Effects of a Solar Cooling System on Sow Performance

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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.

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.

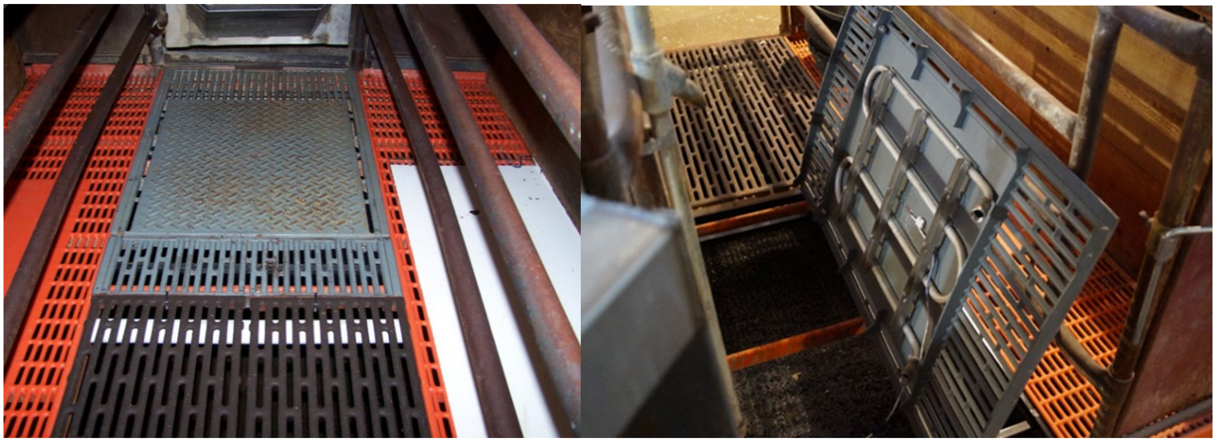

Figure 1. Flooring pad installed in the front portion of the sow's farrowing stall (left) and the cooling loop attached beneath the flooring (right).

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.

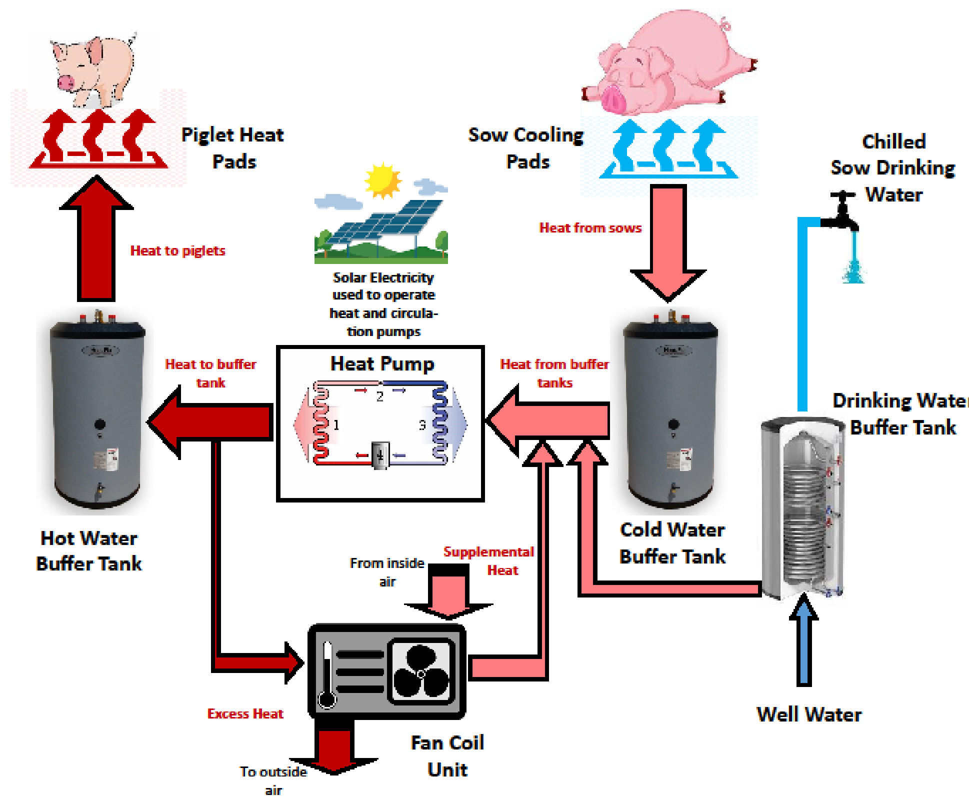

Figure 2. Schematic representation of the sow cooling and piglet heating system used in this experiment.

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).

