ELECTRICITY AND FUEL USE OF AVIARY-LAYING HEN HOUSES IN THE MIDWESTERN UNITED STATES

M. D. Hayes, H. Xin, H. Li, T. A. Shepherd, J. P. Stinn

ABSTRACT. *There is a growing interest in and movement toward alternative housing systems for laying hens. Associated with the movement are many questions to be addressed concerning sustainability of these systems. This study quantified electricity and propane use in two side-by-side aviary houses each with a holding capacity of 50,000 laying hens, located in Iowa. Electricity use was partitioned into different housing components, including ventilation, lighting, and manure-drying. Results indicate that electricity consumption for ventilation had the most variation, accounting for 30% of the total electrical demand in the summer but less than 5% in the winter. Manure-drying blowers ran continuously throughout the flock, using approximately 345 kWh d^{-1} and accounting for approximately 51% of the annual electrical demand. Ventilation efficiency of the exhaust fans was approximately 25.5 m^3 $(h\text{-}W)^{-1}$ (15 CFM W^{-1}) at static pressure of 12.5 Pa (0.05 in. water column). Over the 15-month monitoring period, both houses had an average electricity cost of 3.0 cents per kg (or 2.3 cents per dozen) eggs produced (based on the rate of \$0.09 kWh^{-1}). The propane use was minimal, less than 425 L (112 gal) in one year or 0.6 mL per kg (0.4 L per dozen) eggs produced.*

Keywords. *Aviary hen housing, Energy, Electricity usage, Propane, Ventilation efficiency.*

In the past decade there has been increased pressure to move from conventional cage houses (both high-rise and manure-belt systems) to alternative housing systems such as cage-free and/or enriched colony housing for laying hens. With this pressure there are many questions about the performance of these alternative housing systems. Significantly lower stocking densities in alternative systems raise concerns over utility costs, including electricity and fuel usage per bird. There is an indication from European Union data that utilities are slightly higher.

It has been reported that the largest electricity usage in egg production comes from mechanical ventilation (Fluck and Baird, 1980; Stout, 1984). Most data on electricity usage in the United States are from earlier studies which reflect conventional housing with high-rise manure management and incandescent lighting. With differences in housing and management practices, there are issues concerning results of earlier studies to current energy consumption characteristics. Understanding the efficiency of mechanical components in the houses may affect purchasing consideration, particularly with the major electricity consumers. Sonesson et al. (2009) summarized energy consumption data from housing systems in the European Union and stated that similar to earlier studies ventilation and lighting are a large portion of electricity consumption. To improve energy efficiency the study recommended using energy-efficient lighting, but cautioned not to use normal fluorescent lighting due to flickering. The study recommended not drying manure unless it is necessary for transporting/stacking due to energy demands. Moreover, the study noted up to 10% of the energy could be saved by cleaning and following good maintenance of the houses and fans in particular (Sonesson et al., 2009). While the comments and recommendations from the European study are of practical value, the energy consumption data may not be applicable to U.S. production and management conditions due to differences in farm size and management style. Therefore, the objectives of this study were to quantify electricity and fuel use in two aviary laying-hen barns and provide practical management considerations under the Midwestern U.S. production conditions.

MATERIALS AND METHODS

SITE DESCRIPTION

Two aviary hen houses in a double-wide building located in Iowa were used in this field study. Each house measured 168 × 19.8 m (550 × 65 ft) with a capacity of

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50,000 hens (Hy-Line Brown) and had a production cycle from approximately 17 to 80 weeks of age (new flock started the fourth week of April 2010 in house 3 and the second week of September 2010 in house 2). A cross-sectional schematic of the houses is shown in figure 1. The houses had open litter floor, nest boxes, and perches. To minimize floor eggs and improve manure management, the hens were trained to be off the floor and return to the aviary colonies at night and remained in the colonies until the next morning. Each row had three tiers and manure belt with a manure-drying air duct placed underneath the lower two colony tiers. Further descriptions are given in table 1. The three tiers were divided into nest, feeding, and drinking area from top to bottom. Each house had 20 exhaust fans, all on one sidewall, including twelve 1.2 m (48 in.), four 0.9 m (36 in.), and four 0.5 m (20 in.) fans. Ceiling box air inlets were used (75 bi-directional toward the sidewalls, 0.6 × 0.6 m each). Compact fluorescent lighting was used in the inspection and litter floor aisles. Four 73.25 kW (250,000 BTU h^{-1}) vented heaters were placed equidistant on the sidewall to provide supplemental heat. Air temperature (type-T thermocouple, Cole-Parmer, Ill.), relative humidity (RH) (HMW60, Vaisala, Mass.), and building static pressure (264, Serta, Mass.) were measured near the middle of the house at 1 s intervals and reported as 30 s averages. Air temperature was also measured near the two minimum ventilation fans closest to each endwall.

The exhaust fans, air inlets, and heaters for the houses were controlled by management software based on eight temperature sensors placed throughout each house (Command III, Poultry Management Systems, Inc., Saranec, Mich.). Based on a selected setpoint temperature, if the house temperature deviated more than 1.1°C (2°F) from the setpoint, every 2 min the controller would turn on or off the next stage of exhaust fans. If at minimum ventilation rate (VR) the house temperature was still 2.2°C (4°F) below the setpoint, the heaters would run. Setpoint temperatures were adjusted based on age of hens and to control egg weight with overall average temperatures of 22.7°C and 23.2°C (72.9°F and 73.8°F) for houses 2 and 3, respectively. The VR was determined based on *in situ* calibrated fan curves with fan assessment numeration

Table 1. Description of the major mechanical components in the aviary laying-hen houses monitored.

