Identification of energy efficient solutions for broiler house envelopes through the primary energy approach

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Abstract

One of the main concerns about broiler production is the high use of energy for climate control. An improved design of the broiler house envelope could decrease the energy consumption, but an energy analysis performed with the delivered energy approach (state of the art) may lead to misleading results since it is focused on the very last stages of the energy supply chain. On the contrary, an energy analysis based on primary energy (new proposed approach) encompasses all forms of direct energy (e.g. thermal and electrical) that are supplied to the broiler house, including the energy losses along the energy supply chain. In this work, the delivered energy and the primary energy approaches are adopted to identify the most energy-efficient solution in terms of envelope for a typical European broiler houses evaluated in different scenarios that are also evaluated from a financial point of view (global cost) and from the point of view of heat stress risk (overheating index). The results show that a high-insulated envelope is recommended in all the considered outdoor weather conditions, but it is not sustainable from a financial point of view. On the contrary a medium insulated envelope is characterized by a good energy performance and its global cost is similar to a not insulated envelope. The obtained results underline that a case-by-case design of the broiler house envelope could contribute to increase the sustainability of the broiler production.

Keywords: energy analysis; reference values of energy consumption; dynamic energy simulation model; poultry rearing; livestock sustainability; building thermal insulation

Nomenclature

A	area	$[\mathrm{m}^2]$
air	air (subscript)	
C	cooling (subscript)	
C_a	annual cost	$[€\ \mathrm{m}^{-2}]$
C_el	electrical energy cost	$[€\ \mathrm{kWh_{el}}^{-1}]$
C_G	global cost	$[€\ \mathrm{m}^{-2}]$
C_I	initial investment cost	$[€\ \mathrm{m}^{-2}]$
C_m	total building fabric heat capacity	$[\mathrm{kJ\ K}^{-1}]$
C_th	thermal energy cost	$[€\ \mathrm{kWh_{th}}^{-1}]$
cycle	referred to the productive cycle (subscript)	
DE	Germany	
E	energy consumption	$[\mathrm{kWh\ m^{-2}\ K^{-1}}]$
ec	evaporative cooling (subscript)	
el	electrical (subscript)	
ES	Spain	
f	primary energy conversion factor	$[\mathrm{kWh_p\ kWh^{-1}}]$
FR	France	
g_gl	solar factor of the glazed surface	[-]
glob	global (subscript)	
H	heating (subscript)	
H	total solar radiation	$[\mathrm{GJ\ m^{-2}}]$
hor	horizontal (subscript)	
i	indoor (subscript)	
IAQ	Indoor Air Quality	
IT	Italy	
j	generic building element of the broiler house	
k	generic hourly time step	
l	generic component of the global cost	
m	number of hours with broilers inside the house	
meat	referred to the kg of saleable meat (subscript)	
n	number of building elements of the house	
o	outdoor (subscript)	

th	thermal (subscript)	
tot	total (subscript)	
p	primary energy (subscript)	
PL	Poland	
q	generic year of the broiler house lifespan	
$\mathcal{R}^{+}$	set of real positive numbers	
R_{d}	discount rate	[%]
R_{R}	real interest rate	[%]
RH	relative humidity	[%]
set	set point (subscript)	
sol	solar (subscript)	
sup	supply (subscript)	
TMY	Typical Meteorological Year	
$U-value$	stationary thermal transmittance	[W m^{-2} K^{-1}]
$\overline{U}-value$	averaged stationary thermal transmittance	[W m^{-2} K^{-1}]
UK	United Kingdom	
V_{f}	final value	[€ m^{-2}]
ven	ventilation (subscript)	
α	solar absorption coefficient	[-]
γ_{LPI}	cost conversion factor	[-]
Δp	static pressure difference	[Pa]
$\Delta\tau$	time interval	[h]
θ	temperature	[°C]
$\bar{\theta}$	average temperature	[°C]
κ	internal aerial heat capacity	[kJ m^{-2} K^{-1}]
τ_{ls}	broiler house lifespan	[year]
Ω_{oH}	overheating index	[°C h^{-1}]

1 Introduction

Intensive livestock production systems are expanding (Firfiris et al., 2019) to cover the world food demand that is increasing due to the world population growth and the simultaneous increase in wealth that drives up the per-capita consumption of animal products (Maia et al., 2020) such as poultry meat, which consumption is estimated to increase by 125% before 2050 if compared to 2010 (FAO, 2011a). Currently, more than 70% of the globally produced poultry come from intensive production systems (FAO, 2011b). Even though poultry production has been considered as the most environmentally efficient among livestock production (Roma et al., 2015), the increasing general concerns about the environmental sustainability of livestock production systems have put even this sector under investigation (Costantini et al., 2020).

One of the main concerns about broiler production is the high use of energy that is directly used for the production (e.g. thermal and electrical energy) or is embedded in the inputs (e.g. machinery and feed). According to Heidari et al. (2011), the highest indirect energy input of poultry production is feed that represent around 32% of the total energy inputs of the production, while other inputs (e.g. machinery and human labour) are negligible. The importance of feed as an energy input for broiler houses was underlined in literature by emergy analyses that assess the overall energy inputs of broiler production as units of equivalent solar energy (Odum, 1995). Castellini et al. (2006), for example, compared conventional and organic broiler production highlighting how the use of organic crops could reduce the emergy inputs by around 60%. Allegretti et al. (2018) performed an emergy assessment that showed the potentialities of insect-based feed in decreasing the emergy inputs of broiler production in Brazil.

The highest direct energy inputs in broiler houses are fuel and electrical energy which represent around 59% and 9% of the total energy inputs, respectively (Heidari et al., 2011). Fuel and electrical energy are mainly used on-farm for climate control that is by far the highest on-farm energy consumption share. According to Costantino et al. (2016), in fact, around 96% of thermal energy and around 76% of electrical energy are used for maintaining the adequate indoor climate conditions. Similar shares of energy consumption highlight how an energy-efficient climate control of livestock houses is fundamental to reach a cleaner and sustainable agriculture (Ecim-Djuric and Topisirovic, 2010) also with a view on the expected climate changes (Izar-Tenorio et al., 2020). Several works present in literature investigate solutions to decrease the energy consumption for climate control of broiler houses and most of them are focused on the improvement of the system performance. Manolakos et al. (2019), for example, studied the potentiality of an aerothermal heat pump for climate control in a broiler house in the Northern Greece while Choi et al. (2012) focused their analysis in the potentiality of the adoption of a geothermal heat pump. Gad et al. (2020) analyzed the use of both photovoltaics and thermal solar systems in an experimental broiler house, evaluating the effects from the point of view of energy, costs, indoor climate conditions and production. El Mogharbel et al. (2014) evaluated the possibility to improve the energy performance of broiler houses using a parabolic solar concentrator for localized heating. The work of Coulombe et al. (2020) was focused on improving the integration of heat recovery systems in broiler houses located in cold climate regions.

While many works in literature are focused on the improvement of the performance of energy and climate control systems, very few of them are focused on the improvement of the energy performance of broiler house and livestock houses envelope (the outer elements of the house, namely walls, roof, floor, and windows) (Axaopoulos et al., 2014). The envelope in fact, represents the boundary of the broiler house thermodynamic system that modulates the exchange of energy (e.g. heat and solar irradiation) and mass (e.g. ventilation air and moisture) between the indoor environment (the enclosure) and the outdoor. The design of the envelope, hence, should aim at increasing the energy efficiency for climate control of the broiler house through the decrease of the overall consumption of thermal and electrical energy. On the contrary, in the current practice, the envelope design of a broiler house is a shallow process that provided standardized solutions for contexts that are considerably different between them. In this sense, a design process targeted at increasing the energy efficiency of the broiler house envelope is strongly needed. Energy analysis (Pimentel et al., 1973) is a powerful method to evaluate improvement of the energy performance, but the robustness of this method should be increased, as underlined by Vigne et al. (2012). Most of the previously presented energy analyses, in fact, evaluated the energy performance of broiler house systems focusing only on thermal and electrical energy delivered on farm. This delivered energy approach (the current state of the art) neglects an important share of the energy consumption since its focus in only on the very last stages of the energy supply chain. On the contrary a new approach based on the primary energy should be adopted. Primary energy assessments, in fact, is a single metric for assessing all forms of direct energy (e.g. thermal and electrical) that are supplied to the broiler house and encompasses all the stages of the energy supply chain. The primary energy, therefore, accounts also for the energy losses (e.g. due to conversion and transportation) and the energy embedded in the infrastructures (e.g. in turbines and pipes) along the supply chain with a specific view on the adopted energy carrier (e.g. natural gas or electricity from grid) and considered country (ISO, 2017a). The importance of primary energy is also testified by its adoption as major metric by the Energy Performance of Buildings Directive of European Union (European Commission, 2018) and it is becoming widely adopted in different sector. Bilardo et al. (2020), for example, adopted the primary energy approach to evaluate the energy performance of a solar cooling system in the residential sector. Krstić-Furundžić et al. (2019) analyse the primary energy performance of different façade configurations of an office building. Dunkelberg et al. (2018) adopted the primary energy approach to reduce the energy demand of the plastics industry. On the contrary, energy analyses of broiler houses that adopt the primary energy approach are limited in literature and are focused on very specific case studies and geographical context. Costantino et al. (2020), for example, estimated the variation of the primary energy consumption due to the increase of ventilation for maintaining established thresholds of gas concentrations in a Spanish broiler house. Baxevanou et al. (2017) used the primary energy approach to evaluate the energy consumption of eight broiler houses in different climate contexts of Greece. Given this picture, improving the energy performance of the broiler house envelope through the assessment of the primary energy could contribute to decrease the energy consumption of this production system and, hence, of the entire livestock sector.

