

The reduction of gas concentrations in broiler houses through ventilation: Assessment of the thermal and electrical energy consumption

*Original*

The reduction of gas concentrations in broiler houses through ventilation: Assessment of the thermal and electrical energy consumption / Costantino, A., Fabrizio, E., Villagrà, A., Estellés, F., Calvet, S.. - In: BIOSYSTEMS ENGINEERING. - ISSN 1537-5110. - STAMPA. - 199:(2020), pp. 135-148. [10.1016/j.biosystemseng.2020.01.002]

*Availability:*

This version is available at: 11583/2920332 since: 2021-10-08T22:49:40Z

*Publisher:*

Elsevier

*Published*

DOI:10.1016/j.biosystemseng.2020.01.002

*Terms of use:*

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

*Publisher copyright*

(Article begins on next page)



33 **Keywords:** broiler production; climate control; animal breeding; energy assessment;  
 34 ammonia emission; animal welfare

35

36 **Nomenclature**

37	Air	air (subscript)	
38	b	broiler (subscript)	
39	$b_0$	coefficient for <i>SFP</i> calculation	[m <sup>3</sup> Wh <sup>-1</sup> ]
40	$b_1$	coefficient for <i>SFP</i> calculation	[m <sup>3</sup> Wh <sup>-1</sup> Pa <sup>-1</sup> ]
41	$b_2$	coefficient for <i>SFP</i> calculation	[m <sup>3</sup> Wh <sup>-1</sup> Pa <sup>-2</sup> ]
42	C	cooling (subscript)	
43	c	central (subscript)	
44	$C$	gas mass concentration	[ppm]
45	$\bar{C}$	gas mass concentration (mean value)	[ppm]
46	$E$	energy consumption with actual ventilation	[kWh]
47	$E'$	energy consumption with increased ventilation	[kWh]
48	e	exhaust (subscript)	
49	el	electrical energy (subscript)	
50	$f$	primary energy conversion factor	[kWh <sub>p</sub> kWh <sup>-1</sup> ]
51	fan	fan (subscript)	
52	H	heating (subscript)	
53	hor	horizontal (subscript)	
54	$I$	solar irradiance	[W m <sup>-2</sup> ]
55	i	indoor (subscript)	
56	IAQ	Indoor Air Quality	
57	j	generic hourly time step (subscript)	
58	l	large fans (subscript)	
59	lim	gas concentration limit (subscript)	
60	$m$	molecular mass	[kg mol <sup>-1</sup> ]
61	o	outdoor (subscript)	
62	p	primary energy (subscript)	
63	$\dot{q}$	gas emission	[mg h <sup>-1</sup> ]
64	$RH$	air relative humidity	[%]

65	s	small fans (subscript)	
66	set	set point (subscript)	
67	$SFP$	specific fan performance	$[\text{m}^3 \text{Wh}^{-1}]$
68	th	thermal energy (subscript)	
69	tot	total (subscript)	
70	$U$ -value	steady-state thermal transmittance	$[\text{W m}^{-2} \text{K}]$
71	$V_{\text{mol}}$	molar volume	$[\text{m}^3 \text{mol}^{-1}]$
72	$\dot{V}$	actual ventilation air flow rate	$[\text{m}^3 \text{h}^{-1}]$
73	$\dot{V}'$	increased ventilation air flow rate	$[\text{m}^3 \text{h}^{-1}]$
74	$w$	live weight	$[\text{kg}]$
75	x	generic gas (subscript)	
76	$\Delta p$	static pressure difference	$[\text{Pa}]$
77	$\Delta \dot{V}'$	difference between actual and increase ventilation	$[\text{m}^3 \text{h}^{-1}]$
78	$\eta$	conversion efficiency	$[-]$
79	$\theta$	temperature	$[\text{°C}]$
80	$\theta'$	temperature (considering the increased ventilation)	$[\text{°C}]$
81	$\kappa$	areal heat capacity	$[\text{kJ m}^{-2} \text{K}^{-1}]$
82	$\Phi$	heat load	$[\text{kW}]$
83	$\Phi'$	heat load considering the increased ventilation	$[\text{kW}]$
84	$\omega$	percentage of activation time of the fans	$[\%]$

85

## 86 **1 Introduction**

87 The accumulation of aerial pollutants inside animal farms impairs animal health and welfare  
 88 and reduces farm efficiency and productivity. The most relevant among the harmful gases in  
 89 broiler houses are ammonia ( $\text{NH}_3$ ) and carbon dioxide ( $\text{CO}_2$ ). Their effects on broilers depend  
 90 on their concentration as well as on the exposure duration.

91 Atmospheric  $\text{NH}_3$  in poultry facilities has been recognized as a significant environmental  
 92 problem, as well as a detriment to poultry health, performance and welfare (Kristensen,  
 93 Burgess, Demmers, Wathes, 2000). It causes ocular damages when broilers are exposed to 25  
 94 and 50 ppm (1 ppm of  $\text{NH}_3$  is  $0.7 \text{ mg m}^{-3}$  at atmospheric pressure and  $25 \text{ °C}$  of gas  
 95 temperature) for 14 days (Olanrewaju et al., 2007), and keratoconjunctivitis and other eye  
 96 disorders when exposed to 60 ppm (Valentine, 1964; Beker, Vanhooser, Swartzlander, Teeter,

97 2004). Ammonia is also absorbed by the distal airway mucus, which enhances mucosal  
98 inflammation and bacterial contamination of the lungs (Gustin, Urbain, Prouvost, Ansay,  
99 1994). Moreover, exposure to NH<sub>3</sub> also promotes the development of infections (Kristensen  
100 and Wathes, 2000) and enhances susceptibility to respiratory diseases (Beker et al., 2004).  
101 Breast blisters have also been found in environments of 25 and 50 ppm of NH<sub>3</sub> (Quarles and  
102 Kling, 1974). More recently, it was found that broilers exposed to 25 ppm of NH<sub>3</sub> had a  
103 higher expression of genes potentially inhibiting growth and development of breast muscle,  
104 compared to broilers exposed to 3 ppm (Yi et al., 2016).

105 High CO<sub>2</sub> concentrations have negative consequences on broilers due to both the direct effect  
106 of this gas and the decrease in the oxygen concentration (McGovern, Feddes, Zuidhof,  
107 Hanson, Robinson, 2001). According to Gerritzen, Lambooi, Reimert, Stegeman, and Spruijt,  
108 (2007), broilers start to notice instantaneously the presence of CO<sub>2</sub> at 24,000 ppm (1 ppm of  
109 CO<sub>2</sub> is 1.8 mg m<sup>-3</sup> at atmospheric pressure and 25 °C of gas temperature). Higher  
110 concentration values in the breathing air may cause gasp (92,000 ppm) and convulsions  
111 (300,000 ppm). Lower concentrations of CO<sub>2</sub> could affect broiler health when they are in  
112 contemporaneity with high exposure times. For example, when broilers are exposed to CO<sub>2</sub>  
113 concentrations between 3,000 and 6,000 ppm for 14 days, body weight is depressed and late  
114 mortality increases (Olanrewaju et al., 2008).

115 According to these findings, it is recommended to maintain NH<sub>3</sub> and CO<sub>2</sub> concentrations  
116 below certain limits. In some regions, welfare regulations have also established concentration  
117 limits. European Council Directive 2007/43/EC (European Council, 2007) sets the minimum  
118 requirements for the protection of broilers kept for meat production and, among these rules, it  
119 establishes the maximum density for reared broilers at 33 kg m<sup>-2</sup>. However, the maximum  
120 rearing density can be increased up to 42 kg m<sup>-2</sup> when specific environmental control  
121 requirements are accomplished. Among these requirements, NH<sub>3</sub> concentration must be kept  
122 below 20 ppm and CO<sub>2</sub> concentration below 3,000 ppm at the level of the broilers' heads. It  
123 has been reported that most commercial farms across Europe rear broilers at densities higher  
124 than 33 kg m<sup>-2</sup> (Verspecht, Vanhonacker, Verbeke, Zoons, Van Huylbroeck, 2011).  
125 However, gas concentrations exceeding the limits established by the 2007/43/EC Directive  
126 have also been reported in commercial poultry houses for both NH<sub>3</sub> (Groot Koerkamp et al.,  
127 1998) and CO<sub>2</sub> (Knížatová et al., 2010).

128 Ventilation design and operation is critical to maintain gas concentrations below harmful  
129 levels. Increasing the ventilation rate reduces gas concentration by dilution, which is simple in  
130 terms of management and could be easily carried out by the automatic climate control systems  
131 installed in farms. However, increasing the ventilation rates increases energy consumption  
132 and, consequently, may entail an extra cost for the farmer. This is due to the extra electrical  
133 energy needed for operating the fans and to the extra supplemental heating load needed to  
134 maintain the indoor air set point temperature, particularly in cold conditions (Costantino &  
135 Fabrizio, 2020). Furthermore, climate control systems are mostly programmed to control only  
136 air temperature and relative humidity inside livestock houses (Zhang and Barber, 1995) and  
137 therefore installation of specific sensors is required.

138 Rearing broilers involves a high energy consumption compared with other livestock farms.  
139 According to Costantino, Fabrizio, Biglia, Cornale and Battaglini (2016), climate control in  
140 broiler farms uses between 85 and 135 kWh<sub>th</sub> m<sup>-2</sup> a<sup>-1</sup> (1 kWh = 3.6 MJ) of thermal energy and  
141 between 4 and 11 kWh<sub>el</sub> m<sup>-2</sup> a<sup>-1</sup> of electrical energy. These values represent 96% of the total  
142 thermal energy and 75% of the total electrical energy consumptions of the house. These high  
143 energy consumptions reflect also in the running costs of the farm: in the European context, the  
144 energy share represents 20% of the total production cost of a broiler (excluding feedstuff) and  
145 can be estimated between 0.04 and 0.09 € broiler<sup>-1</sup> (Oviedo-Rondón, 2010). Finally,  
146 considering that the meat production is estimated to increase by 70% in 2050 (FAO, 2011),  
147 the use of energy is also expected to increase in the primary sector (Thornton, 2010). For  
148 these reasons, quantifying potential impacts of increasing ventilation on energy consumption  
149 is of a foremost importance.

150 The objective of this work is to explore how energy consumption is affected by the increase  
151 of the ventilation rates in a commercial broiler house to fulfil the recommended thresholds of  
152 gas concentrations. This kind of analysis is not present in literature and may be useful for both  
153 engineers and farmers.

154 To carry out this work, NH<sub>3</sub> and CO<sub>2</sub> concentrations and their thresholds established by the  
155 European regulation (20 and 3,000 ppm in mass, respectively) are considered. For the  
156 analysis, a mechanically ventilated broiler house located in a Mediterranean area was selected  
157 as a case study and it was monitored during a production cycle carried out in cool (winter)  
158 season. The monitoring campaign provided the gas concentrations and the needed inputs for  
159 estimating the thermal and electrical energy consumption.

