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Yang Zhao
Iowa State University

Hongwei Xin
Iowa State University, hxin@iastate.edu

Timothy A. Shepherd
Iowa State University

Morgan D. Hayes
Iowa State University

John P. Stinn
Iowa State University

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Ventilation Rate, Balance Temperature and Supplemental Heat Need in Alternative vs. Conventional Laying-Hen Housing Systems

Abstract

An Excel-based spreadsheet model was developed to delineate ventilation rate (VR), supplemental heat requirement (Hs), balance temperature (tbal, outdoor temperature below which Hs is required), energy consumption and cost for Hs in alternative (aviary and enriched colony) versus conventional cage laying-hen housing systems. The model was then applied to the Midwestern U.S. housing characteristics at winter weather conditions (-30°C to 5°C temperature, 70% RH). Effects of stocking density, target house temperature and RH (ti, RHi), building insulation level, and light vs. dark period on VR, tbal and Hs were examined. For the housing characteristics considered, tbal for the alternative housing systems was found to be 2.5°C to 3.7°C higher than that for the conventional cage counterpart to maintain the houses at 25°C ti and 60% RHi. The heater capability needs to be at least 26.6 to 28.4 kW per 10,000 birds for the aviary houses (107,000-bird capacity), and 22.7 kW per 10,000 birds for the enriched colony house (124,000-bird capacity). Annual Hs use was estimated to be 0.17 to 0.25 MJ [kg egg]-1 in the alternative houses. Among the influencing factors considered, ti and RHi setpoints have more pronounced impact on tbal and Hs than other factors. The Hs energy cost for the alternative housing systems in the Midwestern US was shown to account for less than 0.5% of the total production cost. The interactive model can be readily used for analysis of other production and climatic conditions.

Keywords

Laying-hen housing, thermal environment control, egg production sustainability

Disciplines

Bioresource and Agricultural Engineering

Comments

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2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Ventilation rate, Balance Temperature and Supplemental Heat Need in Alternative vs. Conventional Laying-Hen Housing Systems

Yang Zhao, PhD, Post-doctoral Research Associate, yangzhao@iastate.edu

Hongwei Xin, PhD, Professor, hxin@iastate.edu

Tim Shepherd, Assistant Scientist, tshep@iastate.edu

Morgan Hayes, Graduate Research Assistant, hayesmd@iastate.edu

John Stinn, Graduate Research Assistant, elwayjr1@iastate.edu

Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA

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Abstract. *An Excel-based spreadsheet model was developed to delineate ventilation rate (VR), supplemental heat requirement (H_s), balance temperature (t_{bal}, outdoor temperature below which H_s is required), energy consumption and cost for H_s in alternative (aviary and enriched colony) versus conventional cage laying-hen housing systems. The model was then applied to the Midwestern U.S. housing characteristics at winter weather conditions (-30°C to 5°C temperature, 70% RH). Effects of stocking density, target house temperature and RH (t_i, RH_i), building insulation level, and light vs. dark period on VR, t_{bal} and H_s were examined. For the housing characteristics considered, t_{bal} for the alternative housing systems was found to be 2.5°C to 3.7°C higher than that for the conventional cage counterpart to maintain the houses at 25°C t_i and 60% RH_i. The heater capability needs to be at least 26.6 to 28.4 kW per 10,000 birds for the aviary houses (107,000-bird capacity), and 22.7 kW per 10,000 birds for the enriched colony house (124,000-bird capacity). Annual H_s use was estimated to be 0.17 to 0.25 MJ [kg egg]$^{-1}$ in the alternative houses. Among the influencing factors considered, t_i and RH_i setpoints have more pronounced impact on t_{bal} and H_s than other factors. The H_s energy cost for the alternative housing systems in the Midwestern US was shown to account for less than 0.5% of the total production cost. The interactive model can be readily used for analysis of other production and climatic conditions.*

Keywords. Laying-hen housing, thermal environment control, egg production sustainability

Introduction

As a result of animal welfare concerns, the European Union (EU) committee enacted its Council Directive 1999/74/EC to ban conventional cage housing systems by January 1, 2012 (CEC, 1999). In the US, a similar agreement to phase out the conventional cage housing system was recently reached between the Human Society of the United States (HSUS) and the United Egg Producers (UEP). If the proposed national legislation is passed by the U.S. Congress, by 2029 enriched colony/cage housing system will be the norm for egg production in the United States.

Maintaining comfortable thermal environment (temperature and RH) and air quality (ammonia level) for the laying hens is essential to ensuring the bird's well-being, maximum productivity, and efficient feed utilization. In wintertime, with a well-insulated building, thermoneutral temperature can generally be maintained by the sensible heat from the birds in conventional cage houses in the Midwest US, hence no need for supplemental heat (H_s). However, H_s may be necessary in alternative housing systems due to the lower stocking density (SD) and thus lower sensible heat production (SHP). Also, the proportion of sensible and latent heat may differ between conventional cage and alternative housing systems in that additional sensible heat may be used to evaporate water from litter/feces on the floor in the alternative systems (Pedersen and Sallvik, 2002). The extra moisture from the litter could call for higher ventilation rate (VR) to maintain the desired inside RH, which in turn may increase H_s. Furthermore, hen's activity and thus heat and moisture production vary from light to dark, being 25-30% higher during light hours of the day (Chepete et al., 2011; Green and Xin, 2009). This diurnal variation in bird SHP has an impact on the design of heater capacity.

