess of that needed to operate the cooling system during the hot summer months. The solar array also produced electricity during periods of the year when the sow cooling system was not needed. This excess electricity could be used other places on the farm to displace electricity purchased from the grid or sold back on the grid in certain situations. The National Renewable Energy Lab (NREL) aggregates and models solar PV costs using data from actual installations around the country and estimated operations and maintenance (O&M) costs at $13/kW/yr in 2018 (as cited by New Energy Update, 2019). Simple recommendations about installing a solar array cannot be made because any economic analysis of installing a solar array must consider the local solar resource as well as the local electricity price. Moreover, PV prices are still decreasing significantly every year while tax and other incentives change over time and vary state to state. Therefore, the decision to include a solar PV array in a sow cooling system should be based on the specific economics of a solar PV installation for the desired site and can be somewhat independent of the sow cooling system.

Table 4. Capital costs and estimated operating costs for solar powered sow cooling system over a 20 year period

Item	Description	Cost
Actual capital costs:		
System design	Engineering designs and drawings to properly size the system	$23,500
Equipment and installation	Purchase of heat pump, fan coil, buffer tanks, circulation pumps, flooring pads, plumbing supplies, installation labor	$148,865
Wiring	Wiring of controls and sensors	$6,500
Solar PV array	Purchase, installation, and commissioning of 20 kW solar photovoltaic array	$59,800
Estimated operating costs:		
Cooling system maintenance	Replace circulation pumps, maintain heat pump, replace sensors and control valves	$14,887
Solar array maintenance	Maintenance including inverter replacement	$5,200

A basic financial assessment of the 20 kW solar PV system installed at the WCROC was conducted. Electricity pricing and tariff fees were used from the bills submitted to the West Central Research and Outreach Center from Runestone Electric Association (REA). REA is a rural electric cooperative. Results of this economic analysis will vary significantly between rural electric cooperatives and investor owned utilities. Considering the capital costs, value of the power produced, and fees charged by the utility; the 20 kW solar PV system will breakeven after 60 years on a straight cash basis (revenues minus expenses). When tax incentives are added and fully utilized, the breakeven point is between 8 and 12 years. The tax incentives include an investment tax credit that currently is 30% in 2019 and will decline each year. The second tax advantage is accelerated depreciation which allows the system to be fully depreciated in either one year or five years.

There are two key takeaway points and recommendations on financial viability of solar PV systems on farms. The first recommendation is to research the electricity pricing, incentives offered, and fees charged by the local utility. Again, these will all vary significantly across electricity utilities. The second, and perhaps most important recommendation, is to determine if available tax incentives can be fully utilized and the value completely realized by the individual or farming operation.

Because the sow cooling system did not improve litter performance and therefore did not increase gross income for pig farmers, the capital investment in this cooling system is not warranted for commercial pork production systems at this time. Possibly, future innovations in sow cooling will result in improved sow and litter performance and result in favorable economic outcomes. Managing drinking water systems (insulating pipes, monitoring drinking water and ambient room temperatures, and increasing water flow) to maintain cooler drinking water for sows may be a more cost effective method for swine producers to improve sow comfort and performance.

5 Conclusions

The 20 kW solar array consistently provided enough electricity to operate the sow cooling system installed in a confinement farrowing barn. The sow cooling system studied in this project was able to significantly reduce heat stress of farrowing and lactating sows but did not completely eliminate heat stress. Unfortunately, the reduced heat stress of sows did not support improvements in litter size at weaning or growth rate of suckling pigs. Consequently, the expenses of installing and operating the cooling system would not be returned to pig farmers through increased income. Thus, commercial installation and operation of the cooling system studied in this project is not recommended at this time.

6 References

Black, J. L., B. P. Mullan, M. L. Lorschy, and L. R. Giles. 1993. Lactation in the sow during heat stress. Livest. Prod. Sci. 35:153-170.

Deen, J., and J. Xue. 1999. Sow mortality in the US: An industry-wide perspective. Proc. Allen D. Leman Swine Conf., Univ. of Minnesota, St. Paul. Pg. 91-94. https://conservancy.umn.edu/bitstream/handle/11299/148140/1/Deen%232.pdf

Jeon, J. H., S. C. Yeon, Y. H. Choi, W. Min, S. Kim, P. J. Kim, and H. H. Chang. 2006. Effects of chilled drinking water on the performance of lactating sows and their litters during high ambient temperatures under farm conditions. Livest. Prod. Sci. 105:86-93.

Johnston, L. J., M. Ellis, G. W. Libal, V. B. Mayrose, W. C. Weldon, and NCR-89 Committee on Swine Management. 1999. Effect of room temperature and dietary amino acid concentration on performance of lactating sows. J. Anim. Sci. 77:1638-1644.

Martin, P. and P. Bateson. 1993. Measuring behavior: An introductory guide. 2nd Edition. Cambridge University Press, Cambridge, U. K.

MWPS (Midwest Plan Service). 1990. MWPS-32: Mechanical ventilating systems for livestock housing. Ames: Midwest Plan Service, Iowa State University.

National Pork Board. 2019. Pork Quality Assurance Plus. Accessed at: http://www.porkcdn.com/sites/all/files/documents/PQAPlus/V4.0/Forms/PQAv4e_Handbook.pdf

New Energy Update. 2019. US solar maintenance costs plummet as tech gains multiply. Feb. 6 newsletter accessed September 24 at: http://newenergyupdate.com/pv-insider/us-solar-maintenance-costs-plummet-tech-gains-multiply?

Nienaber, J. A. and G. L. Hahn. 2007. Livestock production system management responses to thermal challenges. Int. J. Biometerol., 52(2), 149-157.

NOAA (National Oceanic and Atmospheric Administration). 2019. Climate change: Atmospheric Carbon Dioxide. Accessed September 24, 2019 at: https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide

Ross, J. W., B. J. Hale, N. K. Gabler, R. P. Rhoads, A. F. Keating, and L. H. Baumgard. 2015. Physiological consequences of heat stress in pigs. Anim. Prod. Sci. 55:1381-1390.