The objective of this work is to identify the best envelope solution in terms of energy consumption among the most adopted ones in the broiler houses of the European context. To do so, the energy performance for climate control of a broiler house typical of the European context is assessed in different scenarios through both the delivered energy (state of the art) and the primary energy (new proposed approach) approaches to highlight the difference between the obtained results. The results of the energy analysis are also evaluated from the financial point of view and assessing the heat stress risk.

2 Materials and methods

To achieve the objective of this work, the methodology schematized in the workflow of Fig. 1 was followed. The preparatory stage lies in two different tasks. The first one is the identification of the adequate case study for the purpose of this work (section 2.1), that is then used to calibrate a previously developed dynamic energy simulation model (section 2.2). The preparatory stage also concerns the setting of the simulation scenarios by defining different envelope types (section 2.3) and different outdoor weather conditions (section 2.4).

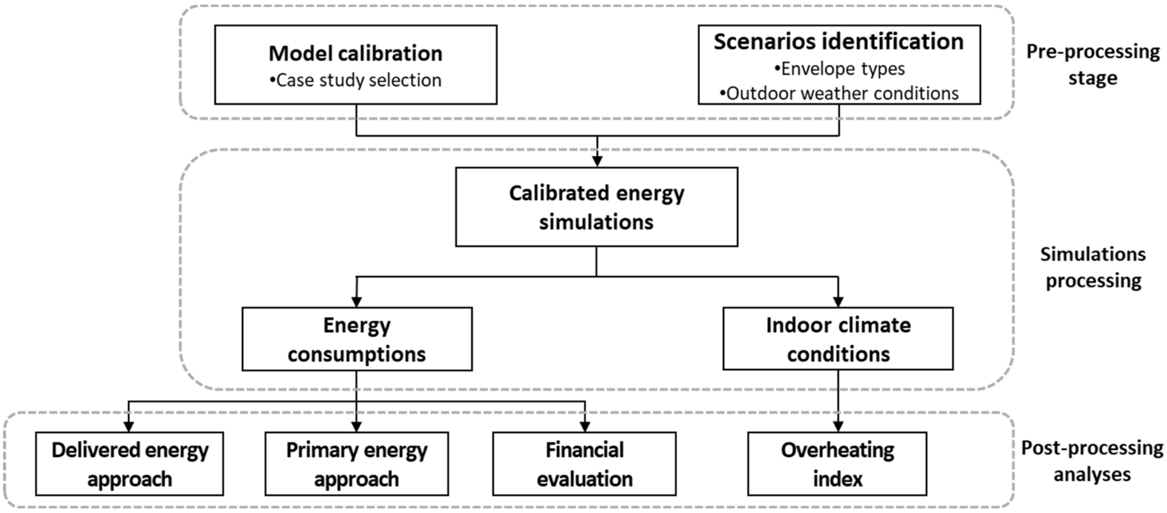

Fig. 1. Schematization of the methodology workflow adopted in the present work.

After the preparatory stage, a calibrated simulation of a typical year of broiler production is performed per each considered scenario, providing the following results:

- energy consumptions for climate control, namely
  - thermal energy for supplemental heating
  - electrical energy for ventilation and evaporative cooling
- indoor climate conditions, namely
  - indoor air temperature
  - indoor air relative humidity.

The obtained energy consumptions are analysed adopting both the delivered and the primary energy approaches and the results of these analyses are presented in section 3.1 and 3.2, respectively. In these sections, reference values of energy consumption for climate control in broiler houses are also provided. The main difference between the delivered and primary energy approaches is conceptualized in the schematization of Fig. 2. The figure shows that the delivered energy approach accounts exclusively for the energy that is converted and used on farm. In this work, the delivered energy consumption is provided directly by the adopted energy simulation model. On the contrary, the primary energy approach encompasses all the stages of the energy supply chain, from the resource extraction to the final on-farm use, as visible in Fig. 2. The primary energy consumption of the analysed scenarios is calculated starting from the model outputs through *ad-hoc* conversion factors. The global primary energy consumption $E_{\mathrm{p,glob}}$, is calculated as the sum of primary energy consumption due to thermal $E_{\mathrm{p,th}}$ and electrical energy $E_{\mathrm{p,el}}$, as

$$E_{\mathrm{p,glob}} = E_{\mathrm{p,th}} + E_{\mathrm{p,el}} \quad [\mathrm{kWh_p}] \tag{1}$$

where

$$E_{\mathrm{p,th}} = E_{\mathrm{th}} \cdot f_{\mathrm{p,th,tot}} \quad [\mathrm{kWh_p}] \tag{2}$$

$$E_{\mathrm{p,el}} = \left(E_{\mathrm{el,ven}} + E_{\mathrm{el,ec}}\right) \cdot f_{\mathrm{p,el,tot}} \quad [\mathrm{kWh_p}] \tag{3}$$

where $f_{\mathrm{p,th,tot}}$ is the total primary energy factor for thermal energy and $f_{\mathrm{p,el,tot}}$ is the total primary energy factor for electrical energy. These factors ($f_{\mathrm{p,th,tot}}$ and $f_{\mathrm{p,el,tot}}$) depend on the considered energy carrier (natural gas and electrical energy in this work) since the overheads for extracting, refining, converting, and transporting energy change significatively depending on the energy carrier. The primary energy factors are calculated at a national level (each country has a different energy mix) and usually provided by national ministries or energy agencies. The terms $f_{\mathrm{p,th,tot}}$ and $f_{\mathrm{p,el,tot}}$ are "total" conversion factors since they account for both the renewable and non-renewable primary energy shares that could be furtherly obtained through specific conversion factors. In this work their calculation is not performed since it is considered out of the scope of the present analysis.

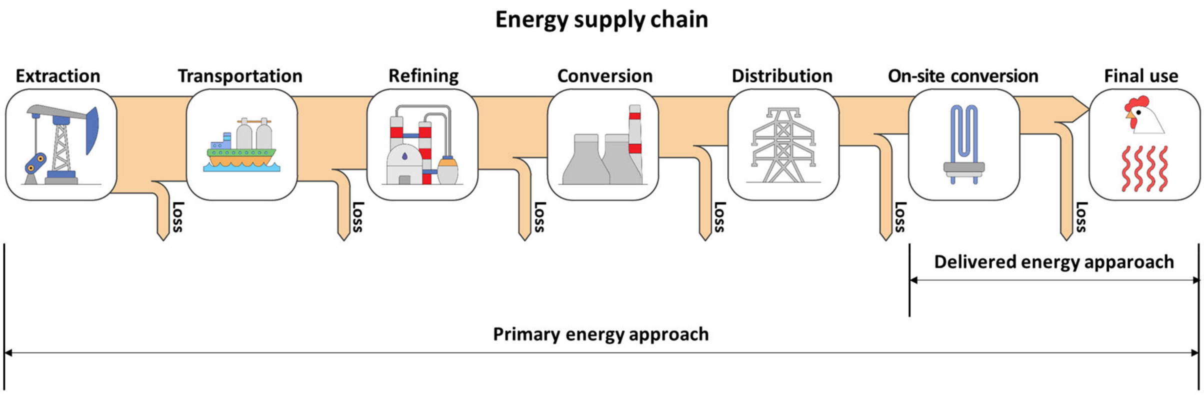

Fig. 2. Conceptualization of the difference between the delivered and the primary energy approach.

In section 3.3, the considered scenarios are analysed from a financial point of view to estimate how the considered types of envelope affect the global cost of the broiler house over its lifespan, in compliance with the EN 15459 international standard (CEN, 2007). The global cost C_{G} (here referred to the unit of floor area) is the sum of the present value of all the costs estimated during the lifespan τ of the considered broiler house and it reads

$$C_{\mathrm{G}}(\tau_{\mathrm{ls}}) = C_{\mathrm{I}} + \sum_{l=1}^{n_{com}} \left[\sum_{q=1}^{\tau_{\mathrm{ls}}} \left(C_{\mathrm{a,q,l}} \cdot R_{\mathrm{d},q}\right) - V_{\mathrm{f},\tau_{\mathrm{ls}},\mathrm{l}} \right] \quad [€\ \mathrm{m}^{-2}] \tag{xxx1}$$

where C_{I} is the initial investment cost (€ m^{-2}), C_{a} is the annual cost regarding the l-th component calculated at the q-th year (€ m^{-2}) while V_{f} is the final value of the l-th component at the end of its lifespan τ_{ls} (€ m^{-2}). The term R_d is the discount rate (%) that is introduced to refer the value of money of the q-th year at the present and reads

$$R_d(q) = \left(\frac{1}{1+R_R}\right)^q \quad [\%] \qquad \text{(xxx2)}$$

where R_R is the real interest rate (%) that considers the market and inflation rates.