## 160 **2 Materials and methods**

## 161 2.1 Overview on the experimental and simulation activity

162 The experimental activity concerned the monitoring of indoor and outdoor gas concentrations  
163 (CO<sub>2</sub> and NH<sub>3</sub>), indoor and outdoor environmental conditions, static pressure difference  
164 between inside and outside the broiler house and the working time of the fans. The monitoring  
165 campaign concerned 40 days out of 47 of a production cycle carried out during the cool  
166 season (December and January). The first week of the production cycle was not monitored.  
167 When NH<sub>3</sub> and CO<sub>2</sub> concentrations exceeded 20 and 3,000 ppm (respectively), the theoretical  
168 extra ventilation flow rate needed to maintain the NH<sub>3</sub> and CO<sub>2</sub> concentrations below the  
169 established limits was estimated through a gas mass balance.

170 The variation of the energy consumption was assessed considering the electrical energy  
171 consumption for the operation of the fans and the thermal energy consumption for heating the  
172 enclosure. The electrical energy consumption was calculated through the Specific Fan  
173 Performance (*SFP*) obtained through regressions on the technical datasheets of the fans. The  
174 thermal energy consumption was estimated using the dynamic energy simulation model for  
175 broiler houses developed by Costantino, Fabrizio, Ghiggini, and Bariani (2018).

## 176 2.2 Case study description

### 177 2.2.1 Housing and reared broilers

178 The experiment was carried out in a commercial mechanically ventilated broiler house located  
179 in Vila-real (Castellón province, eastern Spain), a geographical location in a Mediterranean  
180 climate. The province of Castellón is classified as an hot-humid climate zone (ASHRAE,  
181 2016) characterized by a mild climate with no dry season and hot summer. The heating degree  
182 days are 1579 °C d calculated considering 20 °C as base temperature and the entire year as  
183 calculation period, in compliance with EN ISO 15927-6 (European Committee for  
184 Standardisation, 2007).

185 The selected case study can be considered representative of the commercial broiler farms of  
186 that region. The building floor area is 1,430 m<sup>2</sup> (110 m length and 13 m width). The building  
187 has a gable roof and its height is 2.5 m at the eave level, and 4.5 m at the ridge level. The  
188 building net volume is approximately 5,000 m<sup>3</sup>.

189 The perimetral walls are made of concrete hollow blocks (150 mm of thickness) and cement  
190 plaster (20 mm of thickness). Part of these walls is insulated through polyurethane sandwich  
191 panels (30 mm of thickness). The roof is made of corrugated fibre-cement sheets with

192 fiberglass insulation panels (30 mm of thickness) and polyurethane foam (20 mm of  
193 thickness) that was applied on the inner face. The floor is a lightweight reinforced concrete  
194 screed (100 mm of thickness) in direct contact with the ground. A layer of rice hulls of about  
195 100 mm is used as bedding material and the litter is removed at the end of each production  
196 cycle. To perform the energy simulations, an additional 1.5 m of soil layer is added to the  
197 previously described floor layers with the aim of considering the effect of the ground on the  
198 building thermal behaviour. The heat flow via the ground was calculated using as  
199 thermodynamic driving force the difference between the indoor air temperature ( $\theta_{\text{air,i}}$ ) and the  
200 outdoor air temperature ( $\theta_{\text{air,o}}$ ).

201 The thermal transmittance ( $U$ -value) and the internal areal heat capacity ( $\kappa_i$ ) of the broiler  
202 house envelope were calculated in compliance with ISO 6946 (2017a) and ISO 13786  
203 (2017b) standards. The calculated values (reported in Table 1) are the inputs for the energy  
204 simulation model that was used to estimate the thermal energy consumption of the analysed  
205 broiler house.

206 **Table 1** – Thermal transmittance ( $U$ -value) and internal areal heat capacity ( $\kappa_i$ ) of the considered building  
207 elements.

Building element	$U$ -value [W m <sup>-2</sup> K <sup>-1</sup> ]	$\kappa_i$ [kJ m <sup>-2</sup> K <sup>-1</sup> ]
Not insulated walls	2.40	56.3
Insulated walls	0.67	13.3
Roof	0.42	3.4
Floor	0.44	16.3

208 The production cycle started on December 15<sup>th</sup> with 12,000 male and 12,000 female broiler  
209 chicks and ended on January 31<sup>st</sup> (7 weeks cycle). The monitoring campaign started on the 7<sup>th</sup>  
210 day of the production cycle (December 22<sup>nd</sup>) and lasted 967 hours (around 40 days) until the  
211 end of the production cycle. On January 24<sup>th</sup>, 15% of the 42-day-old broilers were harvested  
212 from the building with an average weight of 2.33 kg broiler<sup>-1</sup>. Total mortality during the  
213 growing period was 3.28%. The final production was 23,212 broilers with a total final live  
214 weight of 62,534 kg (2.69 kg broiler<sup>-1</sup> for 48-day-old broilers), with a feedstuff consumption  
215 of 114,000 kg and a feed conversion rate of 1.82. Rearing density at the end of the cycle was  
216 37.05 kg m<sup>-2</sup>, a value higher than the threshold of 33 kg m<sup>-2</sup> established by the European  
217 Council Directive 2007/43/EC (European Council, 2007), therefore specific environmental  
218 control requirements should be accomplished.

### 219 2.2.2 Climate control system

220 The broiler house is mechanically ventilated using a cross ventilation configuration. Air inlets  
221 are placed on one of the larger walls and they are automatically controlled for maintaining a  
222 constant pressure difference between inside and outside the building ( $\Delta p$ ) during the same  
223 day. On the opposite wall there are 16 lateral exhaust fans that deal with both Indoor Air  
224 Quality (IAQ) control and cooling ventilation. The 16 fans are of two different models: nine  
225 of them are larger than the other ones. The larger fans have a maximum electrical power of  
226 0.75 kW and in free air delivery conditions ( $\Delta p = 0$  Pa) the maximum declared airflow is  
227 around 35,000 m<sup>3</sup> h<sup>-1</sup>. The remaining seven fans are smaller, have a maximum electrical  
228 power of 0.59 kW and the maximum declared airflow in free air delivery conditions is  
229 roughly 12,750 m<sup>3</sup> h<sup>-1</sup>. Both fan models are three-phase and fixed propeller speed fans,  
230 therefore the air flow and the *SFP* vary according to  $\Delta p$  only on a single curve.

231 In the broiler house, a commercial automatic control system measures the value of  $\theta_{\text{air},i}$   
232 (through a probe inside the house) and maintains it within the deadband (2 °C of range)  
233 between the heating set point temperature ( $\theta_{\text{set},H}$ ) and the cooling set point temperature  
234 ( $\theta_{\text{set},C}$ ). When a supplemental heating load is needed to maintain  $\theta_{\text{air},i}$  above  $\theta_{\text{set},H}$ , the farm  
235 automatic control system activates two propane air heaters of 85 kW. Both the air heaters are  
236 placed inside the building, therefore a conversion efficiency ( $\eta_H$ ) of 100% is considered.  
237 Since the air heaters emit the exhaust fumes directly inside the enclosure, they contribute to  
238 the increase the CO<sub>2</sub> concentration.

239 When cooling is needed to maintain  $\theta_{\text{air},i}$  below  $\theta_{\text{set},C}$ , cooling ventilation and evaporative  
240 pads are activated. Climate control system provides also a minimum ventilation flow rate  
241 (based only on the animal density) to control the IAQ.

242 The ventilation is managed through the activation of the 16 fans according to two different  
243 activation cycles. When low ventilation flow rates are needed (usually for IAQ control), the  
244 activation cycle lasts 15 s. When higher ventilation flow rates are needed (usually for cooling  
245 ventilation), the control system manages the fans with activation cycles of 100 s. For  
246 ventilation flow rates below 75,000 m<sup>3</sup> h<sup>-1</sup>, only the small fans are activated.

247 *2.3 Monitoring system*

248 The indoor air temperature  $\theta_{\text{air},i}$  and the indoor air relative humidity ( $RH_i$ ) were monitored  
 249 using four sensors embedded in portable data loggers that were set with an acquisition time  
 250 step of 30 minutes (HOBO U12, Onset Computer Corp., Pocasset, Mass.).

251 The outdoor weather conditions of  $\theta_{\text{air},o}$  and relative humidity ( $RH_o$ ) were monitored using a  
 252 weather station that was set with an acquisition time step of 10 minutes (HOBO, Onset  
 253 Computer Corp., Pocasset, Mass). The daily value of  $\Delta p$  was obtained by the logged data in  
 254 the farm automatic climate control system that manages the window openings to maintain a  
 255 constant  $\Delta p$  on a daily basis.

256 The total horizontal solar irradiance ( $I_{\text{tot,hor}}$ ) was obtained with a 30 minutes time step  
 257 through a third-party weather station. The beam and diffuse components of the solar radiation  
 258 were obtained using the model of Reindl, Beckman, and Duffie (1990).

259 The percentage of activation time of the nine large fans ( $\omega_l$ ) and the seven small ones ( $\omega_s$ ),  
 260 were monitored with a time step of 90 s as described in Calvet, Cambra-López, Blanes-Vidal,  
 261 Estellés, and Torres (2010). The measurement of gas concentration regarded  $\text{NH}_3$  and  $\text{CO}_2$ . A  
 262 photoacoustic multi gas monitor equipped with a gas multiplexer was adopted in this work.  
 263 This instrument enabled sequential measurements in 8 different points in a 2-hour time step  
 264 (15 minutes are needed to complete each measurement). Four sampling points were placed  
 265 next to the fans of the building at 1.2 m of height to determine the exhaust concentrations of  
 266 the gas  $x$  ( $C_{e,x}$ ), and two were placed at the air inlet openings for the characterization of gas  
 267 concentration of the outside air ( $C_{o,x}$ ). The remaining two measurement points were placed in  
 268 the centre of the building at 1.2 m height to obtain further data on the distribution of gas  
 269 concentrations ( $C_{c,x}$ ) within the enclosure. The summary of the measured parameters is  
 270 presented in Table 2, while the locations of the sensors inside the analysed broiler house is  
 271 shown in Fig. 1.

272 Every week, 50 broilers (0.02% of the flock) were weighed for monitoring the trend of their  
 273 live weight ( $w_b$ ) during the experiment.

274

275

**Table 2** – Detail of the monitored parameters.

Monitored parameter	Symbol	Unit of measurement	Number of simultaneous measurements	Acquisition time step
---------------------	--------	---------------------	-------------------------------------	-----------------------

Activation time of large fans	$\omega_l$	%	1	90 seconds
Activation time of small fans	$\omega_s$	%	1	90 seconds
Outdoor air temperature	$\theta_{air,o}$	°C	1	10 minutes
Outdoor relative humidity	$RH_o$	%	1	10 minutes
Indoor air temperature	$\theta_{air,i}$	°C	4	30 minutes
Indoor relative humidity	$RH_i$	%	4	30 minutes
Total horizontal solar irradiance	$I_{tot,hor}$	W m <sup>-2</sup>	1	30 minutes
Exhaust gas concentration	$C_{e,x}$	ppm	4	2 hours
Outdoor gas concentration	$C_{o,x}$	ppm	2	2 hours
Gas concentration (center)	$C_{c,x}$	ppm	2	2 hours
Static pressure difference	$\Delta p$	Pa	1	1 day
Broiler live weight	$w_b$	kg	50	1 week

276

## 277 2.4 Calculation process

### 278 2.4.1 Estimation of the increased ventilation flow rate to fulfil the gas concentration 279 requirements

280 In Fig. 2 the calculation process adopted in this work is resumed and the calculation steps are  
281 presented. In all the calculations, the monitored gas emissions are considered constant in the  
282 hourly time step.