Ventilation	No. Fans	Fan Size[a]	Motor Size	Above Setpoint (°C)
Stage 1	4	0.5 m	250 W	Continuous
Stage 2	4	0.9 m	375 W	1.1
Stage 3	2	1.2 m	750W	1.1
Stage 4	2	1.2 m	750 W	1.1
Stage 5	2	1.2 m	750W	1.1
Stage 6	2	1.2 m	750 W	1.1
Stage 7	2	1.2 m	750W	1.1
Stage 8	2	1.2 m	750 W	1.1
Heater	No. Heaters		Capacity	Below Setpoint (°C)
	4		73.25 kW	2.2
Manure drying blower	No. Blowers		Motor Size	
	3		5.6 kW	
Lighting	No. Lights	Bulb Type	Nominal Size	Light Mode
Inspection aisle	315	CFL	9W	Dimmable
Litter aisle	180	CFL	15W	Dimmable
Worker area	16	Incandescent	75W	
Timing of events				
Feeding	5:45 A.M.	11:15 A.M.	3:30 P.M.	7:15 P.M.
Lights on/off	Lights on	5:30 A.M.	Light off	9:45 P.M.
Floor access	On floor	11:30 A.M.	Off floor	9:30 P.M.
Daily manure belt movement	1/3 belt (winter)	15 min	1/7 belt (summer)	7 min
Spacing allowance (50,000 hens)				
Wire floor	676	cm^2 $bird^{-1}$		
Litter floor	613	cm^2 $bird^{-1}$		
Nest space	60	cm^2 $bird^{-1}$		
Perch length	15.9	cm $bird^{-1}$		
Feeder space	10.6	cm $bird^{-1}$		
Nipple drinker	8.55	Birds $nipple^{-1}$		

[a]Unit conversion: 1 m = 3.28 ft; 1 cm^2 = 0.155 in^2; 1 W = 3.41 BTU h^{-1}; 1°C (increment) = 1.8°F (increment)

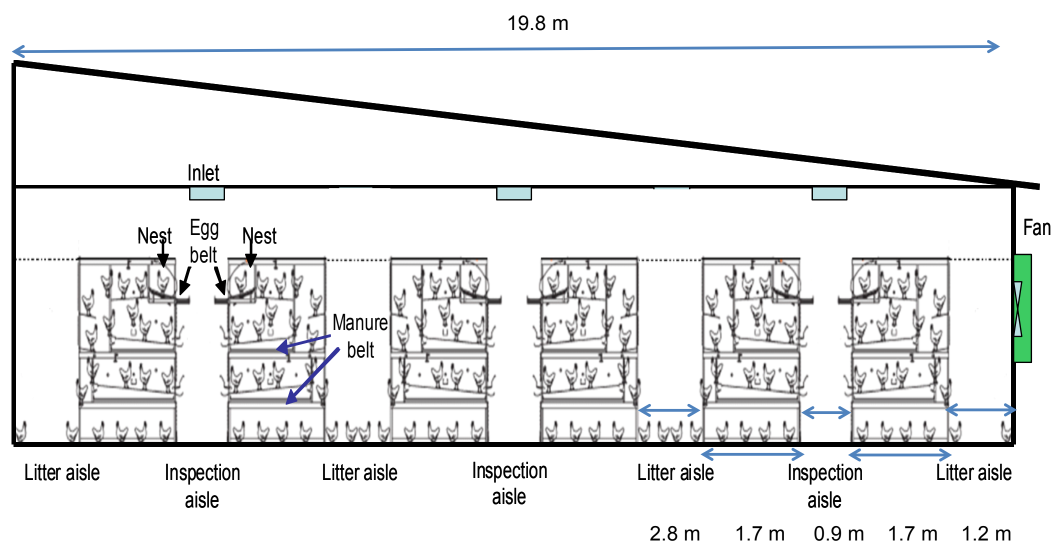

Figure 1. Cross-sectional view of the aviary hen house (one side of the double-wide house) monitored in this study (conversion: 1 m = 3.28 ft).

systems (FANS) sized 0.9, 1.2, and 1.35 m (36, 48, and 54 in.) (Gates et al., 2004) and continuous monitoring of each fan runtime. Individual fan curves were established for each stage (1-8), including operational ranges of the variable-speed control of the lower stages.

Electricity Monitoring

A 3-phase delta service of 240V power supply was provided to each house, and a shared 240V service was dedicated to the manure belts of both houses and the exterior manure storage building. In this study, continuous monitoring was made on the power supplies of each house, but not the manure management power supply. Electrical service of each house was separated into three service panels. The first panel included lower ventilation stages, two of the manure-belt blowers, and a portion of lighting. The second and third panels included feeding and egg collection systems, higher ventilation stages, remaining lighting, the remaining blower, 20 mixing fans, electrical outlets, and the automatic fan curtains (Hired Hand Inc., Bremen, Ala.).

