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# 1 Identification of energy-efficient solutions for broiler house envelopes 2 through a primary energy approach

3  
4 Andrea Costantino<sup>1,2\*</sup>, Salvador Calvet<sup>2</sup>, Enrico Fabrizio<sup>1</sup>

5 <sup>1</sup>*DENERG, Politecnico di Torino, TEBE Research Group, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

6 <sup>2</sup>*Institute of Animal Science and Technology, Universitat Politècnica de València, Camino de Vera s/n, 46022,*  
7 *València, Spain*

8 \*Corresponding author. Tel: +39 0110904552

9 E-mail address: andrea.costantino@polito.it

## 10 Abstract

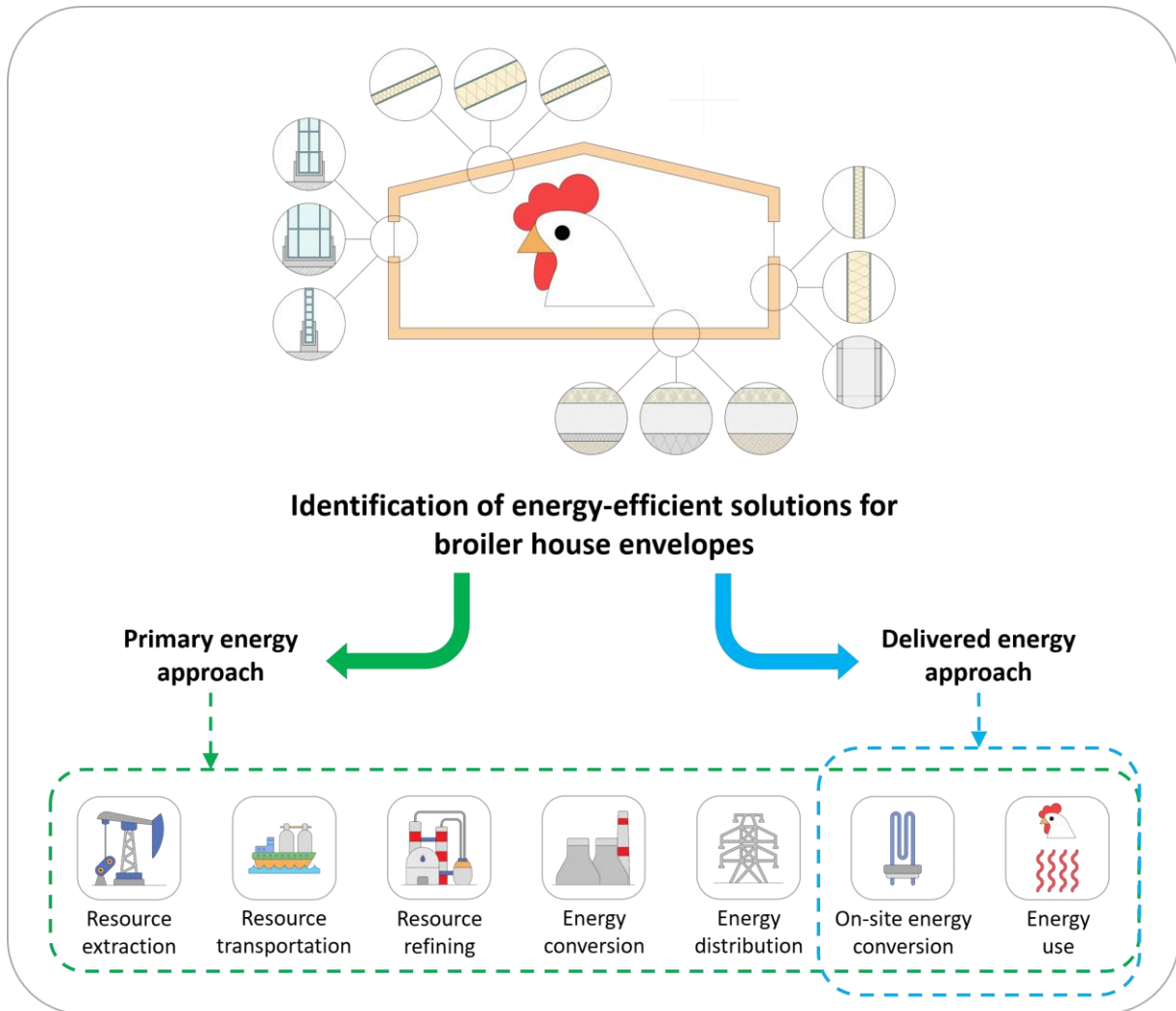
11 One of the main concerns regarding intensive broiler production is the high use of energy for  
12 climate control. An improved design of broiler house envelopes could decrease this energy  
13 consumption. Current evaluation methods only consider the delivered energy, which is  
14 misleading because it does not consider the entire energy supply chain. By contrast, primary  
15 energy encompasses all forms of direct energy, e.g. thermal and electrical, that are supplied to  
16 the broiler house, including the energy losses along the energy supply chain. In this work,  
17 delivered energy and primary energy approaches are adopted to identify the most energy-  
18 efficient solution for envelopes in typical European broiler houses. This work evaluates 18  
19 scenarios characterized by three different envelope types and six different outdoor weather  
20 conditions. Financial aspects are evaluated through global cost analysis. The results of this  
21 study show that a high-insulated envelope is suitable in the considered outdoor weather  
22 conditions, but it is not sustainable from a financial point of view. By contrast, a medium  
23 insulated envelope shows a favourable energy performance and its global cost is similar to  
24 that of a non-insulated envelope. A comparison of the results reveals that the delivered energy  
25 approach considerably underestimates the broiler house energy consumption compared to the  
26 primary energy approach. These results strongly suggest that a primary energy approach is  
27 well-suited for the assessment of the energy performance of broiler houses and livestock  
28 houses. This is because it accounts for the total direct energy supplied to the broiler house  
29 considering the specificity of the energy mix of the analysed country and the considered  
30 energy carrier. The proposed approach lays the groundwork for future research regarding the  
31 assessment of the energy performance of livestock houses.

32

33 **Keywords:** energy analysis; energy benchmarks; dynamic energy simulation model; poultry  
34 farming; global cost analysis; livestock sustainability

35  
36

37 **Graphical abstract**



## 40 Nomenclature

|                                 |   |
|---------------------------------|---|
| $A$                             | Area of opaque envelope element   |
| $C_a$                           | Annual cost [ $\text{€ m}^{-2}$ ]   |
| $C_{el}$                        | Electrical energy cost [ $\text{€ kWh}_{el}^{-1}$ ]   |
| $C_m$                           | Total building fabric heat capacity [ $\text{kJ K}^{-1}$ ]  |
| $C_G$                           | Global cost [ $\text{€ m}^{-2}$ ]   |
| $C_I$                           | Investment cost [ $\text{€ m}^{-2}$ ]   |
| $C_{th}$                        | Thermal energy cost [ $\text{€ kWh}_{th}^{-1}$ ]  |
| DE                              | Germany   |
| $E_{\text{cycle}_p\text{el}}$   | Primary energy consumption of a production cycle (electrical energy share) [ $\text{kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ ] |
| $E_{\text{cycle}_p\text{glob}}$ | Global primary energy consumption of a production cycle [ $\text{kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ ]                    |
| $E_{\text{cycle}_p\text{th}}$   | Primary energy consumption of a production cycle (thermal energy share) [ $\text{kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ ]    |
| $E_{p\text{el}}$                | Electrical share of primary energy consumption [ $\text{kWh}_p \text{ m}^{-2} \text{ y}^{-1}$ ]                                 |
| $E_{p\text{glob}}$              | Global primary energy consumption [ $\text{kWh}_p \text{ m}^{-2} \text{ y}^{-1}$ ]  |
| $E_{p\text{th}}$                | Thermal share of primary energy consumption [ $\text{kWh}_p \text{ m}^{-2} \text{ y}^{-1}$ ]                                    |
| $E_{el}$                        | Total electrical energy consumption [ $\text{kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$ ]   |
| $E_{el\text{ec}}$               | Electrical energy consumption for evaporative cooling [ $\text{kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$ ]                       |
| $E_{el\text{ven}}$              | Electrical energy consumption for ventilation [ $\text{kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$ ]                               |
| $E_{\text{meat}_el}$            | Electrical energy consumption for unit of mass of produced meat [ $\text{Wh}_{el} \text{ kg}_{\text{meat}}^{-1}$ ]              |
| $E_{\text{meat}_p\text{glob}}$  | Primary energy consumption for unit of mass of produced meat [ $\text{kWh}_p \text{ kg}_{\text{meat}}^{-1}$ ]                   |
| $E_{\text{meat}_th}$            | Thermal energy consumption for unit of mass of produced meat [ $\text{Wh}_{th} \text{ kg}_{\text{meat}}^{-1}$ ]                 |
| $E_{th}$                        | Thermal energy consumption for heating [ $\text{kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ ]                                      |
| ES                              | Spain   |
| $f_{p\text{el}_\text{tot}}$     | Total primary energy conversion factor for electrical energy [ $\text{kWh}_p \text{ kWh}_{el}^{-1}$ ]                           |
| $f_{p\text{th}_\text{tot}}$     | Total primary energy conversion factor for thermal energy [ $\text{kWh}_p \text{ kWh}_{th}^{-1}$ ]                              |
| FR                              | France  |
| $g_{gl}$                        | Solar factor of the glazed surface [-]  |
| $H_{\text{sol}_\text{hor}}$     | Annual total solar radiation on horizontal surface [ $\text{GJ m}^{-2}$ ]   |
| IAQ                             | Indoor Air Quality  |
| IT                              | Italy   |
| $j$                             | $j$ -th opaque element of the envelope  |
| $k$                             | $k$ -th time step   |
| $l$                             | $l$ -th component of cost   |
| $n_{\text{comp}}$               | Number of opaque envelope elements  |
| $n_{\text{step}}$               | Number of time steps  |
| PL                              | Poland  |
| $q$                             | $q$ -th year of broiler house lifespan  |
| $\mathcal{R}^+$                 | Set of positive real numbers  |
| $R_d$                           | Discount rate [%]   |
| $R_R$                           | Real interest rate [%]  |
| $RH_i$                          | Indoor air relative humidity [%]  |

|                                  |  |
|----------------------------------|--|
| $U$ -value                       | Stationary thermal transmittance of a generic envelope component [ $\text{W m}^{-2} \text{K}^{-1}$ ]         |
| $\bar{U}$ -value                 | Average stationary thermal transmittance of the entire building envelope [ $\text{W m}^{-2} \text{K}^{-1}$ ] |
| UK                               | United Kingdom   |
| $V_f$                            | Final value [ $\text{€ m}^{-2}$ ]  |
| $\alpha_{\text{sol}}$            | Solar absorption coefficient [–]   |
| $\gamma_{\text{PLI}}$            | Cost conversion factor [–]   |
| $\Delta p_{\text{st}}$           | Static pressure difference between inside and outside [Pa]   |
| $\Delta\tau$                     | Time interval [h]  |
| $\theta_{\text{air}_i}$          | Indoor air temperature [ $^{\circ}\text{C}$ ]  |
| $\theta_{\text{air}_o}$          | Outdoor air temperature [ $^{\circ}\text{C}$ ]   |
| $\bar{\theta}_{\text{air}_o}$    | Average annual outdoor air temperature [ $^{\circ}\text{C}$ ]  |
| $\theta_{\text{air}_\text{sup}}$ | Supply air temperature [ $^{\circ}\text{C}$ ]  |
| $\theta_{\text{set}_C}$          | Cooling set point temperature [ $^{\circ}\text{C}$ ]   |
| $\theta_{\text{set}_H}$          | Heating set point temperature [ $^{\circ}\text{C}$ ]   |
| $\kappa_i$                       | Internal heat capacity [ $\text{kJ m}^{-2} \text{K}^{-1}$ ]  |
| $\tau_{\text{Is}}$               | Broiler house lifespan [y]   |
| $\Omega_{\text{OH}}$             | Overheating index [ $^{\circ}\text{C h}$ ]   |

## 42 **1 Introduction**

43 Intensive livestock production systems are expanding to cover the increasing world food  
44 demand (Firfiris et al., 2019). Poultry meat consumption is estimated to increase by 125%  
45 before 2050 compared to 2010 (FAO, 2011a). Currently, more than 70% of the globally  
46 produced poultry derives from intensive production systems (FAO, 2011b). Poultry  
47 production is often considered the most environmentally efficient type of livestock production  
48 (Roma et al., 2015). However, increasing environmental concerns have raised questions about  
49 the sustainability of livestock production systems (Costantini et al., 2020).

