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

Andrea Costantino[1,2*], Salvador Calvet[2], Enrico Fabrizio[1]

[1]*DENERG, Politecnico di Torino, TEBE Research Group, Corso Duca degli Abruzzi 24, 10129 Torino, Italy*

[2]*Institute of Animal Science and Technology, Universitat Politècnica de València, Camino de Vera s/n, 46022, València, Spain*

*Corresponding author. Tel: +39 0110904552

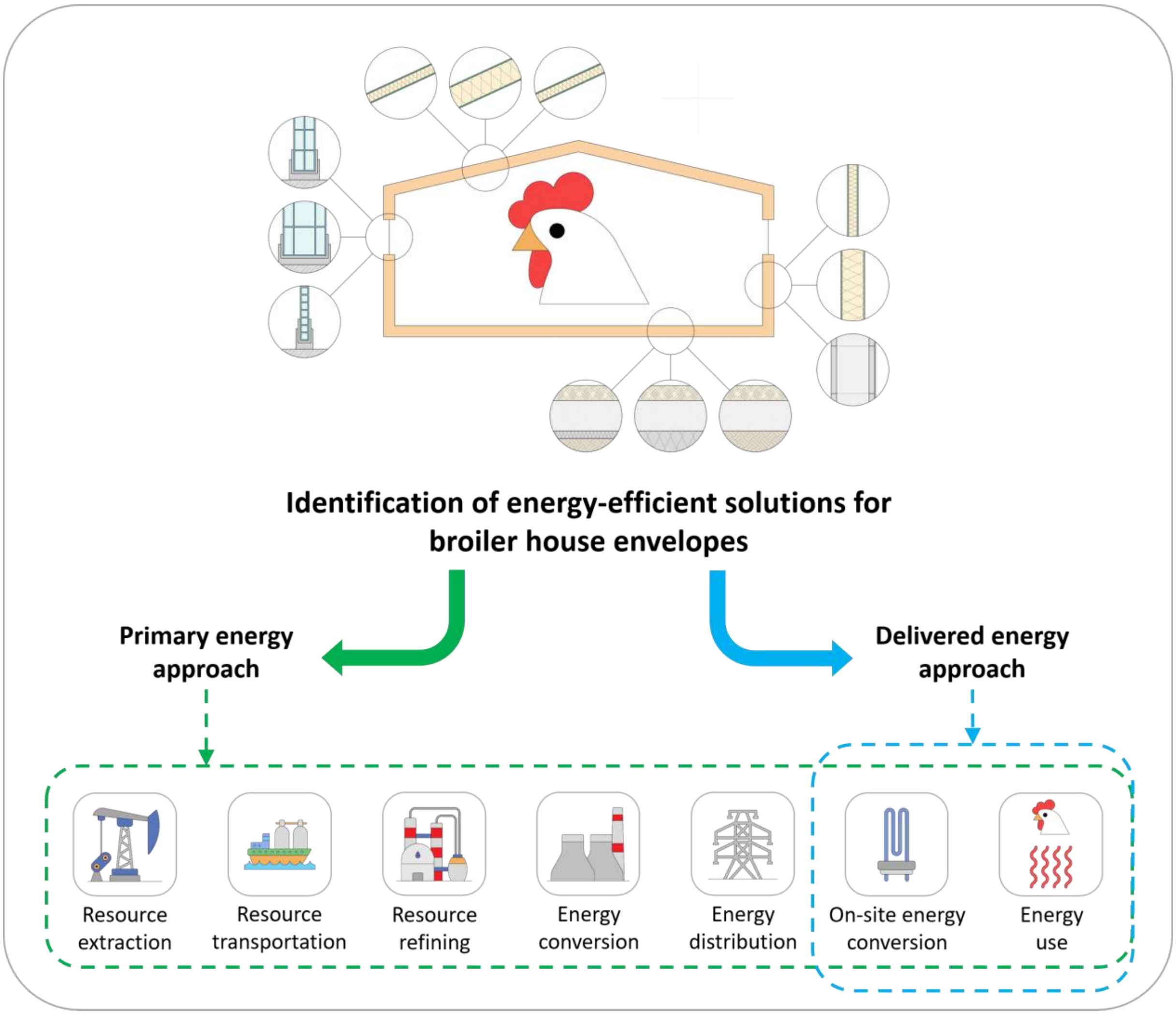
E-mail address: andrea.costantino@polito.it