Inductive current sensors (AcuAmp ACTR 200) were used to collect data on the total house electrical supply and individual circuits of ventilation fans, lighting, and manure-drying blowers. Individual circuits such as feeding and egg collection systems, mixing fans, electrical outlets, and the automatic fan curtains were not measured. Electric current for the whole house was measured from six current sensors, each measuring one phase of a supply. Current for the eight ventilation stages was monitored through measurement of individual legs using three current sensors. The lighting current was measured with one current sensor. Finally, the three legs of one manure-drying blower were run through another current sensor. It was assumed that all three manure-drying blowers operated in the same manner (continuously). Current measurements were recorded for all 11 sensors in each barn every second with a data acquisition system (Compact Fieldpoint, National Instruments, Tex.). The 1 s data were averaged to 30 s values and output to the on-site PC.

A power logger (Fluke 1735, Everett, Wash.) was used to collect data on each independent electrical service for 4 days, monitoring and recording: current and voltage from each leg, power factor, total, reactive, and apparent power for the circuit as a whole. These data were used first to verify current measurements from the current sensors. Then these data were used to develop appropriate power factors for use in calculating total power from the current sensors. After logging the supply power consumption for the whole house, individual circuits were checked for short periods of time (~10 min per circuit to identify power consumption by individual systems). From the four days of whole house monitoring the variations in line voltage were determined. Voltage (mean±SD) for the services ranged from 246±1.55 to 248±1.25 V. Variations in voltage from the short duration monitoring of the 120V systems showed less variability with only 0.3 V measured. These small variations in line voltage led to a strong relationship between the current-based monitoring and electricity usage.

Propnae Fuel Monitoring

For fuel monitoring, temperature-compensated diaphragm gas meters (AM-205, Elster American, Nebraska City, Neb.) were installed in-line between the propane tanks (1,890 L or 500 gal each) and the two 73.25 kW (250,000 BTU h^{-1}) supplemental heaters mounted in the sidewall they each serviced. There were two tanks for each house, and therefore two meters. The gas meters had digital counters, which were checked weekly. In addition, each meter had pulse output collected at 1 s intervals to the data acquisition system, where each pulse represented 0.028 m^3 (1 ft^3). The data, similar to current metering, were output as 30 s averages.

The on-site management program controlled heater operation. The management software (Command III, Poultry Management Systems, Inc., Saranec, Mich.) had an input for the setpoint of the house. If the temperature dropped below the setpoint by more than 1.1°C (2°F), every 2 min the controller would turn off another ventilation stage. Heaters were exclusively controlled by

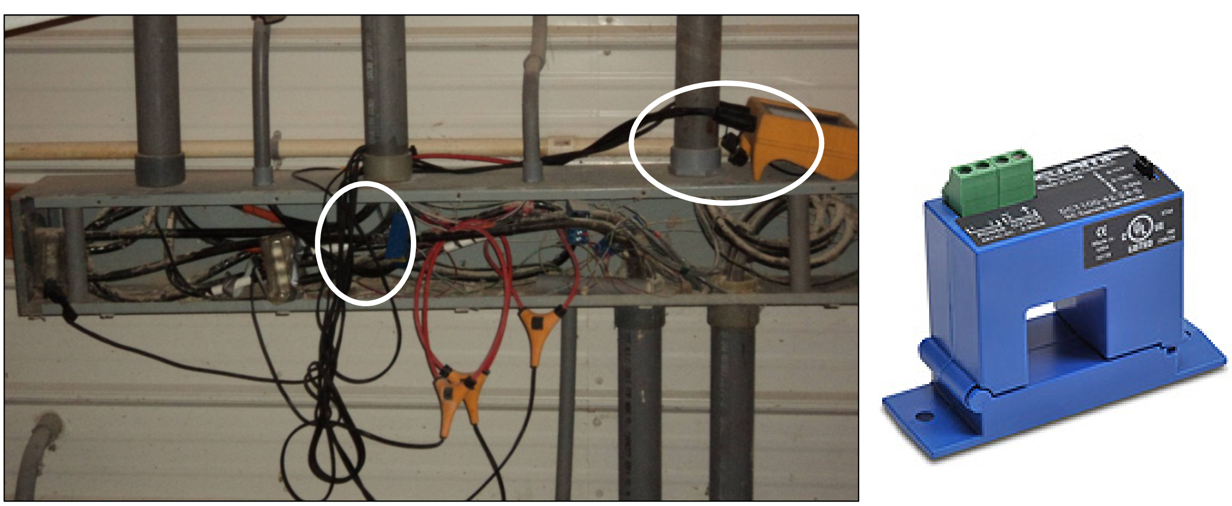

Figure 2. Left: the power logger (right oval) used to verify and develop power relationships for the inductive current sensors (left oval). The electric conduit cover was temporarily removed for making the measurement. Right: Close-up view of the current sensor.

the house temperature, if the house temperature dropped by 2.2°C (4°F) from the setpoint at minimum ventilation, the heaters were turned on. The fuel usage was compared to theoretical value based on supplemental heat demand. To compare measured and theoretical supplemental heat requirement of the houses, a balance temperature (T_{bal}) analysis was employed to predict the outside temperature below which supplemental heat was required (Chepete and Xin, 2004). The comparison was made based on average setpoint temperatures, while RH was set at 60% or 80% to yield two theoretical supplemental heating requirements. These RH levels were relevant only to the theoretical supplemental heat needs because the houses were managed primarily based on temperature with a varying RH. The T_{bal} equation and target indoor temperature used were as follows:

$$t_{bal} = t_i - \frac{3.6\times10^6 \cdot SHP \cdot BW \cdot n \cdot (W_i - W_o)}{MP \cdot BW \cdot n \cdot C_P + 3.6\times10^6 \cdot (W_i - W_o) \cdot (BHLF)} \quad (1)$$

where

t_{bal} = temperature below which supplemental heat is used to maintain house temperature and RH setpoints

t_i = average indoor setpoint temperature (21.7°C; 23.6°C for houses 2 and 3, respectively)