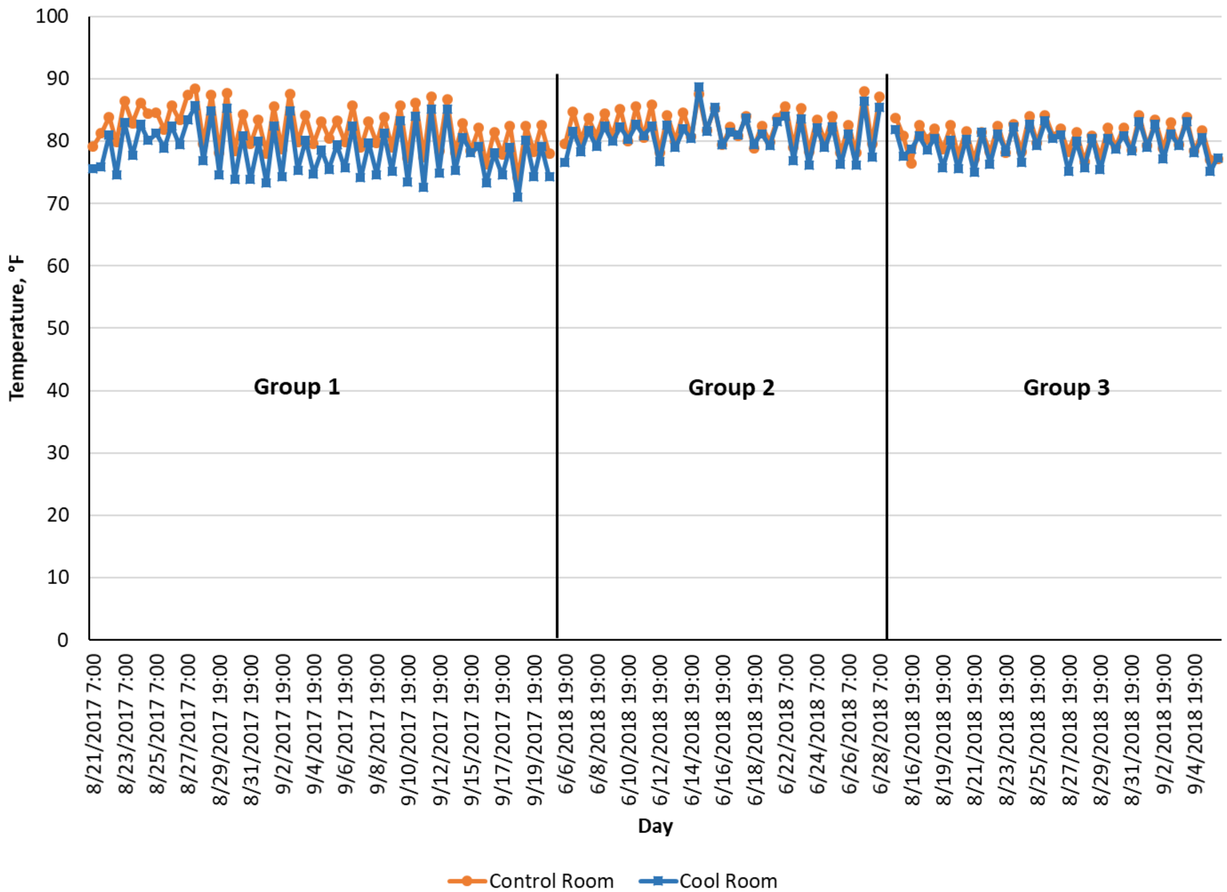

Figure 4. Temperatures recorded in farrowing rooms averaged over 12-hour periods (7:00 am to 7:00 pm) each day of all three farrowing groups.

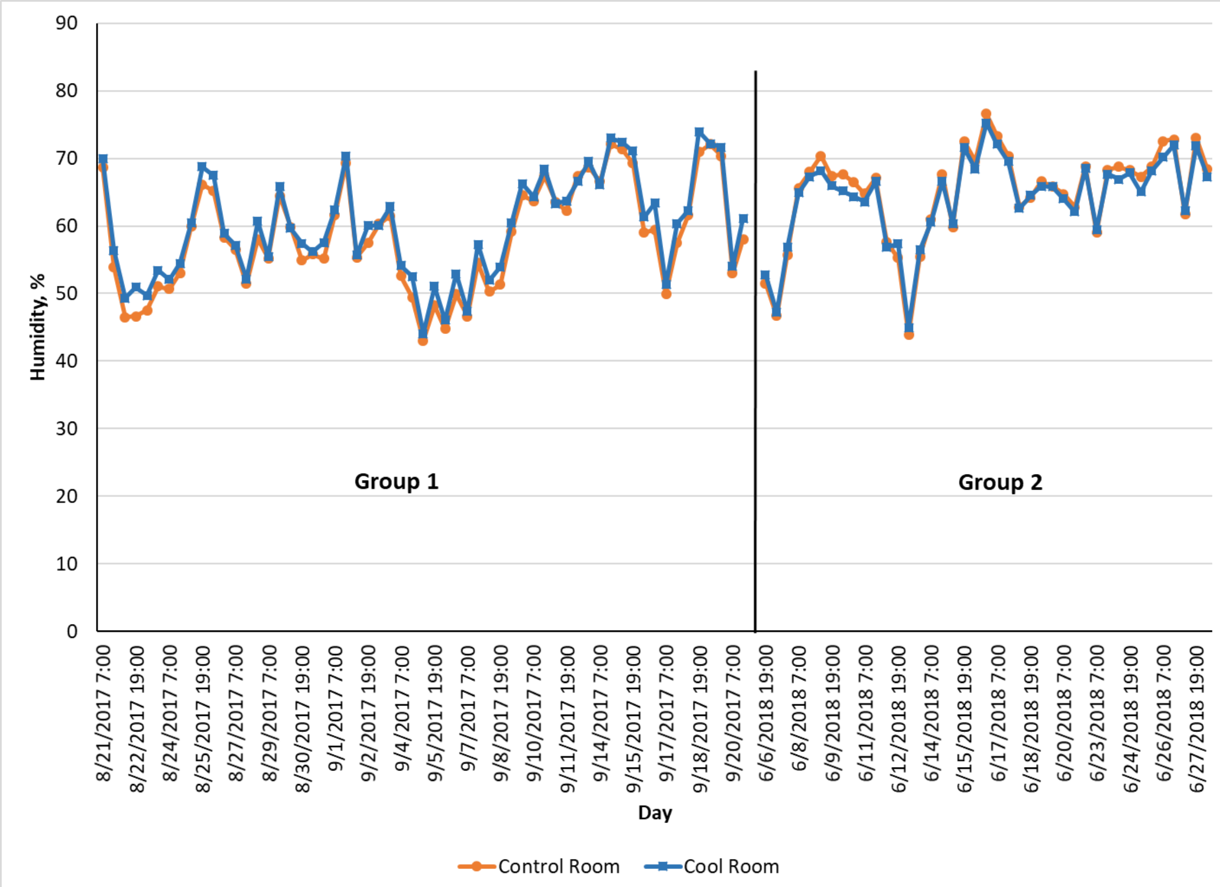

Figure 5. Humidity recorded in farrowing rooms averaged over 12-hour periods (7:00 am to 7:00 pm) each day in two farrowing groups.