The last analysis performed in the present work (section 3.4) regard a comparison of the indoor environmental conditions of the different scenarios for of comparing how the different solutions in terms of envelope affect not only the energy consumption but also the indoor environmental conditions. For this purpose, the overheating index Ω_{oH} is assessed for all the scenarios, 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 it reads

$$\Omega_{oH} = \sum_{k=1}^{m} \left(\Omega_{oH,k} \cdot \Delta\tau\right) \quad [°C\ h] \qquad (4)$$

with

$$\Omega_{oH,k} \in \mathcal{R}^+ \qquad (5)$$

where

$$\Omega_{oH,k} = \theta_{air,i,k} - \theta_{air,set,C,k} \quad [°C] \qquad (6)$$

where $\Omega_{oH,k}$ is the overheating index calculated at the hour k, and m is the yearly number of hours in which broilers are present inside the house. The value of m in this work is 7,200 h (sanitary empty periods are not considered) and $\Delta\tau$ is equal to one hour. The terms $\theta_{air,i,k}$ and $\theta_{set,C,k}$ are the indoor air temperature and the cooling set point temperature at hour k, respectively.

2.1 Description of the case study

The broiler house selected for this work is in Italy, has a useful floor area of 1,200 m^2 (120 m long and 10 m wide) and is schematized in Fig. 3. The considered broiler house has a gable roof which height is 4.4 m of at the ridge level and 2.1 m at the eave level. The useful volume is around 3,900 m^3 and the largest walls of the house face east and west.

The walls and the roof are made of sandwich panels, while the windows are made of polycarbonate alveolar panels. The floor is a reinforced concrete screed above a waterproofing sheet in direct contact with the ground.

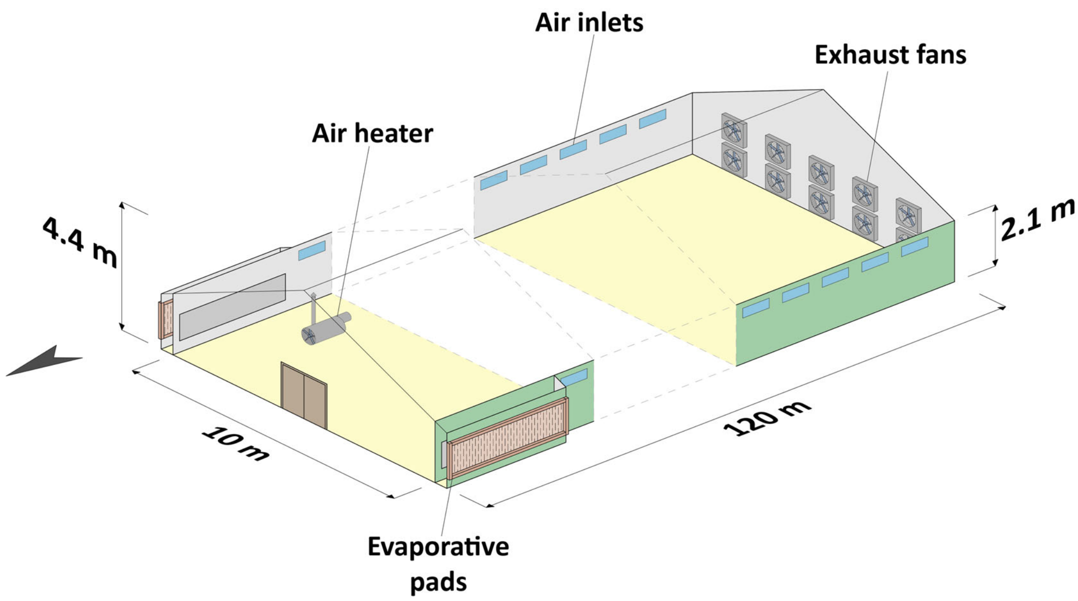

Fig. 3. Schematization of the typical broiler house chosen as case study for the present work.

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

When cooling ventilation cannot maintain the cooling set point temperature $\theta_{air,set,C}$, evaporative cooling is activated, and the supply air temperature $\theta_{air,sup}$ is decreased through the evaporative pads that are installed in the north part of the longest walls. Climate control system activates the evaporative cooling when the difference between $\theta_{air,set,C}$ and outdoor air temperature $\theta_{air,o}$ is lower than 3 °C. The evaporative pads are 150 mm thick and are made of impregnated and corrugated cellulose paper sheets. The direct saturation effectiveness of the pads (as defined by ASHRAE, 2012) is equal to 87%, as reported in the technical datasheet provided by the manufacturer. Two submersible pumps are used to pump the water from the tanks at the basis of the pads to the top of them. The electrical motor of each pump is estimated to deliver 0.55 kW (0.75 hp) of mechanical power and to absorb 0.85 kW of electrical power.

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

When young chicks are present inside the house, the climate control system maintains $\theta_{\mathrm{air,i}}$ at 32 °C and provides 2.3 $m^3\ h^{-1}\ kg^{-1}$ of minimum ventilation to control the IAQ. At the end of the cycle $\theta_{\mathrm{air,i}}$ is maintained at 17 °C and the minimum ventilation flow rate is 0.4 $m^3\ h^{-1}\ kg^{-1}$. More details about $\theta_{\mathrm{air,set,H/C}}$ and minimum ventilation flow rates that were adopted in this work can be found in Cobb (2008). Please note that inside the broiler house, the only environmental parameter that is controlled by climate control with a feedback loop is $\theta_{\mathrm{air,i}}$, while indoor air relative humidity $RH_{\mathrm{air,i}}$ is not controlled in a feedback loop.

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

2.2 Model calibration

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

The adopted energy simulation model was *ad hoc* calibrated for this work using real monitored data acquired on the real case study presented in section 2.1 for increasing the reliability of the results of the simulations. To do so, a long-term monitoring campaign was carried out in the selected case study to acquire the needed data for the calibration that was performed through an optimization-based calibration (Fabrizio and Monetti, 2015).

2.3 Types of broiler house envelopes

Three types of building envelopes that are commonly used in broiler houses of the European context are considered in this work and are presented in Table 1. They are characterized by different values of average stationary thermal transmittance $\overline{U}-value$ (calculated in compliance with ISO, 2017b) and total building fabric heat capacity C_{m} that is calculated as

$$C_{\mathrm{m}}=\sum_{j=1}^{n}\left(\kappa_{\mathrm{i,j}}\cdot A_{\mathrm{j}}\right)\quad\left[\frac{\mathrm{kJ}}{\mathrm{K}}\right] \tag{7}$$

where $\kappa_{\mathrm{i,j}}$ is the internal heat capacity of the opaque elements j (calculated according to EN ISO 13786 standard European Committee for Standardisation, 2018). The internal heat capacity describes the ability of a building component to buffer heat during a diurnal cycle and is defined as the amount of heat to be supplied to a unit of area of a building component to produce a unit change in its temperature. The term n is the number of building components that are considered in the calculation of C_{m}. In this work, κ_{i} of the transparent elements is considered negligible if compared to the one of the opaque ones, thus was not considered in the simulations.

Table 1 – The average stationary thermal transmittance $\overline{U}-value$ and total building fabric heat capacity C_{m} of the envelope types considered in this work.

Envelope	Envelope features	Use	$\overline{U}-value$ [W m^{-2} K^{-1}]	C_{m} [kJ K^{-1}]
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

The values reported in Table 1 are calculated starting from the thermophysical properties proper of each component of the broiler house envelope that are reported in Fig. 4, where the stationary thermal transmittances $U-value$, the internal aerial heat capacities κ_{i} and the solar factors of the glazed surfaces g_{gl} are shown. All the adopted thermo-physical properties were calculated from the values reported in international standards (ISO, 2017b), technical handbooks (ASHRAE, 2017) or technical datasheets of commercial products.