Abstract

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

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

Graphical abstract



Nomenclature

A	Area of opaque envelope element
C_{a}	Annual cost [€ m^{-2}]
C_{el}	Electrical energy cost [€ $\mathrm{kWh}_{\mathrm{el}}^{-1}$]
C_{m}	Total building fabric heat capacity [$\mathrm{kJ\ K}^{-1}$]
C_{G}	Global cost [€ m^{-2}]
C_{I}	Investment cost [€ m^{-2}]
C_{th}	Thermal energy cost [€ $\mathrm{kWh}_{\mathrm{th}}^{-1}$]
DE	Germany
$E_{\mathrm{cycle\_p\_el}}$	Primary energy consumption of a production cycle (electrical energy share) [$\mathrm{kWh_p\ m^{-2}\ cycle^{-1}}$]
$E_{\mathrm{cycle\_p\_glob}}$	Global primary energy consumption of a production cycle [$\mathrm{kWh_p\ m^{-2}\ cycle^{-1}}$]
$E_{\mathrm{cycle\_p\_th}}$	Primary energy consumption of a production cycle (thermal energy share) [$\mathrm{kWh_p\ m^{-2}\ cycle^{-1}}$]
$E_{\mathrm{p\_el}}$	Electrical share of primary energy consumption [$\mathrm{kWh_p\ m^{-2}\ y^{-1}}$]
$E_{\mathrm{p\_glob}}$	Global primary energy consumption [$\mathrm{kWh_p\ m^{-2}\ y^{-1}}$]
$E_{\mathrm{p\_th}}$	Thermal share of primary energy consumption [$\mathrm{kWh_p\ m^{-2}\ y^{-1}}$]
E_{el}	Total electrical energy consumption [$\mathrm{kWh_{el}\ m^{-2}\ y^{-1}}$]
$E_{\mathrm{el\_ec}}$	Electrical energy consumption for evaporative cooling [$\mathrm{kWh_{el}\ m^{-2}\ y^{-1}}$]
$E_{\mathrm{el\_ven}}$	Electrical energy consumption for ventilation [$\mathrm{kWh_{el}\ m^{-2}\ y^{-1}}$]
$E_{\mathrm{meat\_el}}$	Electrical energy consumption for unit of mass of produced meat [$\mathrm{Wh_{el}\ kg_{meat}^{-1}}$]
$E_{\mathrm{meat\_p\_glob}}$	Primary energy consumption for unit of mass of produced meat [$\mathrm{kWh_p\ kg_{meat}^{-1}}$]
$E_{\mathrm{meat\_th}}$	Thermal energy consumption for unit of mass of produced meat [$\mathrm{Wh_{th}\ kg_{meat}^{-1}}$]
E_{th}	Thermal energy consumption for heating [$\mathrm{kWh_{th}\ m^{-2}\ y^{-1}}$]
ES	Spain
$f_{\mathrm{p\_el\_tot}}$	Total primary energy conversion factor for electrical energy [$\mathrm{kWh_p\ kWh_{el}^{-1}}$]
$f_{\mathrm{p\_th\_tot}}$	Total primary energy conversion factor for thermal energy [$\mathrm{kWh_p\ kWh_{th}^{-1}}$]
FR	France
g_{gl}	Solar factor of the glazed surface [$-$]
$H_{\mathrm{sol\_hor}}$	Annual total solar radiation on horizontal surface [$\mathrm{GJ\ m^{-2}}$]
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_{comp}	Number of opaque envelope elements
n_{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 [$\mathrm{W\ m^{-2}\ K^{-1}}$]
$\bar{U}$-value	Average stationary thermal transmittance of the entire building envelope [$\mathrm{W\ m^{-2}\ K^{-1}}$]
UK	United Kingdom
V_{f}	Final value [$€\ \mathrm{m^{-2}}$]
α_{sol}	Solar absorption coefficient [$-$]
γ_{PLI}	Cost conversion factor [$-$]
Δp_{st}	Static pressure difference between inside and outside [Pa]
$\Delta\tau$	Time interval [h]
$\theta_{\mathrm{air\_i}}$	Indoor air temperature [℃]
$\theta_{\mathrm{air\_o}}$	Outdoor air temperature [℃]
$\bar{\theta}_{\mathrm{air\_o}}$	Average annual outdoor air temperature [℃]
$\theta_{\mathrm{air\_sup}}$	Supply air temperature [℃]
$\theta_{\mathrm{set\_C}}$	Cooling set point temperature [℃]
$\theta_{\mathrm{set\_H}}$	Heating set point temperature [℃]
κ_{i}	Internal heat capacity [$\mathrm{kJ\ m^{-2}\ K^{-1}}$]
τ_{ls}	Broiler house lifespan [y]
Ω_{oH}	Overheating index [℃ h]