Indoor temperature (t_i) and relative humidity (RH_i) are controlled by providing adequate VR to remove excess SHP and moisture production (MP) from the animals and their surroundings. VR for temperature control (VR_t) and humidity control (VR_h) can be plotted in a ventilation graph as a function of outdoor temperature (t_o) for maintaining a desired indoor thermal environment. When VR_h overrides VR_t, H_s is needed to compensate the heat deficiency; otherwise, no H_s is necessary. The t_o at which VR_t and VR_h curves intersect is referred to as the balance temperature (t_{bal}) below which H_s is needed to maintain the desired t_i.

The objective of this study was to develop an Excel-based spreadsheet model to delineate VR, t_{bal}, and H_s in the alternative hen housing systems – aviary and enriched colony housing as compared to the conventional cage system to maintain desired t_i and RH_i over a range of t_o (-30 to 5ºC) in winter season. The effects of house capacity, SD, t_i setpoint, RH_i setpoint, house insulation level, and light vs. dark hours of the day on VR, t_{bal} and H_s were examined. Annual H_s energy use (E_{tot}) and cost were also estimated using the hourly historical weather data for Des Moines, Iowa, USA (Midwest Plan Service, 1983).

Materials and method

Model description

The model was developed on Excel 2010. The input variables of the model were categorized into five categories (Table 1).

Category 1: Weather data, including t_o and RH_o. In this analysis, the range of t_o under consideration was -30°C to 5°C. RH_o at the cold weather condition was set at 70%. This value was chosen based on the monthly average RH_o in winter (December –February) in the last 30 years (1981 – 2010) in Des Moines, Iowa (National Climate Data Center, NCDC).

Category 2: Building factor, encompassing the dimensions of all the building components (wall, celling, door and fan) and their insulation (R-values or heat loss factor). It allows the model to calculate the building heat loss factor (BHLF) that is used to determine the heat transfer through the building envelope at a given difference between t_i and t_o. Dimensions of the conventional and alternative houses were chosen based on those of commercial farms in Iowa and other parts of the United States. The conventional cage house measures 141 × 26 × 6 m (L × W × H) with a catwalk deck at 2.5 m height (i.e., two stories), housing 233,000 white-egg hens at a SD of 443 cm^2/hen (68.6 in^2/hen). The double-wide aviary housing system was 141 × 52 × 3 m (one story), housing 107,000 hens (in 14 cage rows with eight serving aisles). The enriched colony house was set to have the same dimensions as the conventional cage system, housing 124,000 hens at a SD of 774 cm^2 hen^{-1} (120 in^2 hen^{-1}).

Table 1. Input variables of the model for calculating ventilation rate (VR), balance temperature (t_{bal}) and supplemental heat need (H_s).

Model variable	Conventional	Aviary	Aviary	Enriched
Weather data				
t_o	-30°C to 5°C			
RH_o	70%			
Building factor				
Dimension (L × W × H)	141 × 26 × 6 m	141 × 52 × 3 m	141 × 52 × 3 m	141 × 26 × 6 m
Door area	16.0 m^2	20.0 m^2	20.0 m^2	16.0 m^2
Fan area	81.0 m^2	59 m^2	59 m^2	59 m^2
Insulation				
walls R-value	2.65 m^2 °C W^{-1}			
roof-ceiling R-value	5.30 m^2 °C W^{-1} (20 cm blown-in cellulose)			
doors R-value	0.29 m^2 °C W^{-1}			
fan R-value	0.15 m^2 °C W^{-1}			
perimeter heat loss factor	1.60 W m^{-1} °C^{-1} (uninsulated perimeter)			
BHLF	2529 W °C^{-1}	2840 W °C^{-1}	2840 W °C^{-1}	2381 W °C^{-1}
Hen				
Number of birds	233K	107K	107K	124K
Body weight	1.5 kg	1.5 kg	1.8 kg	1.5 kg
Density	443 cm^2 $bird^{-1}$	1217 cm^2 $bird^{-1}$	1217 cm^2 $bird^{-1}$	774 cm^2 $bird^{-1}$
Time-weighted average THP (24°C)	6.5 W kg^{-1}	6.5 W kg^{-1}	6.2 W kg^{-1}	6.5 W kg^{-1}
THP during light period (24°C)	7.2 W kg^{-1}	7.2 W kg^{-1}	6.9 W kg^{-1}	7.2 W kg^{-1}
THP during dark period at (24°C)	5.4 W kg^{-1}	5.4 W kg^{-1}	5.2 W kg^{-1}	5.4 W kg^{-1}
Indoor environment set-points				
Temperature	15°C to 25°C			
RH	60% to 80%			
Other heat and moisture sources				
Light power	2.2 W m^{-2}			
Heating system	Indoor unvented LPG heating			
E_c	100%			
Combustion moisture	33.65 g MJ^{-1}			