50 One of the main concerns regarding broiler production is the high use of energy required to  
51 farm the animals, e.g. thermal and electrical energy, or to provide the inputs, e.g. machinery  
52 and feed. According to Heidari et al. (2011), the highest indirect energy input of poultry  
53 production is feed, that represents around 32% of the total energy inputs. Other energy inputs,  
54 e.g. for machinery and human labour, are negligible. The importance of feed as an energy  
55 input for broiler production has been underlined in literature by energy analyses, which are  
56 analyses that assess the overall energy inputs of broiler production as units of equivalent solar  
57 energy (Odum, 1995). Castellini et al. (2006), for example, compared conventional and  
58 organic broiler farming in terms of energy inputs. Allegretti et al. (2018) performed an  
59 energy assessment to show the potentialities of insect-based feed for broiler production.

60 The highest direct energy inputs in broiler production are fuel and electrical energy needed in  
61 broiler houses, that represent around 59% and 9% of the total (direct *plus* indirect) energy  
62 inputs, respectively (Heidari et al., 2011). Fuel and electrical energy are mainly used on farms  
63 for climate control, that is by far the highest share of on-farm energy consumption. According  
64 to Costantino et al. (2016), in fact, around 96% of thermal energy and around 76% of  
65 electrical energy are used for maintaining adequate indoor climate conditions. Such high  
66 shares of energy consumption highlight how an energy-efficient climate control of livestock  
67 houses could contribute to improving the environmental sustainability of livestock sector with  
68 a view to climate change (Izar-Tenorio et al., 2020). In literature, several works have  
69 investigated solutions to decrease the energy consumption for climate control of broiler  
70 houses. Most of these works focus on the improvement of the climate control system  
71 performance through the use of aerothermal heat pumps (Manolakos et al., 2019), geothermal  
72 heat pumps (Choi et al., 2012), solar systems (Gad et al., 2020) including those based on  
73 experimental parabolic concentrators (El Mogharbel et al., 2014), and heat recovery systems  
74 (Coulombe et al., 2020).

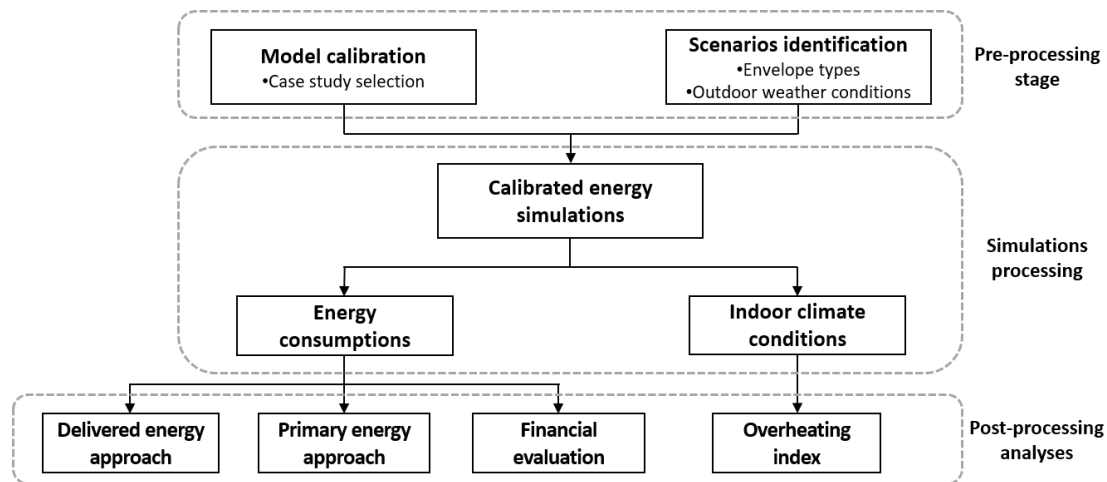
75 Whilst some research has been carried out on the improvement of the energy performance of  
76 climate control systems, there have been few investigations into the improvement of the  
77 energy performance of broiler house envelopes (Axaopoulos et al., 2014). The envelope is  
78 composed of the outer elements of a broiler house, i.e. walls, roof, floor and windows. It  
79 constitutes the boundary of thermodynamic system of the broiler house that modulates the  
80 exchange of energy - e.g. heat and solar irradiation - and mass - e.g. ventilation air and  
81 moisture - between the indoor environment - the enclosure - and the outdoor. The design of  
82 the envelope, hence, should aim at improving the energy performance for climate control  
83 through the decrease of the overall consumption of thermal and electrical energy. By contrast,  
84 in current practice, the envelope design of a broiler house is often a shallow process that  
85 provides standardized solutions for contexts that are considerably different. Therefore, there is  
86 a strong need for a design process targeted at improving the energy performance of the broiler  
87 house envelope. Energy analysis (Pimentel et al., 1973) is a powerful method to evaluate  
88 improvements of the energy performance, but research has pointed out that the robustness of  
89 this method may need to be improved (Vigne et al., 2012). Most of the energy analyses  
90 described above, in fact, evaluated the energy performance of broiler houses focusing only on  
91 thermal and electrical energy delivered on farms. Thus, the current state of the art adopts a  
92 delivered energy approach that focuses only on the very last stages of the energy supply  
93 chain, neglecting the energy consumption that occurs in the previous stages. A new approach  
94 based on primary energy could encompass all the stages of the energy supply chain. Primary  
95 energy assessment, in fact, is a single metric for assessing all forms of direct energy, e.g.  
96 thermal and electrical, that are supplied to the broiler house. Primary energy accounts for the  
97 energy losses - e.g. due to conversion and transportation - and for the energy embedded in the  
98 infrastructures - e.g. in turbines and pipes - along the energy supply chain in addition to the  
99 on-farm energy consumption. Furthermore, primary energy focuses on the adopted energy  
100 carrier, e.g. natural gas or electricity from grid, and on the considered country (ISO, 2017a).  
101 The importance of primary energy is testified by its adoption as major metric by the Energy  
102 Performance of Buildings Directive of European Union (European Commission, 2018) and it  
103 is becoming widely adopted in the energy assessment of residential (Bilardo et al., 2020) and  
104 office (Krstić-Furundžić et al., 2019) buildings and industrial processes (Dunkelberg et al.,  
105 2018). By contrast, there are few primary energy analyses of broiler houses in literature and  
106 they focus on very specific case studies and geographical contexts. Costantino et al. (2020),  
107 for example, estimated the variation of the primary energy consumption due to different  
108 ventilation strategies in a Spanish broiler house. Baxevanou et al. (2017) used the primary

109 energy approach to evaluate the energy consumption of eight broiler houses in different Greek  
110 climate contexts. Thus, improving the energy performance of broiler house envelopes through  
111 the assessment of primary energy could contribute to decreasing the energy consumption of  
112 this production system and of the entire livestock sector.

113 In this work, delivered energy and primary energy approaches are adopted to identify the  
114 most energy-efficient solution for envelopes in typical European broiler houses. For this  
115 purpose, 18 different scenarios characterized by three different envelope types and six  
116 different outdoor weather conditions are simulated. The results of the simulations are  
117 evaluated from the financial point of view and considering the heat stress risk.

## 118 2 Materials and methods

119 This work is based on the methodology workflow schematized in Fig. 1. The pre-processing  
120 stage lies in two different tasks. The first one is the identification of the adequate case study  
121 for the purpose of this work (section 2.1). The identified case study is then used to calibrate a  
122 previously developed dynamic energy simulation model (section 2.2). In the pre-processing  
123 stage the simulation scenarios are set by defining different envelope types (section 2.3) and  
124 different outdoor weather conditions (section 2.4).



125

126

**Fig. 1.** Schematization of the methodology workflow.

127 After the pre-processing stage, a calibrated simulation of a typical year of broiler production  
128 is performed per each considered scenario. The following results are obtained:

- 129 • energy consumptions for climate control, namely
  - 130 ▪ thermal energy for supplemental heating
  - 131 ▪ electrical energy for ventilation and evaporative cooling

- 132 • indoor climate conditions, namely  
133                   ▪ indoor air temperature  
134                   ▪ indoor air relative humidity.

135 The obtained energy consumptions are analysed adopting both the delivered and the primary  
136 energy approaches and the results are presented in section 3.1 and 3.2, respectively, where,  
137 additionally, reference values of energy consumption are provided. The main difference  
138 between delivered and primary energy approach is conceptualized in Fig. 2. As shown in the  
139 figure, the delivered energy approach accounts exclusively for the energy that is converted  
140 and used on farm. In this work, the delivered energy consumption of the analysed broiler  
141 house is provided directly by the energy simulation model. By contrast, the primary energy  
142 approach encompasses all the stages of the energy supply chain, from the resource extraction  
143 to the final on-farm use, as visible in Fig. 2. The primary energy consumption of the analysed  
144 scenarios is calculated from the simulation results through *ad-hoc* conversion factors. The  
145 global primary energy consumption  $E_{p\_glob}$ , is calculated as the sum of primary energy  
146 consumption due to thermal  $E_{p\_th}$  and electrical energy  $E_{p\_el}$ , as

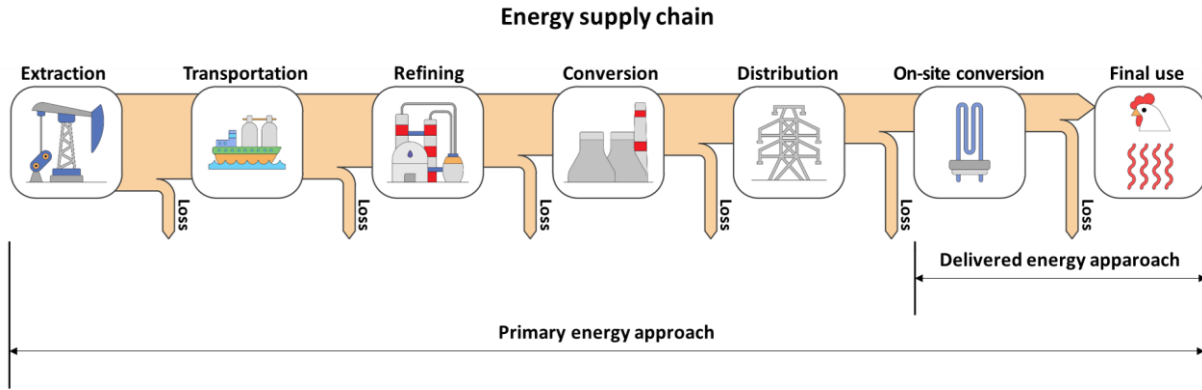
$$E_{p\_glob} = E_{p\_th} + E_{p\_el} \quad [\text{kWh}_p] \quad (1)$$

147 where

$$E_{p\_th} = E_{th} \cdot f_{p\_th\_tot} \quad [\text{kWh}_p] \quad (2)$$

$$E_{p\_el} = (E_{el\_ven} + E_{el\_ec}) \cdot f_{p\_el\_tot} \quad [\text{kWh}_p] \quad (3)$$

148 where  $f_{p\_th\_tot}$  is the total primary energy conversion factor for thermal energy and  $f_{p\_el\_tot}$  is  
149 the total primary energy conversion factor for electrical energy. These factors depend on the  
150 considered energy carrier since the overheads for extracting, refining, converting, and  
151 transporting energy change significantly depending on it. The primary energy factors are  
152 calculated at a national level since each country should consider its own energy mix. The  
153 terms  $f_{p\_th\_tot}$  and  $f_{p\_el\_tot}$  are “total” conversion factors since they account for the renewable  
154 and non-renewable primary energy shares.



155

156

**Fig. 2.** Conceptualization of the differences between the delivered and the primary energy approach.

157

As shown in Fig. 1, the scenarios are analysed from a financial point of view according to the methodology provided in section 2.5. The financial evaluation estimates how the considered types of envelope affect the global cost of the broiler house over its lifespan and the results are presented in section 3.3.