1 Introduction

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

One of the main concerns regarding broiler production is the high use of energy required to farm the animals, e.g. thermal and electrical energy, or to provide the inputs, e.g. machinery and feed. According to Heidari et al. (2011), the highest indirect energy input of poultry production is feed, that represents around 32% of the total energy inputs. Other energy inputs, e.g. for machinery and human labour, are negligible. The importance of feed as an energy input for broiler production has been underlined in literature by emergy analyses, which are 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 farming in terms of emergy inputs. Allegretti et al. (2018) performed an emergy assessment to show the potentialities of insect-based feed for broiler production.

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

Whilst some research has been carried out on the improvement of the energy performance of climate control systems, there have been few investigations into the improvement of the energy performance of broiler house envelopes (Axaopoulos et al., 2014). The envelope is composed of the outer elements of a broiler house, i.e. walls, roof, floor and windows. It constitutes the boundary of thermodynamic system of the broiler house 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 improving the energy performance for climate control through the decrease of the overall consumption of thermal and electrical energy. By contrast, in current practice, the envelope design of a broiler house is often a shallow process that provides standardized solutions for contexts that are considerably different. Therefore, there is a strong need for a design process targeted at improving the energy performance of the broiler house envelope. Energy analysis (Pimentel et al., 1973) is a powerful method to evaluate improvements of the energy performance, but research has pointed out that the robustness of this method may need to be improved (Vigne et al., 2012). Most of the energy analyses described above, in fact, evaluated the energy performance of broiler houses focusing only on thermal and electrical energy delivered on farms. Thus, the current state of the art adopts a delivered energy approach that focuses only on the very last stages of the energy supply chain, neglecting the energy consumption that occurs in the previous stages. A new approach based on primary energy could encompass all the stages of the energy supply chain. Primary energy assessment, 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. Primary energy accounts for the energy losses - e.g. due to conversion and transportation - and for the energy embedded in the infrastructures - e.g. in turbines and pipes - along the energy supply chain in addition to the on-farm energy consumption. Furthermore, primary energy focuses on the adopted energy carrier, e.g. natural gas or electricity from grid, and on the considered country (ISO, 2017a). The importance of primary energy is 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 the energy assessment of residential (Bilardo et al., 2020) and office (Krstić-Furundžić et al., 2019) buildings and industrial processes (Dunkelberg et al., 2018). By contrast, there are few primary energy analyses of broiler houses in literature and they focus on very specific case studies and geographical contexts. Costantino et al. (2020), for example, estimated the variation of the primary energy consumption due to different ventilation strategies in a Spanish broiler house. Baxevanou et al. (2017) used the primary

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

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

2 Materials and methods

This work is based on the methodology workflow schematized in Fig. 1. The pre-processing 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). The identified case study is then used to calibrate a previously developed dynamic energy simulation model (section 2.2). In the pre-processing stage the simulation scenarios are set by defining different envelope types (section 2.3) and different outdoor weather conditions (section 2.4).