Category 3: The animal data, including the number of birds, body weight, and HP and MP data for the housing system. In this study, the size of single cage is 61 × 51 cm with 7 birds in conventional system (443 cm^2 cage area $bird^{-1}$), and 366 × 128 cm with 60 birds in enriched colony system (774 cm^2 cage area $bird^{-1}$). To examine the effect of hen SD on VR, t_{bal} and H_s, different density levels were created as follows: change the number of birds in a conventional cage to 5 or 6, thus cage area per bird is increased to 620 and 516 cm^2 $bird^{-1}$ which corresponded to a decrease of 71% and 86%, respectively, in SD; adjust the number of bird per enriched colony between 50 and 75 (i.e., space allocation of 937 – 625 cm^2 $bird^{-1}$), or 83% – 125% of the original SD. The SD of aviary system was altered from 80% to 120% of the default or original value (1217 cm^2 hen^{-1}). The most recent data on total heat production (THP) for Hy-Line W36 white birds from (Green and Xin, 2009); and for Hy-Line brown birds from Hayes et al. (2012) were used. SHP was calculated according to Pedersen and Sallvik (2002), and it averaged about 60% of THP at interested t_i levels (15°C to 25°C). MP was calculated from latent HP (LHP), which was obtained by subtracting SHP from THP. Bird's HP and MP follow a clear circadian pattern that is affected by lighting condition, which means VR, t_{bal} and H_s during light and dark periods should be separately calculated. In this study, 7.1 W kg^{-1} and 5.2 W kg^{-1}

were assigned as THP for white birds during light and dark period, respectively; and 6.7 W kg^{-1} and 5.0 W kg^{-1} as the light and dark THP for brown birds. This assignment was based on the fact that reduction of THP in dark is about 25% compared to THP in light (Green and Xin, 2009; Xin et al., 1996).

Category 4: Indoor thermal condition (t_i and RH_i) setpoints, including t_i in the range of 15°C to 25°C, and RH_i in range of 60% to 80%.

Category 5: Sensible heat and moisture contribution by housing components, including sensible heat from lights and moisture from combustion of liquid propane gas (LPG). HP input from the motors of feeders and exhaust fans were not considered because it was either negligible in magnitude relative to the total HP or was immediately exhausted to outside. Solar radiation was negligible because the layer houses were well insulated.

Calculations of VR, t_{bal}, H_s, E_{tot} and cost

Calculations of VR, t_{bal} and H_s were based on heat and moisture energy/mass balance by inputting variables listed in Table 1. The equations for VR and t_{bal} calculations have been documented by Chepete and Xin (2004). H_s was calculated with equation 1. Where SHP is hen sensible heat production (W kg^{-1}), ,MP is hen moisture production (g kg^{-1} h^{-1}), M is hen body weight (kg), N is housing capacity (hen $house^{-1}$), M_c is total combustion moisture (g h^{-1}), C_p is specific heat of air (1006 J kg^{-1} K^{-1}), t_i and t_o are indoor and outdoor temperature (°C), W_i and W_o are humidity ratio of indoor and outdoor air (kg water per kg dry air), A is surface area of building component (m^2), R is thermal resistance of building component (m^2 °C W^{-1}), F is perimeter heat loss factor (W m^{-1} °C^{-1}), L_p is perimeter (m), P_l is light power (W m^{-2}), A_h is area of hen house (m^2).

$$H_s = \frac{(MP \cdot M \cdot N + M_c) \cdot C_P \cdot (t_i - t_o)}{3.6 \times 10^6 \cdot (W_i - W_o) \cdot N} + \frac{(\sum \frac{A}{R} + F \cdot L_p)(t_i - t_o)}{N} - SHP \cdot M - \frac{P_l \cdot A_h}{N}$$

The annual E_{tot} in Iowa area was estimated by summing up the energy use (MJ) at t_o from -30°C to 5°C with an increment of 1°C (Equation 2). The hourly t_o occurrence [hr(t_o), total number of hours of an integer t_o occurrence in a year] was regressed from the data provided in Structures and Environment Handbook (Midwest Plan Service, 1983), and was expressed by Equation 3.

$$E_{tot} = \sum_{t_o=-30°C}^{5°C} (H_s(t_o)/1000 \cdot hr(t_o))$$

$$hr(t_o) = \begin{cases} 0.36 & (-30°C \le t_o \le -27°C) \\ 0.013t_o^3 + 0.978t_o^2 + 26.616t_o + 267 & (-27°C < t_o < 0°C, R^2 = 0.99) \\ 0.325t_o^3 - 2.636t_o^2 - 10.735t_o + 269 & (0°C \le t_o \le 5°C, R^2 = 0.99) \end{cases}$$

The annual energy cost of H_s was calculated on "per bird" basis. The energy cost per kilogram egg was estimated by assuming annual egg production of 280 eggs $bird^{-1}$ yr^{-1} and 0.06 kg egg^{-1}.

Results and discussion

VR, t_{bal} and H_s in different housing systems

Figure 1 shows that VR_h in the conventional cage system with white birds ranges from 0.3 to 0.6 m^3 h^{-1} $bird^{-1}$ for t_o of -30°C to 5°C. This range is comparable with that reported by Chepete and Xin (2004) in a high-rise layer house. The VR_h curves in all the housing systems are influenced by the MP of the birds, not the housing system or SD. Brown birds were assumed to have a MP of 11.2 W $bird^{-1}$ and white birds had a MP of 9.8 W $bird^{-1}$ (Table 1). Therefore all the systems with white birds have identical VR_h curves that are 13% lower than the brown bird VR_h curve.