160

161

Finally, a comparison of the scenarios regarding the indoor climate conditions to assess the potential heat stress risk for broilers is performed. For this purpose, the overheating index  $\Omega_{OH}$  is assessed, as similarly done in previous works (Fabrizio et al., 2014). The overheating index indicates the extent to which indoor air temperature  $\theta_{air,i}$  exceeds the set point temperature  $\theta_{set,C}$  during a considered time interval  $\Delta\tau$  and reads

165

$$\Omega_{OH} = \sum_{k=1}^{n_{step}} (\Omega_{OH,k} \cdot \Delta\tau) \quad [^{\circ}\text{C h}] \quad (4)$$

166 with

$$\Omega_{OH,k} \in \mathcal{R}^+ \quad (5)$$

167 where

$$\Omega_{OH,k} = \theta_{air,i,k} - \theta_{set,C,k} \quad [^{\circ}\text{C}] \quad (6)$$

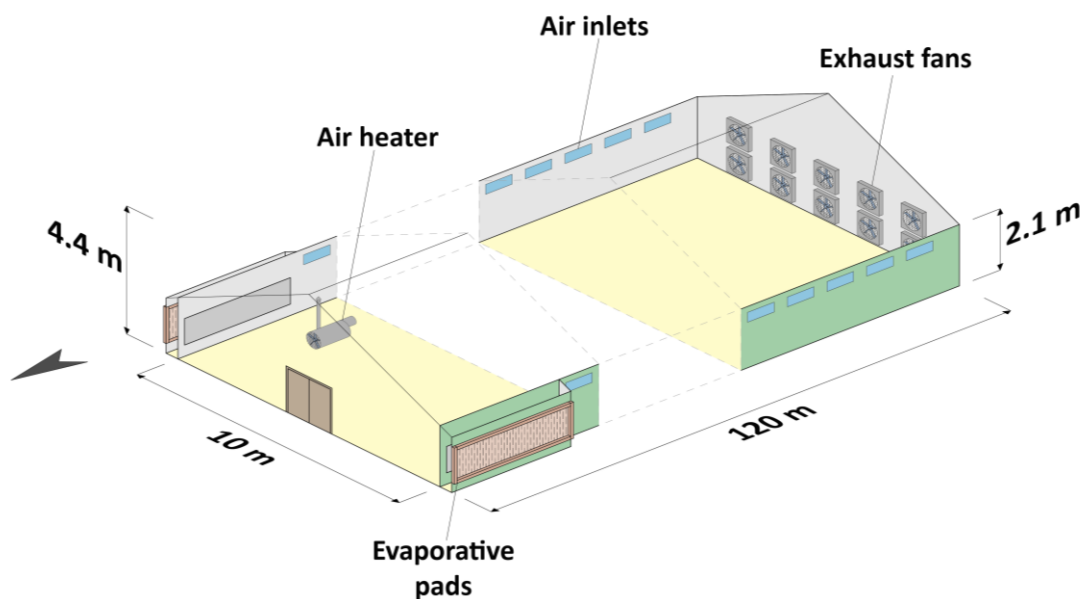
168

where  $\mathcal{R}^+$  is the set of positive real numbers,  $\Omega_{OH,k}$  is the overheating index calculated at the  $k$ -th hour and  $n_{step}$  is the number of hours in which broilers are present inside the house. The value of  $n_{step}$  in this work is 7,200 h (the total hours of the years *minus* the hours of sanitary empty periods) and  $\Delta\tau$  is equal to one hour (the simulation time step). The terms  $\theta_{air,i,k}$  and  $\theta_{set,C,k}$  are the indoor air temperature and the cooling set point temperature at the  $k$ -th hour, respectively. The results of this analysis are presented in section 3.4.

173

174 *2.1 Description of the case study*

175 The broiler house selected for this work is located in Italy, has a useful floor area of 1,200 m<sup>2</sup>  
176 (120 m long and 10 m wide) and is schematized in Fig. 3. The considered broiler house has a  
177 gable roof which height is 4.4 m of at the ridge level and 2.1 m at the eave level. The useful  
178 volume is around 3,900 m<sup>3</sup> and the largest walls of the house face east and west.  
179 The walls and the roof are made of sandwich panels, while the windows are made of  
180 polycarbonate alveolar panels. The floor is a reinforced concrete screed above a  
181 waterproofing sheet in direct contact with the ground.



182

183

**Fig. 3.** Schematization of the typical European broiler house selected as case study.

184 The considered broiler house is mechanically ventilated through a tunnel ventilation  
185 configuration, one of the most common strategy adopted in broiler house design. On the south  
186 wall, ten exhaust fans deal with both Indoor Air Quality (IAQ) control and tunnel ventilation.  
187 The mechanical power of the installed fan model is 0.75 kW (1 hp) and the diameter of the  
188 propeller (six blades) is 1.27 m. The maximum flow rate of the fan in free air delivery  
189 conditions (static pressure difference between inside and outside the house  $\Delta p_{st}$  equal to 0 Pa)  
190 is around 42,000 m<sup>3</sup> h<sup>-1</sup>. The climate control system manages the window opening to  
191 maintain  $\Delta p_{st}$  constant at 20 Pa during the production cycle.

192 When cooling ventilation cannot maintain the cooling set point temperature  $\theta_{set,C}$ ,  
193 evaporative cooling is activated, and the supply air temperature  $\theta_{air,sup}$  is decreased through  
194 the adiabatic saturation performed by the evaporative pads installed in the north part of the  
195 longest walls. Climate control system activates the evaporative cooling when the difference

196 between  $\theta_{\text{set}_C}$  and outdoor air temperature  $\theta_{\text{air}_o}$  is lower than 3 °C. The evaporative pads are  
197 150 mm thick and are made of impregnated and corrugated cellulose paper sheets. The direct  
198 saturation effectiveness of the pads (as defined by ASHRAE, 2012) is equal to 87%, as  
199 reported in the technical datasheet provided by the manufacturer. Two submersible pumps are  
200 used to pump the water from the tanks at the basis of the pads to the top of them. The  
201 electrical motor of each pump is estimated to deliver 0.55 kW (0.75 hp) of mechanical power  
202 and to absorb 0.85 kW of electrical power.

203 In the monitored broiler house, four gas air heaters provide the supplemental heating to  
204 maintain the heating set point temperature  $\theta_{\text{set}_H}$ . Each gas heater has 36 kW of heating  
205 capacity and their heating efficiency is estimated to be 100%, since they are placed directly  
206 inside the enclosure.

207 When broiler chicks are present inside the house, the climate control system maintains  $\theta_{\text{air}_i}$   
208 at 32 °C and provides  $2.3 \text{ m}^3 \text{ h}^{-1} \text{ kg}^{-1}$  of minimum ventilation to control the IAQ. At the end  
209 of the cycle,  $\theta_{\text{air}_i}$  is maintained at 17 °C and the minimum ventilation flow rate is  
210  $0.4 \text{ m}^3 \text{ h}^{-1} \text{ kg}^{-1}$ . More details about the adopted  $\theta_{\text{set}_H}$ ,  $\theta_{\text{set}_C}$  and minimum ventilation flow  
211 rates can be found in Cobb (2008). Please note that inside the broiler house, the only climate  
212 parameter that is controlled by climate control with a feedback loop is  $\theta_{\text{air}_i}$ . Indoor air  
213 relative humidity  $RH_i$  is not controlled in a feedback loop.

214 In the analysed case study, broilers are reared to reach a final live weight of around 3.6 kg in a  
215 production cycle that lasts 50 days. After each production cycle, a sanitary empty period of 11  
216 days is considered for sanitization tasks. Six production cycles are completed each year.

## 217 *2.2 Model calibration*

218 The energy consumption in the different scenarios is estimated using the previously validated  
219 energy simulation model of Costantino et al. (2018). The adopted model relies on an *ad hoc*  
220 customization of the simple hourly method in compliance with ISO 13790 standard (European  
221 Committee for Standardisation and EN ISO, 2008). The reliability of this model was proved  
222 by Costantino et al. (2018) through a validation against real monitored data in compliance  
223 with ASHRAE Guideline 14 (ANSI/ASHRAE, 2002). The adoption of a numerical model is  
224 essential for the aim of this work since enhances the comparison of the scenarios in the same  
225 standardized boundary conditions, e.g. animal stocking density and heating system efficiency,  
226 varying only the envelope thermo-physical properties and the outdoor weather conditions.

227 The adopted energy simulation model was *ad hoc* calibrated to improve the reliability of the  
 228 results of this work through an optimization-based calibration (Fabrizio and Monetti, 2015)  
 229 based on real monitored data. To do so, a long-term monitoring campaign was carried out in  
 230 the case study presented in section 2.1.

### 231 2.3 Types of broiler house envelopes

232 Three types of building envelope that are commonly used in typical European broiler houses  
 233 are considered in this work and they are presented in Table 1. The considered envelopes are  
 234 characterized by different values of average stationary thermal transmittance  $\bar{U}$ -value and  
 235 total building fabric heat capacity  $C_m$ . The term  $\bar{U}$ -value reported in Table 1 represents the  
 236 averaged stationary thermal transmittance of the entire building envelope and is calculated as

$$\bar{U} - \text{value} = \frac{\sum_{j=1}^{n_{\text{comp}}} (U - \text{value}_j \cdot A_j)}{\sum_{j=1}^{n_{\text{comp}}} A_j} \left[ \frac{\text{W}}{\text{m}^2\text{K}} \right] \quad (7)$$

237 where  $U$ -value is the stationary thermal transmittance of the  $j$ -th element of the building  
 238 envelope ( $\text{W m}^{-2} \text{K}^{-1}$ ) and  $A_j$  is its area ( $\text{m}^2$ ). The term  $n_{\text{comp}}$  is the number of building  
 239 components of the envelope.

240 The total building fabric heat capacity  $C_m$  reported in Table 1 is calculated as

$$C_m = \sum_{j=1}^{n_{\text{comp}}} (\kappa_{i,j} \cdot A_j) \left[ \frac{\text{kJ}}{\text{K}} \right] \quad (8)$$

241 where  $\kappa_{i,j}$  ( $\text{kJ m}^{-2} \text{K}^{-1}$ ) is the internal heat capacity of the  $j$ -th opaque element -calculated  
 242 according to EN ISO 13786 standard (European Committee for Standardisation, 2018)- and  
 243  $A_j$  is its area. The internal heat capacity is the amount of heat to be supplied to a unit of area  
 244 of the building component to produce a unitary change in its temperature. This parameter is  
 245 needed since describes the capacity of the building component to buffer heat during a diurnal  
 246 cycle. The term  $n_{\text{comp}}$  is the number of building components that are considered in the  
 247 calculation of  $C_m$ . In this work,  $\kappa_i$  of the transparent elements is considerably lower than the  
 248 one of the opaque ones, thus it was neglected in the simulations.