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

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

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

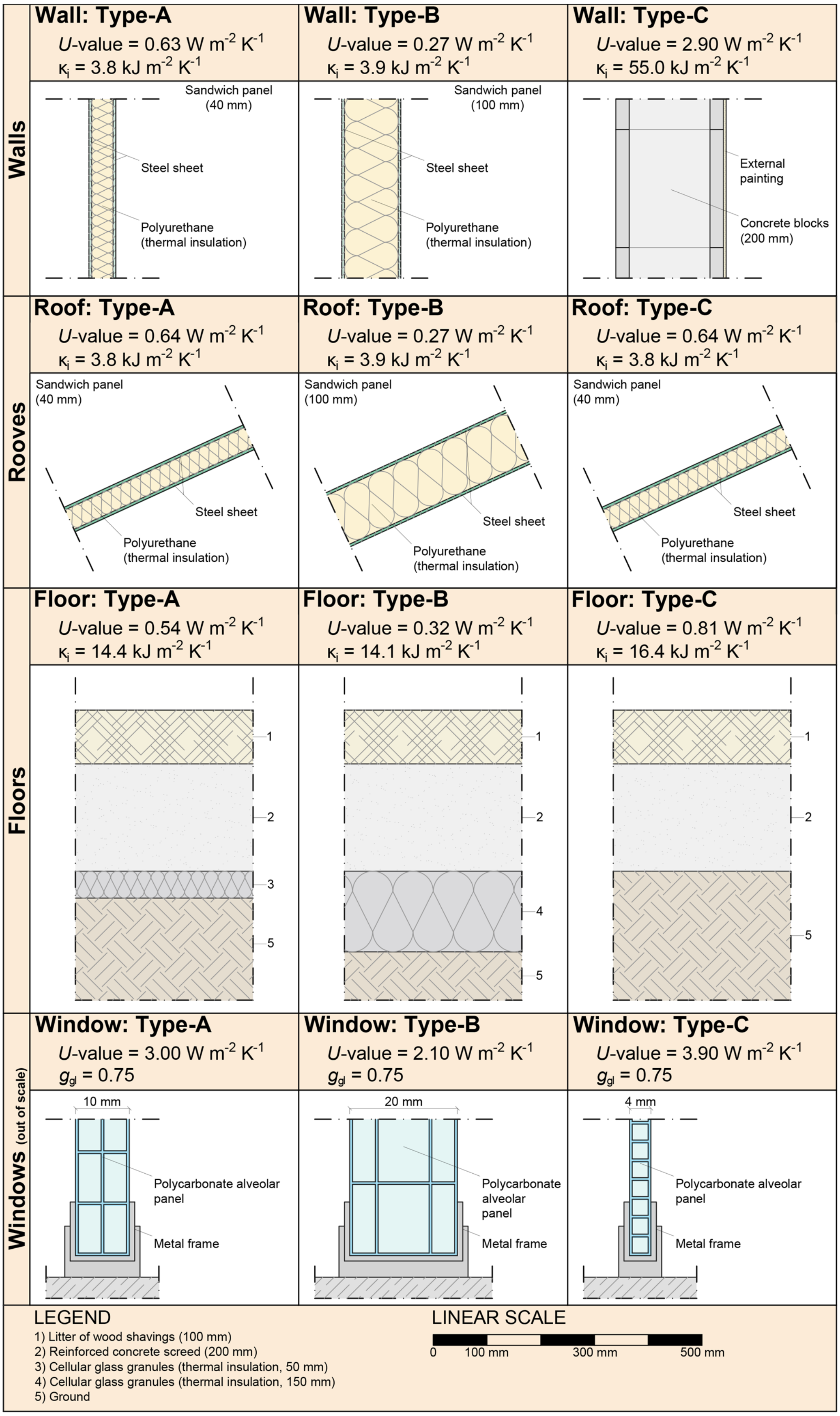

Fig. 4. Details of the components (walls, rooves, floors and windows) of the three analysed envelope types (A, B and C). In the figure, the stationary thermal transmittances $U - value$, the internal aerial heat capacities κ_i and the solar factors of the glazed surfaces g_{gl} are shown.

2.4 Outdoor weather conditions

The energy performance of the analysed broiler house was assessed considering different weather conditions across Europe. The chosen weather conditions are proper of the geographical locations characterized by the highest poultry meat production in Europe and are Poland, France, United Kingdom, Germany, Spain, and Italy. In these six countries more than 70% of the European poultry meat is produced (Van Horne, 2018). Among these countries, two are from Western Europe, two from Central Europe and the last two from Southern Europe. For each country, the region with the highest poultry production at a national level was individuated to perform the simulations. A reference city representative of each one of these regions was selected for obtaining the Typical Meteorological Year (TMY) to be used as input data for the energy simulation model. In Table 2, the six selected locations with their countries and geographical regions are presented. In addition, the main parameters useful to characterize the weather conditions of the considered locations are shown. The reference locations are characterized by different values of average annual outdoor air temperature $\bar{\theta}_{\mathrm{air,o}}$ and annual total solar radiation on horizontal surface $H_{\mathrm{sol,hor}}$. In the framework of the present work, $\bar{\theta}_{\mathrm{air,o}}$ is the arithmetic mean of the hourly $\theta_{\mathrm{air,o}}$ values over the entire year, while $H_{\mathrm{sol,hor}}$ is the integral of the hourly values of solar irradiance over the entire year. From Table 2 it stands out that Barcelona is characterized by the highest value of $\bar{\theta}_{\mathrm{air,o}}$ (15.7 °C) and the highest annual solar radiation (5.2 GJ m^{-2} y^{-1}). Warsaw results the location with the lowest $\bar{\theta}_{\mathrm{air,o}}$ (8.4 °C), while Finninglay and Bremen are the ones characterized by the lowest $H_{\mathrm{sol,hor}}$ (3.4 GJ m^{-2} y^{-1}).

Table 2 – The locations used in this work with the details of the reference cities, acronyms, and geographical regions. For each location, the table shows also the average annual outdoor air temperature $\bar{\theta}_{\mathrm{air,o}}$, and the annual total solar radiation on horizontal surface $H_{\mathrm{sol,hor}}$.

Location (reference city)	Acronym	Geographical region	$\bar{\theta}_{\mathrm{air,o}}$ [°C]	$H_{\mathrm{sol,hor}}$ [GJ m^{-2}]
Poland (Warsaw)	PL	Central Europe	8.4	3.6
France (Brest)	FR	Western Europe	11.2	3.9
United Kingdom (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

Considering the six different locations and the three envelope types (A, B and C), 18 simulation scenarios are formulated. Each scenario is identified by a code in which the first two characters indicate the reference country (using the acronyms from Table 2), while the last one (separated by a dash) indicates the considered envelope type (A, B or C, as shown in Fig. 4).

3 Results and discussion

The calibrated energy model is used to perform a year-based simulation for each one of the 18 considered scenarios in standardized conditions. In this section, the results of the simulations are analysed to identify the best envelope solution in terms of delivered and the primary energy, showing the differences between the adopted approaches. The results are also analysed in terms of indoor climate conditions through the comparison of the overheating index.

3.1 Delivered energy approach

The energy performance of the 18 scenarios is assessed considering the delivered energy (thermal and electrical energy) that represents the state-of-the-art approach. For this purpose, the thermal energy consumption for heating E_{th}, the electrical energy consumption for ventilation $E_{\mathrm{el,ven}}$ and for evaporative cooling $E_{\mathrm{el,ec}}$ are evaluated. The values of E_{th} and $E_{\mathrm{el,ven}}$ are calculated by the model considering the efficiency of the heating system and the features of the ventilation system. The value of $E_{\mathrm{el,ec}}$ is calculated by the model considering the electrical energy consumption of the circulation pumps used to move the water from the storage to the top of the pad for wetting them.

3.1.1 Thermal and electrical energy consumption

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

Looking at the values of $\bar{\theta}_{\mathrm{air,o}}$ presented in Table 2, it stands out that the highest E_{th} values come from those outdoor weather conditions characterized by the lowest $\bar{\theta}_{\mathrm{air,o}}$ values. Solar radiation seems to not have the same influence of $\theta_{\mathrm{air,o}}$ on E_{th} because, even though PL-C is characterized by a slightly higher value of $H_{\mathrm{sol,hor}}$ than DE-C, its $E_{\mathrm{th}}$is considerably higher than the one of DE-C. An interesting analysis in this sense is the comparison between the sensible heat load from the animals with the heat load from solar radiation. Considering the last day of the production cycle in August, the maximum solar heat load that should be removed from the enclosure in scenario ES-C (where the solar gains are the maximum ones) is 47 W m^{-2} of useful floor area. At the same moment, the sensible heat load due to the animals is 176 W m^{-2} of useful floor area, a value that is nearly four times higher the one of the solar heat load. This difference means that in broiler houses, sensible heat load from animals represents the major issue for cooling ventilation even in mild climates, such as the one of ES-C scenario. Please note that in this work, the total solar radiation on any surface was calculated from the hourly values of direct normal radiation and diffuse horizontal solar radiation reported in the TMY adopting the transposition model of ASHRAE (2017). The calculation of the solar gains from the solar irradiance on opaque and transparent envelope components was performed in compliance with EN ISO 13790 standard (European Committee for Standardisation and EN ISO, 2008).

The results of the simulations show that, from the delivered energy point of view, the adoption of the high-insulation and low-massive building envelope (type-B) represents an interesting strategy to reduce E_{th} in all the considered weather conditions, because the type-B envelope entails the lowest E_{th}. The relative differences between the thermal energy performance of the considered envelopes in the same weather conditions are important. The choice of a high-insulation building envelope (type-B) reduces E_{th} between 63 and 67% if compared to a no thermal insulated envelope (type-C). The increase of the thermal insulation layer (from type-A to type-B envelope) entails a decrease of E_{th} between 41 and 46%.