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.

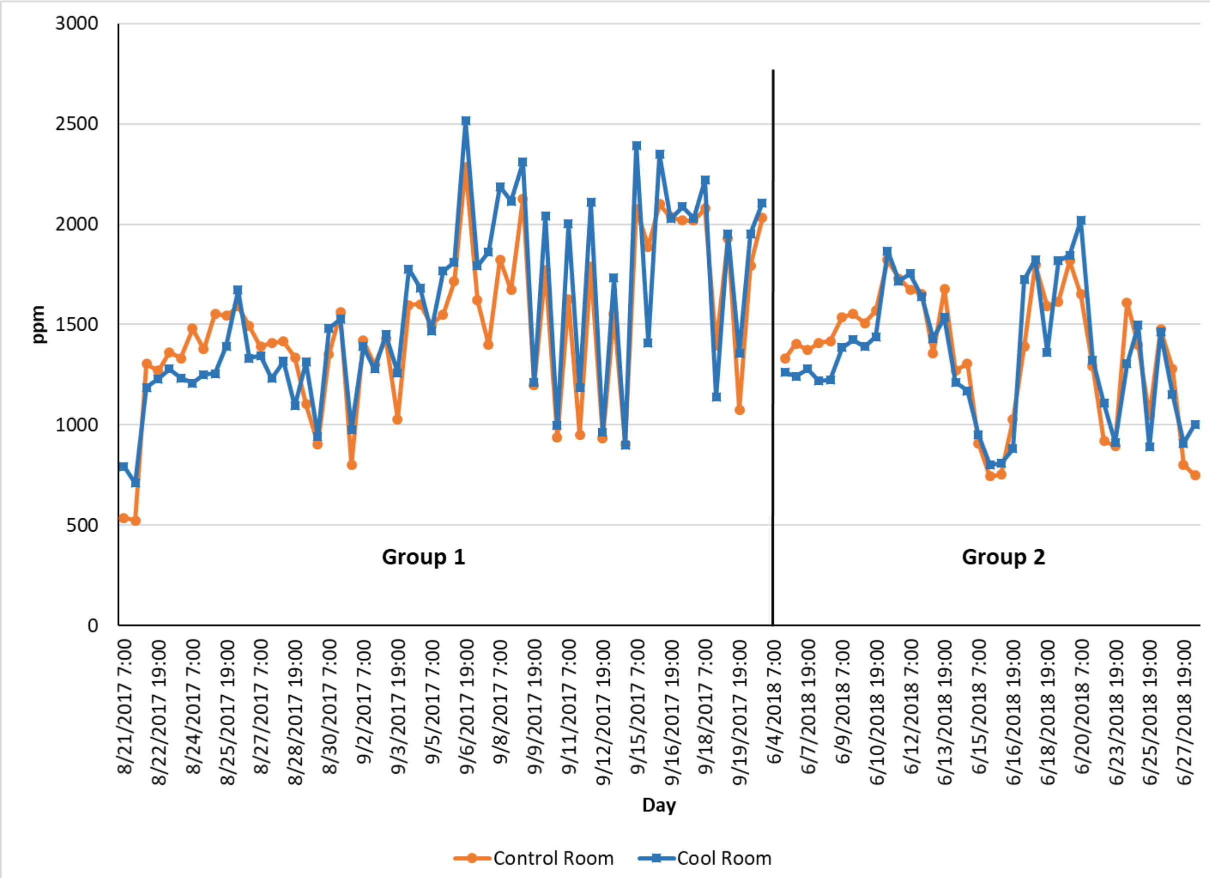

Figure 6. Carbon dioxide concentration in farrowing rooms averaged over 12-hour intervals (7:00 am to 7:00 pm) for each day of farrowing groups one and two

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).