249 **Table 1** – The average stationary thermal transmittance of the entire envelope  $\bar{U}$ -value and total building fabric  
 250 heat capacity  $C_m$  of the considered envelope types.

| Envelope | Envelope features | Use | $\bar{U}$ -value<br>[W m <sup>-2</sup> K <sup>-1</sup> ] | $C_m$<br>[kJ K <sup>-1</sup> ] |
|----------|-------------------|-----|--|--------------------------------|
|----------|-------------------|-----|--|--------------------------------|

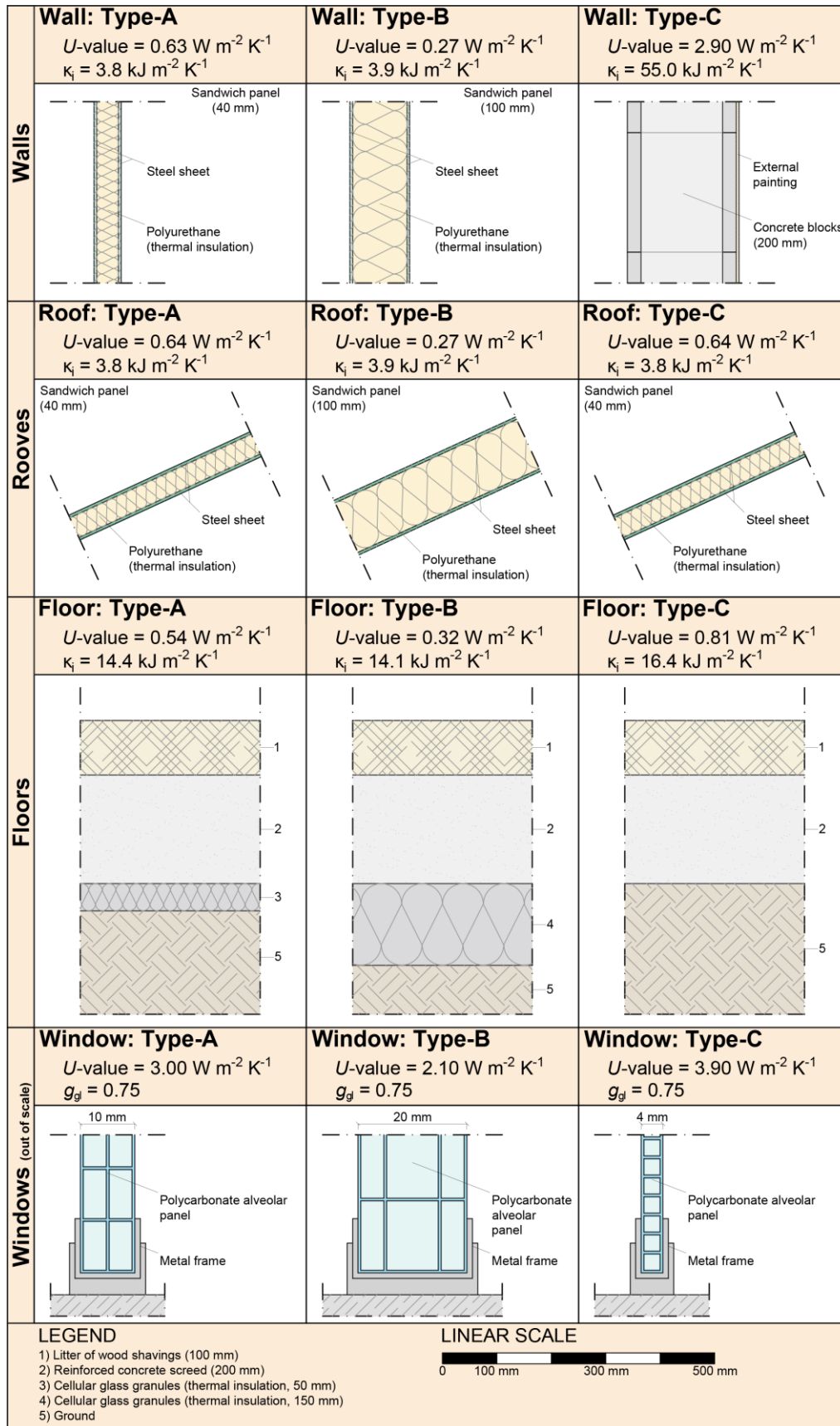
|        |                                |                       |      |        |
|--------|--------------------------------|-----------------------|------|--------|
| Type-A | Medium insulation and low mass | Modern broiler houses | 0.69 | 24,231 |
| Type-B | High insulation and low mass   | Modern broiler houses | 0.36 | 24,045 |
| Type-C | Low insulated and high mass    | Older broiler houses  | 1.15 | 49,322 |

251 The  $U$ -values (Eq. (7)) and the values of  $\kappa_i$  (Eq. (8)) for each considered envelope that are  
 252 used in this work are reported in Fig. 4 together with the solar factors of the glazed surfaces  
 253  $g_{gl}$ . All the adopted thermo-physical properties were calculated from the values reported in  
 254 international standards (ISO, 2017b), technical handbooks (ASHRAE, 2017) or technical  
 255 datasheets of commercial products.

256 The walls of type-A and type-B envelopes and all the rooves are sandwich panels made of a  
 257 double pre-painted steel sheet with the thermal insulation layer interposed (high density  
 258 spread polyurethane). The panel thickness changes according to the envelope type. The walls  
 259 of type-C envelope are made up of hollow concrete blocks. The outdoor surface of all the  
 260 walls is painted of a light colour (solar absorption coefficient  $\alpha_{sol}$  equal to 0.3), while the roof  
 261 has an intermediate colour ( $\alpha_{sol} = 0.6$ ).

262 The floors of the three envelopes are made by a reinforced concrete screed with litter of wood  
 263 shavings above. The thermo-physical properties of the litter are the ones calculated by Ahn,  
 264 Sauer, Richard, & Glanville (2009). A thermal insulation layer of cellular glass granules is  
 265 considered below the concrete screed in type-A and type-B envelopes (with different  
 266 thickness), while the floor of type-C envelope has no thermal insulation.

267 The windows of the broiler house ( $114 \text{ m}^2$  of the envelope) have metal frames and  
 268 polycarbonate alveolar panels of different thicknesses. The value of  $g_{gl}$  is considered equal to  
 269 0.75 for all the envelopes.



270

271

272

273

**Fig. 4.** Details of the building components (walls, rooves, floors and windows) of the three analysed envelope types (A, B and C). In the figure, the stationary thermal transmittances  $U$ -value, the internal aerial heat capacities  $\kappa_i$  and the solar factors of the glazed surfaces  $g_{gl}$  are shown.

## 274 2.4 Outdoor weather conditions

275 The energy performance of the analysed broiler house was assessed considering different  
 276 outdoor weather conditions of the European context. The chosen weather conditions are  
 277 proper of geographical locations characterized by the highest poultry production in Europe  
 278 and are Poland (PL), France (FR), United Kingdom (UK), Germany (DE), Spain (ES), and  
 279 Italy (IT). In these six countries more than 70% of the European poultry meat is produced  
 280 (Van Horne, 2018). For each country, the region with the highest poultry production at a  
 281 national level was individuated to perform the simulations. A reference city representative of  
 282 each one of these regions was selected for obtaining the Typical Meteorological Year (TMY),  
 283 needed for the simulation inputs. In Table 2, the six selected locations with their countries and  
 284 geographical regions are presented. In addition, the main parameters useful to characterize  
 285 their weather conditions are shown. The reference locations are characterized by different  
 286 values of average annual outdoor air temperature  $\bar{\theta}_{\text{air,o}}$  and annual total solar radiation on  
 287 horizontal surface  $H_{\text{sol,hor}}$ . In the framework of the present work,  $\bar{\theta}_{\text{air,o}}$  is the arithmetic  
 288 mean of the hourly  $\theta_{\text{air,o}}$  values over the entire year, while  $H_{\text{sol,hor}}$  is the integral of the  
 289 hourly values of solar irradiance over the entire year. From Table 2, it stands out that  
 290 Barcelona is characterized by the highest value of  $\bar{\theta}_{\text{air,o}}$  (15.7 °C) and the highest  $H_{\text{sol,hor}}$   
 291 (5.2 GJ m<sup>-2</sup> y<sup>-1</sup>). Warsaw results the location with the lowest  $\bar{\theta}_{\text{air,o}}$  (8.4 °C), while  
 292 Finninglay and Bremen are the ones characterized by the lowest  $H_{\text{sol,hor}}$  (3.4 GJ m<sup>-2</sup> y<sup>-1</sup>).

293 **Table 2** – The locations used in this work with the reference cities, acronyms, and geographical regions. For  
 294 each location, the average annual outdoor air temperature  $\bar{\theta}_{\text{air,o}}$  and the annual total solar radiation on horizontal  
 295 surface  $H_{\text{sol,hor}}$  are shown.

| Location (reference city)      | Acronym | Geographical region | $\bar{\theta}_{\text{air,o}}$<br>[°C] | $H_{\text{sol,hor}}$<br>[GJ m <sup>-2</sup> y <sup>-1</sup> ] |
|--------------------------------|---------|---------------------|---------------------------------------|---|
| Poland (Warsaw)                | PL      | Central Europe      | 8.4                                   | 3.6   |
| France (Brest)                 | FR      | Western Europe      | 11.2                                  | 3.9   |
| United Kingdom<br>(Finninglay) | UK      | Western Europe      | 9.5                                   | 3.4   |
| Germany (Bremen)               | DE      | Central Europe      | 8.9                                   | 3.4   |
| Spain (Barcelona)              | ES      | Southwest Europe    | 15.7                                  | 5.2   |
| Italy (Verona)                 | IT      | Southern Europe     | 12.3                                  | 3.9   |

296 Considering the six different locations and the three envelope types (A, B and C), 18  
 297 simulation scenarios are formulated. Each scenario is identified by a code in which the first

298 two characters indicate the reference country (acronyms from Table 2), while the last one  
 299 (separated by a dash) indicates the considered envelope type (A, B or C, Fig. 4).

300 *2.5 Financial evaluation: global cost methodology*

301 After the delivered and primary energy analyses, the scenarios are analysed from a financial  
 302 point of view to estimate how the considered types of envelope affect the global cost of the  
 303 broiler house over its lifespan. This analysis is performed in compliance with the EN 15459  
 304 international standard (CEN, 2007). The global cost  $C_G$ , here referred to the unit of useful  
 305 floor area, is the sum of the present value of all the costs estimated during the lifespan  $\tau_{ls}$  of  
 306 the broiler house and reads

$$C_G(\tau_{ls}) = C_I + \sum_{l=1}^{n_{com}} \left[ \sum_{q=1}^{\tau_{ls}} (C_{a,q,l} \cdot R_{d,q}) - V_{f,\tau_{ls},l} \right] \quad [\text{€ m}^{-2}] \quad (9)$$

307 where  $C_I$  is the initial investment cost ( $\text{€ m}^{-2}$ ),  $C_{a,q,l}$  is the annual cost regarding the  $l$ -th  
 308 component of cost calculated at the  $q$ -th year ( $\text{€ m}^{-2}$ ) of broiler house lifespan while  $V_{f,\tau_{ls},l}$  is  
 309 the final value of the  $l$ -th component at the end of its lifespan  $\tau_{ls}$  ( $\text{€ m}^{-2}$ ). The term  $R_{d,q}$  is  
 310 the discount rate (%) introduced to refer the value of money of the  $q$ -th year at the present. It  
 311 reads

$$R_d(q) = \left( \frac{1}{1 + R_R} \right)^q \cdot 100 \quad [\%] \quad (10)$$

312 where  $R_R$  is the real interest rate (%) that considers the market and inflation rates.  
 313 In this work, The global cost  $C_G$  of each proposed solution is evaluated considering 30 years  
 314 of broiler house lifespan  $\tau_{ls}$  and a real interest rate  $R_R$  of 3.5% (Hermelink and de Jager,  
 315 2015).

316 The initial investment cost  $C_I$  for IT-A, IT-B, and IT-C scenarios was estimated through an  
 317 analysis on the Italian market aimed at finding the final costs (product *plus* installation *plus*  
 318 taxes) of each considered element of the envelope and climate control system of the broiler  
 319 house. These costs are presented in Table 3 referring to the unit of useful floor area. Other  
 320 costs, such as feeders and lighting system, are not considered since they negligibly affect the  
 321 energy performance of the broiler house.

322 **Table 3** – Costs of envelope and the climate control system elements and initial investment cost  $C_I$  referred to  
 323 unit of useful floor area.

| Element | IT-A<br>[€ m <sup>-2</sup> ] | IT-B<br>[€ m <sup>-2</sup> ] | IT-C<br>[€ m <sup>-2</sup> ] |
|---------|------------------------------|------------------------------|------------------------------|
| Walls   | 17.49                        | 32.07                        | 21.60                        |

|                         |        |        |        |
|-------------------------|--------|--------|--------|
| Roof                    | 45.25  | 76.95  | 45.25  |
| Floor                   | 107.93 | 208.43 | 53.72  |
| Windows                 | 4.03   | 5.03   | 3.39   |
| Fans                    | 4.37   | 4.37   | 4.37   |
| Gas air heaters         | 6.51   | 6.51   | 7.81   |
| Evaporative pads        | 3.30   | 3.30   | 3.30   |
| Pad pumps and pipelines | 4.55   | 4.55   | 4.55   |
| $C_I$                   | 193.43 | 341.21 | 143.99 |

324 The  $C_I$  values for the other considered countries can be estimated assuming that the difference  
 325 between the  $C_I$  values of two countries depends on the difference between their purchasing  
 326 powers due to the fluctuations in currency exchange rates, as reported in Eurostat (2019).  
 327 Hence, the  $C_I$  values for the other considered countries are obtained by multiplying the  $C_I$   
 328 values for the Italian context -last row of Table 3- by the dimensionless cost conversion factor  
 329  $\gamma_{PLI}$ . This factor is the ratio between the construction price level of the considered European  
 330 country and the Italian one. In this work,  $\gamma_{PLI}$  values are obtained by elaborating the Price  
 331 Level Indices for non-residential buildings construction provided by Eurostat (2019). The  
 332 considered  $\gamma_{PLI}$  values are presented in Table 4.