High-insulation building envelope (type-B) resulted the best option for decreasing E_{th}, but the better thermal insulation properties of this envelope favour the overheating of the enclosure and higher electrical energy consumptions for ventilation $E_{\mathrm{el,ven}}$ and evaporative cooling $E_{\mathrm{el,ec}}$ are expected if compared with the other envelope types. In Fig. 5b the electrical energy consumptions $E_{\mathrm{el,ven}}$ and $E_{\mathrm{el,ec}}$ are presented and the bar chart indicates that, actually, $E_{\mathrm{el,ven}}$ is higher when type-B envelope is considered. The highest value of $E_{\mathrm{el,ven}}$ come from Spain (ES-B, 15.5 kWh_{el} m^{-2} y^{-1}) while the lowest one from United Kingdom (UK-C, 5.8 kWh_{el} m^{-}

^{2} y^{-1}). Even in this case, the higher $E_{\mathrm{el,ven}}$ values come from those weather conditions characterized by the higher values of $\bar{\theta}_{\mathrm{air,o}}$, namely Spain (15.7 °C) and Italy (12.3 °C). The $E_{\mathrm{el,ec}}$ values presented in Fig. 5b are the same for each considered geographical location regardless of the analysed envelope type. This is because the adopted energy model simulates the activation of the evaporative cooling only depending on the temperature difference between $\theta_{\mathrm{set,C}}$ and $\theta_{\mathrm{air,o}}$. The bar chart of Fig. 5b shows greater $E_{\mathrm{el,ec}}$ for those scenarios where also the $E_{\mathrm{el,ven}}$ is higher, such as Spain and Italy. The estimated $E_{\mathrm{el,ec}}$ values are considerably smaller than $E_{\mathrm{el,ven}}$, being 2.5 kWh$_{\mathrm{el}}$ m^{-2} y^{-1} or lower for all the considered scenarios.

Considering the total electrical energy consumption E_{el} (sum of $E_{\mathrm{el,ven}}$ and $E_{\mathrm{el,ec}}$), the bar chart shows that it ranges between 18.0 kWh$_{\mathrm{el}}$ m^{-2} y^{-1} and 6.4 kWh$_{\mathrm{el}}$ m^{-2} y^{-1}. The adoption of a low insulated envelope (type-C) decreases the electrical energy consumption from 6 to 13% if compared to a high-insulation thermal envelope (type-B).

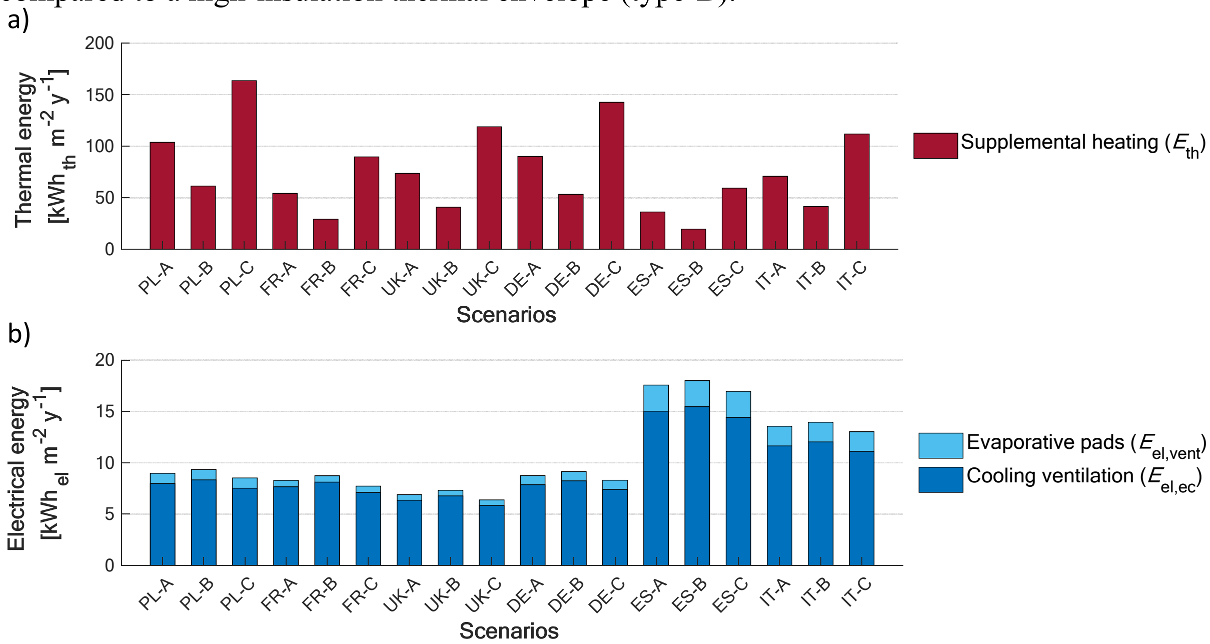

Fig. 5. Thermal (E_{th}, figure a), and electrical energy consumption (figure b) both for ventilation ($E_{\mathrm{el,ven}}$) and evaporative cooling ($E_{\mathrm{el,ec}}$) from the 18 scenarios.

3.1.2 Reference values of embedded delivered energy consumption

The energy consumptions that were obtained from the previously presented scenarios are now used to formulate reference values about the use of energy in broiler houses. Similar values are interesting from the scientific point of view with a perspective on the improvement of the energy efficiency of broiler production but very few of them are present in literature, as highlighted by the review of Costantino et al. (2016). Most of the reference values present in literature, in fact, refers to specific case studies or geographical contexts, as done by Hörndahl (2008) for the Swedish context, the Technical Institute of Poultry (2010) for the France and Rossi et al. (2013) for Italy. In addition, those reference values were not assessed in standardized conditions, a feature that may jeopardize their reliability. On the contrary, the reference values present in this section are calculate in standardized conditions, refer to different European context and consider different types of building envelope. Nevertheless, more accurate results would be obtained performing simulations using Monte Carlo method to consider a higher variations of boundary conditions and using sensitivity analysis to better understand the influence of the considered parameters on the final results.

The results obtained from the analysed scenarios are normalized on the $\mathrm{kg_{meat}}$ and grouped to obtain ranges of embedded delivered energy consumption for climate control. This normalization is necessary to make the results independent from the assumptions made for this work, such as the farming features. Furthermore, the adopted unit of measure ($\mathrm{Wh\ kg_{meat}^{-1}}$) is useful for engineers and farmers since they can refer production costs and revenues to the unit of final product. The saleable meat from each broiler is calculated considering a carcass yield (percentage of the saleable meat over the final live weight) of 73% (Costantino et al., 2016). Consequently, a meat production of 2.60 $\mathrm{kg_{meat}}$ per reared broiler is estimated. The main limitation in the formulation of these reference values is in the estimation of the broiler final live weigh since the adopted energy simulation model does not consider the decrease of broiler weight gain due to heat stress. This issue can be taken into account in future works using the formulations provided by St-Pierre, Cobanov, & Schnitkey (2003).

In Fig. 6 the ranges of the specific thermal $E_{\mathrm{meat,th}}$ (Fig. 6a) and electrical energy consumption $E_{\mathrm{meat,el}}$ (Fig. 6b) referred to the selected countries are presented. The values of $E_{\mathrm{meat,th}}$ and $E_{\mathrm{meat,el}}$ were calculated dividing the yearly thermal and electrical energy consumption by the meat production over the entire year. The presented ranges consider the minimum and the maximum values of $E_{\mathrm{meat,th}}$ and $E_{\mathrm{meat,el}}$ (the sum of electrical energy consumption for both ventilation and evaporative cooling) of each country considering the three envelope types.

The range of $E_{\mathrm{meat,th}}$ goes from 628 $\mathrm{Wh_{th}\ kg_{meat}^{-1}}$ (Spain) to 5,245 $\mathrm{Wh_{th}\ kg_{meat}^{-1}}$ (Poland). Three countries (France, United Kingdom, and Italy) are in the range from 940 to 3,812 $\mathrm{Wh_{th}\ kg_{meat}^{-1}}$, while the $E_{\mathrm{meat,th}}$ of Germany and Poland is between the range 1,711 – 5,245 $\mathrm{Wh_{th}\ kg_{meat}^{-1}}$. Spain is the country with the narrower range of $E_{\mathrm{meat,th}}$ that goes from 628 to 1,901 $\mathrm{Wh_{th}\ kg_{meat}^{-1}}$.

The ranges presented in Fig. 6b are narrower and of an order of magnitude lower than the the ones of Fig. 6a. The difference between the highest and the lowest value of each country presented in Fig. 6b is between 26 and 33 $Wh_{el}\ kg_{meat}^{-1}$. The lowest $E_{meat,el}$ is the one from Great Britain (205 $Wh_{el}\ kg_{meat}^{-1}$) while the greatest one is from Spain (577 $Wh_{el}\ kg_{meat}^{-1}$). $E_{meat,el}$ of four countries (Poland, France, United Kingdom, and Germany) is between 205 and 299 $Wh_{el}\ kg_{meat}^{-1}$. The $E_{meat,el}$ value from Italy is between 417 and 447 $Wh_{el}\ kg_{meat}^{-1}$, while Spain has the wider $E_{meat,el}$ range (543 - 577 $Wh_{el}\ kg_{meat}^{-1}$).