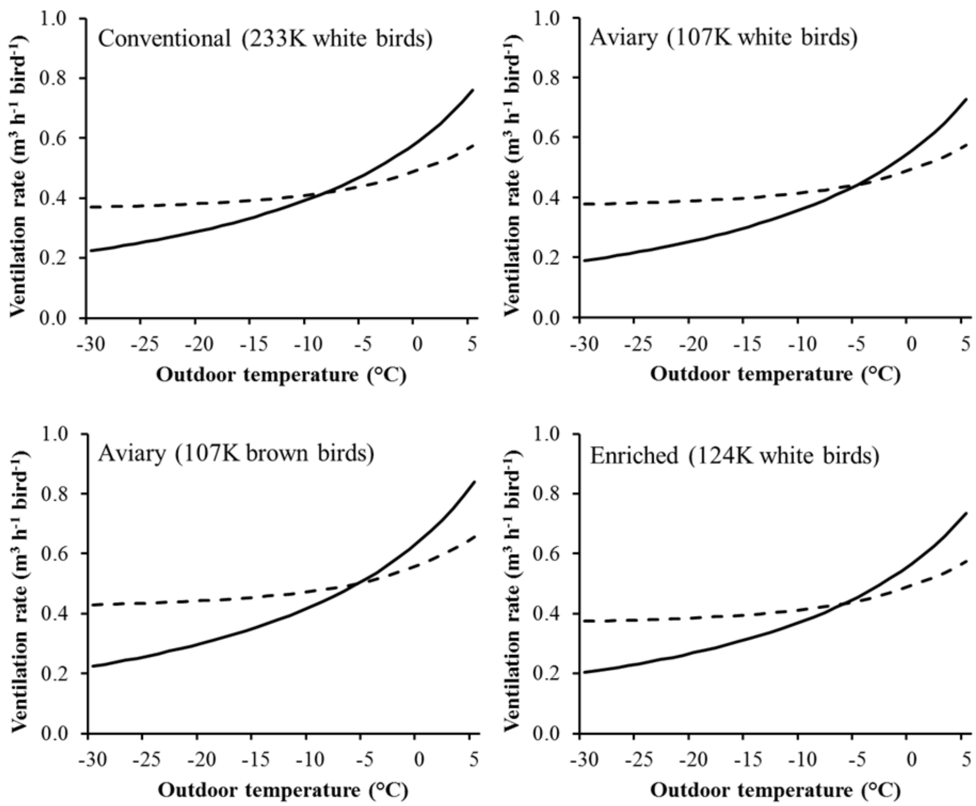

Figure 1. Ventilation rate for humidity control (VR_h, broken line) and for temperature control (VR_t, solid line) in laying-hen houses at different outdoor temperature (t_o). T_i = 25°C, RH_i = 60%, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

VR_t values for aviary system with white birds and enriched colony system are similar, but are about 13% and 7% lower than aviary system with brown birds and conventional cage system, respectively. Unlike moisture, sensible heat is transferred through two pathways, i.e. the building envelope and ventilation. With the same building insulation, more SHP requires higher VR_t, which is the case in aviary system with brown birds. Compared to other systems, the higher VR_t in conventional cage system is because a larger portion of heat (on per bird basis) has to be removed through ventilation versus through building envelope due to the high SD in this system.

Table 2. Balance temperature (t_{bal}), supplemental heat requirement (H_s), energy consumption (E_{tot}) and energy cost of H_s in laying-hen houses. T_i = 25°C, RH_i = 60%, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

	t_o (°C)	Conventional (233K white birds)	Aviary (107K white birds)	Aviary (107K brown birds)	Enriched (124K white birds)
t_{bal} (°C)		-8.8	-5.1	-5.8	-6.3
H_s (W bird^{-1})	-30	3.33	4.36	4.74	3.88
	-25	2.47	3.39	3.65	2.96
	-20	1.67	2.48	2.64	2.10
	-15	0.92	1.63	1.69	1.30
	-10	0.24	0.85	0.83	0.56
	-5	0.00	0.00	0.00	0.00
E_{tot}[a] (MJ bird^{-1} yr^{-1})		1.85	4.17	4.08	2.93
E_{tot}[a] (MJ [kg egg]$^{-1}$)		0.11	0.25	0.24	0.17
Cost[b] (cent bird^{-1} yr^{-1})		2.25	5.08	4.97	3.57
Cost[c] (cent [kg egg]$^{-1}$)		0.13	0.30	0.30	0.21

The t_{bal} of -8.8°C in the conventional cage system (Table 2) is consistent with the previous study by Chepete and Xin (2004) who reported a t_{bal} of -9.0°C in a commercial high-rise layer house. The t_{bal} for the alternative housing systems is 2.5°C to 3.7°C higher than the t_{bal} in conventional cage system. The difference in t_{bal} between the alternative and conventional cage systems is due to the reduced SD in the alternative systems. Therefore, less proportion of sensible heat in the alternative systems is exchange between the building and outside through the ventilation pathway, which leads to lower VR_t and higher t_{bal}.

A look-up table of H_s under different t_o is provided in Table 2. Assuming 97.5% winter design t_o of -21°C for central Iowa (Midwest Plan Service, 1983) and a 100% heating efficiency, the required heater capacity would be 284 kW for an aviary house with 107,000 white birds (26.6 kW per 10,000 birds), 303 kW for an aviary house with 107,000 brown birds (28.4 kW per 10,000 birds), and 281 kW for an enriched system with 124,000 white birds (22.7 kW per 10,000 birds). In the US, 73.3 kW (250,000 BTU h^{-1}) heaters are typically used to provide supplemental space heating in animal houses, therefore, the alternative houses would be equivalent to 4 to 5 such heaters per house.