333 The considered annual costs  $C_a$  over the broiler house lifespan are due to energy and due to  
 334 the replacement of the elements of climate control system. Other annual costs, such as  
 335 insurances and ordinary maintenance, are considered out of the scope of this work. The  
 336 annual cost of energy is estimated multiplying the yearly thermal and electrical energy  
 337 consumptions obtained from the simulations by the cost of thermal  $C_{th}$  and electrical  $C_{el}$   
 338 energy for the considered country. The costs of energy adopted in this work were obtained  
 339 from Eurostat (2020a, 2020b) and are reported in Table 4. The annual cost of element  
 340 replacement for climate control system is estimated considering the initial costs presented in  
 341 Table 3 and estimating a lifespan of 15 years for fans, gas air heaters and pumps and pipeline  
 342 of the evaporative cooling system. The lifespan of the evaporative pads was estimated equal  
 343 to 5 years. At the end of the broiler house lifespan, no final value  $V_f$  (Eq. (9)) is considered for  
 344 envelope and climate control system elements.

345 **Table 4** – Considered cost conversion factor  $\gamma_{PLI}$  and costs of thermal  $C_{th}$  and electrical  $C_{el}$  energy (including  
 346 taxes).

| Country | $\gamma_{PLI}$<br>[–] | $C_{th}$<br>[€ kWh <sub>th</sub> <sup>-1</sup> ] | $C_{el}$<br>[€ kWh <sub>el</sub> <sup>-1</sup> ] |
|---------|-----------------------|--|--|
| PL      | 0.78                  | 0.04   | 0.15   |
| FR      | 1.23                  | 0.08   | 0.19   |

|    |      |      |      |
|----|------|------|------|
| UK | 1.38 | 0.05 | 0.22 |
| DE | 1.67 | 0.06 | 0.30 |
| ES | 0.95 | 0.07 | 0.22 |
| IT | 1.00 | 0.07 | 0.22 |

### 347 **3 Results and discussion**

348 Each one of the 18 considered scenarios is simulated in standardized conditions using the  
 349 calibrated energy model. The results of the simulations are analysed to identify the best  
 350 envelope solution in terms of delivered and the primary energy performance. In addition, the  
 351 results are compared in terms of global cost and overheating index.

#### 352 *3.1 Delivered energy approach*

353 The delivered energy consumption is evaluated considering the thermal energy consumption  
 354 for heating  $E_{th}$ , the electrical energy consumption for ventilation  $E_{el\_ven}$  and for evaporative  
 355 cooling  $E_{el\_ec}$ . The values of  $E_{th}$  and  $E_{el\_ven}$  are calculated by the model considering the  
 356 efficiency of the heating system and the features of the ventilation system. The value of  $E_{el\_ec}$   
 357 is calculated by the model considering the electrical energy consumption of the circulation  
 358 pumps.

##### 359 *3.1.1 Thermal and electrical energy consumption*

360 In the bar charts of Fig. 5,  $E_{th}$ ,  $E_{el\_ven}$  and  $E_{el\_ec}$  are presented normalized per unit of floor  
 361 area. The graph shows that important differences in terms of  $E_{th}$  (Fig. 5a) stand out among the  
 362 analysed scenarios. The highest  $E_{th}$  values are from PL-C ( $163.7 \text{ kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ ), DE-C  
 363 ( $142.7 \text{ kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ ) and UK-C ( $119.0 \text{ kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ ) scenarios, respectively. The  
 364 lowest values of  $E_{th}$  result from ES-B ( $19.6 \text{ kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ ), FR-B ( $29.3 \text{ kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ )  
 365 and ES-A ( $36.3 \text{ kWh}_{th} \text{ m}^{-2} \text{ y}^{-1}$ ). The lowest values of  $E_{th}$  (ES-B scenario) is 88% lower  
 366 than the highest  $E_{th}$  (PL-C scenario) highlighting the effects that outdoor weather conditions  
 367 and envelope type have in terms of thermal energy consumption of broiler houses.

368 Looking at the values of  $\bar{\theta}_{air\_o}$  presented in Table 2, it stands out that the highest  $E_{th}$  values  
 369 come from the outdoor weather conditions characterized by the lowest  $\bar{\theta}_{air\_o}$ . Solar radiation  
 370 seems to not have the same influence of  $\theta_{air\_o}$  on  $E_{th}$  because, even though PL-C is  
 371 characterized by a slightly higher value of  $H_{sol\_hor}$  than DE-C, its  $E_{th}$  is considerably higher  
 372 than the one of DE-C. An interesting analysis in this sense is the comparison between the

373 sensible heat load from broilers with the heat load from solar radiation. Considering the last  
374 day of the production cycle in August, the maximum solar heat load that should be removed  
375 from the enclosure per unit of useful floor area is 47 W in scenario ES-C. At the same  
376 moment, the sensible heat load due to the animals is  $176 \text{ W m}^{-2}$  of useful floor area, a value  
377 that is nearly four times higher the one of the solar heat load. This difference means that  
378 sensible heat load from animals represents the major issue for cooling ventilation broiler  
379 houses, even in mild climates such as the one of ES-C scenario. Please note that in this work,  
380 the total solar radiation on any surface was calculated from the hourly values of direct normal  
381 radiation and diffuse horizontal solar radiation reported in the TMY adopting the transposition  
382 model of ASHRAE (2017). The calculation of the solar gains from the solar irradiance on  
383 opaque and transparent envelope components was performed in compliance with EN ISO  
384 13790 standard (European Committee for Standardisation and EN ISO, 2008).

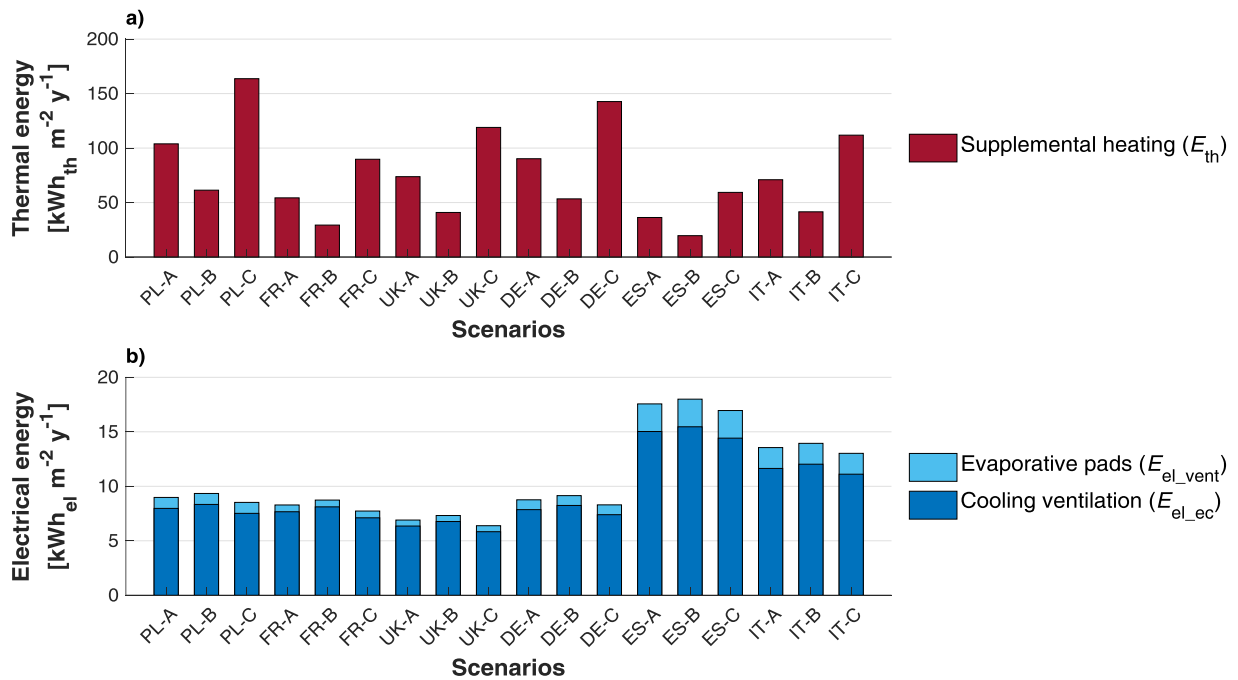
385 The results of the simulations show that, from the delivered energy point of view, the  
386 adoption of the high-insulation and low-massive building envelope (type-B) represents an  
387 interesting strategy to reduce  $E_{\text{th}}$  in all the considered weather conditions, because the type-B  
388 envelope entails the lowest  $E_{\text{th}}$ . The relative differences between the thermal energy  
389 performance of the considered envelopes in the same weather conditions are important. The  
390 choice of a high-insulation building envelope (type-B) reduces  $E_{\text{th}}$  between 63 and 67% if  
391 compared to a non-insulated envelope (type-C). The increase of the thermal insulation layer  
392 (from type-A to type-B envelope) entails a decrease of  $E_{\text{th}}$  between 41 and 46%.

393 High-insulation building envelope (type-B) resulted the best option for decreasing  $E_{\text{th}}$ , but the  
394 better thermal insulation properties favour the overheating of the enclosure. Consequently,  
395 higher electrical energy consumptions for ventilation  $E_{\text{el\_ven}}$  and evaporative cooling  $E_{\text{el\_ec}}$   
396 are expected compared to the other envelope types. In Fig. 5b, the electrical energy  
397 consumptions  $E_{\text{el\_ven}}$  and  $E_{\text{el\_ec}}$  are presented and the bar chart indicates that, actually,  $E_{\text{el\_ven}}$   
398 is higher when type-B envelope is considered. The highest value of  $E_{\text{el\_ven}}$  come from Spain  
399 (ES-B,  $15.5 \text{ kWh}_{\text{el}} \text{ m}^{-2} \text{ y}^{-1}$ ) while the lowest one from United Kingdom (UK-C,  
400  $5.8 \text{ kWh}_{\text{el}} \text{ m}^{-2} \text{ y}^{-1}$ ). Even in this case, the higher  $E_{\text{el\_ven}}$  values come from the weather  
401 conditions characterized by the higher  $\bar{\theta}_{\text{air}_o}$ , namely Spain ( $15.7 \text{ }^\circ\text{C}$ ) and Italy ( $12.3 \text{ }^\circ\text{C}$ ).

402 The  $E_{\text{el\_ec}}$  values presented in Fig. 5b are the same for each considered geographical location  
403 regardless of the analysed envelope type. This is because the adopted energy model simulates  
404 the activation of the evaporative cooling only depending on the temperature difference  
405 between  $\theta_{\text{set}_C}$  and  $\theta_{\text{air}_o}$ . The bar chart of Fig. 5b shows greater  $E_{\text{el\_ec}}$  for those scenarios

406 where the  $E_{el\_ven}$  is higher, such as Spain and Italy. The estimated  $E_{el\_ec}$  values are  
 407 considerably smaller than  $E_{el\_ven}$ , being  $2.5 \text{ kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$ , or lower, for all the considered  
 408 scenarios.

409 The total electrical energy consumption  $E_{el}$  (sum of  $E_{el\_ven}$  and  $E_{el\_ec}$ ) ranges between  
 410  $18.0 \text{ kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$  and  $6.4 \text{ kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$ . The adoption of a low insulated envelope  
 411 (type-C) decreases it from 6 to 13% if compared to a high-insulation envelope (type-B).