SHP = sensible heat production (4.1 W kg^{-1})

BW = average body weight (1.79; 1.78 kg)

N = house population (48,875; 47,125 hens)

W_i, W_o = humidity ratio inside and outside (ambient) (kg water kg dry air^{-1})

MP = moisture production [1.25 g $(kg\text{-}h)^{-1}$]

C_p = specific heat (1006 J $(kg\text{-}°C)^{-1}$)

BHLF = building heat loss factor (1140 W $°C^{-1}$)

The values for t_i, BW, and n were based on average production values for December 2010 to April 2011 (house 2; house 3). The BHLF was calculated based on information from the house design characteristics. SHP and MP values were adopted from Hayes et al. (2012). The humidity ratios varied based on the RH setpoint.

RESULTS AND DISCUSSION

CLIMACTIC CONDITIONS AND VENTILATION

Both houses 2 and 3 maintained temperatures within 0.8°C (1.4°F) of setpoints over the winter months. House 2 had a setpoint that was 1.6°C to 2.8°C (3°F to 5°F) lower than house 3. The setpoint of house 2 was increased by 1.6°C (3°F) in mid-February, while the setpoint of house 3 increased by 1.6°C (3°F) in December and again by 1.1°C (2°F) in mid-February. The average setpoints for the winter months were 21.7°C and 23.6°C (71°F to 74.5°F) for houses 2 and 3, respectively. The higher temperatures in house 3 corresponded to lower VR. The RH in both houses remained below 80% through most of the winter, but it was consistently above 70%. The VR was generally between 0.6 and 11 m^3 $(h\text{-}bird)^{-1}$ (0.35 and 6.5 CFM $bird^{-1}$). Figure 3 plots these trends.

ELECTRICITY USE

From the power logger, the amperage and power factor for some specific circuits were identified (table 2). These specified currents give some valuable insight in the power requirements of each system. In these houses, a portion of the ventilation fans and all the manure-drying blowers ran continuously. Lights were operated 16 h each day and mixing fans were operated intermittently. The egg belts ran for slightly under 2 h day^{-1} and the feed system ran for 15 to 20 min per feeding, 4 times a day. The manure-belt runtime depended on how often the belt was cleaned (every 3 days in winter and every 7 days in summer). The manure belts were on a separate power supply and therefore not included in the continuous current monitoring values calculated below. From the individual circuit demands and the whole house power logging, the continuous current monitoring was converted to power use. Figure 4 shows the breakdown of monthly electricity use for the monitoring period. The value is partitioned into major components.

Ventilation was the most variable component of electricity use, ranging from 18 kWh per day to 245 kWh per day. Electricity use for the manure-drying blowers was essentially constant at about 345±5 kWh per day. Electricity use for lighting and feeding systems was also quite constant at approximately 30±2 kWh and 20±1 kWh per day, respectively. The remaining component included mixing fans, electrical outlets, the egg belts, and the ventilation fan curtains used in place of shutters. Figure 5 displays the partitioning (%) of the total consumption into each component on a monthly basis.

Stout (1984) partitioned energy use for egg production as 64% in mechanical ventilation, 17% in lighting, 5% in operation of feeders, 5% in miscellaneous, and 9% in operation of egg coolers. These values were for housing without manure belts and with incandescent lighting. Although the two sets of data between the current study and the report by Stout (1984) are not directly comparable, the general relationship agreed. Both figures 4 and 5 show the average of both houses. For each month, the difference in total electricity

Table 2. Power logging outputs for some major circuits and systems in the aviary house (numbers on a per house basis).

Circuit	Description	Nominal Voltage (V)	Current (A)	Power Factor
Exhaust fans				
Variable Speed	Stage 1-4×0.5m[a]	240	2.7-6.3	0.53-0.69
Variable Speed	Stage 2-4×0.9m	240	3.3-9	0.68-0.72
Single Speed	Stage 3-2×1.2m	240	8	0.82
Single Speed	Stage 4-2×1.2m	240	8	0.82
Single Speed	Stage 5-2×1.2m	240	8	0.82
Single Speed	Stage 6-2×1.2m	240	8	0.82
Single Speed	Stage 7-2×1.2m	240	8	0.82
Single Speed	Stage 8-2×1.2m	240	8	0.82
Feeding system		240	102	0.43
Manure belt blowers	3 total	240	66.5	0.5
Egg belts		240	10	0.41
Egg rod conveyor		240	4.5	0.4
Lighting	~500 CFL	120	35	0.45
Mixing fans	10 center litter aisles	120	13.4	0.71
Manure belts	12 belts total	240	32	0.59

[a] Stage number - Number of fans in the stage × the diameter of the fan, 1 m = 39.4 in.

