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

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Abstract

Ammonia and carbon dioxide are the most relevant among the harmful gases present in broiler houses and their effects on animal health depend on concentration and exposure time. Inside these houses, increasing ventilation is the most common strategy adopted to control the concentration of these gases. This strategy is effective but increases the electrical energy consumption (for fan operation) and the thermal energy consumption (for inlet air heating). In this work, the variations of the energy consumptions due to the increase of ventilation for maintaining ammonia and carbon dioxide concentrations below established thresholds were evaluated. To carry out this analysis, various parameters (e.g. indoor air temperature and gas concentrations) of a broiler house located in the Mediterranean area were monitored during a production cycle in the cool (winter) season in which outdoor air temperature varied between 2 and 25 °C. The assessment of the increase of the energy consumption for climate control was carried out using the Specific Fan Performance and a customized building energy simulation model.

The analysis showed that during the monitored period, the established thresholds of gas concentrations were exceeded approximately 60% of time. To maintain the desired gas concentration, the ventilation flow rate should be increased by 9%. This variation in the ventilation flow rate entailed a rise in the energy consumption by about 10% for electrical energy and by about 14% for thermal energy. Maintaining the gas concentration below the established thresholds entails an extra cost of around 0.02 € per harvested broiler.

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 ³ Wh ⁻¹]
40	b_1	coefficient for <i>SFP</i> calculation	[m ³ Wh ⁻¹ Pa ⁻¹]
41	b_2	coefficient for <i>SFP</i> calculation	[m ³ Wh ⁻¹ Pa ⁻²]
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 _p kWh ⁻¹]
51	fan	fan (subscript)	
52	H	heating (subscript)	
53	hor	horizontal (subscript)	
54	I	solar irradiance	[W m ⁻²]
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 ⁻¹]
61	o	outdoor (subscript)	
62	p	primary energy (subscript)	
63	\dot{q}	gas emission	[mg h ⁻¹]
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_{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	Δp	static pressure difference	$[\text{Pa}]$
77	$\Delta \dot{V}'$	difference between actual and increase ventilation	$[\text{m}^3 \text{h}^{-1}]$
78	η	conversion efficiency	$[-]$
79	θ	temperature	$[\text{°C}]$
80	θ'	temperature (considering the increased ventilation)	$[\text{°C}]$
81	κ	areal heat capacity	$[\text{kJ m}^{-2} \text{K}^{-1}]$
82	Φ	heat load	$[\text{kW}]$
83	Φ'	heat load considering the increased ventilation	$[\text{kW}]$
84	ω	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 (NH_3) and carbon dioxide (CO_2). Their effects on broilers depend
 90 on their concentration as well as on the exposure duration.

91 Atmospheric 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 NH_3 is 0.7 mg m^{-3} at atmospheric pressure and 25 °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 NH₃ 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 NH₃ (Quarles and
102 Kling, 1974). More recently, it was found that broilers exposed to 25 ppm of NH₃ 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 CO₂ 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 CO₂ at 24,000 ppm (1 ppm of
109 CO₂ is 1.8 mg m⁻³ 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 CO₂ could affect broiler health when they are in
112 contemporaneity with high exposure times. For example, when broilers are exposed to CO₂
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 NH₃ and CO₂ 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⁻². However, the maximum
120 rearing density can be increased up to 42 kg m⁻² when specific environmental control
121 requirements are accomplished. Among these requirements, NH₃ concentration must be kept
122 below 20 ppm and CO₂ 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⁻² (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 NH₃ (Groot Koerkamp et al.,
127 1998) and CO₂ (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_{th} m⁻² a⁻¹ (1 kWh = 3.6 MJ) of thermal energy and
141 between 4 and 11 kWh_{el} m⁻² a⁻¹ 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⁻¹ (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, NH₃ and CO₂ 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 (CO₂ and NH₃), 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 NH₃ and CO₂ concentrations exceeded 20 and 3,000 ppm (respectively), the theoretical
168 extra ventilation flow rate needed to maintain the NH₃ and CO₂ 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 m² (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 m³.