283 At each hourly time step  $j$ , the indoor gas concentrations should be maintained below the  
284 established thresholds. This condition is expressed using the following inequation that must  
285 be fulfilled for both NH<sub>3</sub> and CO<sub>2</sub>

$$\bar{C}_{i,x,j} \leq C_{lim,x} \quad (1)$$

286 where  $\bar{C}_{i,x,j}$  is the average mass concentration of the analysed gas  $x$  (subscript  $x$ ) inside the  
287 building (subscript  $i$ ) at time step  $j$ . The value of  $\bar{C}_{i,x,j}$  is the arithmetic mean between the  
288 average value of the two measured  $C_{c,x,j}$ , and the average value of the four measured  $C_{e,x,j}$ .

289 The term  $C_{lim,x}$  is the mass concentration limit (subscript *lim*) of gas  $x$ .

290 If the constraint of Eq. (1) is respected, the actual ventilation flow rate of large ( $\dot{V}_{l,j}$ ) and small  
291 ( $\dot{V}_{s,j}$ ) fans is calculated on the basis of the real monitored data ( $\omega_l$ ,  $\omega_s$  and  $\Delta p$ ), according to  
292 the method described in Calvet, Cambra-López, Blanes-Vidal, Estellés, and Torres (2010).

293 The total actual ventilation flow rate ( $\dot{V}_{l+s,j}$ ) is the sum of  $\dot{V}_{l,j}$  and  $\dot{V}_{s,j}$ . The obtained values of

294  $\dot{V}_{l,j}$ ,  $\dot{V}_{s,j}$  and  $\dot{V}_{l+s,j}$  are used to calculate the fan electrical energy consumption ( $E_{el,l+s}$ ) through  
 295 the *SFP*, while the needed heating load ( $\Phi_{H,j}$ ) and the thermal energy consumption for  
 296 supplemental heating ( $E_{th}$ ) are calculated through the energy simulation model.  
 297 If the constraint of Eq. (1) is not respected, the theoretical increased ventilation flow rate  
 298 ( $\dot{V}'_{l+s,x,j}$ ) needed to guarantee  $C_{lim,x}$  has to be calculated. At each time step  $j$ ,  $\dot{V}'_{l+s,x,j}$  depends  
 299 on the gas emission rate from internal sources ( $\dot{q}_{x,j}$ ), such as the reared broilers and the  
 300 bedding material. At each time step  $j$ ,  $\dot{q}_{x,j}$  reads

$$\dot{q}_{x,j} = (\bar{C}_{i,x,j} - \bar{C}_{o,x,j}) \cdot \frac{m_x}{V_{mol,x}} \cdot \dot{V}_{l+s,j} \quad \left[ \frac{mg_x}{h} \right] \quad (2)$$

301 where  $\bar{C}_{o,x,j}$  (in ppm) is the average outdoor (subscript  $o$ ) concentration of gas  $x$  at  
 302 hourly time step  $j$ , obtained as the arithmetic mean between the two monitored values of  $C_{o,x,j}$ .  
 303  $m_x$  is the molecular mass of gas  $x$  that is equal to  $0.017031 \text{ kg mol}^{-1}$  for  $\text{NH}_3$  and  
 304  $0.04401 \text{ kg mol}^{-1}$  for  $\text{CO}_2$ .  $V_{mol}$  is the molar volume of gas  $x$ , that in this work is considered  
 305 constant and equal to  $0.02445 \text{ m}^3 \text{ mol}^{-1}$  for  $\text{NH}_3$  and  $\text{CO}_2$ .  $\dot{V}_{l+s,j}$  is the actual ventilation flow  
 306 rate, calculated using the real monitored data calculated as previously stated. In Eq. (2), some  
 307 simplifications are assumed, since  $\dot{q}_{x,j}$  is considered constant and not influenced by the  
 308 variation of the indoor environmental conditions in the considered time step  $j$ .  
 309 Once estimated  $\dot{q}_{x,j}$ ,  $\dot{V}'_{l+s,x,j}$  is calculated through the following gas mass balance in steady-  
 310 state conditions

$$\dot{V}'_{l+s,x,j} = \frac{\dot{q}_{x,j}}{C_{lim,x} - \bar{C}_{o,x,j}} \cdot \frac{V_{mol,x}}{m_x} \quad \left[ \frac{m^3}{h} \right] \quad (3)$$

311 Eqs. (2) and (3) are applied at each time step of the analysed period for which the constraint  
 312 of Eq. (1) is not respected. Considering  $\text{NH}_3$  and  $\text{CO}_2$  in Eqs. (2) and (3),  $\dot{V}'_{l+s,\text{NH}_3,j}$  and  
 313  $\dot{V}'_{l+s,\text{CO}_2,j}$  are obtained, respectively. At the time step  $j$ , the total theoretical ventilation flow  
 314 rate ( $\dot{V}'_{l+s,j}$ ) is calculated as

$$\dot{V}'_{l+s,j} = \max\{\dot{V}'_{l+s,\text{NH}_3,j}; \dot{V}'_{l+s,\text{CO}_2,j}\} \quad \left[ \frac{m^3}{h} \right] \quad (4)$$

315 The obtained  $\dot{V}'_{l+s,j}$  is split into the flow rate provided by large ( $\dot{V}'_{l,j}$ ) and small fans ( $\dot{V}'_{s,j}$ )  
 316 according to the control logic of the automatic climate control system of the broiler house  
 317 (below 75,000 m<sup>3</sup> h<sup>-1</sup> only small fans are activated). The obtained values of  $\dot{V}'_{l+s,j}$ ,  $\dot{V}'_{l,j}$  and  $\dot{V}'_{s,j}$   
 318 are used to calculate the fan electrical energy consumption ( $E'_{el,l+s}$ ), the theoretical heating  
 319 load ( $\Phi'_{H,j}$ ), the simulated indoor air temperature ( $\theta'_{air,i}$ ) and the thermal energy consumption  
 320 for heating ( $E'_{th}$ ), as described in the following section.

#### 321 2.4.2 Estimation of the electrical and thermal energy consumption

322 The estimation of the electrical energy consumption due to ventilation was carried out  
 323 characterizing each fan model with the *SFP* curve. The *SFP* of a generic fan represents the  
 324 energy needed by the fan to provide a cubic meter of airflow. For a generic fixed propeller  
 325 speed fan, Costantino et al. (2018) expressed the *SFP* as a function of the static pressure  
 326 difference between inside and outside of the house  $\Delta p$  as

$$SFP_{fan} = b_2 \cdot \Delta p^2 + b_1 \cdot \Delta p + b_0 \quad \left[ \frac{\text{m}^3}{\text{Wh}} \right] \quad (5)$$

327 where  $b_2$ ,  $b_1$  and  $b_0$  are empirical coefficients that in this work are obtained by a regression  
 328 from the technical datasheets of the fans.

329 Values of  $b_2$ ,  $b_1$  and  $b_0$  are presented in Table 3 for both fan models.

330

331 **Table 3** – Regression coefficients  $b_2$ ,  $b_1$  and  $b_0$  for the *SFP* of both the fan models.

Fan model	Coefficient	Value	Unit
Large fans	$b_{l,2}$	$-5.0000 \cdot 10^{-8}$	m <sup>3</sup> Wh <sup>-1</sup> Pa <sup>-2</sup>
	$b_{l,1}$	$+2.0250 \cdot 10^{-4}$	m <sup>3</sup> Wh <sup>-1</sup> Pa <sup>-1</sup>
	$b_{l,0}$	+0.0316	[ - ]
Small fans	$b_{s,2}$	0	m <sup>3</sup> Wh <sup>-1</sup> Pa <sup>-2</sup>
	$b_{s,1}$	$+3.7110 \cdot 10^{-5}$	m <sup>3</sup> Wh <sup>-1</sup> Pa <sup>-1</sup>
	$b_{s,0}$	+0.0486	[ - ]

332

333 The electrical energy consumption due to the actual ventilation ( $E_{el,l+s}$ ) of the analysed period  
 334 is calculated as

$$E_{el,l+s} = \left[ \sum_{j=1}^{967} \left( \frac{\dot{V}_{l,j}}{SFP_l} + \frac{\dot{V}_{s,j}}{SFP_s} \right) \right] \cdot 10^{-3} \quad [\text{kWh}_{el}] \quad (6)$$

335 where  $\dot{V}_{l,j}$  and  $\dot{V}_{s,j}$  are the actual ventilation flow rates provided the large and small fans at the  
336 time step  $j$ ,  $SFP_l$  and  $SFP_s$  are the  $SFP$  of large and small fans respectively, and 967 is the  
337 number of hours of the analysed period.

338 In a similar way, the electrical energy consumption due to the increased ventilation ( $E'_{el,l+s}$ ) is  
339 calculated as

$$E'_{el,l+s} = \left[ \sum_{j=1}^{967} \left( \frac{\dot{V}'_{l,j}}{SFP_l} + \frac{\dot{V}'_{s,j}}{SFP_s} \right) \right] \cdot 10^{-3} \quad [\text{kWh}_{el}] \quad (7)$$

340 The estimation of the thermal energy consumption was carried out by the application of the  
341 dynamic energy simulation model developed by Costantino, Fabrizio, Ghiggini, and Bariani  
342 (2018). This model was specifically developed for mechanically ventilated broiler houses and  
343 is in compliance with ISO 13790 standard (2008). The adopted simulation model estimates  
344 the indoor environmental conditions ( $\theta_{air,i}$  and  $RH_i$ ) and the thermal and electrical energy  
345 consumption for climate control by solving a resistance–capacitance electrical network that is  
346 equivalent to the analysed building. The electrical network has 5 resistances and 1 capacitance  
347 (5R1C) and is solved using a finite difference method (Crank–Nicolson scheme) that analyses  
348 the 5R1C network with a time discretization of one hour. The reliability of the application of  
349 this model to broiler house was proven by previous works (Costantino et al., 2018;  
350 Costantino, Ballarini, Fabrizio, 2017).

351 In the framework of this paper, the energy simulation model of Costantino et al. (2018) is  
352 used for estimating the thermal energy consumption ( $E_{th}$ ) considering the actual ventilation  
353 and the thermal energy consumption ( $E'_{th}$ ) considering the theoretical ventilation needed to  
354 maintain  $C_{lim,NH_3}$  and  $C_{lim,CO_2}$ . The simulations were performed for the 967 hours of the  
355 monitoring period with an hourly time step.

356 To calculate  $E_{th}$  and  $E'_{th}$ , the boundary conditions of the analysed case study were inputted in  
357 the model, in particular:

- 358 • the geometrical and the thermophysical properties (e.g.  $U$ -values and  $\kappa_i$ ) of the  
359 analysed broiler house;
- 360 • the farming features (e.g. stocking density and duration of the production cycle);  
361 the broiler weight was expressed as a function of the time based on the monitored  
362 data of  $w_b$ ;
- 363 • the outdoor weather conditions of  $\theta_{air,o}$  and  $I_{tot,hor}$  (obtained from a third-party  
364 weather station);
- 365 • the main features of the climate control system (e.g. control logic of the fans and  
366  $\eta_H$ );
- 367 • the  $\theta_{set,H}$  adopted in the case study (31 °C at the beginning and 18 °C at the end of  
368 the production cycle).