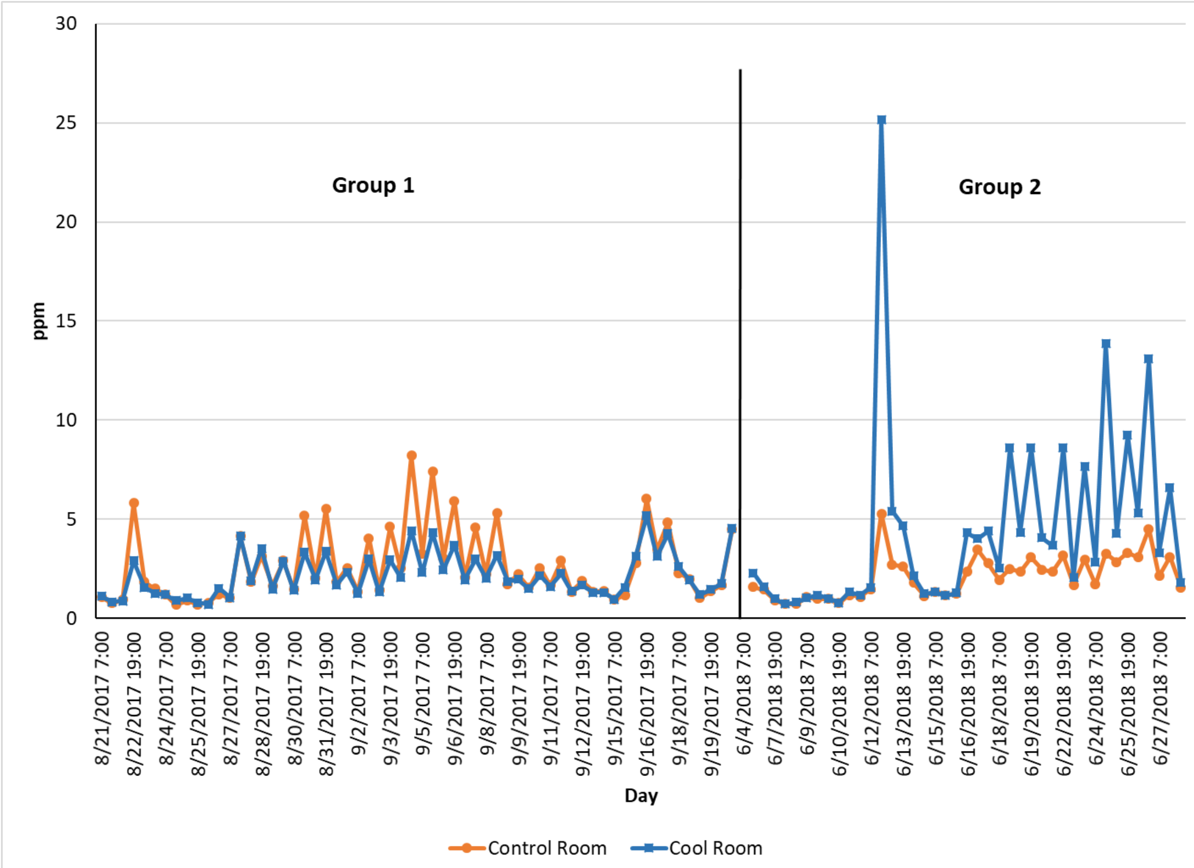

Figure 7. Ammonia concentrations in farrowing room air averaged over 12-hour periods (7:00 am to 7:00 pm) for each day of farrowing groups one and two

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.

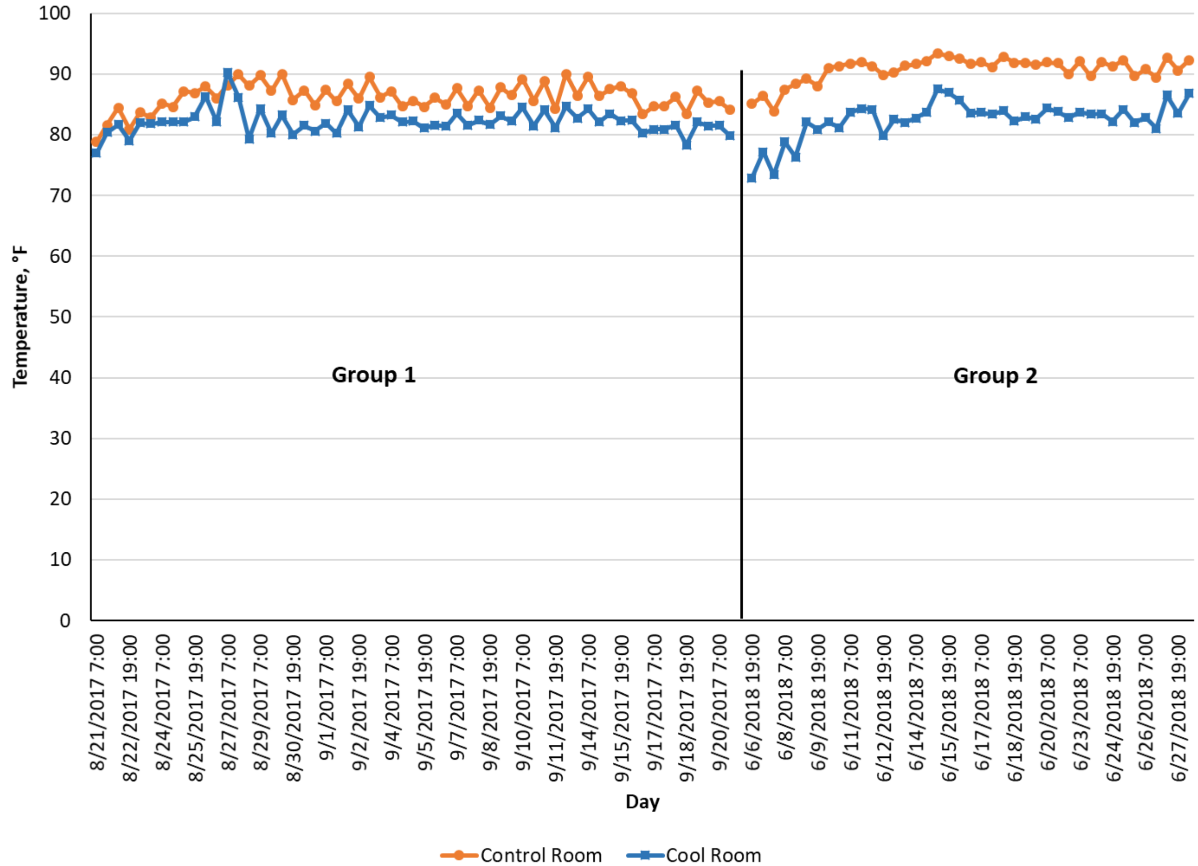

Figure 8. Temperature of flooring pads in Cool and Control rooms averaged over 12-hour periods (7:00 am to 7:00 pm) for each day of farrowing groups one and two.