412  
 413 **Fig. 5.** Thermal ( $E_{th}$ , figure a), and electrical energy consumption (figure b) both for ventilation ( $E_{el\_ven}$ ) and  
 414 evaporative cooling ( $E_{el\_ec}$ ) from the 18 scenarios.

### 415 3.1.2 Reference values of delivered energy consumption

416 The delivered energy consumption values are now used to provide reference values about the  
 417 use of energy in broiler houses. Similar values are interesting from the scientific point of view  
 418 with a perspective on the improvement of the energy efficiency of broiler production, but very  
 419 few of them are present in literature, as highlighted by Costantino et al. (2016). Most of the  
 420 existing reference values, in fact, refers to specific case studies or geographical contexts, as  
 421 done by Hörndahl (2008) for the Swedish context, the Technical Institute of Poultry (2010)  
 422 for the France and Rossi et al. (2013) for Italy. In addition, those reference values were not  
 423 assessed in standardized conditions, a feature that may jeopardize their reliability. By  
 424 contrast, the reference values present in this section were calculated in standardized  
 425 conditions, refer to different European context and consider different types of building  
 426 envelope. Nevertheless, more accurate results would be obtained performing simulations

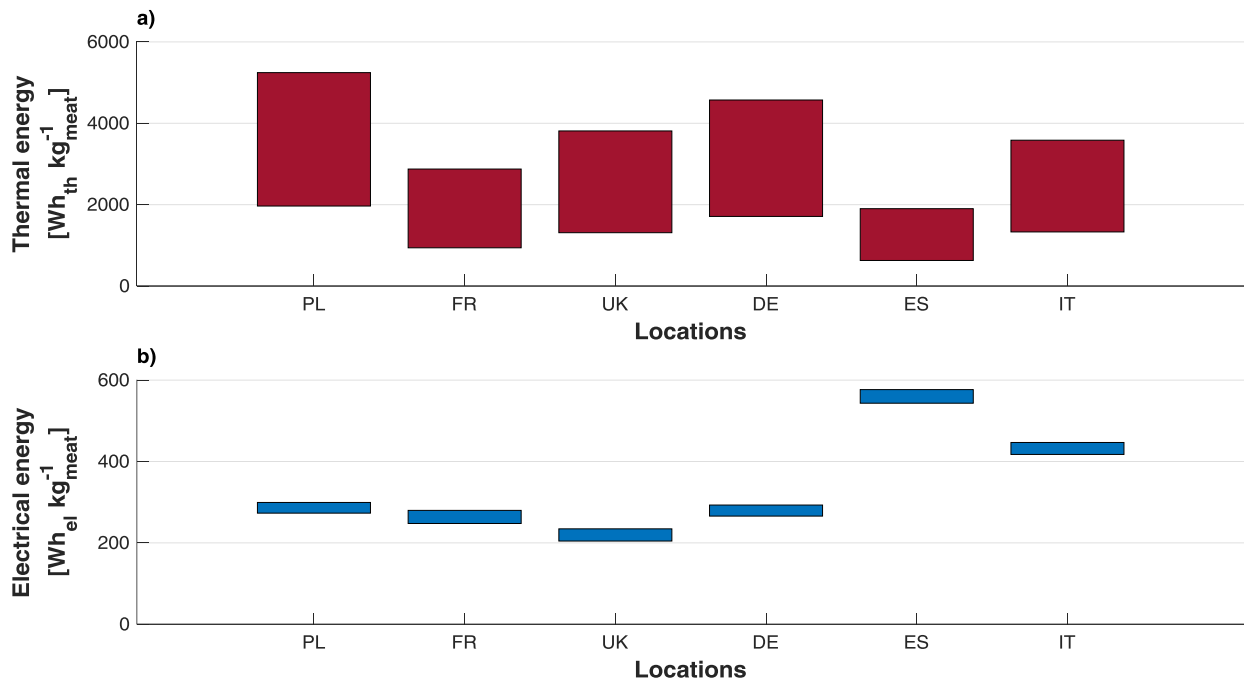
427 using Monte Carlo method to consider a higher variations of boundary conditions and  
428 sensitivity analysis can better investigate the influence of each parameter on the final results.  
429 The results obtained from the simulated scenarios are normalized on the  $\text{kg}_{\text{meat}}$  and grouped  
430 to obtain ranges of delivered energy consumption for climate control. This normalization is  
431 necessary to make the results independent from the assumptions made for this work, such as  
432 the farming features. Furthermore, the adopted unit of measure ( $\text{Wh kg}_{\text{meat}}^{-1}$ ) is useful for  
433 engineers and farmers since they can refer production costs and revenues to the unit of final  
434 product. The saleable meat from each broiler is calculated considering a carcass yield,  
435 percentage of the saleable meat over the final live weight, of 73% (Costantino et al., 2016).  
436 Consequently, a meat production of 2.60  $\text{kg}_{\text{meat}}$  per harvested broiler is estimated. The main  
437 limitation in the formulation of these reference values is the estimation of the broiler final live  
438 weight that does not consider eventual decrease of weight gain due to, for example, heat  
439 stress. This issue could be considered in future works using the formulations provided by St-  
440 Pierre, Cobanov, & Schnitkey (2003).

441 In Fig. 6, the ranges of the specific thermal  $E_{\text{meat\_th}}$  (Fig. 6a) and electrical energy  
442 consumption  $E_{\text{meat\_el}}$  (Fig. 6b) referred to the selected countries are presented. The values of  
443  $E_{\text{meat\_th}}$  and  $E_{\text{meat\_el}}$  were calculated dividing the yearly thermal and electrical energy  
444 consumption by the meat production over the entire year. The presented ranges consider the  
445 minimum and the maximum values of  $E_{\text{meat\_th}}$  and  $E_{\text{meat\_el}}$  (sum of electrical energy  
446 consumption for ventilation and evaporative cooling) of each country considering the three  
447 envelope types.

448 The range of  $E_{\text{meat\_th}}$  goes from 628  $\text{Wh}_{\text{th}} \text{kg}_{\text{meat}}^{-1}$  (Spain) to 5,245  $\text{Wh}_{\text{th}} \text{kg}_{\text{meat}}^{-1}$  (Poland).  
449 Three countries (France, United Kingdom, and Italy) are in the range from 940 to  
450 3,812  $\text{Wh}_{\text{th}} \text{kg}_{\text{meat}}^{-1}$ , while the  $E_{\text{meat\_th}}$  of Germany and Poland is between the range 1,711 –  
451 5,245  $\text{Wh}_{\text{th}} \text{kg}_{\text{meat}}^{-1}$ . Spain is the country with the narrower range of  $E_{\text{meat\_th}}$  that goes from  
452 628 to 1,901  $\text{Wh}_{\text{th}} \text{kg}_{\text{meat}}^{-1}$ .

453 The ranges presented in Fig. 6b are narrower and of an order of magnitude lower than the  
454 ones of Fig. 6a. The difference between the highest and the lowest value of each country  
455 presented in Fig. 6b is between 26 and 33  $\text{Wh}_{\text{el}} \text{kg}_{\text{meat}}^{-1}$ . The lowest  $E_{\text{meat\_el}}$  is the one from  
456 Great Britain (205  $\text{Wh}_{\text{el}} \text{kg}_{\text{meat}}^{-1}$ ) while the greatest one is from Spain (577  $\text{Wh}_{\text{el}} \text{kg}_{\text{meat}}^{-1}$ ).  
457  $E_{\text{meat\_el}}$  of four countries (Poland, France, United Kingdom, and Germany) is between 205

458 and  $299 \text{ Wh}_{\text{el}} \text{ kg}_{\text{meat}}^{-1}$ . The  $E_{\text{meat}_{\text{el}}}$  value from Italy is between  $417$  and  $447 \text{ Wh}_{\text{el}} \text{ kg}_{\text{meat}}^{-1}$ ,  
 459 while Spain has the wider  $E_{\text{meat}_{\text{el}}}$  range ( $543 - 577 \text{ Wh}_{\text{el}} \text{ kg}_{\text{meat}}^{-1}$ ).



460  
 461 **Fig. 6.** Ranges of specific thermal ( $E_{\text{meat}_{\text{th}}}$ , figure a) and electrical energy consumption ( $E_{\text{meat}_{\text{el}}}$ , figure b) for  
 462 the considered locations.

### 463 3.2 Primary energy approach

464 The previous analysis assessed the delivered energy consumption. Type-B envelope resulted  
 465 the best solution to decrease  $E_{\text{th}}$ , while type-C envelope was the worst one by far in all the  
 466 considered locations. On the contrary, type-C envelope was characterized by the best  
 467 performance considering the electrical energy consumption for ventilation and evaporative  
 468 cooling. Type-A envelope is the intermediate solution for both thermal and electrical energy  
 469 consumption.

470 To identify the best global solution, the primary energy performance is assessed for the 18  
 471 scenarios. In this way, the thermal and electrical energy consumption can be correctly  
 472 weighted considering their respective energy overheads for extracting, refining, converting,  
 473 and transporting energy.

#### 474 3.2.1 Primary energy consumption

475 The conversion from delivered energy to primary energy can be performed according to Eqs.  
 476 (1)-(3) using the total (renewable and non-renewable) primary energy consumption factors  
 477  $f_{\text{p}_{\text{th}_{\text{tot}}}}$  and  $f_{\text{p}_{\text{el}_{\text{tot}}}}$  reported in Table 5. The energy carriers that are considered are natural

478 gas and electrical energy from the national grid. From Table 5, two main aspects can be  
 479 highlighted. The first aspect is that  $f_{p\_el\_tot}$  is always higher than  $f_{p\_th\_tot}$ . This difference is  
 480 since the production and transport of electrical energy is characterized by higher energy  
 481 overheads than the thermal one. The second aspect is that quite important differences stand  
 482 out among the considered countries especially concerning  $f_{p\_el\_tot}$ . These differences could be  
 483 attributable to the different energy mixes proper of each country and, consequently, different  
 484 energy overheads.

485 **Table 5** – Total (renewable and non-renewable) primary energy factors for thermal  $f_{p\_th\_tot}$  and electrical  
 486  $f_{p\_el\_tot}$  energy.

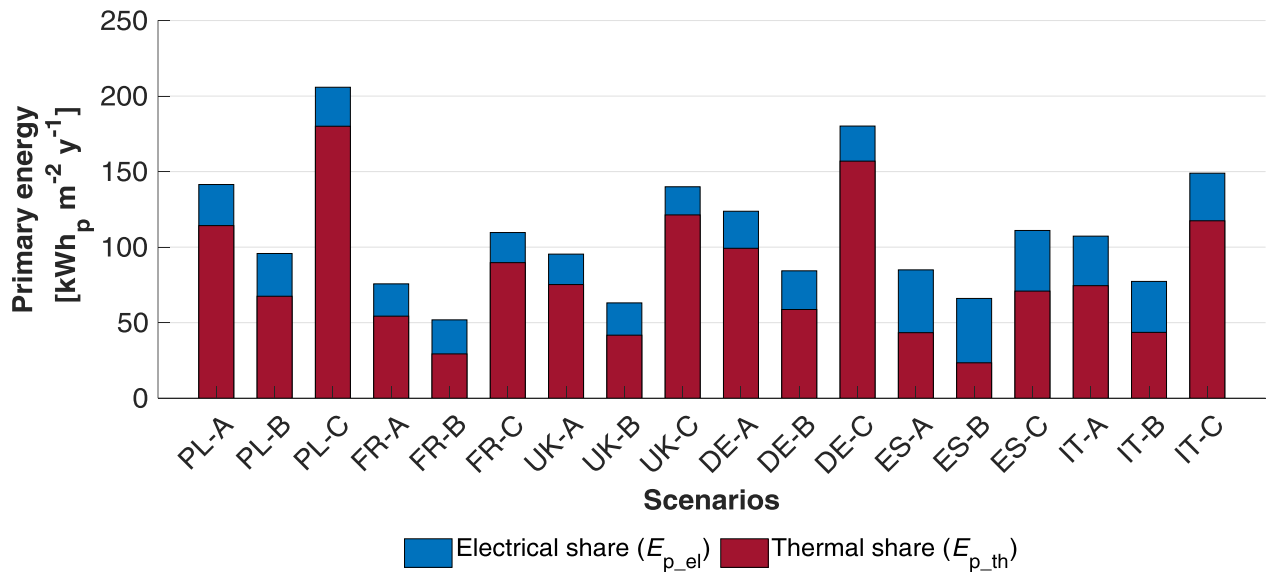
| Country           | $f_{p\_th\_tot}$<br>(natural gas)<br>[kWh <sub>p</sub> kWh <sub>th</sub> <sup>-1</sup> ] | $f_{p\_el\_tot}$<br>(electrical grid)<br>[kWh <sub>p</sub> kWh <sub>el</sub> <sup>-1</sup> ] | Source   |
|-------------------|--|--|--|
| Poland            | 1.10   | 3.03   | Polish Ministry of Economy (2014)                                  |
| France            | 1.00   | 2.58   | French Ministry of Territorial<br>Equality and Housing (2011)      |
| United<br>Kingdom | 1.02   | 2.92   | E. Molenbroek, E. Stricker (2011)                                  |
| Germany           | 1.10   | 2.80   | German Association of Energy and<br>Water Industries (BDEW) (2015) |
| Spain             | 1.195  | 2.368 <sup>a</sup>   | Spanish Ministry of Industry<br>Energy and Tourism (2016)          |
| Italy             | 1.05   | 2.42   | Italian Ministry of Economic<br>Development (2015)                 |

<sup>a</sup> $f_{p\_el\_tot}$  referred to Peninsular Spain; the national values is 2.403 kWh<sub>p</sub> kWh<sub>el</sub><sup>-1</sup>.