369 Finally,  $\dot{V}_{1+s}$  and  $\dot{V}'_{1+s}$  were input into the model to obtain  $E_{th}$  and  $E'_{th}$ , respectively.

### 370 **3 Results and discussion**

#### 371 *3.1 Analysis of the monitored data*

372 In Fig. 3a, the hourly values of  $\theta_{air,i}$  and  $\theta_{air,o}$  during the monitored period are shown. The  
373 pattern of  $\theta_{air,i}$  strictly followed the settings of the automatic control system of the farm and it  
374 can be considered similar to those obtained in other regions with different outdoor climate  
375 conditions (Jones, Donnelly, Stamp Dawkins, 2005.). At the beginning of the monitored  
376 period, (December 22<sup>nd</sup>, the 8<sup>th</sup> day of the production cycle)  $\theta_{air,i}$  had an average daily value  
377 of around 27 °C; during the production cycle,  $\theta_{air,i}$  gradually decreased reaching an average  
378 daily value of around 18 °C at the end of the production cycle (January 31<sup>st</sup>). This decreasing  
379 trend had an exception on January 19<sup>th</sup>, when  $\theta_{air,i}$  was considerably higher than in the  
380 previous days. This  $\theta_{air,i}$  peak was caused by  $\theta_{air,o}$  that reached the highest value (26 °C) of  
381 the entire monitored period on that day. Before January 19<sup>th</sup>, the trend of  $\theta_{air,o}$  was quite  
382 constant daily, and the average value of the period from December 22<sup>nd</sup> to January 18<sup>th</sup> was  
383 around 10 °C. After the peak of January 19<sup>th</sup>,  $\theta_{air,o}$  remained higher than in the previous days  
384 with an average daily value of around 14.5 °C (January 19<sup>th</sup> – 21<sup>st</sup>). From January 22<sup>nd</sup> to the  
385 end of the monitored period,  $\theta_{air,o}$  decreased to an average value of 7.6 °C.

386 The trend of the total actual ventilation flow rate  $\dot{V}_{1+s}$  during the monitored period is  
387 presented in Fig. 3b. From the beginning of the monitored period to January 18<sup>th</sup>,  $\dot{V}_{1+s}$

388 gradually increased. On January 18<sup>th</sup>, a considerable increase in  $\dot{V}_{1+s}$  can be noticed and a  
389 peak of about 266,000 m<sup>3</sup> h<sup>-1</sup> (the maximum monitored value of  $\dot{V}_{1+s}$ ) occurred on January  
390 19<sup>th</sup>, corresponding to the sudden increase of  $\theta_{air,o}$ . From January 22<sup>nd</sup> to the end of the  
391 production cycle,  $\dot{V}_{1+s}$  falls off due to the decrease of  $\theta_{air,o}$  during the last days and due to the  
392 reduction of the number of broilers (15% of them was harvested on January 24<sup>th</sup>).

393 The actual ventilation flow rate can be expressed in air changes per hour (ach). During the  
394 monitored period, the minimum ventilation flow rate was around 1 ach, the maximum one  
395 was higher than 50 ach while the average was around 9 ach.

396 As stated before, intensive broiler farms usually are designed, equipped and operated to  
397 maintain the adequate indoor air temperature to ensure an optimum animal development but,  
398 on the contrary, farm installations are not usually designed and operated to maintain  
399 established NH<sub>3</sub> and CO<sub>2</sub> concentration levels. Consequently, concentration thresholds are  
400 normally exceeded in winter periods, when ventilation rates are low, as evidenced by Groot  
401 Koerkamp et al. (1998) and by the monitored emission trend presented in Fig. 3c and d.

402 In Fig. 3c, the monitored NH<sub>3</sub> mass concentration is presented. During the analysed  
403 period,  $\bar{C}_{o,NH_3}$  remained quite constant with an average value (during the entire period) lower  
404 than 1 ppm.  $\bar{C}_{i,NH_3}$  had an average value of 18.3 ppm (the minimum was 1.4 ppm, the  
405 maximum 38.1 ppm) but it varied considerably and exceeded the threshold mainly in the  
406 central portion of the monitored period. Although this tendency is also described in literature  
407 (Knížatová et al., 2010), the evolution of NH<sub>3</sub> concentration is, to some extent, hard to  
408 predict, being influenced by litter management, environmental conditions, ventilation rates  
409 and broiler health status (Weaver and Meijerhof, 1991). In Fig. 3c it stands out that during the  
410 first days,  $\bar{C}_{i,NH_3}$  was considerably below the  $\bar{C}_{lim,NH_3}$  but, later, it sudden increased since the  
411 chicks were growing and because the excreta quantity in the bedding material increased over  
412 time, affecting the NH<sub>3</sub> emissions. From December 28<sup>th</sup> to January 18<sup>th</sup>,  $\bar{C}_{i,NH_3}$  remained  
413 higher than  $C_{lim,NH_3}$  for most of the time. After January 18<sup>th</sup> to the end of the production  
414 cycle, the increased  $\dot{V}_{1+s}$  (due to the high values of  $\theta_{air,o}$ ) improved the indoor environmental  
415 conditions in terms of gas concentration, and  $\bar{C}_{i,NH_3}$  decreased below  $C_{lim,NH_3}$  for most of the  
416 time. The reduction of the animal stocking density inside the house of January 24<sup>th</sup> may have  
417 partially affected this decrease.

418 Despite CO<sub>2</sub> production from broilers and manure increases as broilers grow (Calvet, Estelles,  
419 Cambra-Lopez, Torres, Van den Weghe, 2011), CO<sub>2</sub> concentrations inside the house followed

420 a decreasing trend in the analysed period due to the diluting effect of increasing ventilation  
421 rates. During the first days of the monitored period,  $\bar{C}_{i,CO_2}$  had higher values than in the  
422 remaining days and was considerably higher than  $C_{lim,CO_2}$ , as shown in Fig. 3d. This  
423 difference was due to the need to maintain  $\theta_{set,H}$  during the first days of the production cycle.  
424 Combining the high temperature needs of broilers during their first days of life with their low  
425 sensible thermal emission, supplemental heating had to be provided to reach  $\theta_{set,H}$ . The  
426 supplemental heating was provided by propane air heaters that emitted the exhaust fumes  
427 directly inside the enclosure, increasing  $\theta_{air,i}$  and  $\bar{C}_{i,CO_2}$ . During these days (December 22<sup>nd</sup> –  
428 January 6<sup>th</sup>),  $\dot{V}_{1+s}$  was at minimum values (below 50,000 m<sup>3</sup> h<sup>-1</sup>) and the CO<sub>2</sub> in the house  
429 could not be diluted through the ventilation. When  $\theta_{set,H}$  was maintained without the  
430 supplemental heating,  $\bar{C}_{i,CO_2}$  decreased considerably and after January 6<sup>th</sup> remained stably  
431 below  $C_{lim,CO_2}$ . During the monitored period, the average value of  $\bar{C}_{i,CO_2}$  was 2,517 ppm (the  
432 minimum was 819 ppm, the maximum 5,765 ppm), while the average value of  $\bar{C}_{o,CO_2}$  was  
433 around 480 ppm and it was almost constant. The outdoor concentration  $\bar{C}_{o,CO_2}$  had a mean  
434 value of 484 ppm during the monitoring period, with the minimum value of 430 ppm and the  
435 maximum one of 763 ppm.

436 The absolute and cumulative frequencies of  $\bar{C}_{i,NH_3}$  and  $\bar{C}_{i,CO_2}$  are presented in Fig. 4a and b,  
437 respectively. Comparing the trends of the two cumulative frequencies, the control of  $\bar{C}_{i,NH_3}$   
438 appears more problematic than the control of  $\bar{C}_{i,CO_2}$ . Analysing separately the concentrations  
439 of NH<sub>3</sub> and CO<sub>2</sub>, it stands out that 43% of the  $\bar{C}_{i,NH_3}$  values are above 20 ppm, while around  
440 30% of the  $\bar{C}_{i,CO_2}$  values result above 3,000 ppm. Considering the analysed gas concentration  
441 together,  $\bar{C}_{i,NH_3}$  and  $\bar{C}_{i,CO_2}$  are below their thresholds only for 40% of the monitored time,  
442 therefore for 60% of time the gas concentration limits were not respected in the monitored  
443 broiler house.

444 The negative effects of a stressor on the animal's welfare are dependent on both its severity  
445 and its duration (Gerritzen, Lambooi, Hillebrand, Lankhaar, Pieterse, 2000; Ritz, Fairchild,  
446 Lacy, 2004). Although acute exposure to lethal concentrations of gases may occur in livestock  
447 buildings, the effects of chronic exposure are more insidious (Wathes and Charles, 1994). For  
448 example, a long exposure to NH<sub>3</sub> (around 42 days) at 20 ppm (the concentration limit) may  
449 cause pulmonary congestion, oedema and haemorrhage (Anderson, Beard, Hanson 1964;  
450 Quarles and Kling, 1974). Broilers exposed to 25 and 50 ppm of NH<sub>3</sub> concentration for 35

451 days increased the respiratory rate, the haemoglobin and haematocrit, which could indicate an  
 452 increase in the metabolic activity to meet energy demands under stressful situations  
 453 (Olanrewaju et al., 2007). For this reason, it is important to consider both the concentration  
 454 values and the exposure time. In Table 4, the number of events (periods of time in which the  
 455 gas concentration limit is continuously exceeded) and their duration (time in which the gas  
 456 concentration is continuously above the established limit) are reported. The number of events  
 457 in which  $C_{lim,NH_3}$  was exceeded in the monitored period was 30. About half of these events  
 458 (14) lasted less than 8 hours with maximum  $\bar{C}_{i,NH_3}$  values lower than 27 ppm, while 11 events  
 459 lasted more than 18 hours reaching concentration values considerably higher than  $C_{lim,NH_3}$   
 460 (e.g. 36.5 and 38.1 ppm). Such high concentration may have a deleterious effect on growth  
 461 (Beker et al., 2004; Valentine, 1964; Quarles and Kling, 1974), may cause alterations in blood  
 462 physiological parameters (Olanrewaju et al., 2007) and aversion to atmospheres (Kristensen,  
 463 Burgess, Demmers, Wathes, 2000; Wathes, Jones, Kristensen, Jones, Webster, 2002).  
 464 The number of events in which  $\bar{C}_{i,CO_2}$  exceeded  $C_{lim,CO_2}$  was 12: in 5 of them the duration  
 465 was higher than 18 hours with concentrations considerably higher than the limit (up to  
 466 5,796 ppm of maximum value). These high concentrations can be considered tolerated by  
 467 broilers if intermittent (Verstegen, Tamminga, Greers, 1994), otherwise they represent a risk  
 468 for the animal health.  
 469 According to literature, it seems easy for most of the farms to maintain CO<sub>2</sub> levels below the  
 470 limits that can cause damages to the broilers (Olanrewaju et al., 2008). The results reported in  
 471 Fig. 4 and Table 4 confirm what stated in literature; in the analysed case study the control of  
 472 CO<sub>2</sub> concentration was easier than the one of NH<sub>3</sub>.