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).

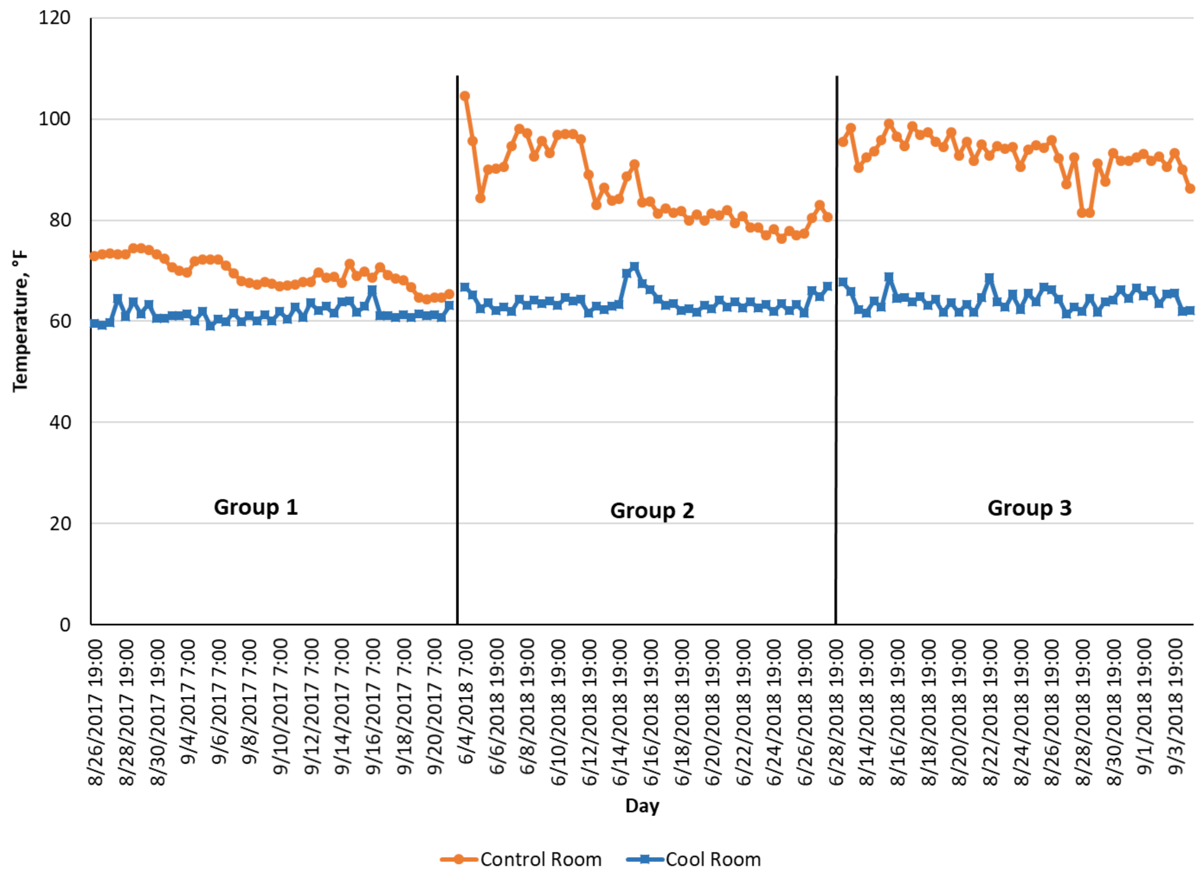

Figure 9. Temperature of drinking water in Control and Cool rooms averaged over 12-hour periods (7:00 am to 7:00 pm) each day for all three farrowing groups.

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.