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 (κ_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 (κ_i) of the considered building
 207 elements.

Building element	U -value [W m ⁻² K ⁻¹]	κ_i [kJ m ⁻² K ⁻¹]
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 15th with 12,000 male and 12,000 female broiler
 209 chicks and ended on January 31st (7 weeks cycle). The monitoring campaign started on the 7th
 210 day of the production cycle (December 22nd) and lasted 967 hours (around 40 days) until the
 211 end of the production cycle. On January 24th, 15% of the 42-day-old broilers were harvested
 212 from the building with an average weight of 2.33 kg broiler⁻¹. 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⁻¹ 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⁻², a value higher than the threshold of 33 kg m⁻² 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 (Δp) 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 m³ h⁻¹. 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 m³ h⁻¹. Both fan models are three-phase and fixed propeller speed fans,
230 therefore the air flow and the *SFP* vary according to Δp 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 (η_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 CO₂ 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 m³ h⁻¹, 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 Δp was obtained by the logged data in
 254 the farm automatic climate control system that manages the window openings to maintain a
 255 constant Δp 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 (ω_l) and the seven small ones (ω_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 NH_3 and 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	ω_l	%	1	90 seconds
Activation time of small fans	ω_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 ⁻²	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	Δp	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 NH₃ and CO₂

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

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 (ω_l , ω_s and Δp), 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 NH_3 and
 304 $0.04401 \text{ kg mol}^{-1}$ for 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 NH_3 and 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 NH_3 and 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 m³ h⁻¹ 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 Δp 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	$b_{l,2}$	$-5.0000 \cdot 10^{-8}$	$\text{m}^3 \text{Wh}^{-1} \text{Pa}^{-2}$
	$b_{l,1}$	$+2.0250 \cdot 10^{-4}$	$\text{m}^3 \text{Wh}^{-1} \text{Pa}^{-1}$
	$b_{l,0}$	+0.0316	[-]
Small fans	$b_{s,2}$	0	$\text{m}^3 \text{Wh}^{-1} \text{Pa}^{-2}$
	$b_{s,1}$	$+3.7110 \cdot 10^{-5}$	$\text{m}^3 \text{Wh}^{-1} \text{Pa}^{-1}$
	$b_{s,0}$	+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 κ_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 η_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 22nd, the 8th 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 31st). This decreasing
379 trend had an exception on January 19th, 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 19th, the trend of $\theta_{air,o}$ was quite
382 constant daily, and the average value of the period from December 22nd to January 18th was
383 around 10 °C. After the peak of January 19th, $\theta_{air,o}$ remained higher than in the previous days
384 with an average daily value of around 14.5 °C (January 19th – 21st). From January 22nd 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 18th, \dot{V}_{1+s}

388 gradually increased. On January 18th, a considerable increase in \dot{V}_{1+s} can be noticed and a
389 peak of about 266,000 m³ h⁻¹ (the maximum monitored value of \dot{V}_{1+s}) occurred on January
390 19th, corresponding to the sudden increase of $\theta_{air,o}$. From January 22nd 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 24th).

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 NH₃ and CO₂ 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 NH₃ 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 NH₃ 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 NH₃ emissions. From December 28th to January 18th, \bar{C}_{i,NH_3} remained
413 higher than \bar{C}_{lim,NH_3} for most of the time. After January 18th 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 \bar{C}_{lim,NH_3} for most of the
416 time. The reduction of the animal stocking density inside the house of January 24th may have
417 partially affected this decrease.

418 Despite CO₂ production from broilers and manure increases as broilers grow (Calvet, Estelles,
419 Cambra-Lopez, Torres, Van den Weghe, 2011), CO₂ 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 22nd –
428 January 6th), \dot{V}_{1+s} was at minimum values (below 50,000 m³ h⁻¹) and the CO₂ 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 6th 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 NH₃ and CO₂, 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 NH₃ (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 NH₃ 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 CO₂ 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 CO₂ concentration was easier than the one of NH₃.