487 In Fig. 7,  $E_{p\_glob}$  and its shares  $E_{p\_th}$  and  $E_{p\_el}$  from the analysed scenarios are presented. The  
 488 graph shows that PL-C is characterized by the highest  $E_{p\_glob}$  (205.9 kWh<sub>p</sub> m<sup>-2</sup> y<sup>-1</sup>). This is  
 489 since the considered Polish weather conditions entail a considerable high  $E_{th}$  that represents  
 490 around 87% of  $E_{p\_glob}$ .

491 In all the considered weather conditions, type-B envelope provides the best global primary  
 492 energy performance entailing the minimum  $E_{p\_glob}$ . In particular, the scenario characterized  
 493 by the lowest value of  $E_{p\_glob}$  is FR-B (51.9 kWh<sub>p</sub> m<sup>-2</sup> y<sup>-1</sup>). This scenario, in fact, is  
 494 characterized by a quite low  $E_{th}$  (the lowest one after ES-B) that is not increased by  $f_{p\_th\_tot}$   
 495 that, for France, is equal to 1 kWh<sub>p</sub> kWh<sub>el</sub><sup>-1</sup>. Furthermore,  $\bar{\theta}_{air\_o}$  (the highest one after ES and

IT), entails a reduced  $E_{el\_vent}$  ( $8.1 \text{ kWh}_{el} \text{ m}^{-2} \text{ y}^{-1}$ ) that, converted in  $E_{p\_el}$ , represents 43% of  $E_{p\_glob}$ .  
 The analysis of the primary energy consumption highlights that type-B envelope is the actual best solution to decrease the energy consumption for climate control of the analysed broiler house in all the outdoor weather conditions. The thermal energy analysis showed that type-B envelope can reduce  $E_{th}$  between 63 and 67% if compared to type-C envelope. This result is quite misleading since the actual decrease of that energy consumption (evaluated through the primary energy consumption) is lower, being between 41 and 55%.



504  
 505 **Fig. 7.** Primary energy consumption  $E_{p\_glob}$  of each scenario. In addition, the energy shares due to electrical  
 506 ( $E_{p\_el}$ ) and thermal ( $E_{p\_th}$ ) energy consumptions are shown.

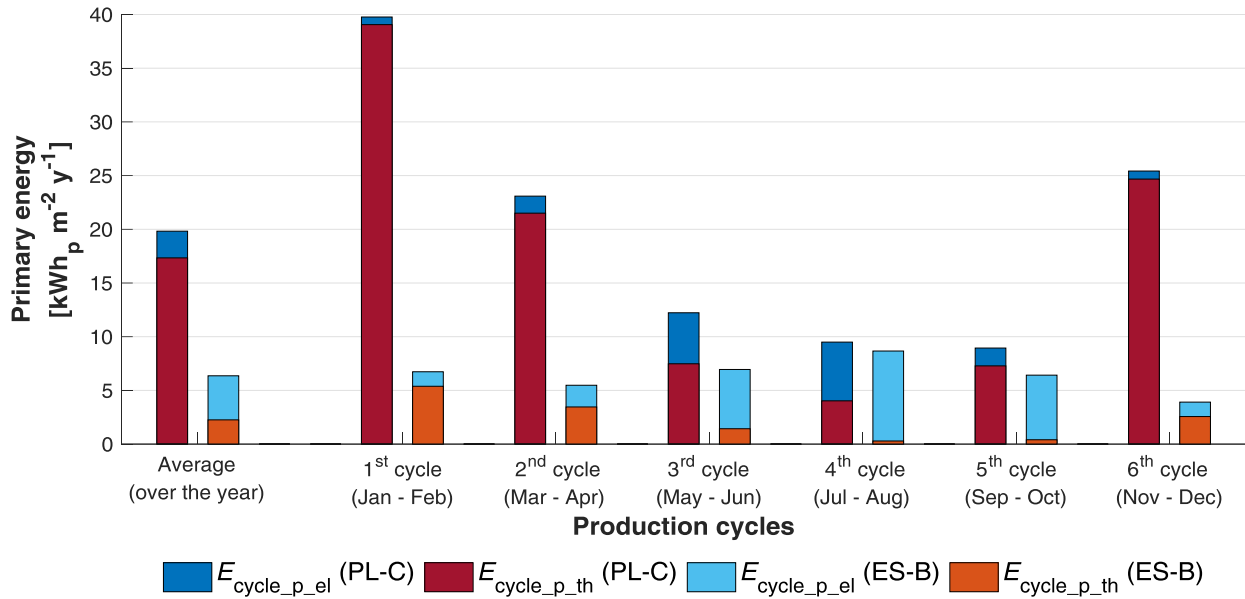
507 The values of  $E_{p\_glob}$  presented in Fig. 7 refer to the entire year but each production cycle  
 508 could be characterized by considerably different values of primary energy consumption, if  
 509 compared to the other cycles, depending on the period of the year in which is carried out.  
 510 To analyse these differences, the global primary energy consumption of each production cycle  
 511  $E_{cycle\_p\_glob}$  ( $\text{kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ ) from PL-C and ES-B scenarios are shown in Fig. 8. The  
 512 comparison between PL-C and ES-B is interesting since these scenarios are characterized by  
 513 the highest  $E_{p\_th}$  and  $E_{p\_el}$ , respectively. The sum of  $E_{cycle\_p\_glob}$  of each production cycle is  
 514 equal to  $E_{p\_glob}$  reported in Fig. 7. In Fig. 8, the primary energy shares due to thermal  
 515  $E_{cycle\_p\_th}$  and electrical  $E_{cycle\_p\_el}$  energy are reported. In addition, the average  $E_{cycle\_p\_glob}$   
 516 calculated over the six production cycles is provided for both the considered scenarios.  
 517 The bar chart of Fig. 8 shows that the average  $E_{cycle\_p\_glob}$  values of the considered scenarios  
 518 are different, being  $E_{cycle\_p\_glob}$  of PL-C scenario around  $19.8 \text{ kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$  (around

519 87% due to  $E_{\text{cycle,p,th}}$  and 13% due to  $E_{\text{cycle,p,el}}$ ), while  $E_{\text{cycle,p,glob}}$  of the ES-B scenario is  
520  $6.4 \text{ kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$  (35% due to  $E_{\text{cycle,p,th}}$  and 65% due to  $E_{\text{cycle,p,el}}$ ).

521 From Fig. 8, important differences between the production cycles of the warm and the cool  
522 seasons can be highlighted. Analysing the Polish scenario, it stands out that the production  
523 cycles of the cool season (1<sup>st</sup>, 2<sup>nd</sup>, and 6<sup>th</sup>) are characterized by  $E_{\text{cycle,p,tot}}$  values that are  
524 higher than  $23.0 \text{ kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ . This energy consumption is greater than the one from  
525 the 3<sup>rd</sup>, 4<sup>th</sup>, and 5<sup>th</sup> production cycles, that is always lower than  $10.0 \text{ kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ .

526 Looking at the shares of  $E_{\text{cycle,p,glob}}$ , in 1<sup>st</sup>, 2<sup>nd</sup>, 5<sup>th</sup> and 6<sup>th</sup> production cycles in PL-C  
527 scenario,  $E_{\text{cycle,p,th}}$  is always higher than 80% of the total, with a maximum value of 98%  
528 during the 1<sup>st</sup> production cycle. In 3<sup>rd</sup> and 4<sup>th</sup> production cycles (during the warm season),  
529  $E_{\text{cycle,p,th}}$  is lower, being around 60% and 40%, respectively.

530 In PL-C scenario, great differences stand out between the production cycles that are carried  
531 out during the warm and the cool season, while in ES-B scenario this difference is negligible.  
532 In ES-B scenario, in fact,  $E_{\text{cycle,p,glob}}$  is quite constant during all the year being the minimum  
533 and the maximum values  $3.9$  and  $8.7 \text{ kWh}_p \text{ m}^{-2} \text{ cycle}^{-1}$ , respectively. Another difference  
534 between the PL-C and ES-B scenarios concerns the shares of  $E_{\text{cycle,p,th}}$  and  $E_{\text{cycle,p,el}}$ . In PL-  
535 C scenario  $E_{\text{cycle,p,el}}$  is the lowest one in all the production cycles with the only exception of  
536 the 4<sup>th</sup> one. In ES-B scenario,  $E_{\text{cycle,p,el}}$  is the highest share during warm season production  
537 cycles (3<sup>rd</sup>, 4<sup>th</sup>, and 5<sup>th</sup>), reaching the maximum relative value of 97% during the 4<sup>th</sup>  
538 production cycle.



539

540 **Fig. 8.** Primary energy consumption for each production cycle ( $E_{cycle\_p\_glob}$ ) and shares due and electrical  
 541 ( $E_{cycle\_p\_el}$ ) and thermal ( $E_{cycle\_p\_th}$ ) energy from PL-C and ES-B scenario.

542 **3.2.2 Reference values of primary energy consumption**

543 Reference values are provided for primary energy consumption, considering the global energy  
 544 performance of the broiler houses. In Table 6, the primary energy consumption for climate  
 545 control needed to produce a unit of mass of broiler meat ( $E_{meat\_p\_glob}$ ) is presented with the  
 546 shares due to heating, ventilation, and evaporative cooling. The results show that the range of  
 547  $E_{meat\_p\_glob}$  values goes from 1.7 to 6.6 kWh<sub>p</sub> kg<sup>-1</sup><sub>meat</sub>. Heating represents the highest share of  
 548  $E_{meat\_p\_glob}$  in almost all the scenarios (the only exceptions is ES-B) being between 51 and  
 549 87% of the total. Ventilation goes from 11 to 55% of  $E_{meat\_p\_glob}$ . Evaporative cooling is  
 550 equal or lower than 6% in all the scenario except for ES-A and ES-B where it represents 7%  
 551 and 9%, respectively. This result proves that in the assessment of the energy performance of a  
 552 broiler house, the energy consumption for evaporative cooling can be neglected due to its  
 553 minor relevance, especially in cool climate conditions and in presence of low-insulated  
 554 envelopes.

555 **Table 6** – Primary energy consumption embedded in a unit of mass (kg) of broiler meat ( $E_{meat\_p\_glob}$ ) and shares  
 556 due to heating, ventilation, and evaporative cooling.