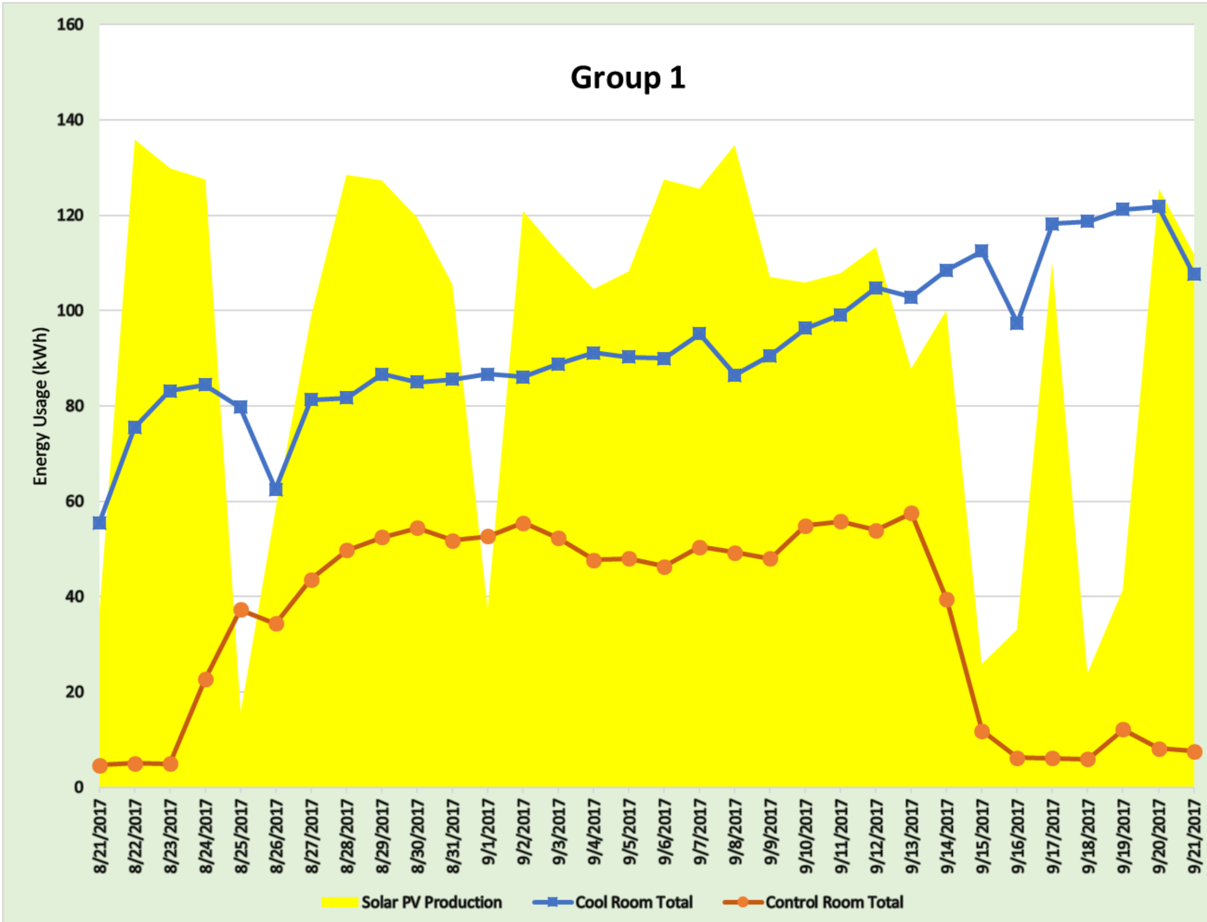

Figure 10. Electricity used in Control and Cool rooms and solar PV electricity produced for the first farrowing group. Average daily use of electricity in the Control and Cool rooms was 35.3 and 93.0 kWh, respectively. Average daily solar electricity production was 95.3 kWh.

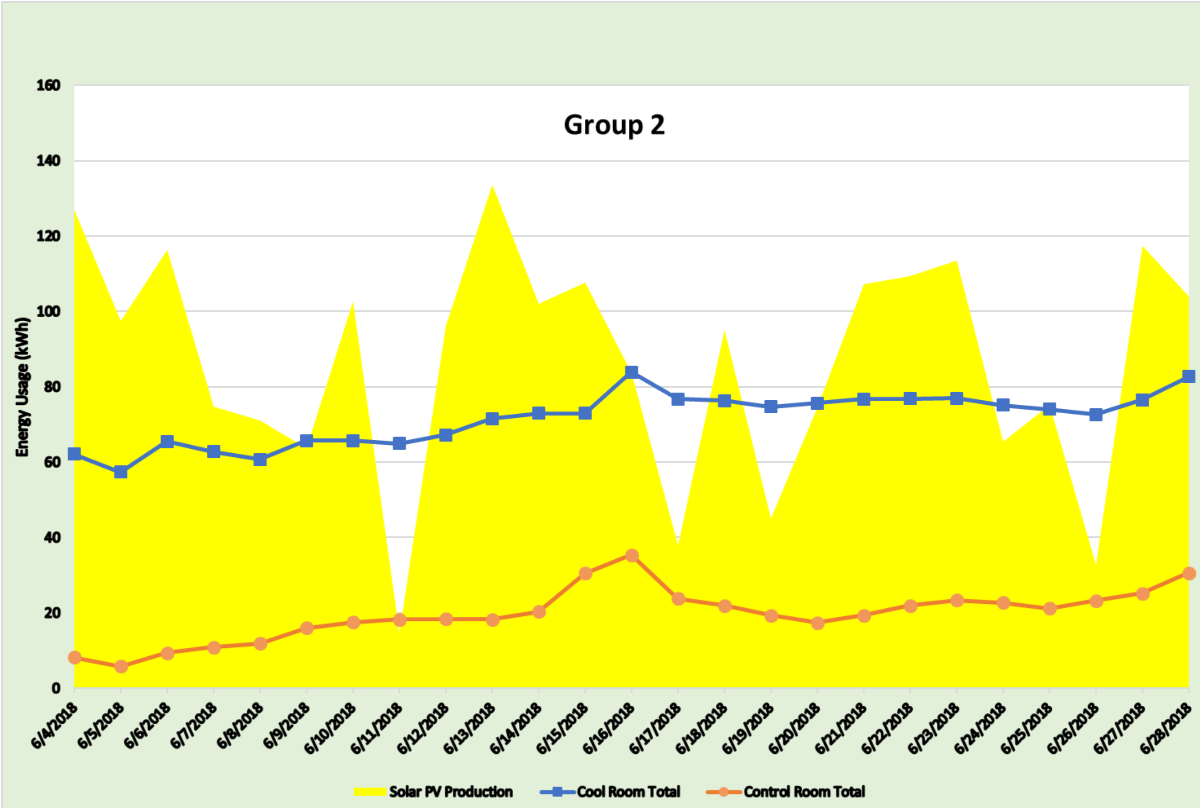

Figure 11. Electricity used in Control and Cool rooms and solar PV electricity produced for the second farrowing group. Average daily use of electricity in the Control and Cool rooms was 19.7 and 71.5 kWh, respectively. Average daily solar electricity production was 86.7 kWh.