473 **Table 4** – Number of events and duration in which the indoor average NH₃ (\bar{C}_{i,NH_3}) and CO₂ (\bar{C}_{i,CO_2})
 474 concentrations exceeded the established thresholds.

Duration [h]	NH ₃		CO ₂	
	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 NH₃ and
477 CO₂ 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 NH₃ and CO₂. 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 NH₃
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 NH₃ (Weaver and Meijerhof,
489 1991). There is no evidence of variations in CO₂ 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 m³ h⁻¹.
499 The graph shows that $\Delta\dot{V}'_{1+s}$ is higher from January 7th to 18th, when peaks that exceed
500 25,000 m³ h⁻¹ are present. These considerable values of $\Delta\dot{V}'_{1+s}$ depend on the increase of
501 \bar{C}_{i,NH_3} that characterizes those days (as reported in Fig. 3c). From January 19th 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 24th to 30th 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,NH_3} below the established limit.

505 From the beginning of the monitored period to January 6th, $\Delta\dot{V}'_{1+s}$ values rarely exceed
506 10,000 m³ h⁻¹. These increases in ventilation are needed to dilute the high CO₂ 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 NH₃ and CO₂ 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 CO₂ 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 CO₂ concentration by less than 3% on average.
520 This is because the CO₂ 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 m³ 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 m³ 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_{el} ($E_{el,1+s}$) to
532 2,137 kWh_{el} ($E'_{el,1+s}$), 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_{el}
535 ($E_{el,s}$) to 1,883 kWh_{el} ($E'_{el,s}$). On the other hand, the electrical energy consumption due to the

536 operation of large fans slightly decreases by 1.2%, from 257 kWh_{el} ($E_{el,1}$) to 254 kWh_{el} ($E'_{el,1}$).
 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 m³ h⁻¹) 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_{th}, while considering \dot{V}'_{1+s} , E'_{th}
 546 becomes 36,190 kWh_{th}, 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
¹ $E_{el,1}$ 257 kWh _{el}	$E'_{el,1}$ 254 kWh _{el}	-1.2%
² $E_{el,s}$ 1,689 kWh _{el}	$E'_{el,s}$ 1,883 kWh _{el}	+11.5%
$E_{el,1+s}$ 1,946 kWh _{el}	$E'_{el,1+s}$ 2,137 kWh _{el}	+9.8%
E_{th} 31,816 kWh _{th}	E'_{th} 36,190 kWh _{th}	+13.7

¹ 1 = large fans
² 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} (Φ_H) and
 553 the theoretical heating load considering \dot{V}'_{1+s} (Φ'_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 Φ_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 Φ_H was estimated to be

558 around 33 kW, with a maximum value of around 94 kW. The average value of Φ'_H is not far
559 from the one of Φ_H , being around 37 kW, but the charts shows that Φ'_H trend is characterized
560 by some peaks that are not present in Φ_H trend, especially from January 7th to 18th, when the
561 highest values of $\Delta\dot{V}'_{1+s}$ were estimated. The Φ'_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 19th when the peak of $\theta_{air,o}$ was
573 monitored. On January 24th, 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_p kWh_{el}⁻¹] for the electrical energy from the grid;
- 595 • $f_{p,tot}=1.195$ [kWh_p kWh_{th}⁻¹] 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_p with 12% (4,676 kWh_p) due to ventilation and the
598 remaining 88% (38,020 kWh_p) due to heating. Increasing the ventilation flow rate, the
599 primary energy consumption reaches 48,383 kWh_p with similar shares of energy for
600 ventilation 5,135 kWh_p (9%) and heating 43,248 kWh_p (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_{el}⁻¹ (EUROSTAT, 2019) and 0.08 € kWh_{th}⁻¹ 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 NH₃ and CO₂ 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, NH₃ and CO₂ concentrations were both below the established
616 thresholds at the same time during 40% of time. The control of CO₂ concentration represented
617 a major issue during the first part of the analysed period, while the control of NH₃
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_{el}), while the thermal energy increased roughly by 14%, rising from
622 31,816 kWh_{th} to 36,190 kWh_{th}. 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 NH₃ and CO₂ emissions.