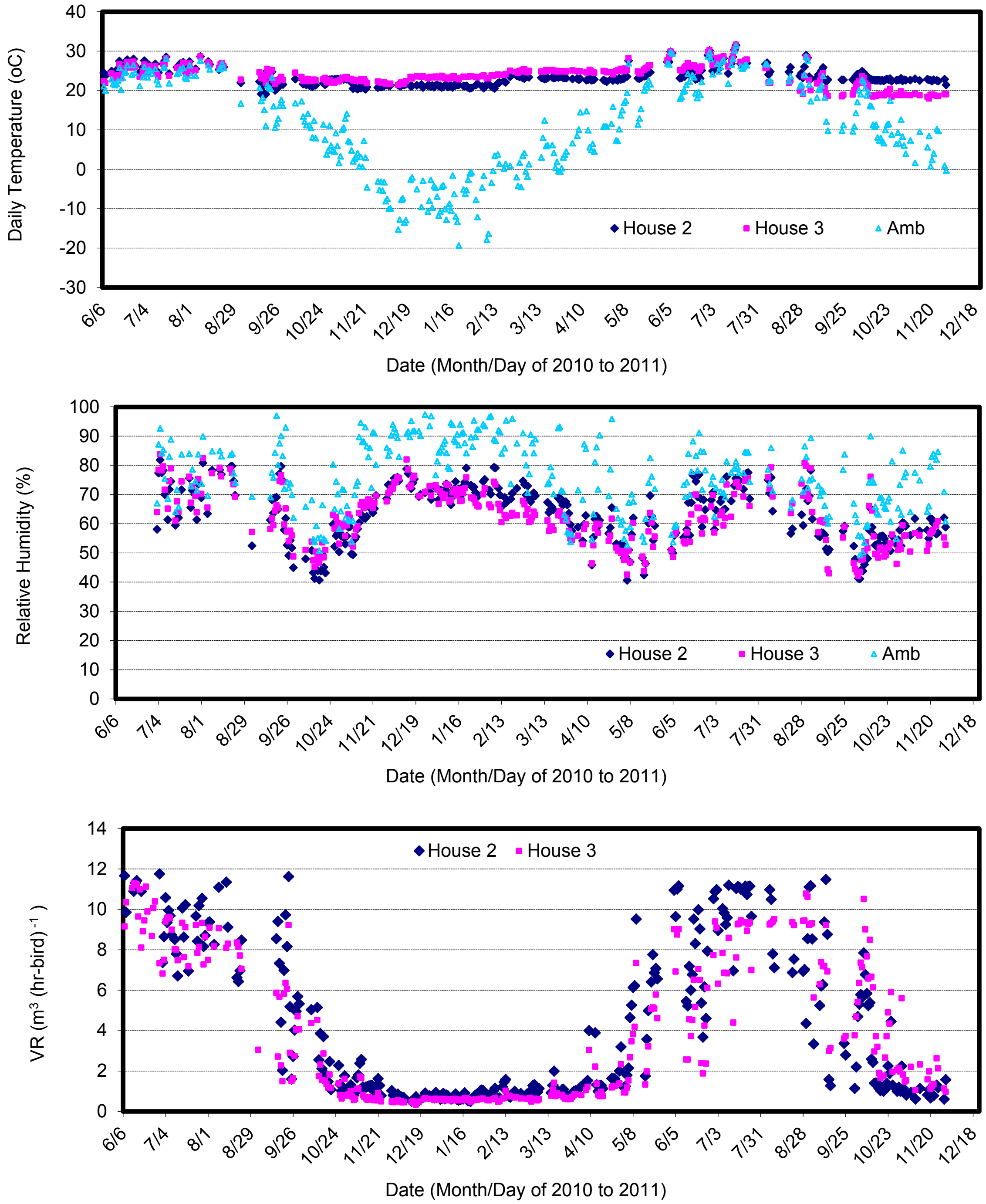

Figure 3. Daily temperature, relative humidity (RH), and ventilation rate (VR) of the two aviary houses monitored and the ambient (unit conversion: °F = 1.8×°C + 32; $m^3\ h^{-1}$ = 0.589 CFM).

consumption between the two houses was less than 10%. The exceptions are September and October 2011, where house 3 was repopulated with a new flock and had ventilation demands that nearly doubled those in house 2. When ventilation power consumption was removed, the houses' monthly total consumption difference was less than 3%.

From these monthly values, total electricity use from both houses for the 15 months can be calculated. This results in total power use of approximately 300 MWh house^{-1} over the 15 months. In order to calculate electric energy use on a per kg egg basis, farm production data were used to obtain the average monthly egg production of 60,575 kg egg house^{-1}. A summary of European studies by Sonesson et al. (2009) suggested electricity use between 175 and 450 kWh per metric ton of eggs. The current study showed 329 kWh per metric ton of eggs. Assuming an electricity rate of 9 cents per kWh, the electricity cost amounted to 3.0 cents per kg egg (64 g per brown egg).