As estimated in this study, 0.17 to 0.25 MJ energy is required per kg egg produced in the alternative housing systems in Iowa area, or 0.21 to 0.30 cent [kg egg]$^{-1}$ based on the current whole LPG price of \$0.012 MJ^{-1} (\$0.32 L^{-1}). If a retail LPG price of \$0.029 MJ^{-1} (\$0.75 L^{-1}) is assumed, the cost becomes 0.51 to 0.72 cents per kg egg. Considering the production cost of \$1.45 per kg egg for non-cage production systems (Sumner et al., 2011), the H_s cost for the climatic conditions considered would account for less than 0.5% of the total production cost.

Effect of stocking density (SD)

VR_h remains unchanged when SD varies. This is because decrease or increase in SD results in a proportional change in VR for moisture removal. VR_t is affected by SD, but the effect is slight within the investigated SD range (<0.02 m^3 h^{-1} $bird^{-1}$, or 10%).

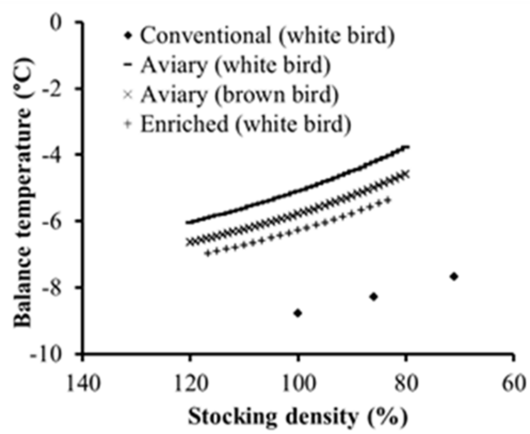

Figure 2. Balance temperature (t_{bal}) as affected by stocking density in laying-hen houses. T_i = 25°C, RH_i = 60%, RH_o = 70%. One hundred percent SD indicates a capacity of 233K, 107K and 124K birds in conventional, aviary and enriched colony systems, respectively. See Table 1 for building characteristics of each housing system.

Figure 2 shows that SD has some but not substantial impact on t_{bal}. t_{bal} increases by 1.1°C (from -8.8°C to -7.7°C) if each conventional cage houses 5 birds (71% original SD) instead of 7 birds. In alternative housing system, changing SD between 80% and 125% yields about 2°C difference in t_{bal}.

H_s is negatively affected by SD at a given t_o (Table 3). In alternative systems, E_{tot} increases by 24% – 33% and decreases by 17% – 20% when SD was reduced to 80% – 83% and increased to 120% – 125%, respectively. The energy cost changes accordingly with E_{tot}. The cost of H_s is quite small (< 0.7%), even with the sizable reduction in density, relative to the total production cost per kg egg.

Table 3. Supplemental heat requirement (H_s), energy consumption (E_{tot}) and energy cost of H_s at different stocking density levels in laying-hen houses. T_i = 25°C, RH_i = 60%, RH_o = 70%. One hundred percent stocking density indicates a capacity of 233K, 107K and 124K birds in conventional, aviary and enriched colony systems, respectively. See building characteristics of each housing system in Table 1.

	t_o (°C)	Conventional (white bird)			Aviary (white bird)			Aviary (brown bird)			Enriched (white bird)		
		71%	86%	100%	80%	100%	120%	80%	100%	120%	83%	100%	125%
H_s (W bird^{-1})	-30	3.61	3.45	3.33	4.79	4.36	4.07	5.17	4.74	4.45	4.13	3.88	3.63
	-25	2.72	2.58	2.47	3.78	3.39	3.13	4.04	3.65	3.40	3.19	2.96	2.74
	-20	1.89	1.76	1.67	2.82	2.48	2.25	2.98	2.64	2.41	2.30	2.10	1.90
	-15	1.11	1.00	0.92	1.93	1.63	1.43	2.00	1.69	1.49	1.48	1.30	1.12
	-10	0.41	0.31	0.24	1.11	0.85	0.68	1.09	0.83	0.65	0.72	0.56	0.41
	-5	0.00	0.00	0.00	0.37	0.00	0.00	0.27	0.00	0.00	0.00	0.00	0.00
	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E_{tot}[a] (MJ bird^{-1} yr^{-1})		2.37	2.04	1.85	5.47	4.17	3.39	5.25	4.08	3.37	3.55	2.93	2.39
E_{tot}[a] (MJ [kg egg]$^{-1}$)		0.14	0.12	0.11	0.33	0.25	0.20	0.31	0.24	0.20	0.21	0.17	0.14
Cost[b] (cent bird^{-1} yr^{-1})		2.88	2.49	2.25	6.67	5.08	4.14	6.41	4.97	4.11	4.33	3.57	2.91
Cost[c] (cent [kg egg]$^{-1}$)		0.17	0.15	0.13	0.40	0.30	0.25	0.38	0.30	0.24	0.26	0.21	0.17

Effect of t_i

For the same alternative housing system, VR_h at 15°C and 20°C averages 66% and 28%, respectively, higher than VR_h at 25°C. This difference results from the reduced humidity ratio of the indoor air at lower temperature while keeping a constant RH_i (60% in this case) and assuming a constant MP. The humidity ratio is 6.4 g kg^{-1} (g of water vapor per kg of dry air) at 15°C dry-bulb temperature and 60% RH, 8.8 g kg^{-1} at 20°C and 60%, and 11.9 g kg^{-1} at 25°C and 60%. In the alternative houses, VR_t at 15°C and 20°C averages 142% and 57% higher than VR_t at 25°C because less sensible heat is required to be preserved at lower t_i.