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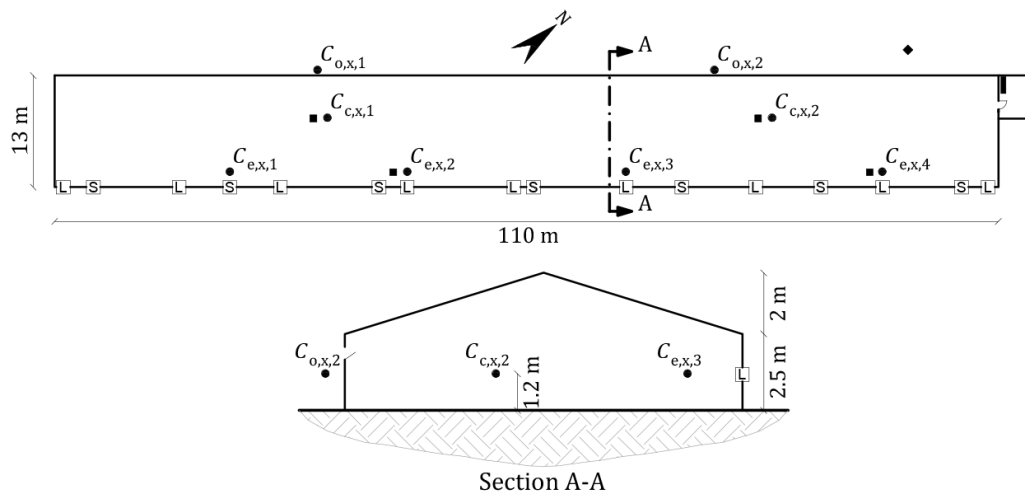
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Legend

- 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

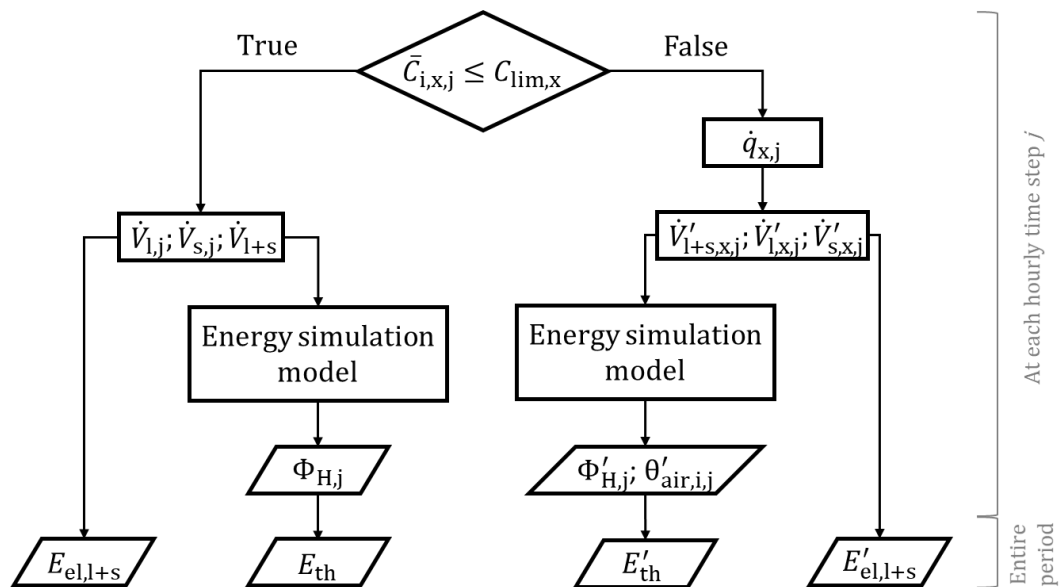
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Fig. 1. Position of the sensors inside the broiler house. The figure shows also the main geometrical dimensions of the analysed house. Plan and cross section view (not at the same scale).