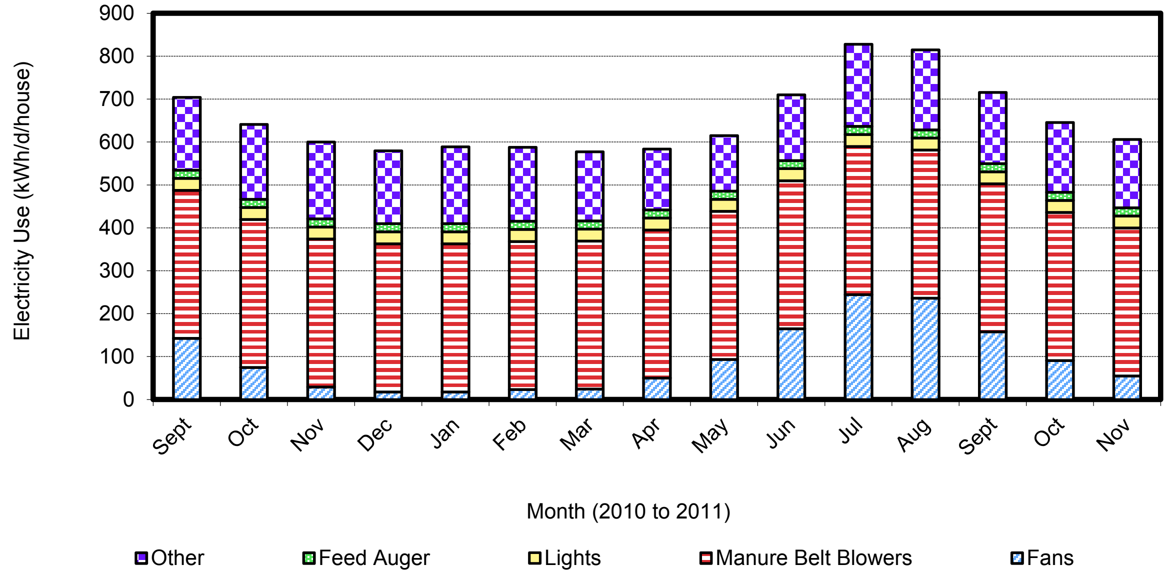

Figure 4. Monthly mean daily electricity use (kWh d^{-1}) partitioned into major components for the monitored aviary hen houses (~50,000 hens per house). Other components include egg belts, mixing fans, curtains on fans, and electrical outlets.

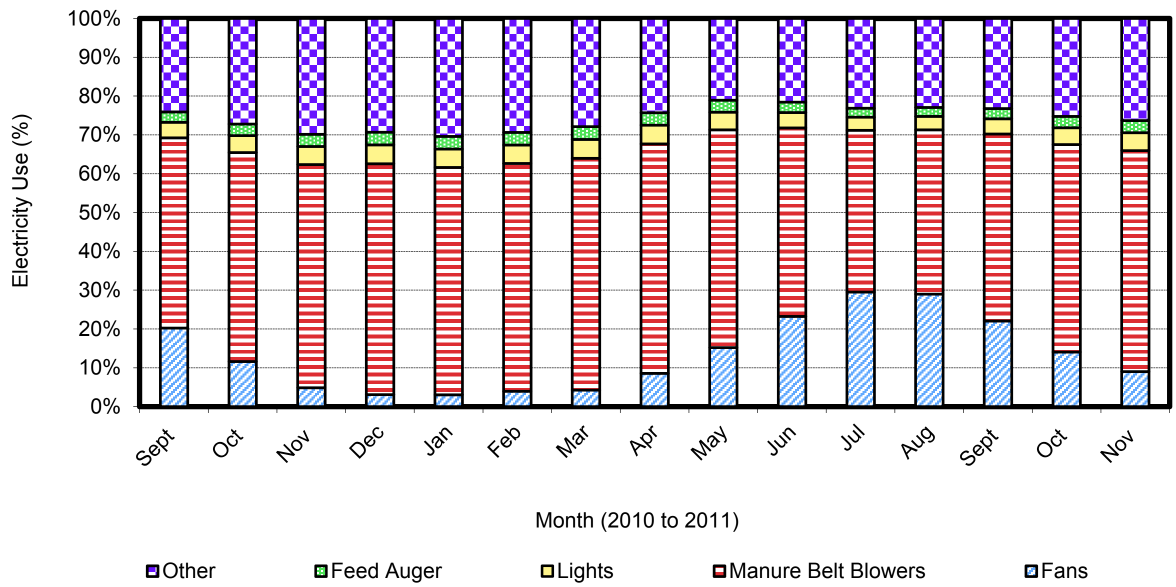

Figure 5. Electricity use distribution among major components (as % of monthly total) for the monitored aviary hen houses (~50,000 hens per house). Other components include egg belts, mixing fans, curtains on fans, and the electrical outlets.

With the Hy-Line Brown hens used in this current study, this equates to an electrical cost of 2.3 cents per dozen eggs. The European Union has been in transition towards alternative housing systems for a number of years. In one study of this transition, utility costs were summarized (table 3). The 10 European countries involved showed an average increase of 20% in utility cost when moving from conventional cage housing to cage-free barn housing. Although our value cannot be directly compared, a recent value for conventional cage barns in the Midwestern United States has been estimated to be 1.6 cent (kg egg)$^{-1}$ during a producer survey for life cycle analysis of egg production and processing (Ibarburu, 2012, Personal Communication, Egg Industry Center, Ames, Iowa).

Because the ventilation was monitored using current sensors, a relationship between building VR and power usage can be identified. The current and power factors were determined for the variable speed fans at various speeds and operating static pressures (table 4). For the larger fans the m^3 h^{-1} and $m^3(h\text{-}W)^{-1}$ (CFM per fan and CFM W^{-1}) were determined at the static pressures of 12.5 and 25 Pa (0.05 and 0.1 in. W.C.). These values were compared to the

Table 3. Typical utility costs for 10 EU countries during the transition from cage housing to alternative housing.