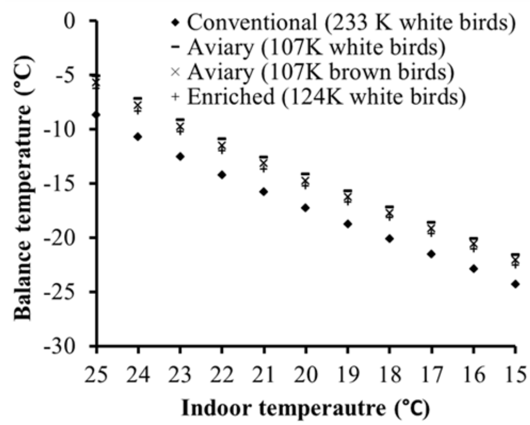

Figure 3. Balance temperature (t_{bal}) as affected by indoor temperature setpoint in laying-hen houses. RH_i = 60%, RH_o = 70%.See Table 1 for building characteristics and hen capacity of each housing system.

Table 4. Supplemental heat requirement (H_s), energy consumption (E_{tot}) and energy cost of H_s at three indoor temperature (t_i) levels (15°C, 20°C and 25°C) in laying-hen houses. RH_i = 60%, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

	t_o (°C)	Conventional (233K white birds)			Aviary (107K white birds)			Aviary (107K brown birds)			Enriched (124K white birds)		
		15°C	20°C	25°C	15°C	20°C	25°C	15°C	20°C	25°C	15°C	20°C	25°C
H_s (W bird^{-1})	-30	1.48	2.55	3.33	2.41	3.53	4.36	2.53	3.80	4.74	1.98	3.07	3.88
	-25	0.23	1.51	2.47	1.04	2.37	3.39	1.00	2.50	3.65	0.66	1.97	2.96
	-20	0.00	0.55	1.67	0.00	1.30	2.48	0.00	1.30	2.64	0.00	0.95	2.10
	-15	0.00	0.00	0.92	0.00	0.33	1.63	0.00	0.22	1.69	0.00	0.00	1.30
	-10	0.00	0.00	0.24	0.00	0.00	0.85	0.00	0.00	0.83	0.00	0.00	0.56
	-5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E_{tot} (MJ bird^{-1} yr^{-1})		0.01	0.31	1.85	0.10	0.87	4.17	0.08	0.84	4.08	0.05	0.57	2.93
E_{tot} (MJ [kg egg]$^{-1}$)		0.00	0.02	0.11	0.01	0.05	0.25	0.00	0.05	0.24	0.00	0.03	0.17
Cost (cent bird^{-1} yr^{-1})		0.02	0.38	2.25	0.12	1.06	5.08	0.10	1.03	4.97	0.06	0.70	3.57
Cost (cent [kg egg]$^{-1}$)		0.00	0.02	0.13	0.01	0.06	0.30	0.01	0.06	0.30	0.00	0.04	0.21

As shown in Figure 3, t_i setpoint significantly affects t_{bal} in that lowering t_i by 1°C will reduce t_{bal} by 1.6°C in both conventional and alternative housing systems. The H_s energy use in alternative housing system is reduced by 0.20 MJ [kg egg]$^{-1}$ in aviary system and 0.14 MJ [kg egg]$^{-1}$ in enriched colony system when t_i is set at 20°C instead of 25°C (Table 4). These reductions translate into approximately 80% reduction in H_s energy use in the alternative housing systems. If t_i is allowed to further decrease to 15°C, almost no H_s would be required. Therefore, temporally decreasing t_i could be an option to avoid/reduce H_s usage in alternative housing systems. However, lower t_i will increase birds' feed consumption to compensate their extra metabolic heat production to maintain homeostasis. It is of economic significance to find a t_i at which total H_s cost and feed consumption are the lowest.

Effect of RH_i

Changing RH_i has no influence on VR_t while significantly reducing VR_h, and results in lower t_{bal} (fig. 4) and less H_s (Table 5). Every 5% increase in RH_i would reduce t_{bal} by an average of 3.1°C to 3.3°C in the alternative housing systems (fig. 4). For the alternative hen houses in Iowa area with building characteristics presented in Table 1, a 10% RH_i elevation (from 60% to 70%) reduces H_s E_{tot} by 73% to 77%, and a 20% RH_i elevation (from 60% to 80%) reduces E_{tot} by 94% to 96%.

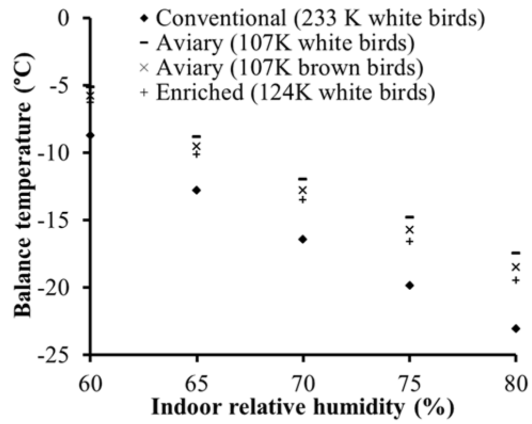

Figure 4. Balance temperature (t_{bal}) as affected by indoor relative humidity setpoint in laying-hen houses. T_i = 25°C, RH_o = 70%. See Table 1 for building characteristics and hen capacity of each housing system.