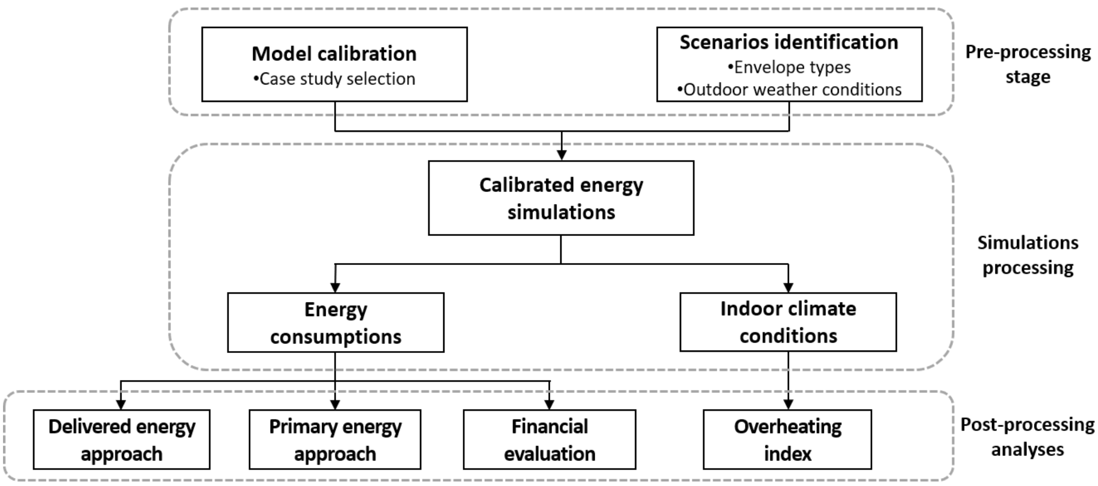

Fig. 1. Schematization of the methodology workflow.

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

- 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 are presented in section 3.1 and 3.2, respectively, where, additionally, reference values of energy consumption are provided. The main difference between delivered and primary energy approach is conceptualized in Fig. 2. As shown in the figure, the delivered energy approach accounts exclusively for the energy that is converted and used on farm. In this work, the delivered energy consumption of the analysed broiler house is provided directly by the energy simulation model. By contrast, 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 from the simulation results 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 conversion factor for thermal energy and $f_{\mathrm{p\_el\_tot}}$ is the total primary energy conversion factor for electrical energy. These factors depend on the considered energy carrier since the overheads for extracting, refining, converting, and transporting energy change significatively depending on it. The primary energy factors are calculated at a national level since each country should consider its own energy mix. The terms $f_{\mathrm{p\_th\_tot}}$ and $f_{\mathrm{p\_el\_tot}}$ are "total" conversion factors since they account for the renewable and non-renewable primary energy shares.

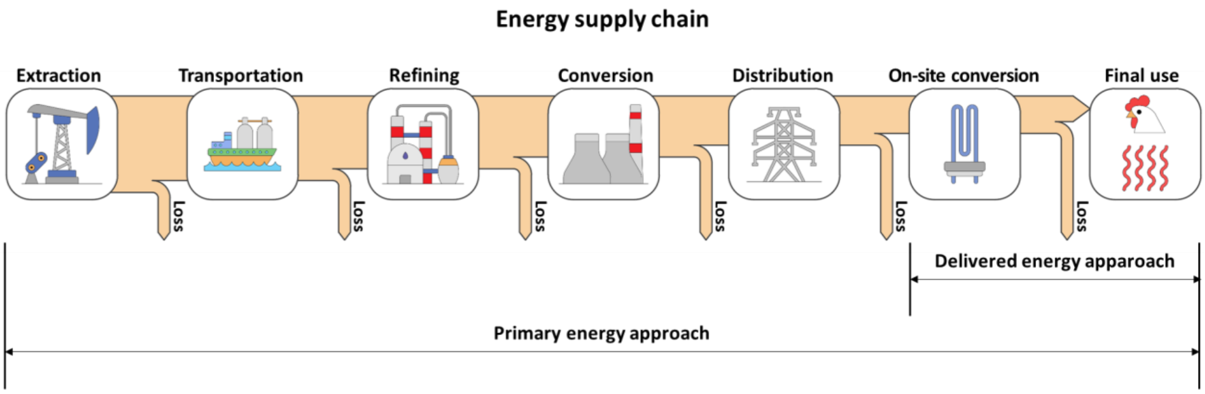

Fig. 2. Conceptualization of the differences between the delivered and the primary energy approach.