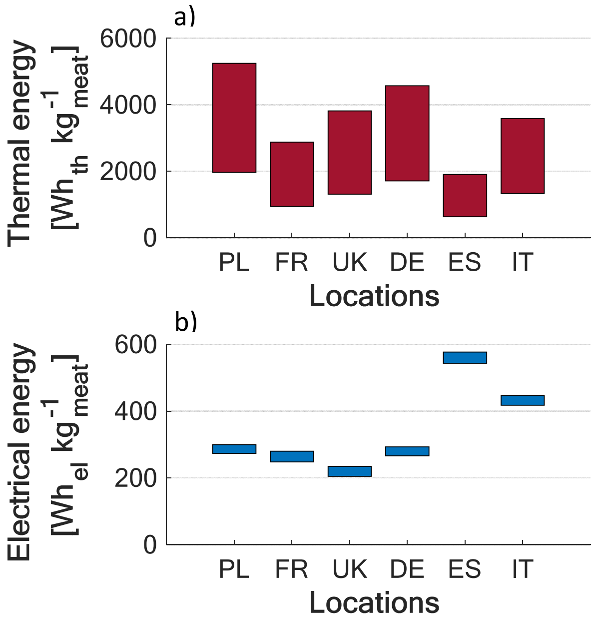

Fig. 6. Ranges of specific thermal ($E_{meat,th}$, figure a) and electrical energy consumption ($E_{meat,el}$, figure b) for the considered locations.

3.2 Primary energy approach

The previous analysis was based on the assessment of the delivered energy (considered the state-of-the-art approach) and showed that type-B envelope is the best strategy to decrease E_{th} while type-C envelope is the worst one by far in all the considered locations. On the contrary, type-C envelope guarantees the best performance considering the electrical energy consumption for ventilation and evaporative cooling. Type-A envelope is the intermediate solution for both thermal and electrical energy consumption. To identify the actual best solution among the three considered envelopes, the global energy performance is assessed for the 18 scenarios considering the primary energy consumption. In this way, the thermal and electrical energy consumption can be correctly weighted considering their respective energy overheads for extracting, refining, converting, and transporting the energy.

3.2.1 Primary energy consumption

The conversion from delivered energy to primary energy can be performed according to Eq. (1)-(3) using the total (renewable and non-renewable) primary energy consumption factors $f_{\mathrm{p,th,tot}}$ and $f_{\mathrm{p,el,tot}}$ that are reported in Table 3. The energy carriers that are used in the considered case study are natural gas and electrical energy from the national grid. From Table 3, two main aspects can be highlighted. The first aspect is that $f_{\mathrm{p,el,tot}}$ is always higher than $f_{\mathrm{p,th,tot}}$. This is since the production and transport of electrical energy is characterized by higher energy overheads than the thermal one. The second aspect is that quite important differences stand out among the countries especially concerning $f_{\mathrm{p,el,tot}}$ because different countries are characterized by different energy mixes and, consequently, different energy overheads.

For the previously stated reasons, its essential to consider the primary energy when the energy performance of a broiler house (and, in general, of a livestock house) is evaluated to avoid misleading results.

Table 3 – Total (renewable and non-renewable) primary energy factors for thermal $f_{\mathrm{p,th,tot}}$ and electrical $f_{\mathrm{p,el,tot}}$ energy used in this work. The considered energy carriers are natural gas and electrical energy from the electrical grid.

Country	$f_{\mathrm{p,th,tot}}$ (natural gas) [$kWh_p\ kWh_{th}^{-1}$]	$f_{\mathrm{p,el,tot}}$ (electrical grid) [$kWh_p\ kWh_e^{-1}$]	Reference
Poland	1.10	3.03	Polish Ministry of Economy (2014)
France	1.00	2.58	French Ministry of Territorial Equality and Housing (2011)
United Kingdom	1.02	2.92	E. Molenbroek, E. Stricker (2011)
Germany	1.10	2.80	German Association of Energy and Water Industries (BDEW) (2015)
Spain	1.195	2.368[a]	Spanish Ministry of Industry Energy and Tourism (2016)
Italy	1.05	2.42	Italian Ministry of Economic Development (2015)

[a] $f_{\mathrm{p,el,tot}}$ referred to Peninsular Spain; the national values is 2.403 $kWh_p\ kWh_e^{-1}$.

In Fig. 7, $E_{\mathrm{p,glob}}$ and its shares $E_{\mathrm{p,th}}$ and $E_{\mathrm{p,el}}$ from the analysed scenarios are presented. The graph shows that PL-C is characterized by the highest $E_{\mathrm{p,glob}}$ (205.9 $kWh_p\ m^{-2}\ y^{-1}$). This is since the considered Polish weather conditions entail a considerable high E_{th} that represents around 87% of $E_{\mathrm{p,glob}}$.

In all the considered weather conditions, type-B envelope provides the best global primary energy performance entailing the minimum $E_{\mathrm{p,glob}}$. In particular, the scenario characterized by the lowest value of $E_{\mathrm{p,glob}}$ is FR-B (51.9 $\mathrm{kWh_p\ m^{-2}\ y^{-1}}$). This scenario, in fact, is characterized by a quite low E_{th} (the lowest one after ES-B) that is not increased by the $f_{\mathrm{p,th}}$ that, for France, is equal to 1 $\mathrm{kWh_p\ kWh_{el}^{-1}}$. Furthermore, the $\bar{\theta}_{\mathrm{air,o}}$ value (the highest one after ES and IT), entails a reduced $E_{\mathrm{el,vent}}$ (8.1 $\mathrm{kWh_e{\cdot}m^{-2}\ y^{-1}}$) that, converted in $E_{\mathrm{p,el}}$, represents 43% of $E_{\mathrm{p,tot}}$.

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%.

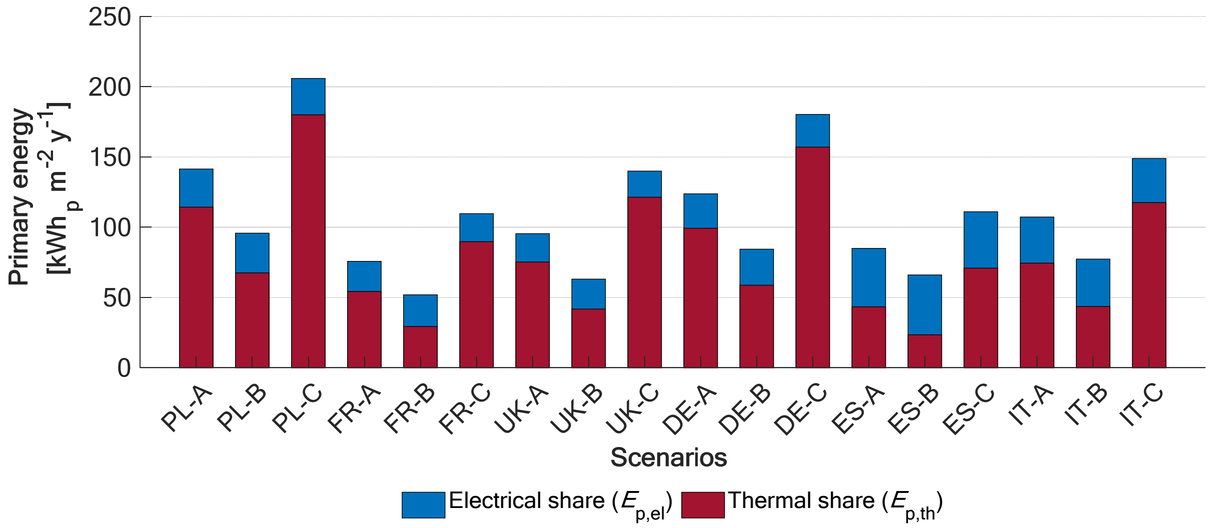

Fig. 7. Primary energy consumption $E_{\mathrm{p,glob}}$ of each scenario. The energy shares due to electrical ($E_{\mathrm{p,el}}$) and thermal ($E_{\mathrm{p,th}}$) energy consumptions are also shown.

The values of $E_{\mathrm{p,tot}}$ presented in Fig. 7 refer to the entire year but each production cycle could be characterized by considerably different values of primary energy consumption, if compared to the other cycles, depending on the period of the year in which is carried out. To analyse these differences, the global primary energy consumption of each production cycle $E_{\mathrm{cycle,p,glob}}$ ($\mathrm{kWh_p\ m^{-2}\ cycle^{-1}}$) from PL-C and ES-B scenarios are shown in Fig. 8. The comparison between PL-C and ES-B is interesting since these scenarios are characterized by the highest $E_{\mathrm{p,th}}$ and $E_{\mathrm{p,el}}$, respectively. The sum of $E_{\mathrm{cycle,p,glob}}$ of each production cycle is equal to $E_{\mathrm{p,tot}}$ reported in Fig. 7. In Fig. 8 the primary energy shares due to thermal $E_{\mathrm{cycle,p,th}}$ and electrical $E_{\mathrm{cycle,p,el}}$ energy are also reported. In addition, the average $E_{\mathrm{cycle,p,glob}}$ calculated over the six production cycles is provided for both the considered scenarios.