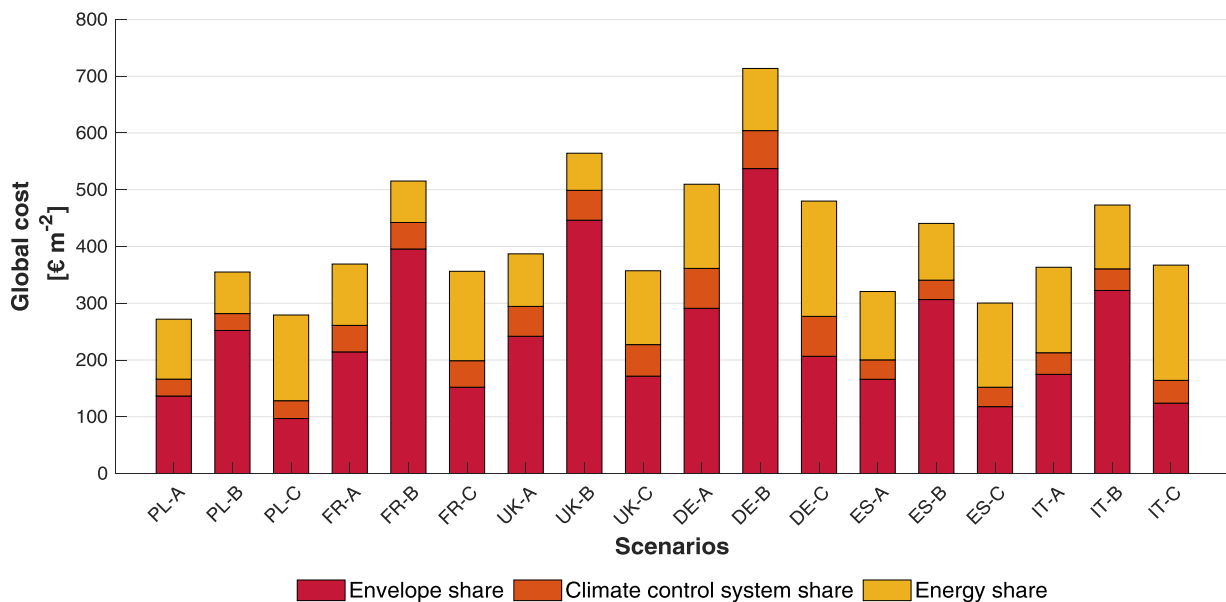
| Scenario | $E_{meat\_p\_glob}$<br>[kWh <sub>p</sub> kg <sup>-1</sup> <sub>meat</sub> ] | Heating<br>[%] | Ventilation<br>[%] | Evaporative cooling<br>[%] |
|----------|---|----------------|--------------------|----------------------------|
| PL-A     | 4.5   | 81%            | 17%                | 2%                         |
| PL-B     | 3.1   | 71%            | 26%                | 3%                         |

|      |     |     |     |    |
|------|-----|-----|-----|----|
| PL-C | 6.6 | 87% | 11% | 2% |
| FR-A | 2.4 | 72% | 26% | 2% |
| FR-B | 1.7 | 57% | 40% | 3% |
| FR-C | 3.5 | 82% | 17% | 1% |
| UK-A | 3.1 | 79% | 19% | 2% |
| UK-B | 2.0 | 66% | 31% | 3% |
| UK-C | 4.5 | 87% | 12% | 1% |
| DE-A | 4.0 | 80% | 18% | 2% |
| DE-B | 2.7 | 70% | 27% | 3% |
| DE-C | 5.8 | 87% | 12% | 1% |
| ES-A | 2.7 | 51% | 42% | 7% |
| ES-B | 2.1 | 36% | 55% | 9% |
| ES-C | 3.6 | 64% | 31% | 5% |
| IT-A | 3.4 | 70% | 26% | 4% |
| IT-B | 2.5 | 56% | 38% | 6% |
| IT-C | 4.8 | 79% | 18% | 3% |

### 557 3.3 Financial evaluation

558 The previously presented scenarios are analysed from the financial point of view to  
559 understand the differences in terms of cost-benefit analysis. The global cost  $C_G$  of each  
560 scenario was estimated according to the methodology described in section 2.5.  
561 In Fig. 9, the shares of  $C_G$  due to envelope, climate control system and energy of each  
562 considered scenario are presented in a stacked bar chart. The graph shows that the highest  
563 overall  $C_G$  is  $714 \text{ € m}^{-2}$  of DE-B scenario, while the lowest one is  $272 \text{ € m}^{-2}$  of PL-A  
564 scenario. These absolute values can be explained with a view on Table 4 since  $\gamma_{PLI}$ ,  $C_{th}$  and  
565  $C_{el}$  considerably affects the difference between countries. Germany, in fact, is characterized  
566 by the highest  $\gamma_{PLI}$  (1.67) that entails considerably higher  $C_l$  and  $C_a$  (due to climate control  
567 system replacement) than the other countries, especially, Poland where  $\gamma_{PLI}$  is only 0.78. A  
568 similar difference can be found analysing  $C_{th}$  and  $C_{el}$  that are the lowest ones for Poland  
569 ( $0.04 \text{ € kWh}_{th}^{-1}$  and  $0.15 \text{ € kWh}_{el}^{-1}$ , respectively), while Germany is characterized by the  
570 highest  $C_{el}$ .  
571 The results of the global cost analysis presented in Fig. 9 show that, in all the considered  
572 countries, type-B envelope is characterized by the highest  $C_G$ , while type-A and type-C  
573 envelopes are characterized approximatively by the same  $C_G$ , with a maximum relative  
574 difference of 8% (UK-A and UK-C scenarios). The relative difference between type-B

575 envelope and the other two types is considerable, being between 29% (IT-C) and 58% (UK-  
 576 C). The stacks of the bar chart explain why type-B envelope is characterized by a  
 577 considerably high  $C_G$  although it was characterized by the best primary energy performance,  
 578 as previously showed in Fig. 7. The costs related to the building envelope, in fact, represent  
 579 between 68% and 79% of  $C_G$  in the considered countries. The good energy performance of  
 580 type-B envelope reflects on very low shares of  $C_G$  for energy (between 12% and 21%) but it  
 581 is not enough to make type-B envelope a good option from the financial point of view. In this  
 582 sense, type-A envelope could represent a good compromise since it is a solution that  
 583 guarantee a favourable primary energy performance (considerably better than the one of type-  
 584 C, as visible in Fig. 7) and a  $C_G$  similar to the one of type-C envelope, with a good impact  
 585 form the financial sustainability point of view.



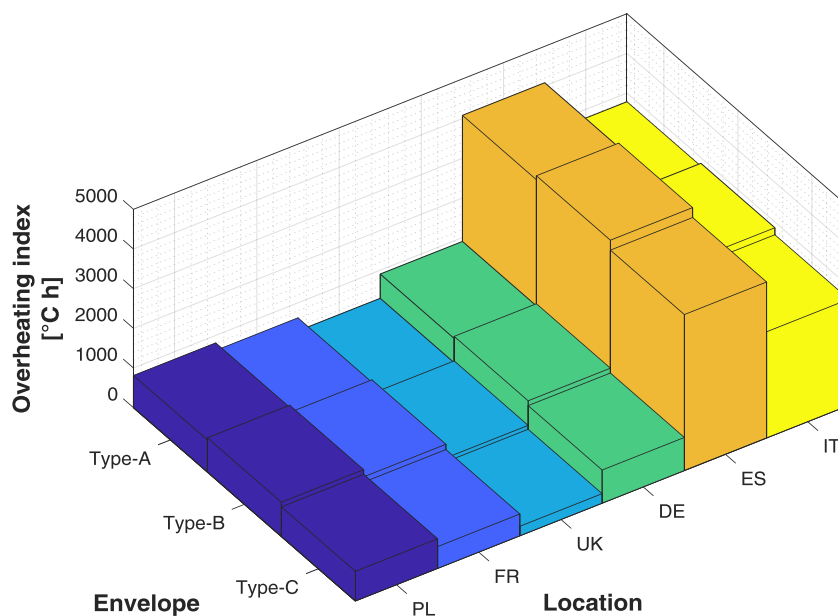
586  
 587 **Fig. 9.** Global cost  $C_G$  and shares due to envelope, climate control system and energy for each of the analysed  
 588 scenarios.

### 589 3.4 Comparison of indoor climate conditions

590 The free cooling systems with which broiler houses are usually equipped could be not able to  
 591 maintain the required  $\theta_{set,C}$  especially in warm season and broilers can be exposed to heat  
 592 stress especially in presence of thermal insulated envelopes. For this reason, it is important to  
 593 evaluate the envelope considering the indoor climate conditions to assure that low energy  
 594 consumptions are not related to excessively poor indoor climate conditions.

595 For this purpose, the overheating index  $\Omega_{OH}$  is calculated according to Eq. (4) for the  
 596 considered scenarios and the results are presented in the bar chart of Fig. 10. From the bar

597 chart, it stands out that overheating problems are evident in the scenarios with the outdoor  
598 weather conditions of Spain and Italy, while the other scenarios are characterized by low  $\Omega_{oH}$ .  
599 The minimum  $\Omega_{oH}$  value is from UK-C scenario.  
600 Through the bar chart of Fig. 10, the differences between the three types of envelope in the  
601 same outdoor weather conditions in terms of  $\Omega_{oH}$  can be assessed. In the same outdoor  
602 weather conditions, the maximum  $\Omega_{oH}$  come from the scenarios with type-B envelope, while  
603 the minimum  $\Omega_{oH}$  comes from the scenario with type-C envelope. The higher thermal  
604 insulation of the type-B envelope, in fact, decreases the energy need for heating but does not  
605 foster the heat losses through transmission, increasing the cooling need. During the warm  
606 season (or in presence of high thermal load from the animals) these transmission heat losses  
607 would decrease  $\theta_{air,i}$  mitigating the overheating of the enclosure. In the scenarios  
608 characterized by milder weather conditions (Spain and Italy), the relative difference between  
609 the type-B envelope (with the maximum  $\Omega_{oH}$ ) and type-A and type-C envelopes (with the  
610 minimum  $\Omega_{oH}$ ) is equal or less than 6%. In the scenarios with cooler outdoor weather  
611 conditions, those differences are higher. The greatest difference is from United Kingdom  
612 scenarios where the maximum relative difference between type-C and type-B is around 30%.  
613 In all the other weather conditions this difference is always lower than 20%, but in absolute  
614 terms,  $\Omega_{oH}$  is low.



615  
616

**Fig. 10.** Overheating index ( $\Omega_{oH}$ ) of the analysed scenarios.

## 617 **4 Conclusions**

618 In the present work, the best energy-efficient solution in terms of envelope for a typical  
619 broiler house in the European context was identified in different scenarios. This identification  
620 was performed through the assessment of the delivered energy consumption (state of the art)  
621 and the primary energy consumption (new proposed approach). The results highlight that,  
622 from the delivered and the primary energy points of view, a high-insulated envelope is  
623 strongly recommended for all the analysed outdoor weather conditions, but it is not  
624 sustainable from a financial point of view. This is because the financial savings due to the  
625 reduction of energy consumption enhanced by the improved energy performance do not pay  
626 back the high initial investment cost of the envelope. By contrast, a medium insulated  
627 envelope could be interesting since is a compromise between a good energy performance and  
628 a sustainable cost without increasing considerably the overheating of the enclosure.

629 The previous analyses lay the groundwork for future research into the energy efficiency of  
630 livestock house through two main contributions. First, this work shows the importance of a  
631 case-by-case design of the building envelope in improving the energy performance of broiler  
632 houses, while in literature most of the works are focused on the improvement of climate  
633 control systems. The second contribution relies in the methodology that is adopted in this  
634 paper to evaluate the energy performance. The performed energy analyses are not limited to  
635 the delivered energy consumed on farm, but they encompass the entire energy supply chain  
636 adopting an approach based on primary energy. In this way, important issues can be  
637 considered such as the energy losses along the energy supply chain of the considered energy  
638 carrier and different energy mixes proper of the country. This last aspect is essential to  
639 evaluate how the transition toward cleaner energy mixes undertaken by several countries  
640 affects the sustainability of the livestock production. To do so, future works could further  
641 deepen the energy analysis based on the primary energy approach to assess the share of  
642 primary energy from renewable and non-renewable sources. That distinction would  
643 considerably improve the assessment of the environmental sustainability of livestock  
644 production. In addition, primary energy approach could represent the core of a new energy  
645 certification scheme *ad-hoc* developed for livestock houses. It would represent the first step of  
646 new legislation frameworks that, establishing minimum energy performances and incentive  
647 systems, could boost to a cleaner livestock production through a top-down approach.

648

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