473 **Table 4** – Number of events and duration in which the indoor average NH<sub>3</sub> ( $\bar{C}_{i,NH_3}$ ) and CO<sub>2</sub> ( $\bar{C}_{i,CO_2}$ )  
 474 concentrations exceeded the established thresholds.

Duration [h]	NH <sub>3</sub>		CO <sub>2</sub>	
	Number of events	Maximum $\bar{C}_{i,NH_3}$ [ppm]	Number of events	Maximum $\bar{C}_{i,CO_2}$ [ppm]
From 2 to 4	7	22.3	2	3,121
From 6 to 8	7	27.0	1	3,101
From 10 to 12	1	22.0	1	3,178
From 14 to 16	4	33.1	3	3,508
From 18 to 20	9	36.5	2	4,113
From 22 to 24	0	-	2	4,744
More than 24	2	38.1	1	5,796

---

Total

30

12

---

### 475 3.2 Evaluation of the theoretical ventilation increase

476 As described in the previous sections, during the monitored period, the thresholds of NH<sub>3</sub> and  
477 CO<sub>2</sub> were exceeded repeatedly, with various time durations. In the case study, the adopted  
478 strategy to reduce those concentrations is to increase the ventilation rate. In other words, gas  
479 concentrations were used as additional control parameters of ventilation (in addition to  $\theta_{\text{air},i}$   
480 that is commonly used), and the required ventilation was modelled assuming a constant  
481 emission rate of NH<sub>3</sub> and CO<sub>2</sub>. Although other options are also available, this strategy may be  
482 the most readily convenient for a farmer. A critical assumption of the approach in this study is  
483 that gas emissions do not differ for different ventilation rates. Despite it is known that NH<sub>3</sub>  
484 emissions are affected by airflow rates and patterns (Morsing, Strom, Zhang, Kai, 2008), the  
485 effect of changing ventilation rate on gas emissions is unclear in research. On the one hand,  
486 Knížatová et al. (2010) suggested that higher ventilation is the reason of increased emissions  
487 in summer. However, higher ventilation rates at certain air temperature and relative humidity  
488 also contribute to litter drying thus reducing the emission of NH<sub>3</sub> (Weaver and Meijerhof,  
489 1991). There is no evidence of variations in CO<sub>2</sub> emissions due to changes in ventilation rates,  
490 and therefore the hypothesis of constant emission of this gas seems adequate. Furthermore,  
491 the variation in percentage between  $\dot{V}_{1+s}$  and  $\dot{V}'_{1+s}$  is generally small, being lower than 60% in  
492 90% of the considered time steps. In the primary axis of Fig. 5 the relative variation between  
493  $\dot{V}'_{1+s}$  and  $\dot{V}_{1+s}$  is shown expressed as a percentage. From the graph it stands out that during the  
494 first days the difference in percentage is higher than in the following ones, reaching its  
495 maximum value (116%). After the first days, the difference decreases, and a further increase  
496 can be noticed in the half of the monitored period. To better understand the trend of the  
497 increased ventilation flow rate, the absolute variation between  $\dot{V}'_{1+s}$  and  $\dot{V}_{1+s}$  ( $\Delta\dot{V}'_{1+s}$ ) is  
498 analysed. This trend is reported in the secondary axis of Fig. 5 and it is expressed in m<sup>3</sup> h<sup>-1</sup>.  
499 The graph shows that  $\Delta\dot{V}'_{1+s}$  is higher from January 7<sup>th</sup> to 18<sup>th</sup>, when peaks that exceed  
500 25,000 m<sup>3</sup> h<sup>-1</sup> are present. These considerable values of  $\Delta\dot{V}'_{1+s}$  depend on the increase of  
501  $\bar{C}_{i,\text{NH}_3}$  that characterizes those days (as reported in Fig. 3c). From January 19<sup>th</sup> to the end of  
502 the cycle,  $\Delta\dot{V}'_{1+s}$  is not needed because higher values of  $\dot{V}_{1+s}$  were monitored due to the  
503 increase of  $\theta_{\text{air},o}$ . The only exception is from January 24<sup>th</sup> to 30<sup>th</sup> when the decrease of  $\theta_{\text{air},o}$   
504 entails a reduction in  $\dot{V}_{1+s}$  that is not enough to maintain  $\bar{C}_{i,\text{NH}_3}$  below the established limit.

505 From the beginning of the monitored period to January 6<sup>th</sup>,  $\Delta\dot{V}'_{1+s}$  values rarely exceed  
506 10,000 m<sup>3</sup> h<sup>-1</sup>. These increases in ventilation are needed to dilute the high CO<sub>2</sub> concentration  
507 of those day that are caused by the low values of  $\dot{V}_{1+s}$  and the activation of the propane air  
508 heaters that emit exhaust fumes directly inside the house.

509 In this work, the increased ventilation flow rate was calculated considering each gas emission  
510  $\dot{q}_x$  constant and not influenced by the variation of the indoor environmental conditions. A  
511 future improvement of the present work may involve the evaluation of the theoretical increase  
512 of the ventilation flow rate considering a not constant gas emission but considering different  
513 parameters that influence NH<sub>3</sub> and CO<sub>2</sub> emissions, such as the litter conditions.

514 In the present work, the extra ventilation flow rate to control gas concentration was calculated  
515 considering that the extra supplemental heat needed to maintain  $\theta_{set,H}$  is provided by systems  
516 that do not emit exhaust fumes inside the house and, consequently, do not further increase the  
517 CO<sub>2</sub> concentration. Anyway, it was verified that if the supplemental heat would be provided  
518 by the same propane heaters that are present inside the analysed livestock house, the emitted  
519 exhaust fumes are estimated to increase the CO<sub>2</sub> concentration by less than 3% on average.  
520 This is because the CO<sub>2</sub> emissions from broilers are considerably higher than the one from the  
521 propane air heaters.

### 522 *3.3 Evaluation of the energy consumptions*

523 The analysis shows that during the monitored period around 41,900,000 m<sup>3</sup> of fresh air were  
524 provided by the fans to the broiler house. To maintain the required gas concentration during  
525 all the monitored period, around 45,800,000 m<sup>3</sup> of fresh air are theoretically needed, an  
526 increase by about 9.3%. This increase in ventilation flow rate makes it possible to respect the  
527 established gas concentration threshold but, at same time, entails a rise of the energy  
528 consumption of both electrical energy (for operating the fans) and thermal energy (for  
529 maintaining  $\theta_{set,H}$ ). In Table 5 the thermal and electrical energy consumption considering  
530  $\dot{V}_{1+s}$  and  $\dot{V}'_{1+s}$  are presented and compared. From the table it stands out that considering the  
531 increased ventilation, the electrical energy consumption rises from 1,946 kWh<sub>el</sub> ( $E_{el,1+s}$ ) to  
532 2,137 kWh<sub>el</sub> ( $E'_{el,1+s}$ ), an increase by 9.8%. Focusing on the share of the electrical energy  
533 consumption of large and small fans, the table shows that, on the one hand, the electrical  
534 energy consumption of the small fans increases by about 11.5%, rising from 1,689 kWh<sub>el</sub>  
535 ( $E_{el,s}$ ) to 1,883 kWh<sub>el</sub> ( $E'_{el,s}$ ). On the other hand, the electrical energy consumption due to the

536 operation of large fans slightly decreases by 1.2%, from 257 kWh<sub>el</sub> ( $E_{el,1}$ ) to 254 kWh<sub>el</sub> ( $E'_{el,1}$ ).  
 537 This slight decrease depends on the control logic that is set in the climate control system for  
 538 activating the fans. Most of the estimated values of  $\dot{V}'_{1+s}$ , in fact, are below the threshold of  
 539 activation of the large fans (75,000 m<sup>3</sup> h<sup>-1</sup>) and the increased ventilation flow rate is provided  
 540 almost only by the small fans which energy consumption increases. Little differences between  
 541 the real control logic of the fans and the modelled one may exist, and they may slightly affect  
 542 the results.  
 543 The increase of ventilation air flow rate entails also an increase in the thermal energy  
 544 consumption for heating, as reported in Table 5. During the monitored period, the energy  
 545 simulation model estimates  $E_{th}$  to be around 31,816 kWh<sub>th</sub>, while considering  $\dot{V}'_{1+s}$ ,  $E'_{th}$   
 546 becomes 36,190 kWh<sub>th</sub>, an increase by 13.7%.

547 **Table 5** – Comparison between the electrical ( $E_{el}$ ) and thermal energy consumption ( $E_{th}$ ) considering the actual  
 548 ventilation flow rate ( $\dot{V}_{1+s}$ ) and the electrical ( $E'_{el}$ ) and thermal energy consumption ( $E'_{th}$ ) considering the  
 549 increased ventilation flow rate ( $\dot{V}'_{1+s}$ ).

Energy consumption considering $\dot{V}_{1+s}$	Energy consumption considering $\dot{V}'_{1+s}$	Difference in percentage
<sup>1</sup> $E_{el,1}$ 257 kWh <sub>el</sub>	$E'_{el,1}$ 254 kWh <sub>el</sub>	-1.2%
<sup>2</sup> $E_{el,s}$ 1,689 kWh <sub>el</sub>	$E'_{el,s}$ 1,883 kWh <sub>el</sub>	+11.5%
$E_{el,1+s}$ 1,946 kWh <sub>el</sub>	$E'_{el,1+s}$ 2,137 kWh <sub>el</sub>	+9.8%
$E_{th}$ 31,816 kWh <sub>th</sub>	$E'_{th}$ 36,190 kWh <sub>th</sub>	+13.7

<sup>1</sup> 1 = large fans

<sup>2</sup> s = small fans

550  
 551 The increase in thermal energy consumption is focused especially on the central part of the  
 552 analysed period, as shown in Fig. 6 where the heating load needed considering  $\dot{V}_{1+s}$  ( $\Phi_H$ ) and  
 553 the theoretical heating load considering  $\dot{V}'_{1+s}$  ( $\Phi'_H$ ) are shown on the primary axis. The  
 554 monitored value of  $\theta_{air,i}$ , the values of  $\theta_{set,H}$ ,  $\theta_{set,C}$  and the simulated indoor air temperature  
 555 ( $\theta'_{air,i}$ ) are displayed on the secondary axis of the same graph. The analysis of the heating  
 556 loads shows that the  $\Phi_H$  does not reach 170 kW, that is the maximum heating load capacity of  
 557 the two propane air heaters of the broiler house. The average value of  $\Phi_H$  was estimated to be

558 around 33 kW, with a maximum value of around 94 kW. The average value of  $\Phi'_H$  is not far  
559 from the one of  $\Phi_H$ , being around 37 kW, but the charts shows that  $\Phi'_H$  trend is characterized  
560 by some peaks that are not present in  $\Phi_H$  trend, especially from January 7<sup>th</sup> to 18<sup>th</sup>, when the  
561 highest values of  $\Delta\dot{V}'_{1+s}$  were estimated. The  $\Phi'_H$  peaks exceed the threshold of 170 kW (the  
562 maximum heat capacity of the two air heaters), reaching a value around 227 kW. It means  
563 that, adopting  $\dot{V}'_{1+s}$  as ventilation profile, the propane gas heaters would not be able to  
564 maintain the established  $\theta_{set,H}$  during few hours of the monitored period. This aspect  
565 represents a further issue in increasing the ventilation flow rate to control gas concentration  
566 beyond the increase in energy consumption since in an existing broiler house, it may happen  
567 that the existing climate control system (air heaters and fans) would not be sized and designed  
568 to provide the needed ventilation flow rate and/or to the adequate heating load when  $NH_3$  and  
569  $CO_2$  concentrations should be controlled.