The bar chart of Fig. 8 shows that the average $E_{\mathrm{cycle,p,glob}}$ values of the considered scenarios are different, being $E_{\mathrm{cycle,p,glob}}$ of PL-C scenario around 19.8 kWh$_{\mathrm{p}}$ m^{-2} cycle^{-1} (around 87% due to $E_{\mathrm{cycle,p,th}}$ and 13% due to $E_{\mathrm{cycle,p,el}}$,), while $E_{\mathrm{cycle,p,glob}}$ of the ES-B scenario is 6.4 kWh$_{\mathrm{p}}$·m^{-2}·cycle^{-1} (35% due to $E_{\mathrm{cycle,p,th}}$ and 65% due to $E_{\mathrm{cycle,p,el}}$).

In Fig. 8 important differences can be highlighted between the production cycles of the warm and the cool seasons. Analysing the Polish scenario, it stands out that the production cycles of the cool season (1$^{\mathrm{st}}$, 2$^{\mathrm{nd}}$, and 6$^{\mathrm{th}}$) are characterized by $E_{\mathrm{cycle,p,tot}}$ values that are higher than 23.0 kWh$_{\mathrm{p}}$ m^{-2} cycle^{-1}. This energy consumption is greater than the one from the 3$^{\mathrm{rd}}$, 4$^{\mathrm{th}}$, and 5$^{\mathrm{th}}$ production cycles, that is always lower than 10.0 kWh$_{\mathrm{p}}$ m^{-2} cycle^{-1}. Looking at the shares of $E_{\mathrm{cycle,p,glob}}$, in 1$^{\mathrm{st}}$, 2$^{\mathrm{nd}}$, 5$^{\mathrm{th}}$ and 6$^{\mathrm{th}}$ production cycles in PL-C scenario, $E_{\mathrm{cycle,p,th}}$ is always higher than 80% of the total, with a maximum value of 98% during the 1$^{\mathrm{st}}$ production cycle. In 3$^{\mathrm{rd}}$ and 4$^{\mathrm{th}}$ production cycles (during the warm season), $E_{\mathrm{cycle,p,th}}$ is lower, being around 60% and 40%, respectively.

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

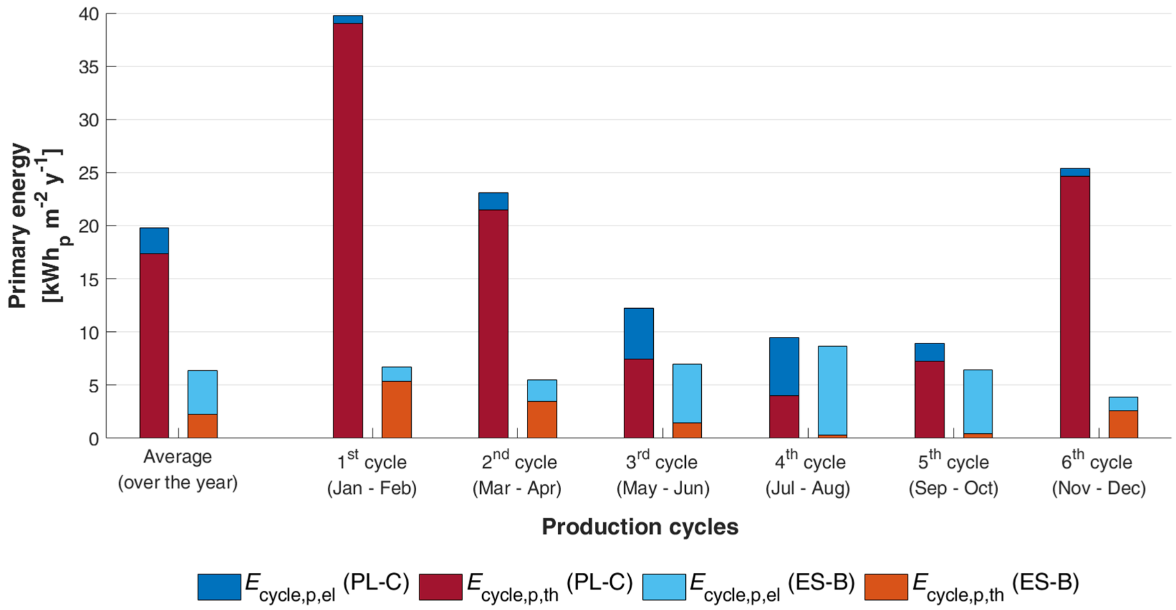

Fig. 8. Primary energy consumption for each production cycle ($E_{\mathrm{cycle,p,global}}$) and shares due and electrical ($E_{\mathrm{cycle,p,el}}$) and thermal ($E_{\mathrm{cycle,p,th}}$) energy from PL-C and ES-B scenario. These scenarios are compared since they are the ones characterized by the highest $E_{\mathrm{p,th}}$ and $E_{\mathrm{p,el}}$, respectively.

3.2.2 Reference values of embedded primary energy consumption

Reference values are also provided using primary energy for considering the global energy performance of the houses. In Table 4, the global primary energy embedded to produce a kg of meat ($E_{\mathrm{meat,p,glob}}$) is presented with the shares due to heating, ventilation, and evaporative cooling. The results show that the range of $E_{\mathrm{meat,p,glob}}$ values goes from 1.7 to 6.6 $\mathrm{kWh_p\ kg_{meat}^{-1}}$. Heating represents the highest share of $E_{\mathrm{meat,p,glob}}$ in almost all the scenarios (the only exceptions is ES-B) being between 51 and 87% of the total. Ventilation goes from 11 to 55% of $E_{\mathrm{meat,p,glob}}$. Evaporative cooling is equal or lower than 6% in all the scenario except for ES-A and ES-B where it represents 7% and 9%, respectively. This result proves that in the assessment of the energy performance of a broiler house, the energy consumption for evaporative cooling can be neglected due to its minor relevance, especially in cool climate conditions and in presence of low-insulation envelopes.

Table 4 – Primary energy consumption embedded in a kg of final product ($E_{\mathrm{meat,p,glob}}$) and shares due to heating, ventilation, and evaporative cooling.

Scenario	$E_{\mathrm{meat,p,glob}}$ [$\mathrm{kWh_p\ kg_{meat}^{-1}}$]	Heating [%]	Ventilation [%]	Evaporative cooling [%]
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%

3.3 Financial evaluations

The previously presented scenarios are analysed from the financial point of view to understand the differences in terms of financial costs between them. The global cost C_{G} is evaluated according to Eq. () considering 30 years of broiler house lifespan τ_{ls} and a real interest rate R_{R} of 3.5% (Hermelink and de Jager, 2015). The first step of this evaluation is the estimation of the initial investment cost C_{I} for the construction of the building envelope and climate control system. To obtain C_{I} for IT-A, IT-B, and IT-C scenarios, an analysis on the Italian market was performed to find the final costs (product, installation, and taxes) of each considered element. The costs of each element and the obtained C_{I} are presented in Table 5 for IT-A, IT-B, and IT-C scenarios. The other costs of the broiler house (e.g. feeders and lighting system) are not considered since they negligibly affect the energy performance of the building envelope.

Table 5 –Costs of envelope and the climate control system elements and initial investment cost C_{I}.

Element	IT-A [€ m^{-2}]	IT-B [€ m^{-2}]	IT-C [€ m^{-2}]
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
Pads pump and pipeline	4.55	4.55	4.55
C_{I}	193.43	341.21	143.99

The obtained C_{I} presented in Table 5 are then multiplied by γ_{PLI} to obtain C_{I} of the other considered countries. The term γ_{PLI} is a dimensionless cost conversion factor that indicates the ratio between the construction price of the considered European country and the one of Italy. In the framework of this analysis, γ_{PLI} values are obtained from the Price Level Indices for non-residential buildings construction provided by Eurostat (2019) and they are presented in Table 6.

In the global cost methodology, the annual costs C_a expected over the lifespan of the analysed broiler house should be also accounted. In this work, the replacement costs of the climate control system elements and the energy cost are considered in C_a. Other running costs (e.g. insurances and ordinary maintenance) are considered negligible for the scope of this work. The replacement costs are estimated starting from the costs of the climate control system elements presented in Table 5 and considering a lifespan of 15 years for fans, gas air heaters and the evaporative pads pumps and pipeline, while the lifespan of the evaporative pads was estimated equal to 5 years. At the end of the broiler house lifespan, no final value V_{f} is considered for the envelope and climate control system elements. The C_a of energy is estimated multiplying the yearly E_{th} and E_{el} (obtained from the simulations) by the cost of thermal C_{th} and electrical C_{el} energy of the considered country that are presented in Table 6 (values from Eurostat (2020a, 2020b)).

Table 6 – Cost conversion factor γ_{PLI} and costs of thermal C_{th} and electrical C_{el} energy (including taxes) considered in this work.