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.

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 Ω_{oH} is assessed, as similarly done in previous works (Fabrizio et al., 2014). The overheating index indicates the extent to which indoor air temperature $\theta_{\mathrm{air\_i}}$ exceeds the set point temperature $\theta_{\mathrm{set\_C}}$ during a considered time interval $\Delta\tau$ and reads

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

with

$$\Omega_{\mathrm{oH,k}} \in \mathcal{R}^{+} \tag{5}$$

where

$$\Omega_{\mathrm{oH,k}} = \theta_{\mathrm{air\_i,k}} - \theta_{\mathrm{set\_C,k}} \quad [°\mathrm{C}] \tag{6}$$

where $\mathcal{R}^{+}$ is the set of positive real numbers, $\Omega_{\mathrm{oH,k}}$ 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 $\theta_{\mathrm{air\_i,k}}$ and $\theta_{\mathrm{set\_C,k}}$ 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.

2.1 Description of the case study

The broiler house selected for this work is located 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.

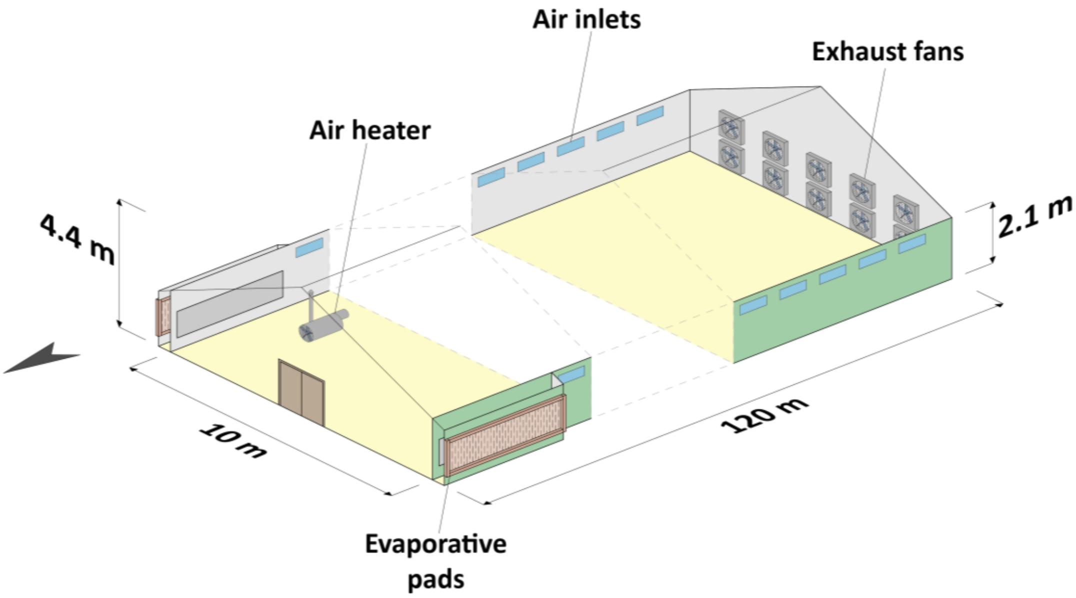

Fig. 3. Schematization of the typical European broiler house selected as case study.

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 tunnel 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_{st} equal to 0 Pa) is around 42,000 m^3 h^{-1}. The climate control system manages the window opening to maintain Δp_{st} constant at 20 Pa during the production cycle.

When cooling ventilation cannot maintain the cooling set point temperature $\theta_{\mathrm{set\_C}}$, evaporative cooling is activated, and the supply air temperature $\theta_{\mathrm{air\_sup}}$ is decreased through the adiabatic saturation performed by the evaporative pads installed in the north part of the longest walls. Climate control system activates the evaporative cooling when the difference between θ_{set_C} and outdoor air temperature θ_{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 θ_{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 broiler chicks are present inside the house, the climate control system maintains θ_{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, θ_{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 the adopted θ_{set_H}, θ_{set_C} and minimum ventilation flow rates can be found in Cobb (2008). Please note that inside the broiler house, the only climate parameter that is controlled by climate control with a feedback loop is θ_{air_i}. Indoor air relative humidity RH_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 each 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 enhances the comparison of the scenarios in the same standardized boundary conditions, e.g. animal stocking density and heating system efficiency, varying only the envelope thermo-physical properties and the outdoor weather conditions.