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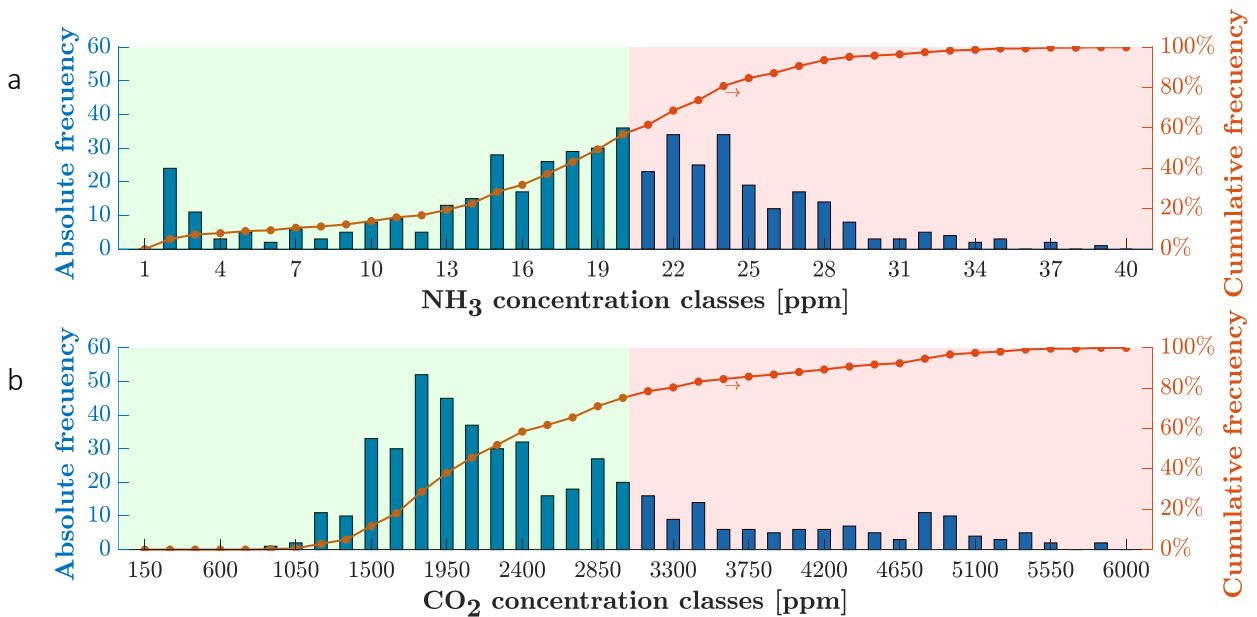
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Fig. 2. Flow chart of the calculation process.



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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}) NH₃ concentrations and indoor concentration limit (C_{lim,NH_3});
d) monitored indoor (\bar{C}_{i,CO_2}) and outdoor (\bar{C}_{o,CO_2}) CO₂ concentrations and indoor concentration limit (C_{lim,CO_2}).