Country	γ_{PLI} [-]	C_{th} [€ kWh_{th}^{-1}]	C_{el} [€ kWh_{el}^{-1}]
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

In Fig. 9 the shares of C_G due to envelope, climate control system and energy of each considered scenario are presented through a stacked bar chart. The graph shows that the highest overall C_G is 714 € m^{-2} of DE-B scenario, while the lowest one is 272 € m^{-2} of PL-A scenario. These absolute values can be explained with a view on Table 6 since γ_{PLI}, C_{th} and C_{el} considerably affects the difference between countries. Germany, in fact, is characterized by the highest γ_{PLI} (1.67) that entails considerably higher C_{I} and C_a (due to climate control system replacement) than the other countries, especially, Poland where γ_{PLI} is only 0.78. A similar difference can be found analysing C_{th} and C_{el} that are the lowest ones for Poland (0.04 € kWh_{th}^{-1} and 0.15 € kWh_{el}^{-1}, respectively), while Germany is characterized by the highest C_{el}.

The results of the global cost analysis presented in Fig. 9 shows that, in all the considered countries, type-B envelope is characterized by the highest C_{G}, while type-A and type-C envelopes are characterized approximatively by the same C_{G}, with a maximum relative difference of 8% (UK-A and UK-C scenarios). The relative difference between type-B envelope and the other two types is considerable, being between 29% (IT-C) and 58% (UK-C). The stacks of the bar chart explain why type-B envelope is characterized by a such high C_{G} although it was characterized by the best primary energy performance, as previously showed in Fig. 7. The costs related to the building envelope, in fact, represent between 68% and 79% of C_{G} in the considered countries. The good energy performance of type-B envelope reflects on very low shares of C_{G} for energy (between 12% and 21%) but it is not enough to make type-B envelope a good option not only from the energy point of view but also from the financial one. In this sense, type-A envelope could represent a good compromise since it is a solution that guarantee a good primary energy performance (considerably better than the one of type-C, as visible in Fig. 7) and a C_{G} similar to the one of type-C envelope, with a good impact form the financial sustainability point of view.

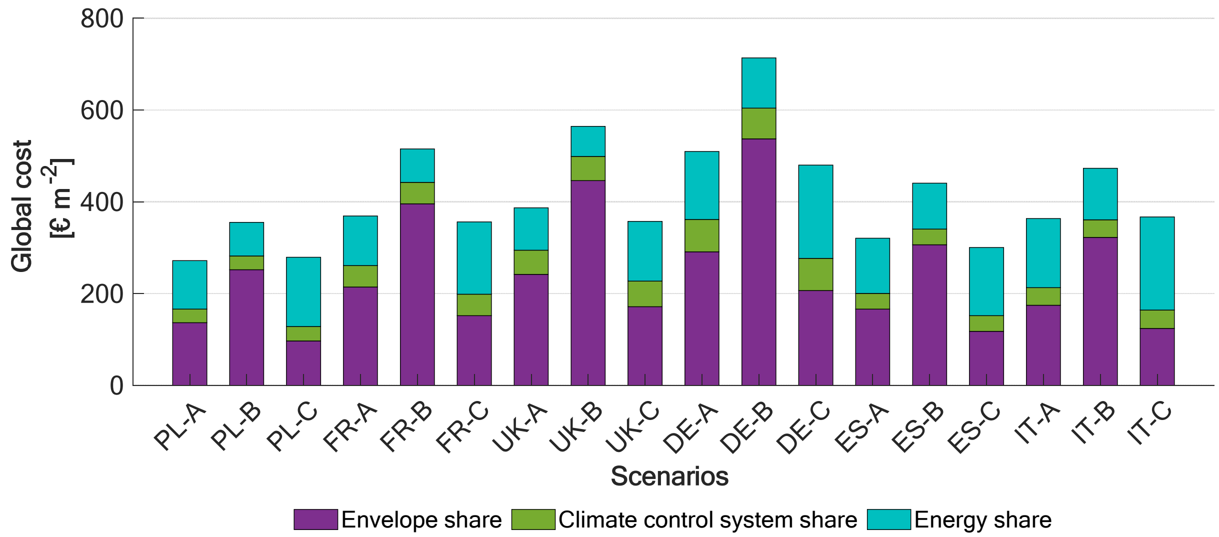

Fig. 9. Global cost C_G and shares due to envelope, climate control system and energy for each of the analysed scenarios.

3.4 Comparison of indoor climate conditions

The free cooling systems with which broiler houses are usually equipped could be not able to maintain the required $\theta_{set,C}$ especially in warm season and broilers can be exposed to heat stress especially in presence of thermal insulated envelopes. For this reason, it is important to evaluate the envelope also considering the indoor environmental conditions to assure that low energy consumptions are not related to excessively poor indoor environmental conditions.
For this purpose, the overheating index Ω_{oH} is calculated according to Eq. (4) for the considered scenarios and the results are presented in the bar chart of Fig. 10. From the bar chart it stands out that overheating problems are evident in the scenarios characterized by the outdoor weather conditions of Spain and Italy, while the other scenarios are characterized by low Ω_{oH} with the minimum value from UK-C scenario.
Through the bar chart of Fig. 10 the differences in terms of Ω_{oH} between the three types of envelope in the same outdoor weather conditions can be assessed. In the same outdoor weather conditions, the maximum Ω_{oH} values come from the scenarios with type-B envelope, while the minimum Ω_{oH} comes from the scenario with type-C envelope. The higher thermal insulation of the type-B envelope, in fact, decreases the energy need for heating but does not foster the heat losses through transmission, increasing the cooling need. During the warm season (or in presence of high thermal load from the animals) these transmission heat losses would decrease $\theta_{air,i}$ mitigating the overheating of the enclosure. In the scenarios characterized by milder weather conditions (Spain and Italy), the relative difference between the type-B envelope (with the maximum Ω_{oH}) and type-A and type-C envelopes (with the

minimum Ω_{oH}) is equal or less than 6%. In the scenarios with cooler outdoor weather conditions, those differences are higher. The greatest difference is from United Kingdom scenarios where the maximum relative difference between type-C and type-B is around 30%. In all the other weather conditions this difference is always lower than 20%, but in absolute terms, Ω_{oH} is low.

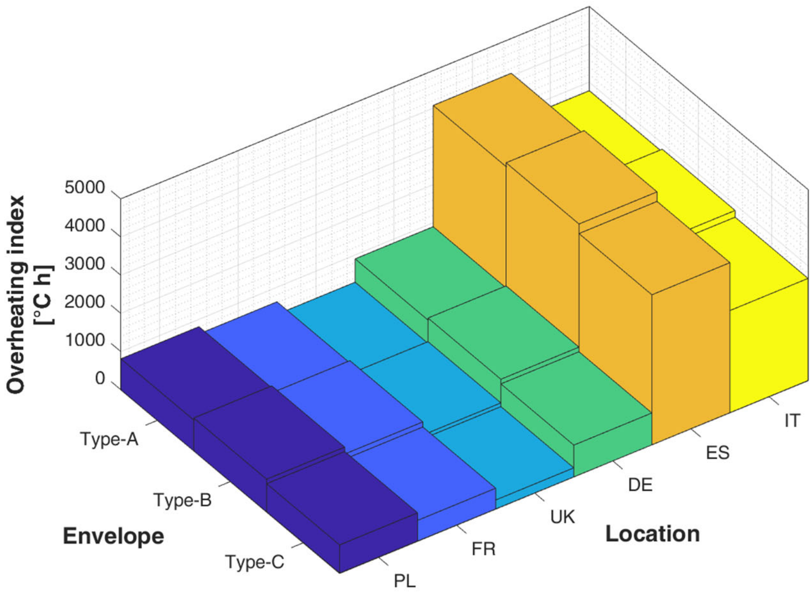

Fig. 10. Overheating index (Ω_{oH}) of the analysed scenarios.

4 Conclusions

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

This work increases the environmental sustainability of the broiler production with two main contributions. First, the performed analyses show the importance of a case-bycase design of the building envelope in improving the energy performance of broiler houses, while in literature most of the works are focused on the improvement of energy and climate control systems. The second contribution relies in the methodology that is adopted in this paper to evaluate the energy performance. The performed energy analyses, in fact, are not limited to the delivered energy consumed on farm, but they encompass the entire energy supply chain adopting an approach based on primary energy. In this way, important issues can be considered such as the energy losses along the energy supply chain and the different energy mixes proper of the different countries. This last aspect is of a foremost importance for evaluating how the transition toward cleaner energy mixes undertaken by several countries affects the sustainability of the livestock production. To do so, future works could further deepen the energy analysis based on the primary energy approach to assess the share of primary energy from renewable and non-renewable sources. That distinction would considerably improve the assessment of the environmental sustainability of livestock production. This approach could represent the core of a new energy certification scheme that could be *ad-hoc* developed for livestock houses. It would represent the first step of new legislation frameworks that, establishing minimum energy performances and incentive systems, could boost to a cleaner livestock production through a top-down approach.

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