570 Analysing the indoor air temperatures, the graph highlights that even though  $\theta_{air,i}$  tends to  
571 fluctuate between  $\theta_{set,H}$  and  $\theta_{set,C}$  more than  $\theta'_{air,i}$ , the two trends are quite similar. Both  $\theta_{air,i}$   
572 and  $\theta'_{air,i}$  increase considerably over  $\theta_{set,C}$  on January 19<sup>th</sup> when the peak of  $\theta_{air,o}$  was  
573 monitored. On January 24<sup>th</sup>, the trends of  $\theta_{air,i}$  and  $\theta'_{air,i}$  differ relevantly. This difference is  
574 due to the broiler harvesting operations of that day that increase the ventilation flow rate (due  
575 to door opening) decreasing  $\theta_{air,i}$ . This increase in the ventilation flow rate is not considered  
576 by the energy simulation model that, consequently, underestimates  $\theta'_{air,i}$ .

577 As stated before, the production of the analysed cycle was 23,212 broilers with a final live  
578 weight of 62,534 kg. Considering a carcass yield of 73% (as stated in Costantino, Fabrizio,  
579 Biglia, Cornale and Battaglini, 2016) a total meat production of roughly 45,650 kg is  
580 estimated. Expressing  $E_{el,1+s}$  and  $E_{th}$  per unit of final product ( $kg_{meat}$ ), values of  
581  $43 Wh_{el} kg_{meat}^{-1}$  and  $697 Wh_{th} kg_{meat}^{-1}$  can be calculated, respectively. These values are  
582 comparable to the average ones found by Costantino et al., 2016, that estimated a specific  
583 energy consumption to produce a kg of broiler meet between 20 and 45  $Wh_{el}$  for ventilation  
584 and between 380 and 760  $Wh_{th}$  for heating. Considering the increase in ventilation, the  
585 previously mentioned values would increase up to 47  $Wh_{el}$  and 793  $Wh_{th}$ , but further analysis  
586 should be carried out for investigating how the improvement in the IAQ conditions may  
587 increase the meat production, entailing a consequent reduction of the specific energy  
588 consumption values.

589 In Fig. 7 the total primary energy consumption and the share due to heating and ventilation  
590 are shown for both the actual and the increased ventilation flow rates. To convert the  
591 electrical and thermal energy into primary energy, the following total conversion factors  
592 (renewable plus non-renewable energy) of Spain were used (Resolución conjunta de los  
593 Ministerios de Industria, Energía y Turismo, y Ministerio de Fomento, 2014):

- 594 •  $f_{p,tot}=2.403$  [kWh<sub>p</sub> kWh<sub>el</sub><sup>-1</sup>] for the electrical energy from the grid;
- 595 •  $f_{p,tot}=1.195$  [kWh<sub>p</sub> kWh<sub>th</sub><sup>-1</sup>] for the natural gas.

596 The chart shows that the primary energy consumption considering the actual ventilation flow  
597 rate is estimated to be about 42,696 kWh<sub>p</sub> with 12% (4,676 kWh<sub>p</sub>) due to ventilation and the  
598 remaining 88% (38,020 kWh<sub>p</sub>) due to heating. Increasing the ventilation flow rate, the  
599 primary energy consumption reaches 48,383 kWh<sub>p</sub> with similar shares of energy for  
600 ventilation 5,135 kWh<sub>p</sub> (9%) and heating 43,248 kWh<sub>p</sub> (91%). The increase of the ventilation  
601 flow rate entails an increase by 13% in terms of total primary energy.

602 A last consideration concerns the financial implications of increasing the ventilation flow rate  
603 to maintain the gas concentrations below the established thresholds. Assuming a cost for the  
604 electrical energy in Spain equal to 0.14 € kWh<sub>el</sub><sup>-1</sup> (EUROSTAT, 2019) and 0.08 € kWh<sub>th</sub><sup>-1</sup> for  
605 the thermal energy from propane (IDAE, 2019) (both costs are considered excluding taxes),  
606 the total cost for climate control considering the actual ventilation flow rate is estimated to be  
607 2,818 €, meaning around 0.117 € per harvested broiler. Increasing the ventilation flow rate,  
608 the production cost due to the energy for climate control will increase up to 3,194 € (0.133 €  
609 per broiler), an increase by 14%.

#### 610 **4 Conclusions**

611 In this work, the variation of the energy consumption due to the increase of ventilation for  
612 maintaining NH<sub>3</sub> and CO<sub>2</sub> concentrations below established thresholds (20 and 3,000 ppm,  
613 respectively) were evaluated. A winter growing cycle of broilers in a Mediterranean broiler  
614 farm was used as a case study.

615 In the monitored case study, NH<sub>3</sub> and CO<sub>2</sub> concentrations were both below the established  
616 thresholds at the same time during 40% of time. The control of CO<sub>2</sub> concentration represented  
617 a major issue during the first part of the analysed period, while the control of NH<sub>3</sub>  
618 concentration was relevant during the central part of the production cycle.

619 To maintain the desired gas concentration, the ventilation flow rate needed to be increased by  
620 around 9%. This resulted in electrical energy consumption increasing around 10% (from

621 1,946 to 2,137 kWh<sub>el</sub>), while the thermal energy increased roughly by 14%, rising from  
622 31,816 kWh<sub>th</sub> to 36,190 kWh<sub>th</sub>. The additional energy cost to maintain the gas concentration  
623 below the thresholds was estimated to be 376 € (+14%).  
624 The methodology presented here can be used for other situations (e.g. different farm designs  
625 and climate conditions) but specific technical limitations of existing farms to provide higher  
626 ventilation rates (limited capacity of fans and heaters) should be considered. This work may  
627 be improved implementing in the adopted simulation model the short-and long-term effects of  
628 changing ventilation on NH<sub>3</sub> and CO<sub>2</sub> emissions.

## 629 **5 Acknowledgements**

630 This work was supported by the Spanish Ministry of Science and Innovation [Project  
631 GASFARM-2 AGL2008-04125].  
632

## 633 **6 References**

- 634 ASHRAE. (2016). Standard 90.1-2016. *Energy Standard for Buildings Except Low-Rise Residential Buildings*.  
635 American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.  
636 <https://doi.org/http://dx.doi.org/10.1108/17506200710779521>
- 637 Anderson, D.P., Beard, C.W., & Hanson, R.P. (1964). The adverse effects of ammonia on chickens including  
638 resistance to infection with Newcastle disease virus. *Avian Research*, 8, 369-379.
- 639 Beker, A., Vanhooser, S.L., Swartzlander, J.H., & Teeter, R.G. (2004). Atmospheric Ammonia Concentration  
640 Effects on Broiler Growth and Performance. *The Journal of Applied Poultry Research*, 13, 5-9.
- 641 Calvet, S., Cambra-López, M., Blanes-Vidal, V., Estellés, F., & Torres, A.G. (2010). Ventilation rates in  
642 mechanically-ventilated commercial poultry buildings in Southern Europe: Measurement system  
643 development and uncertainty analysis. *Biosystems Engineering*, 106, 423-432.
- 644 Calvet, S., Estelles, F., Cambra-Lopez, M., Torres, A.G., & Van den Weghe, H.F.A. (2011). The influence of  
645 broiler activity, growth rate, and litter on carbon dioxide balances for the determination of ventilation  
646 flow rates in broiler production. *Poultry Science*, 90, 2449-2458.
- 647 Costantino, A., Fabrizio, E., Biglia, A., Cornale, P., & Battaglini, L. (2016). Energy use for climate control of  
648 animal houses: the state of the art in Europe. *Energy Procedia*, 101, 184-191.
- 649 Costantino, A., Ballarini, I., & Fabrizio, E. (2017). Comparison between simplified and detailed methods for the  
650 calculation of heating and cooling energy needs of livestock housing: a case study. *Proceedings of the*  
651 *3<sup>rd</sup> IBPSA-Italy Conference*. Bozen-Bolzano, Italy, February 8<sup>th</sup>-10<sup>th</sup>, 2017.
- 652 Costantino, A., Fabrizio, E., Ghiggini, A., and Bariani, M. (2018). Climate control in broiler houses: A thermal  
653 model for the calculation of the energy use and indoor environmental conditions. *Energy & Buildings*,  
654 169, 110–126.