Country	Unit	Conventional Cage	Barn-Cage Free
Belgium[a]	€ cent/ kg egg	2.15	2.47
Denmark[a]	€ cent/ kg egg	0.96	2.00
Finland[a]	€ cent/ kg egg	3.37	5.20
France[a]	€ cent/ kg egg	1.14	1.11
Germany[a]	€ cent/ kg egg	1.80	2.84
Greece[a]	€ cent/ kg egg	0.80	0.80
Ireland[a]	€ cent/ kg egg	2.55	2.67
Italy[a]	€ cent/ kg egg	8.66	9.30
Netherlands[a]	€ cent/ kg egg	0.96	2.00
United Kingdom[a]	€ cent/ kg egg	2.54	1.74
United States[b],[c]	$ cent/ kg egg	1.60	2.96

Data from:
[a] Agra CEAS Consulting (2004);
[b] Ibarburu (2012) for conventional cage housing;
[c] This study for aviary housing.

performance data from the Bioenvironmental and Structural Systems Laboratory (BESS Lab, University of Illinois, Urbana-Champaign, Ill.). For the stage 2 fans the on-farm VR was calculated to be 18,250 m^3 h^{-1} at 12.5 Pa (10,740 CFM at 0.05 in. W.C.) *vs.* the BESS Lab reported value of 18,700 m^3 h^{-1} (11,000 CFM). For stages 3-8, the on-farm VR was 38,105 m^3 h^{-1} (22,428 CFM) *vs.* the BESS Lab reported value of 39,900 m^3 h^{-1} (23,500 CFM). Both sets of fans performed at greater than 92% of their reported performance level at both tested static pressures in the field.

The CFM W^{-1} relationship, namely, fan efficiency, was not as strong compared to BESS Lab reported values. Stage 2 had an efficiency of 15.3 and 13.9 CFM W^{-1} whereas BESS Lab reports 20 and 17.5 CFM W^{-1} for 0.05 and 0.1 in. W.C. static pressure, respectively. For stages 3-8 the 15.7 and 14.5 CFM W^{-1} were also less than the BESS Lab reporting values of 20 and 18 CFM W^{-1} for 0.05 and 0.1 in. w.c. static pressure. For all stages and static pressures, the CFM W^{-1} was 75% to 80% of the reported value. This lower efficiency is likely due to resistance-based power loss in the wiring along the sidewall (168 m or 550 ft maximum sidewall length).

Propane Use

Both barns used heaters throughout the winter 2010-2011 and spring 2011. There was no heater use in fall 2011 because the heaters were intentionally turned off. Over the entire monitoring period house 2 had lower fuel use than house 3. The set-point temperature for house 2 averaged 1.7°C lower than house 3 over the 6 months reported below (fig. 6). It is important to note the propane use was not greatest during the coldest periods, but instead in the later spring when there were major fluctuations in daily ambient temperature. Overall house 2 used less than 75 L (20 gal) of propane while house 3 used approximately 425 L (112 gal). Based on egg production described in the electricity use, the 425 L of propane distributed on an annual basis account for 0.6 mL (kg egg) $^{-1}$ [0.4 mL (dozen eggs) $^{-1}$]. During these spring months, both houses had higher set-point temperature compared to the winter setpoints (fig. 3). Another factor which may have influenced spring fuel use is that manure-drying blowers used outside air primarily during spring whereas they only used recirculated indoor air in winter months. With the higher setpoints, as well as greater amount of outdoor supply air (through manure-drying blowers and higher VR during daytime hours), the barns may have been temporarily over-ventilated when ambient temperatures dropped quickly.

Based on the T_{bal} equation 1 described above, the daily T_{bal} averaged -2.4°C (27.7°F). The average daily ambient temperature generally fell below T_{bal} (64 out of 96 monitored days $T_{amb} < T_{bal}$) for the period of 1 December 2010 through 31 March 2011. However, the heaters only ran 8 days over this period. As stated above, the ventilation control in this house was managed to maintain indoor temperature, not RH, while the T_{bal} prediction controls for

Table 4. The relationship of fan ventilation rate (m^3 h^{-1} and CFM) to power input (W).

Stage	Hz	SP (Pa)	m^3 (h-stage) $^{-1}$ [a]	CFM $Stage^{-1}$	Amp $Stage^{-1}$	PF	kW $Stage^{-1}$	m^3 (h-W) $^{-1}$	CFM W^{-1}
1	30	7.5	13551	7976	2.7	0.53	0.6	22.9	13.5
1	30	15	11676	6872	2.7	0.53	0.6	19.7	11.6
1	30	30	7924	4664	2.7	0.53	0.6	13.4	7.9
1	45	7.5	29658	17456	4.3	0.61	1.1	27.0	15.9
1	45	15	27782	16352	4.3	0.61	1.1	25.3	14.9
1	45	30	24031	14144	4.3	0.61	1.1	21.9	12.9
1	60	7.5	45764	26936	6.3	0.69	1.9	24.8	14.6
1	60	15	43889	25832	6.3	0.69	1.9	23.8	14
1	60	30	40137	23624	6.3	0.69	1.9	21.7	12.8
2	30	7.5	32087	18886	3.3	0.68	0.7	45.9	27
2	30	15	28071	16522	3.3	0.68	0.7	40.1	23.6
2	30	30	20038	11794	3.3	0.68	0.7	28.5	16.8
2	45	7.5	53877	31711	6.3	0.695	1.5	37.2	21.9
2	45	15	49861	29347	6.3	0.695	1.5	34.3	20.2
2	45	30	41828	24619	6.3	0.695	1.5	28.9	17
2	60	7.5	75667	44536	9.0	0.72	2.8	27.0	15.9
2	60	15	71650	42172	9.0	0.72	2.8	25.7	15.1
2	60	30	63617	37444	9.0	0.72	2.8	22.8	13.4
2	60	12.5	72989	42960	9.0	0.72	2.8	26.0	15.3
2	60	25	66295	39020	9.0	0.72	2.8	23.6	13.9
3-8	60	12.5	76209	44855	8.1	0.82	2.9	26.7	15.7
3-8	60	25	70186	41310	8.1	0.82	2.9	24.6	14.5

[a] Air flow rate per fan calculated using *in-situ* performance curves. Highlighted values were compared to the BESS Lab performance data. See table 4.2 for fan stage numbers.