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

2.3 Types of broiler house envelopes

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

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

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

The total building fabric heat capacity C_{m} reported in Table 1 is calculated as

$$C_{\mathrm{m}}=\sum_{j=1}^{n_{\text{comp}}}\left(\kappa_{\mathrm{i,j}}\cdot A_{\mathrm{j}}\right)\quad\left[\frac{\mathrm{kJ}}{\mathrm{K}}\right]\qquad(8)$$

where $\kappa_{\mathrm{i,j}}$ ($\mathrm{kJ\ m^{-2}\ K^{-1}}$) is the internal heat capacity of the j-th opaque element -calculated according to EN ISO 13786 standard (European Committee for Standardisation, 2018)- and A_{j} is its area. The internal heat capacity is the amount of heat to be supplied to a unit of area of the building component to produce a unitary change in its temperature. This parameter is needed since describes the capacity of the building component to buffer heat during a diurnal cycle. The term n_{comp} 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 considerably lower than the one of the opaque ones, thus it was neglected in the simulations.

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

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

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 U-values (Eq. (7)) and the values of κ_i (Eq. (8)) for each considered envelope that are used in this work are reported in Fig. 4 together with the solar factors of the glazed surfaces g_{gl}. 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 thermo-physical 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.

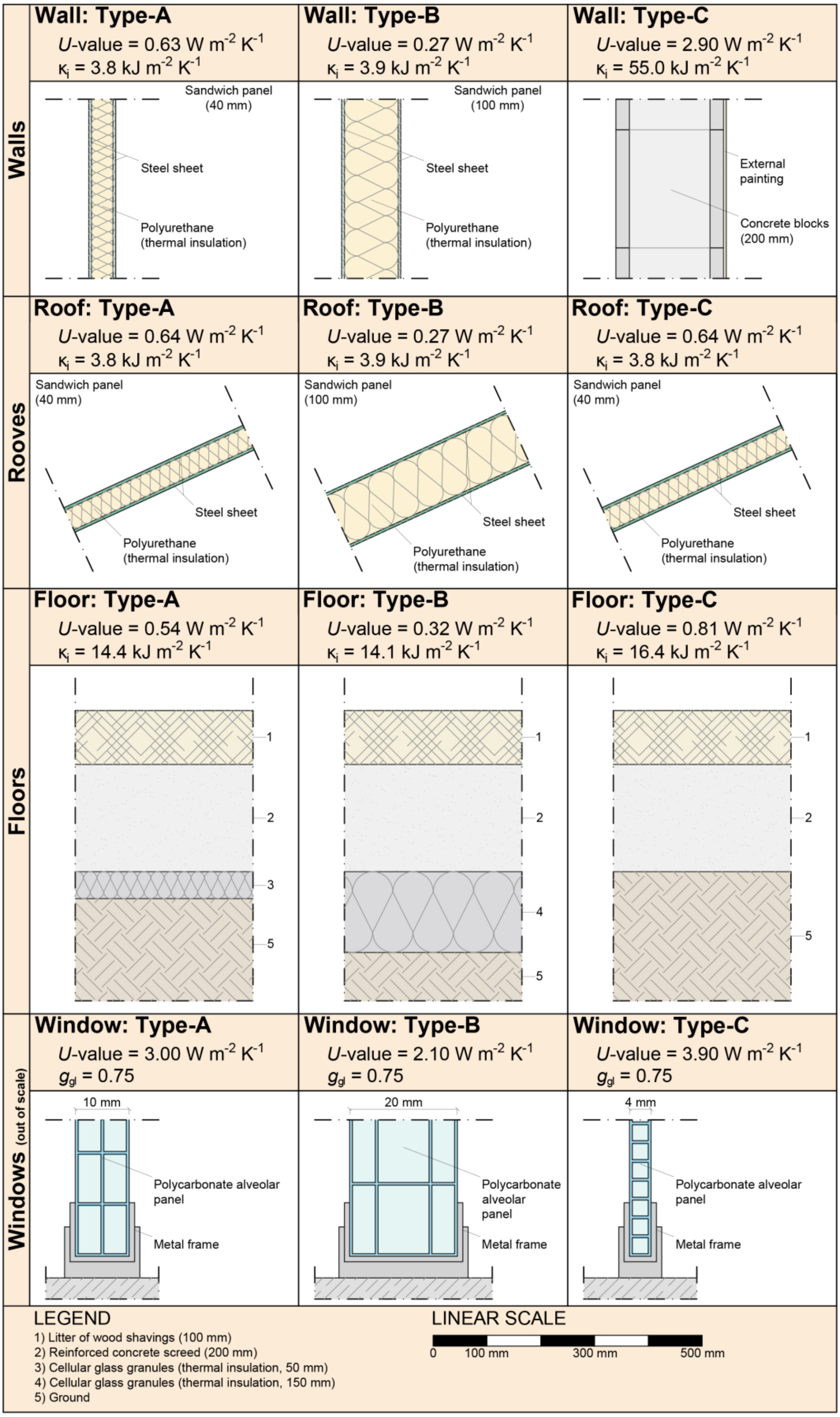

Fig. 4. Details of the building components (walls, rooves, floors and windows) of the three analysed envelope types (A, B and C). In the figure, the stationary thermal transmittances U-value, the internal aerial heat capacities κ_i and the solar factors of the glazed surfaces g_{gl} are shown.

2.4 Outdoor weather conditions

The energy performance of the analysed broiler house was assessed considering different outdoor weather conditions of the European context. The chosen weather conditions are proper of geographical locations characterized by the highest poultry production in Europe and are Poland (PL), France (FR), United Kingdom (UK), Germany (DE), Spain (ES), and Italy (IT). In these six countries more than 70% of the European poultry meat is produced (Van Horne, 2018). 