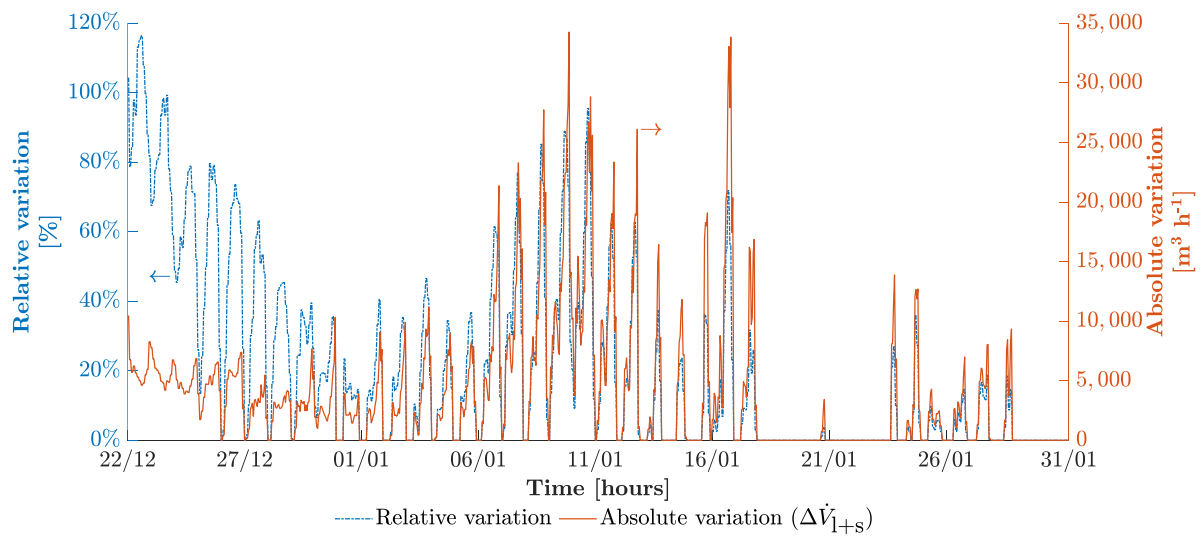


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Fig. 4. Absolute and cumulative frequencies of:
a) monitored indoor average NH₃ concentration (\bar{C}_{i,NH_3});

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b) monitored indoor average CO₂ concentration (\bar{C}_{i,CO_2})
(arrows indicate the reference axis).