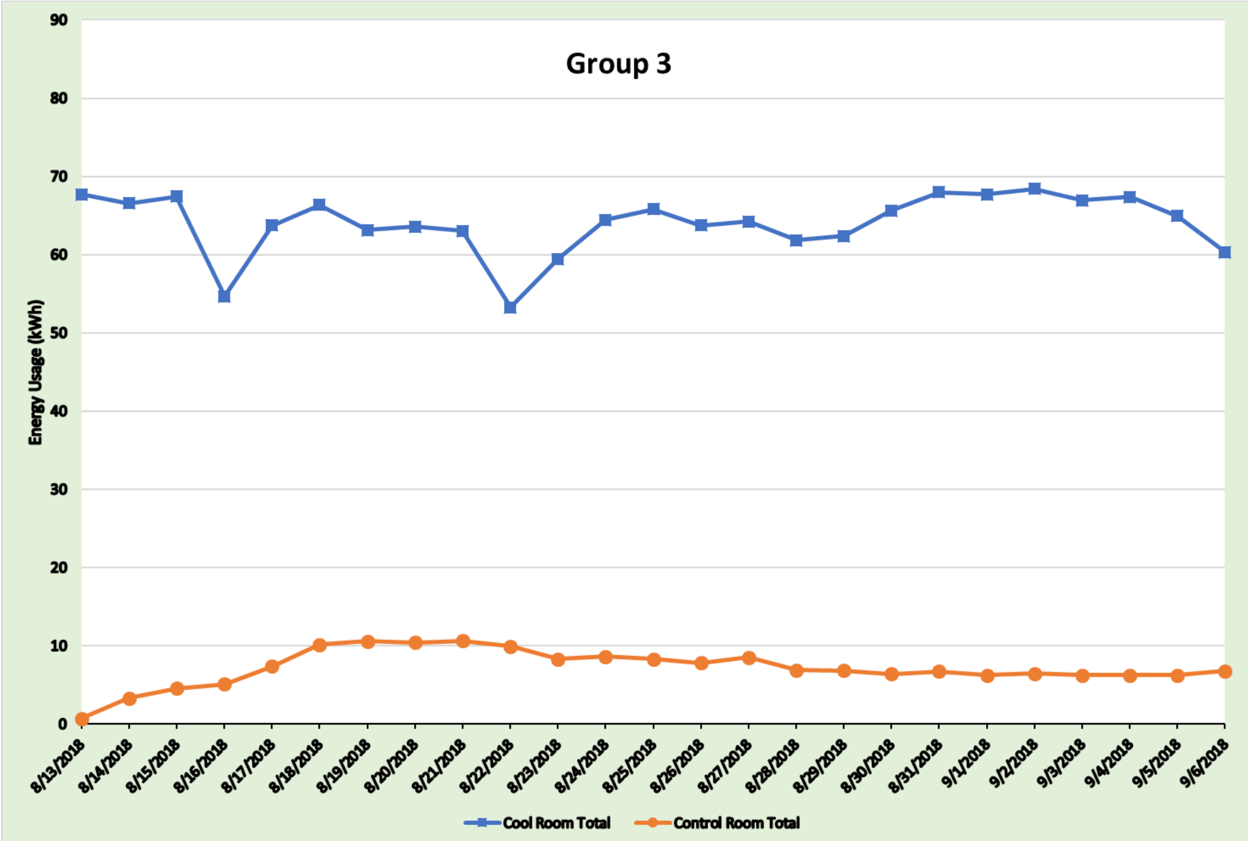

Figure 12. Electricity used in Control and Cool rooms for the third farrowing group. Average daily use of electricity in the Control and Cool rooms was 24.3 and 74.4 kWh, respectively. Average daily solar electricity production was not recorded due to a failure of the monitoring equipment.

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.

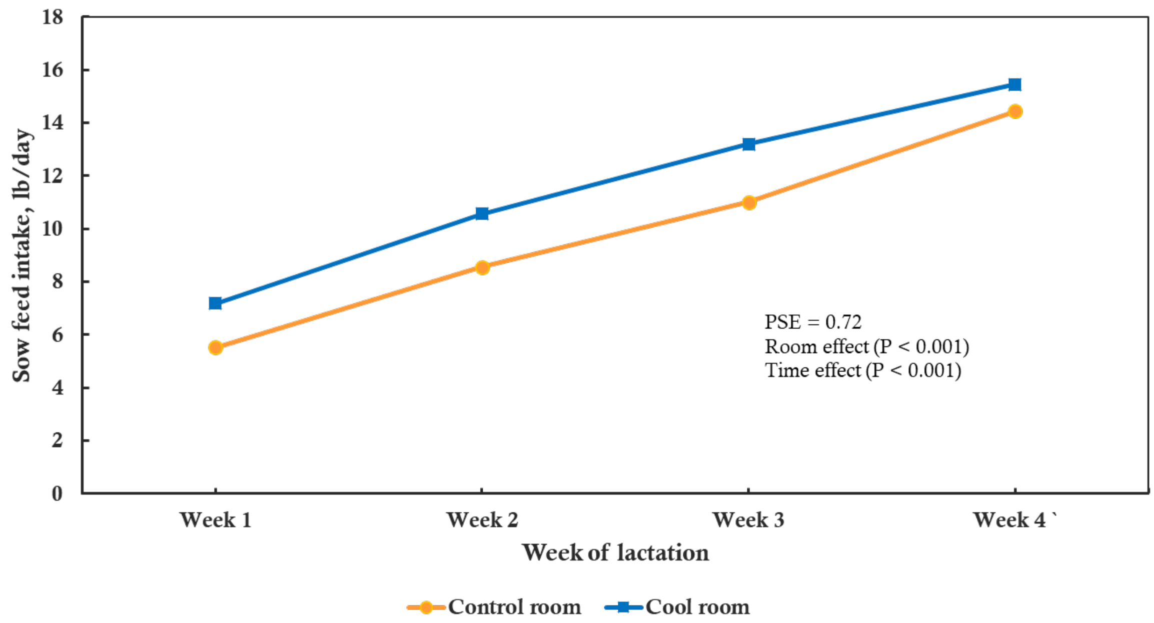

Figure 13. Effect of solar-powered sow cooling on voluntary feed intake of sows after farrowing.