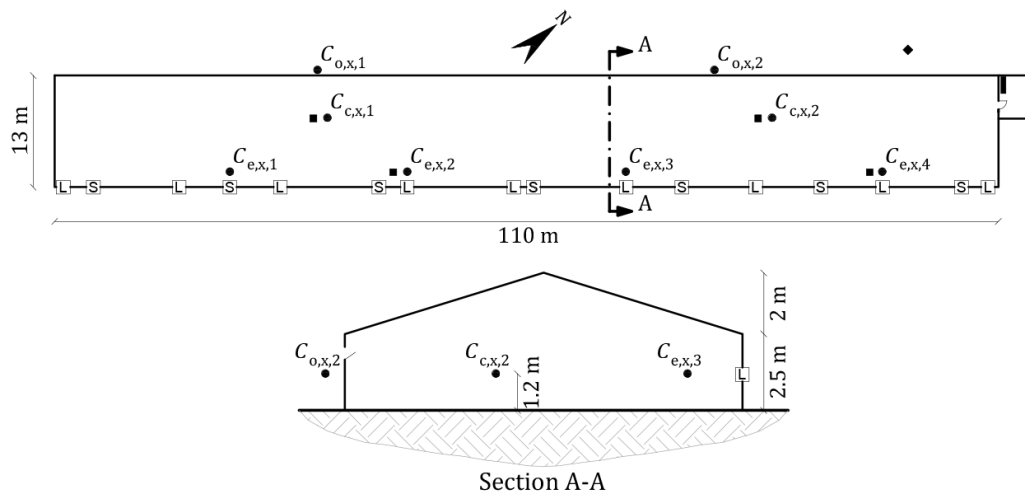
- 655 Costantino, A., & Fabrizio, E. (2020). *Introduction to Biosystems Engineering* (N. M. Holden, M. L. Wolfe, J.  
656 A. Ogejo, & E. J. Cummins, eds.). Blacksburg, Virginia: ASABE, VT Publishing (in press).
- 657 European Committee for Standardisation. *EN ISO 15927-6: Hygrothermal performance of buildings -*  
658 *Calculation and presentation of climatic data.*, CEN § (2007).
- 659 European Council. (2007) Laying down minimum rules for the protection of chickens kept for meat production,  
660 Dir. 2007/43/CE, 28<sup>th</sup> June 2007.
- 661 EUROSTAT (2019). <https://urlzs.com/LEao5>. Accessed in May 2019.
- 662 FAO- Food and Agriculture Organization of the United Nations. (2011). *Energy-smart food for people and*  
663 *climate – Issue Paper*. Rome, Italy: FAO.
- 664 Gerritzen, M.A., Lambooi, E., Hillebrand, S.J., Lankhaar, J.A., & Pieterse, C. (2000). Behavioral responses of  
665 broilers to different gaseous atmospheres. *Poultry Science* 79, 928-933.
- 666 Gerritzen, M., Lambooi, B., Reimert, H., Stegeman, A., & Spruijt, B. (2007). A note on behaviour of poultry  
667 exposed to increasing carbon dioxide concentrations. *Applied Animal Behaviour Science*, 108 (1–2),  
668 179–185.
- 669 Groot Koerkamp, P.W.G.G., Metz, J.H.M., Uenk, G.H., Phillips, V.R., Holden, M.R., Sneath, R.W., Short, J.L.,  
670 White, R.P., Hartung, J., Seedorf, J., Schroder, M., Linkert, K.H., Pedersen, S., Takai, H., Johnsen, J.O.,  
671 & Wathes, C.M. (1998). Concentrations and emissions of ammonia in livestock buildings in Northern  
672 Europe. *Journal of Agricultural Engineering Research*, 70, 79-95.
- 673 Gustin, P., Urbain, B., Prouvost, J.F., & Ansay, M. (1994). Effects of Atmospheric Ammonia on Pulmonary  
674 Hemodynamics and Vascular-Permeability in Pigs - Interaction with Endotoxins. *Toxicology and*  
675 *Applied Pharmacology* 125, 17-26.
- 676 IDAE (Instituto para la Diversificación y ahorro de la Energía). (2019). *Informe de precios energéticos:*  
677 *combustibles y carburantes - Datos a 25 de marzo de 2019*.
- 678 ISO- International Standard Organization. (2008). *Standard ISO 13790:2008. Energy performance of buildings -*  
679 *Calculation of energy use for space heating and cooling*.
- 680 ISO- International Standard Organization. (2017a). *Standard ISO 6946:2017. Building components and building*  
681 *elements - Thermal resistance and thermal transmittance - Calculation methods*.
- 682 ISO- International Standard Organization. (2017b). *Standard ISO 13786:2017. Thermal performance of building*  
683 *components -- Dynamic thermal characteristics -- Calculation methods*.
- 684 Jones, T.A., Donnelly, C.A., & Stamp Dawkins, M. (2005). Environmental and Management Factors Affecting  
685 the Welfare of Chickens on Commercial Farms in the United Kingdom and Denmark Stocked at Five  
686 Densities. *Poultry Science*, 84, 1155-1165.
- 687 Knížatová, M., Mihina, Š., Broucek, J., Karandušovská, I., Sauter, G.J., & Macuhová, J. (2010). Effect of the age  
688 and season of fattening period on carbon dioxide emissions from broiler housing. *Czech Journal of*  
689 *Animal Science*, 55, 436-444.
- 690 Kristensen, H.H., Burgess, L.R., Demmers, T.G.H., & Wathes, C.M. (2000). The preferences of laying hens for  
691 different concentrations of atmospheric ammonia. *Applied Animal Behaviour Science*, 68, 307-318.
- 692 McGovern, R.H., Feddes, J.J.R., Zuidhof, M.J., Hanson, J.A., & Robinson, F.E. (2001). Growth performance,  
693 heart characteristics and the incidence of ascites in broilers in response to carbon dioxide and oxygen  
694 concentrations. *Canadian Biosystems Engineering*, 43, 41-46.

- 695 Morsing S., Strom J.S., Zhang G., & Kai, P. (2008). Scale model experiments to determine the effects of internal  
696 airflow and floor design on gaseous emissions from animal houses. *Biosystems Engineering*, 99, 99-  
697 104.
- 698 Olanrewaju, H. A., Miller, W. W., Maslin, W. R., Thaxton, J. P., Dozier, W. A., Purswell, J., & Branton, S. L.  
699 (2007). Interactive effects of ammonia and light intensity on ocular, fear and leg health in broiler  
700 chickens. *International Journal of Poultry Science*, 6, 762-769.
- 701 Olanrewaju, H.A., Dozier, W.A., Purswell, J.L., Branton, S.L., Miles, D.M., Lott, B.D., Pescatore, A.J., &  
702 Thaxton, J.P. (2008). Growth Performance and Physiological Variables for Broiler Chickens Subjected  
703 to Short-Term Elevated Carbon Dioxide Concentrations. *International Journal of Poultry Science*, 7,  
704 738-742.
- 705 Oviedo-Rondón, E.O. (2010). Ahorro energético en granjas avícolas (Energy savings in poultry farms, in  
706 Spanish). *Proceedings of the XLII Symposium científico de avicultura*. Zaragoza, Spain, October 29<sup>th</sup>-  
707 November 2<sup>nd</sup>, 2009.
- 708 Quarles, C.L., and Kling, H.F. (1974). Evaluation of Ammonia and Infectious Bronchitis Vaccination Stress on  
709 Broiler Performance and Carcass Quality. *Poultry Science*, 53, 1592-1596.
- 710 Reindl, D.T., Beckman, W.A., & Duffie, J.A. (1990). Diffuse Fraction Correlations. *Solar Energy*, 45 (1), 1-7.  
711 [https://doi.org/10.1016/0038-092X\(90\)90060-P](https://doi.org/10.1016/0038-092X(90)90060-P).
- 712 Resolución conjunta de los Ministerios de Industria, Energía y Turismo, y Ministerio de Fomento (2014).  
713 *Factores de emisión de CO<sub>2</sub> y coeficientes de paso a energía primaria de diferentes fuentes de energía*  
714 *final consumidas en el sector de edificios en España*.
- 715 Ritz, C.W., Fairchild, B.D., & Lacy, M.P., (2004). Implications of ammonia production and emissions from  
716 commercial poultry facilities: A review. *Journal of Applied Poultry Research*, 13, 684-692.
- 717 Thornton, P.K. (2010). Livestock production: recent trends, future prospects. *Philosophical Transactions of the*  
718 *Royal Society B (Biological Sciences)*, 365, 2853–2867.
- 719 Valentine, H. (1964). A study of the effect of different ventilation rates on the ammonia concentrations in the  
720 atmosphere of broiler houses. *British Poultry Science*, 5, 149-159.
- 721 Verspecht, A., Vanhonacker, F., Verbeke, W., Zoons, J., & Van Huylenbroeck, G. (2011). Economic impact of  
722 decreasing stocking densities in broiler production in Belgium. *Poultry Science*, 90, 1844-1851.
- 723 Verstegen, M.W.A., Tamminga, S., & Greers, R., (1994). The effect of gaseous pollutants on animals. In I.Ap.  
724 Dewi, R.F.E. Axford, I. Fayed M. Marai, & H. Omed (Eds.), *Pollution in livestock production systems*  
725 (pp. 71-79). Oxon: CAB International.
- 726 Wathes, C.M., & Charles, D.R. (1994). *Livestock Housing, I*. Wallingford: CAB International.
- 727 Wathes, C.M., Jones, J.B., Kristensen, H.H., Jones, E.K.M., & Webster, A.J.F. (2002). Aversion of pigs and  
728 domestic fowl to atmospheric ammonia. *Transactions of the ASAE*, 45, 1605-1610.
- 729 Weaver, W.D., & Meijerhof, R. (1991). The effect of different levels of relative-humidity and air movement on  
730 litter conditions, ammonia levels, growth, and carcass quality for broiler-chickens. *Poultry Science*, 70,  
731 746-755.
- 732 Yi, B., Chen, L., Sa, R., Zhong, R., Xing, H. & Zhang, H. (2016). Transcriptome profile analysis of breast  
733 muscle tissues from high or low levels of atmospheric ammonia exposed broilers (*gallus gallus*). *PLoS*  
734 *one*, 11(9), p.e0162631.

- 735 Zhang, Y., and Barber, E.M. (1995). An Evaluation of Heating and Ventilation Control Strategies for Livestock  
736 Buildings. *Journal of Agricultural Engineering Research*, 60, 217-225.

737

738



### Legend

- Large fan
- ◆ Outdoor air temperature and relative humidity sensor
- Gas concentration ( $C_x$ ) sensor
- ⊗ Small fan
- Indoor air temperature and relative humidity sensor
- Automatic climate control system

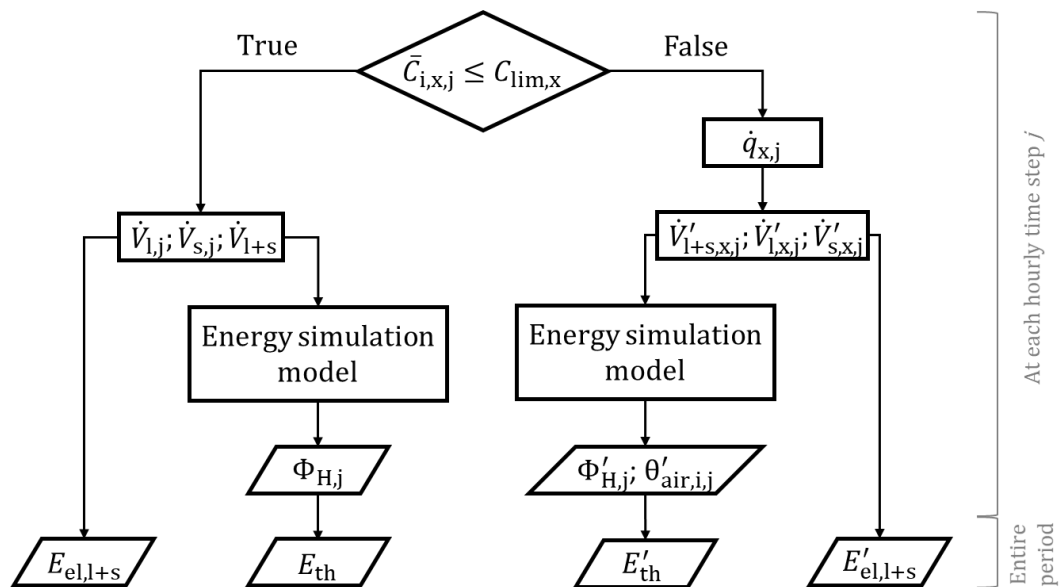
739

740

741

**Fig. 1.** Position of the sensors inside the broiler house. The figure shows also the main geometrical dimensions of the analysed house. Plan and cross section view (not at the same scale).