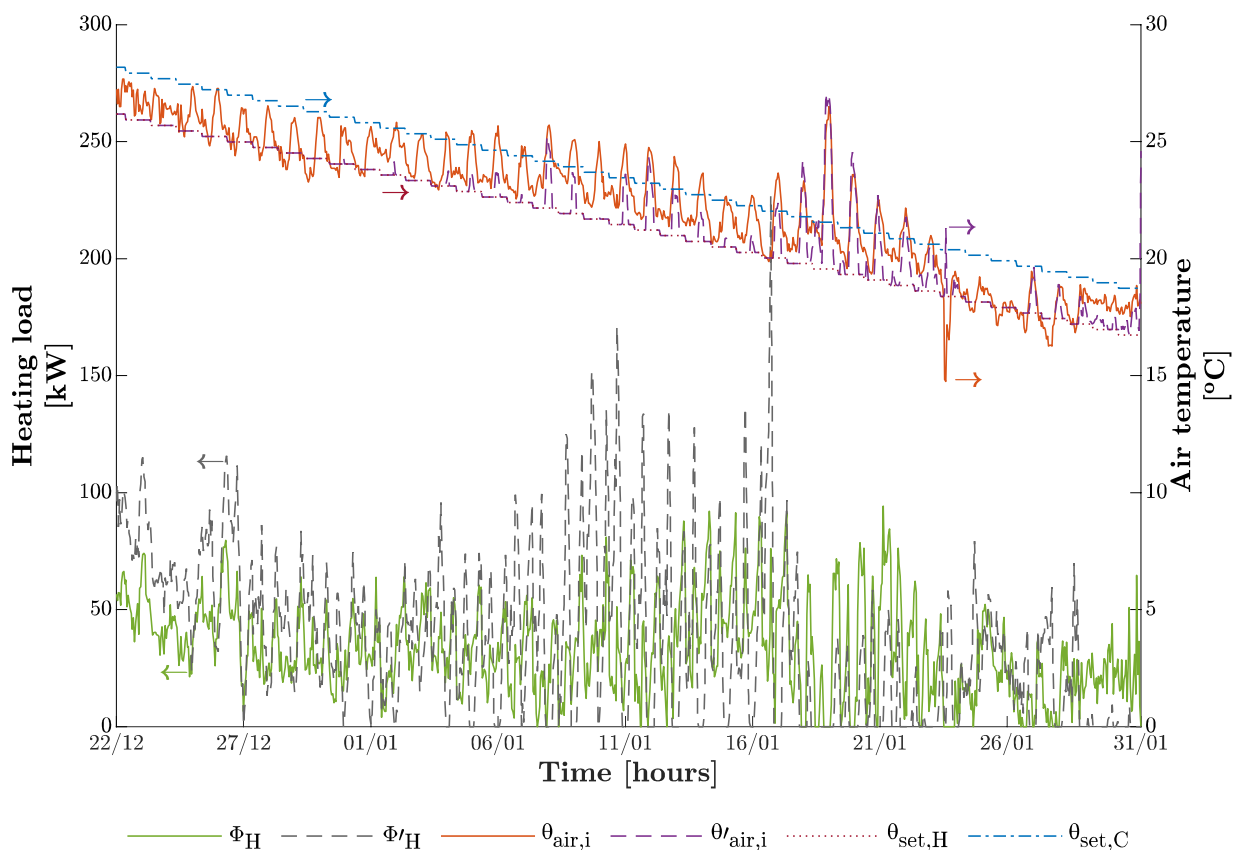


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758 **Fig. 5.** Relative and absolute ventilation variation ($\Delta\dot{V}'_{1+s}$) between increased (\dot{V}'_{1+s}) and actual (\dot{V}_{1+s}) ventilation
759 flow rates (arrows indicate the reference axis).

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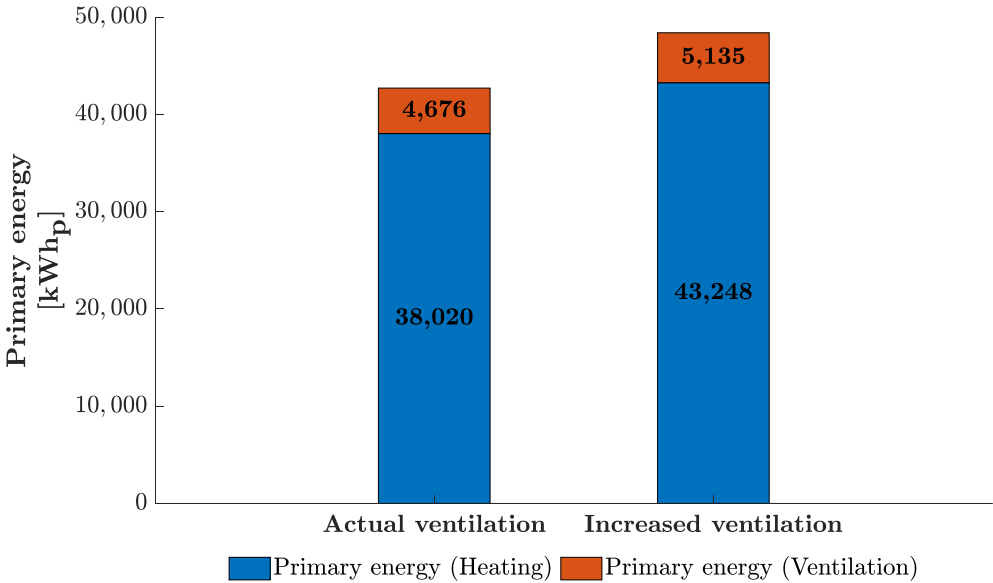
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763 **Fig. 6.** Trend of indoor air temperature ($\theta_{air,i}$), indoor air temperature considering increased ventilation ($\theta'_{air,i}$),
764 heating ($\theta_{set,H}$) and cooling ($\theta_{set,C}$) set point temperatures. On the secondary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

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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.