Table 5. Supplemental heat requirement (H_s), energy consumption (E_{tot}) and energy cost of H_s at three indoor relative humidity (RH_i) levels (60%, 70% and 80%) in laying-hen houses. T_i = 25°C, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

	t_o (°C)	Conventional (233K white birds)			Aviary (107K white birds)			Aviary (107K brown birds)			Enriched (124K white birds)		
		60%	70%	80%	60%	70%	80%	60%	70%	80%	60%	70%	80%
H_s (W bird^{-1})	-30	3.33	1.92	0.92	4.36	2.92	1.90	4.74	3.10	1.93	3.88	2.46	1.44
	-25	2.47	1.21	0.31	3.39	2.10	1.18	3.65	2.19	1.14	2.96	1.68	0.77
	-20	1.67	0.53	0.00	2.48	1.32	0.50	2.64	1.32	0.38	2.10	0.95	0.13
	-15	0.92	0.00	0.00	1.63	0.59	0.00	1.69	0.50	0.00	1.30	0.26	0.00
	-10	0.24	0.00	0.00	0.85	0.00	0.00	0.83	0.00	0.00	0.56	0.00	0.00
	-5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E_{tot} (MJ bird^{-1} yr^{-1})		1.85	0.30	0.02	4.17	1.14	0.27	4.08	1.03	0.21	2.93	0.67	0.11
E_{tot} (MJ [kg egg]$^{-1}$)		0.11	0.02	0.00	0.25	0.07	0.02	0.24	0.06	0.01	0.17	0.04	0.01
Cost (cent bird^{-1} yr^{-1})		2.25	0.37	0.02	5.08	1.39	0.33	4.97	1.26	0.26	3.57	0.81	0.14
Cost (cent [kg egg]$^{-1}$)		0.13	0.02	0.00	0.30	0.08	0.02	0.30	0.07	0.02	0.21	0.05	0.01

Effect of insulation level

Where H_s is provided, buildings with less insulation would require somewhat higher VR_h to remove the combustion moisture than well-insulated counterparts. The aviary house used in this analysis has the ceiling area twice as large as the conventional or the enriched colony house. Therefore, alteration in ceiling insulation level has more significant effect on VR_t in the aviary system than in the conventional or the enriched colony systems.

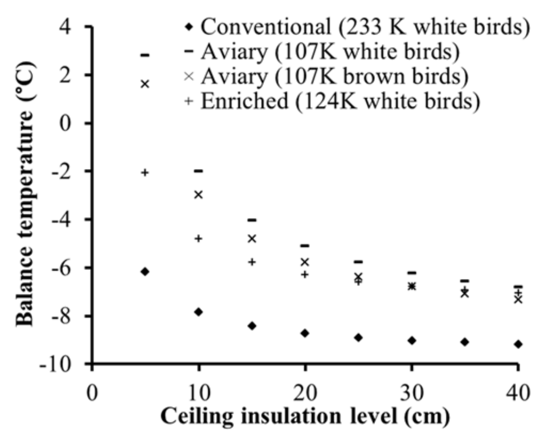

Figure 5. Balance temperature (t_{bal}) as affected by ceiling insulation level in laying-hen houses. T_i = 25°C, RH_i = 60%, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

The t_{bal} (fig. 5), H_s, E_{tot} and cost (Table 6) decrease as the ceiling insulation increases. However, the benefit of energy saving by further increasing ceiling insulation diminishes if the insulation of other building components does not increase (Berry and Miller, 1989). For instance, E_{tot} is reduced by 0.16 to 0.17 MJ [kg egg]$^{-1}$ in aviary system and 0.06 MJ [kg egg]$^{-1}$ in enriched colony system if doubling the thickness of the blown-in ceiling insulation from 10 cm to 20 cm; further doubling (from 20 cm to 40 cm) in the ceiling insulation would reduce E_{tot} at a lower rate of 0.06 to 0.07 MJ [kg egg]$^{-1}$ in aviary system and 0.02 MJ [kg egg]$^{-1}$ in enriched colony system. Nowadays, 20 cm blown-in ceiling (attic) insulation is typical for commercial hen houses in the Midwest USA. Although further increasing ceiling insulation would contribute to H_s reduction, designers must balance the cost and benefit or return of investment.

Table 6. Supplemental heat requirement (H_s), energy consumption (E_{tot}) and energy cost of H_s at four ceiling insulation levels (with blown-in ceiling insulation of 5 cm, 10 cm, 20 cm and 40 cm) in laying-hen houses. T_i = 25°C, RH_i = 60%, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