742



743

744

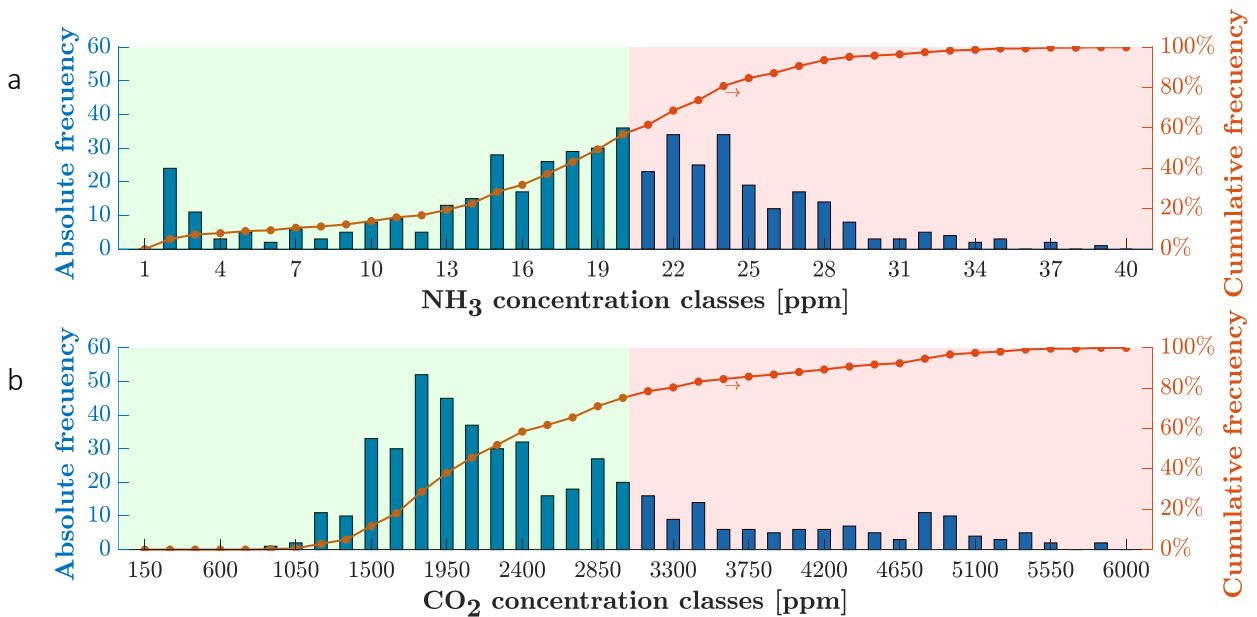
745

**Fig. 2.** Flow chart of the calculation process.



746  
747  
748  
749  
750  
751

**Fig. 3.** a) monitored indoor  $\theta_{air,i}$  and outdoor  $\theta_{air,o}$  air temperatures;  
b) actual total ventilation flow rate  $\dot{V}_{l+s}$ ;  
c) monitored indoor ( $\bar{C}_{i,NH_3}$ ) and outdoor ( $\bar{C}_{o,NH_3}$ ) NH<sub>3</sub> concentrations and indoor concentration limit ( $C_{lim,NH_3}$ );  
d) monitored indoor ( $\bar{C}_{i,CO_2}$ ) and outdoor ( $\bar{C}_{o,CO_2}$ ) CO<sub>2</sub> concentrations and indoor concentration limit ( $C_{lim,CO_2}$ ).

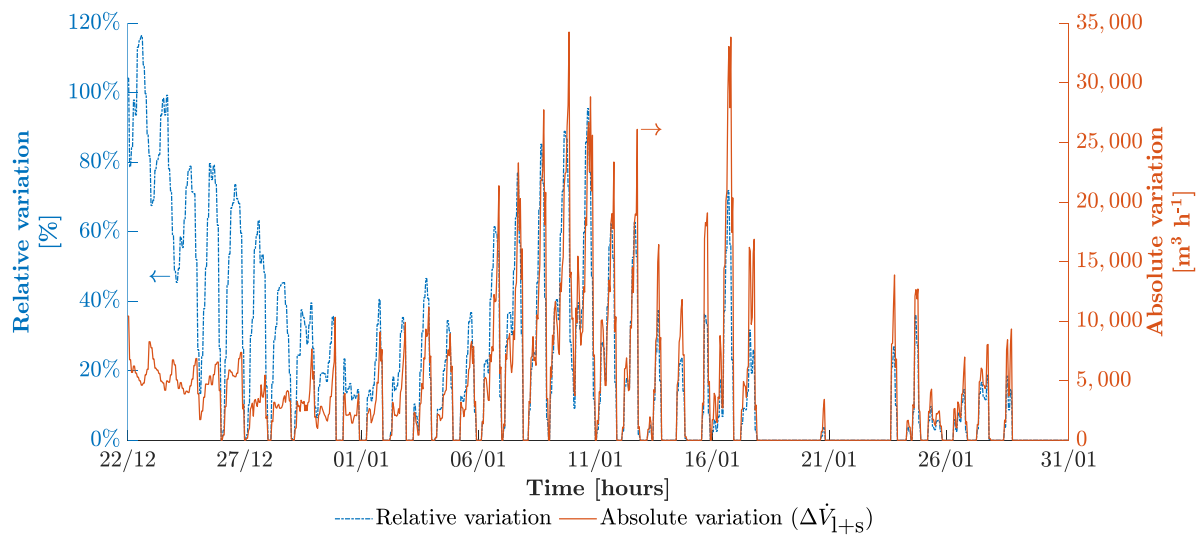


752  
753  
754

**Fig. 4.** Absolute and cumulative frequencies of:  
a) monitored indoor average NH<sub>3</sub> concentration ( $\bar{C}_{i,NH_3}$ );

755  
756

b) monitored indoor average CO<sub>2</sub> concentration ( $\bar{C}_{i,CO_2}$ )  
(arrows indicate the reference axis).

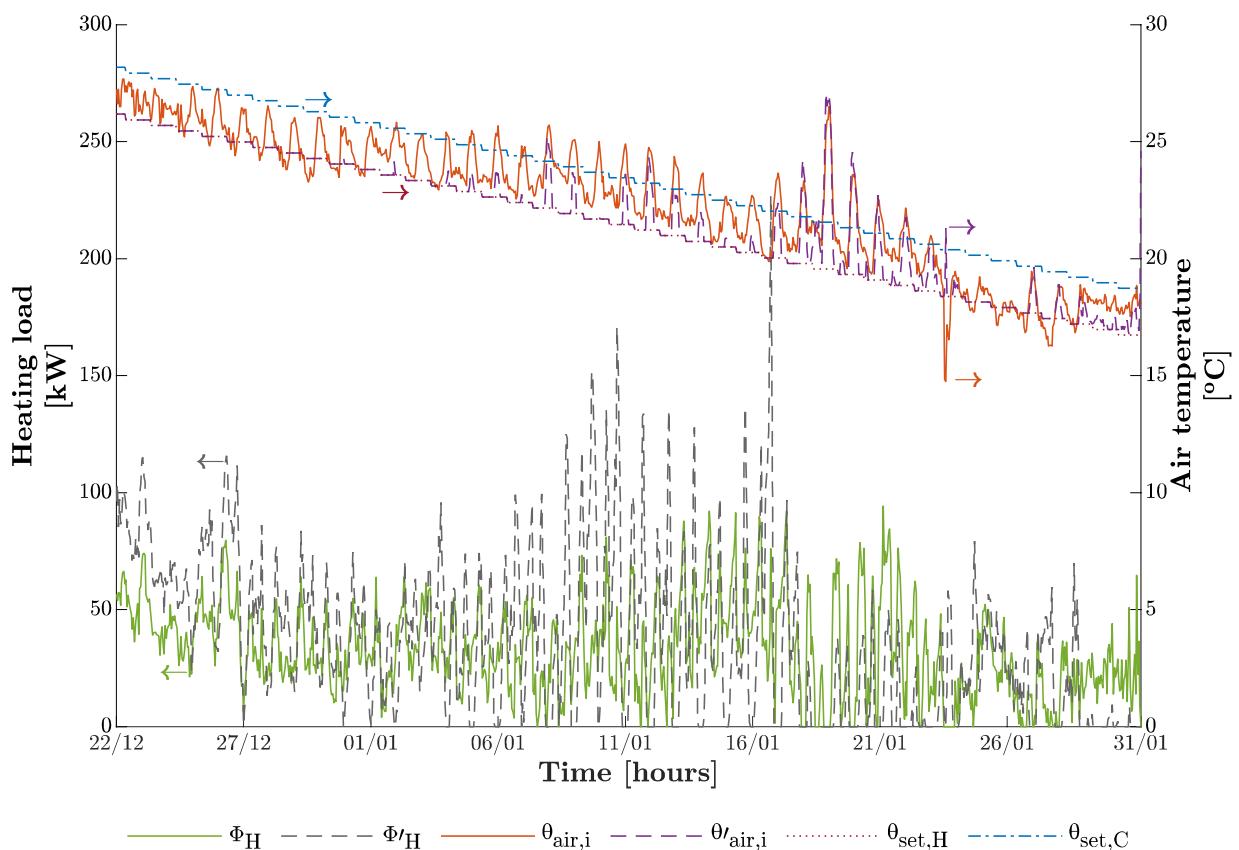


757

758 **Fig. 5.** Relative and absolute ventilation variation ( $\Delta\dot{V}'_{1+s}$ ) between increased ( $\dot{V}'_{1+s}$ ) and actual ( $\dot{V}_{1+s}$ ) ventilation  
759 flow rates (arrows indicate the reference axis).

760

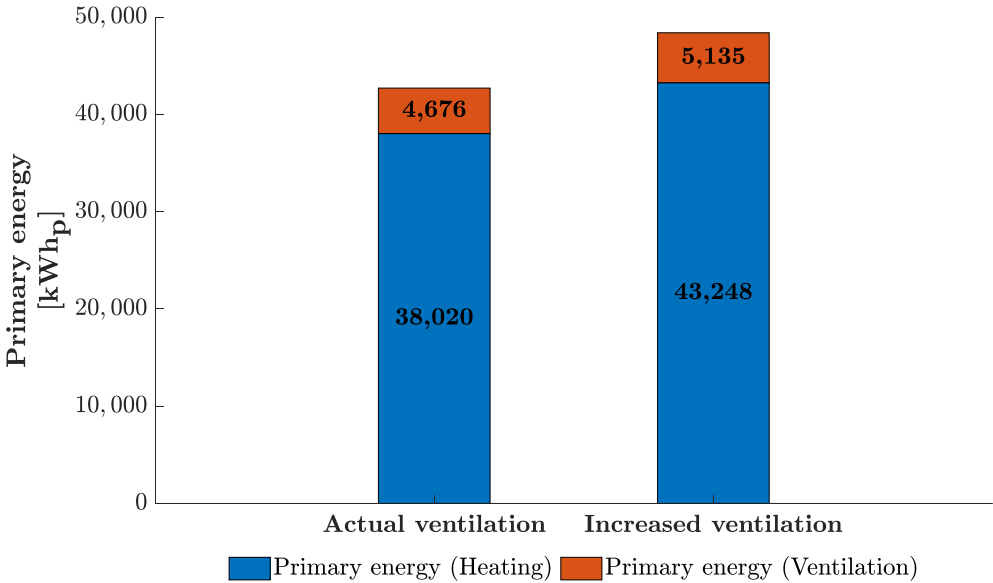
761



762

763 **Fig. 6.** Trend of indoor air temperature ( $\theta_{air,i}$ ), indoor air temperature considering increased ventilation ( $\theta'_{air,i}$ ),  
764 heating ( $\theta_{set,H}$ ) and cooling ( $\theta_{set,C}$ ) set point temperatures. On the secondary axis, heating load ( $\Phi_H$ ) and  
765 theoretical heating load ( $\Phi'_H$ ) are shown (arrows indicate the reference axis).

766



767

768

769

770

**Fig. 7.** Comparison between the total primary energy consumption (and the shares due to heating and ventilation) considering the actual and the increased ventilation flow rate.