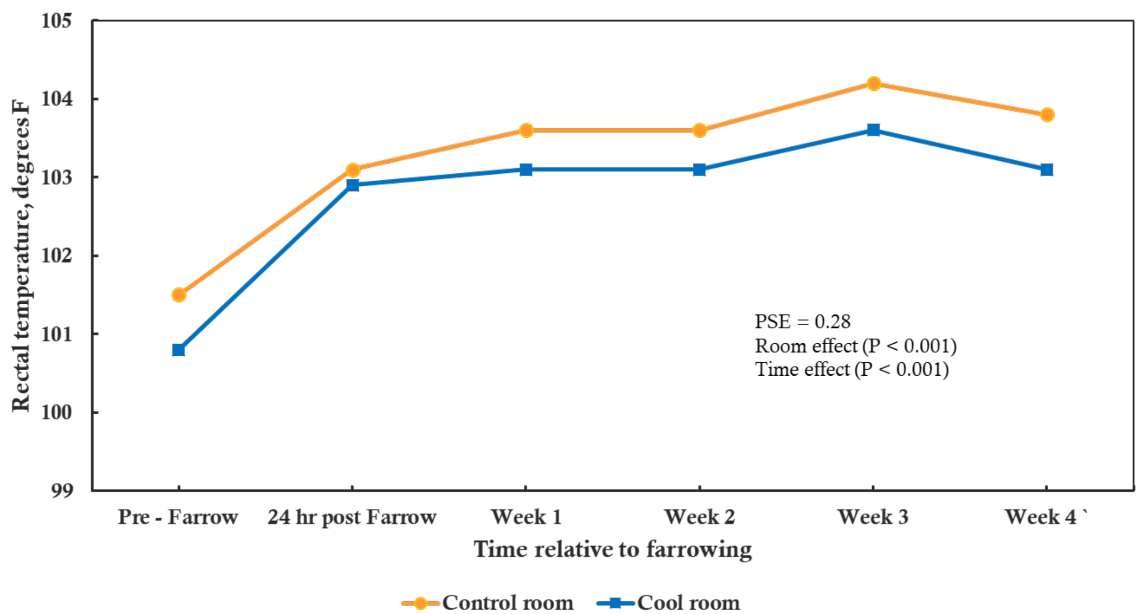

Figure 14. Effect of solar-powered sow cooling on rectal temperatures of sows before and after farrowing.

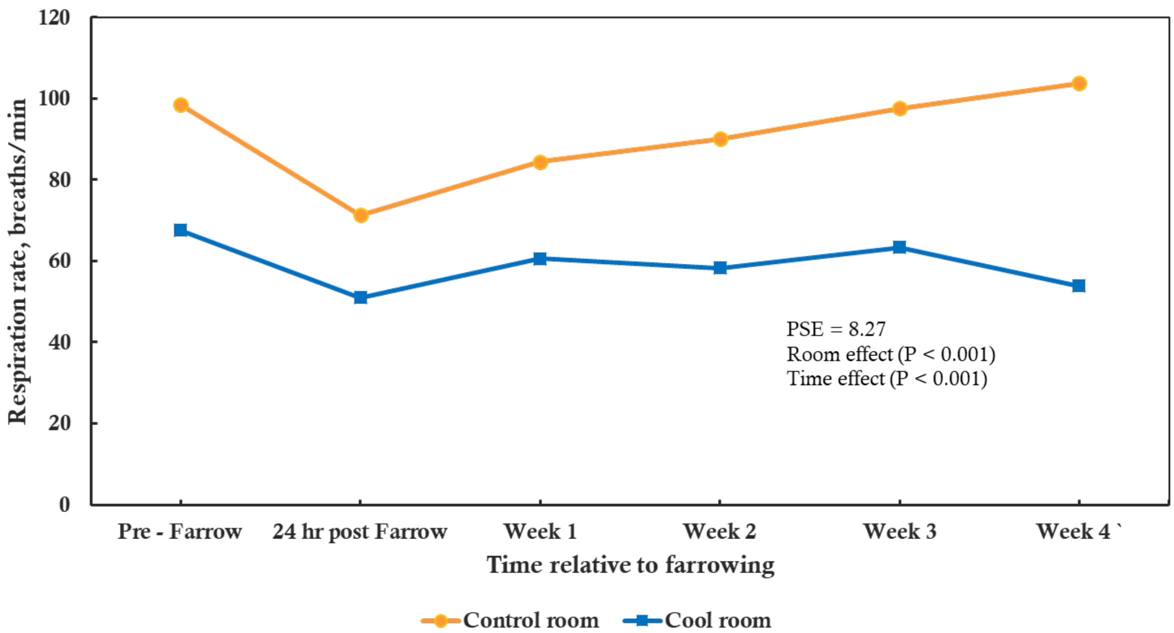

Figure 15. Effect of solar-powered sow cooling on respiration rates of sows before and after farrowing.

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.

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