	t_o (°C)	Conventional (233K white birds)				Aviary (107K white birds)				Aviary (107K brown birds)				Enriched (124K white birds)			
		5	10	20	40	5	10	20	40	5	10	20	40	5	10	20	40
H_s (W bird^{-1})	-30	3.91	3.53	3.33	3.24	6.89	5.20	4.36	3.94	7.27	5.58	4.74	4.31	4.97	4.24	3.88	3.70
	-25	2.99	2.65	2.47	2.38	5.66	4.15	3.39	3.01	5.92	4.41	3.65	3.28	3.94	3.29	2.96	2.80
	-20	2.13	1.82	1.67	1.59	4.49	3.15	2.48	2.14	4.65	3.31	2.64	2.30	2.97	2.39	2.10	1.95
	-15	1.32	1.05	0.92	0.85	3.40	2.22	1.63	1.34	3.46	2.28	1.69	1.40	2.06	1.55	1.30	1.17
	-10	0.59	0.35	0.24	0.18	2.38	1.36	0.85	0.60	2.35	1.33	0.83	0.57	1.22	0.78	0.56	0.45
	-5	0.00	0.00	0.00	0.00	1.45	0.58	0.15	0.00	1.34	0.48	0.00	0.00	0.47	0.09	0.00	0.00
	0	0.00	0.00	0.00	0.00	0.62	0.00	0.00	0.00	0.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
E_{tot} (MJ bird^{-1} yr^{-1})		3.00	2.20	1.85	1.67	15.14	7.03	4.17	3.05	14.08	6.67	4.08	3.04	6.14	3.86	2.93	2.52
E_{tot} (MJ [kg egg]$^{-1}$)		0.18	0.13	0.11	0.10	0.90	0.42	0.25	0.18	0.84	0.40	0.24	0.18	0.37	0.23	0.17	0.15
Cost (cent bird^{-1} yr^{-1})		3.66	2.68	2.25	2.04	18.46	8.57	5.08	3.72	17.16	8.13	4.97	3.70	7.48	4.71	3.57	3.07
Cost (cent [kg egg]$^{-1}$)		0.22	0.16	0.13	0.12	1.10	0.51	0.30	0.22	1.02	0.48	0.30	0.22	0.45	0.28	0.21	0.18
BHLF (W °C^{-1})		4604	3220	2259	2183	6990	4424	2840	2148	6990	4424	2840	2148	4456	3072	2381	2035

Light vs. dark period

VR_h and VR_t average 17% and 59% higher during light period than during dark period in the alternative housing systems. These differences lead to about 7.0°C lower t_{bal} during light period than during dark period (Table 7). Accordingly, higher H_s is needed during dark period at the same t_o level. Moreover, it should be noted that the dark period and lower SHP normally occur at night when the ambient temperature drops to the lowest point of the day.

Table 7. Supplemental heat requirement (H_s) in laying-hen houses, which are determined using heat and moisture production in light period, in dark period and the time-weighted average (TWA). T_i = 25°C, RH_i = 60%, RH_o = 70%. See building characteristics and hen capacity of each housing system in Table 1.

	t_o (°C)	Conventional (233K white birds)			Aviary (107K white birds)			Aviary (107K brown birds)			Enriched (124K white birds)		
		Light	Dark	TWA	Light	Dark	TWA	Light	Dark	TWA	Light	Dark	TWA
t_{bal}		-12.1	-5.3	-8.8	-8.4	-1.4	-5.1	-9.1	-2.2	-5.8	-9.6	-2.6	-6.3
H_s (W bird^{-1})	-30	2.97	3.39	3.33	4.00	4.41	4.36	4.32	4.80	4.74	3.52	3.93	3.88
	-25	2.09	2.61	2.47	3.01	3.53	3.39	3.21	3.81	3.65	2.58	3.10	2.96
	-20	1.26	1.89	1.67	2.08	2.70	2.48	2.17	2.89	2.64	1.70	2.32	2.10
	-15	0.50	1.21	0.92	1.21	1.93	1.63	1.20	2.03	1.69	0.88	1.59	1.30
	-10	0.00	0.60	0.24	0.41	1.21	0.85	0.32	1.24	0.83	0.13	0.93	0.56
	-5	0.00	0.00	0.00	0.00	0.57	0.15	0.00	0.53	0.00	0.00	0.33	0.00
	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Conclusions

An Excel-based spreadsheet model has been developed to estimate ventilation rate (VR), balance temperature (t_{bal}), supplemental heat need (H_s), annual energy consumption (E_{tot}) and H_s energy cost in alternative hen housing – aviary and enriched colony systems as compared to conventional cage system under cold weather conditions. Effects of stocking density (SD), indoor temperature (t_i) and RH (RH_i) setpoints, building insulation level and light vs. dark period on VR, t_{bal}, H_s, E_{tot} and cost were investigated with the model for typical hen houses in the Midwestern US. The following observations and conclusions were made:

- The t_{bal} of the alternative housing systems is 2.5°C to 3.7°C higher than that of the conventional cage system to maintain t_i of 25°C and RH_i of 60%.
- The required heater capacity would be 284 kW for an aviary house with 107,000 white birds (26.6 kW per 10,000 birds), 303 kW for an aviary house with 107,000 brown birds (28.4 kW per 10,000 birds), and 281 kW for an enriched system with 124,000 white birds (22.7 kW per 10,000 birds) for central Iowa area.
- The H_s energy cost for the alternative housing is less than 0.5% of the total production cost.
- Due to higher moisture production by brown birds, aviary housing system with brown birds requires 13% higher VR for humidity control than the system with white birds.
- SD has small impact on t_{bal}. Specifically, t_{bal} rises by 0.9°C to 1.3°C if SD decreases to 80% – 83%; t_{bal} falls by 0.9°C to 1.0°C if SD increases to 120% – 125% in alternative housing systems. t_{bal} increases by 1.1 if SD decreases to 71% in conventional cage system.
- The t_i and RH_i setpoints have profound impact on t_{bal} and E_{tot}.
- The t_{bal} during light hours of the day is about 7.0°C lower than that during dark hours of the day.
- The established interactive model allows users to examine the singular impact of individual factors or synergistic effects of multiple factors on the design requirement (e.g., H_s) and thermal environment of the hen houses.

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