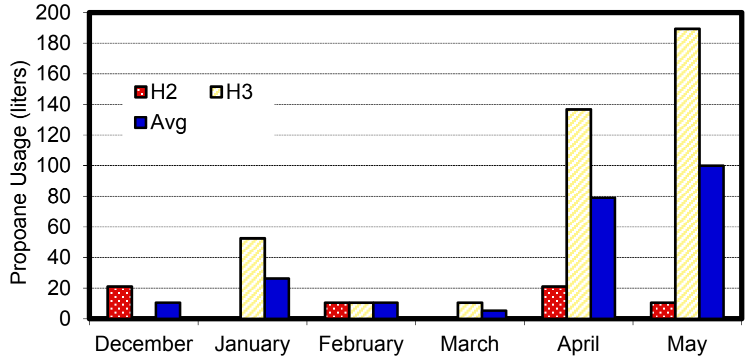

Figure 6. Monthly propane usage per barn of winter and spring 2010-2011.

both T and RH. Because the heaters did not regularly run over the winter months, the minimum ventilation designed was lower than the ventilation needed for RH management. When the humidity ratios were adjusted from maintaining 60% to 80% RH, the T_{bal} dropped by 5.4 °C to -7.8°C. With this drop, the number of days when supplemental heat was needed was reduced to 13 days. The 8 days when heaters did run corresponded to these 13 days. Based on an energy content of 7.1 kWh L^{-1} of propane (DOE, 2013), the propane need in each house to maintain T_{bal} was 1003 L at 80% RH. Again this number is much higher than the monitored fuel use. Because the heater runtime was not actually determined by set-point temperature, but instead it was run 2.2°C lower, this difference was not unexpected. Overall, the VR in this house was managed for indoor temperature. The minimum VR was lower than that needed to maintain RH, as evidenced by the lower propane usage.

SUMMARY

During this study, electric current was continuously monitored for ventilation fans, manure drying blowers, lighting, and the whole house. This information combined with short-term power logging provided measurement of the whole house and component electrical energy use. The ventilation system is the most variable component in that it accounted for 30% of the total electric energy in summer, but approximately 5% in winter. The efficiency of the ventilation system [26 m^3 $(h\ W)^{-1}$] was less than 80% of the BESS Lab-reported fan performance efficiency. The manure-belt blowers were the largest user of electricity, accounting for 42% to 59% of the monthly electricity consumption. Electricity cost over the 15-month production period averaged 3.0 cents per kg of egg produced [i.e., 0.33 kWh $(kg\ egg)^{-1}$ at a cost of \$0.09 kWh^{-1}]. Overall the propane fuel use was minimal [0.26 mL $(kg\ egg)^{-1}$]; demonstrating that the ventilation scheme in this housing system was successful at maintaining set-point temperature using the birds' sensible heat. However, because the ambient temperatures were below the balance temperature (T_{bal}) and the heaters were not running regularly, the ventilation scheme was not necessarily achieving the ideal RH control. RH in the barns was consistently between 70% and 80%, with 23 days having a portion of the day above 80%. The higher propane use in the spring implies possibility of over-ventilation on days with wide ambient temperature swings.

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REFERENCES

Agra CEAS Consulting. (2004). Study on the Socio-economic implications of the various systems to keep laying hens. The European Commission.

BESS Labs, Performance Tests. (2006) Urbana, Ill.: Univ. of Illinois. Retrieved from http://bess.illinois.edu/type.asp

Chepete, H. J., & Xin., H. (2004). Ventilation rates of a laying hen house based on new vs. old heat and moisture production data. *Applied Eng. in Agric., 20*(6), 835-842. doi:http://dx.doi.org/10.13031/2013.17722

Department of Energy. (2013) Alternative Fuel Data Center: Fuel Properties Comparison. Retrieved from http://www.afdc.energy.gov/fuels/fuel_properties.php

Fluck, R. C., & Baird, C. D. (1980). *Agricultural Energetics.* Westport, Conn.: Avi Publishing Co.

Hayes, M. D., Xin, H., Li, H., Shepherd, T. A., Zhao, Y., & Stinn, J. (2012). Heat and moisture production of Hy-line brown hens in the midwestern United States. *Trans. ASABE, 56*(2), 753-761. doi:http://dx.doi.org/10.13031/2013.42663

Ibarburu, M. 2012. Personal Communication. Ames, Iowa: Egg Industry Center.

Sonesson, U., Cederberg, C., & Bergland, M. (2009). Greenhouse gas emissions in egg production. Report 2009:7 Klimatmärkning För Mat.

Stout, B. A. (1984). *Energy Use and Management in Agriculture.* North Scituate, Mass.: Breton Publishers.