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), needed for the simulation inputs. In Table 2, the six selected locations with their countries and geographical regions are presented. In addition, the main parameters useful to characterize their weather conditions are shown. The reference locations are characterized by different values of average annual outdoor air temperature $\bar{\theta}_{\text{air\_o}}$ and annual total solar radiation on horizontal surface $H_{\text{sol\_hor}}$. In the framework of the present work, $\bar{\theta}_{\text{air\_o}}$ is the arithmetic mean of the hourly $\theta_{\text{air\_o}}$ values over the entire year, while $H_{\text{sol\_hor}}$ 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 $\bar{\theta}_{\text{air\_o}}$ (15.7 °C) and the highest $H_{\text{sol\_hor}}$ (5.2 GJ m^{-2} y^{-1}). Warsaw results the location with the lowest $\bar{\theta}_{\text{air\_o}}$ (8.4 °C), while Finninglay and Bremen are the ones characterized by the lowest $H_{\text{sol,hor}}$ (3.4 GJ m^{-2} y^{-1}).

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

Location (reference city)	Acronym	Geographical region	$\bar{\theta}_{\text{air\_o}}$ [°C]	$H_{\text{sol\_hor}}$ [GJ m^{-2} y^{-1}]
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 (acronyms from Table 2), while the last one (separated by a dash) indicates the considered envelope type (A, B or C, Fig. 4).

2.5 Financial evaluation: global cost methodology

After the delivered and primary energy analyses, the 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. This analysis is performed in compliance with the EN 15459 international standard (CEN, 2007). The global cost C_{G}, here referred to the unit of useful floor area, is the sum of the present value of all the costs estimated during the lifespan τ_{ls} of the broiler house and reads

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

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

$$R_{\mathrm{d}}(q) = \left(\frac{1}{1 + R_{\mathrm{R}}} \right)^{q} \cdot 100 \quad [\%] \tag{10}$$

where R_{R} is the real interest rate (%) that considers the market and inflation rates.

In this work, The global cost C_{G} of each proposed solution is evaluated 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 initial investment cost C_{I} for IT-A, IT-B, and IT-C scenarios was estimated through an analysis on the Italian market aimed at finding the final costs (product *plus* installation *plus* taxes) of each considered element of the envelope and climate control system of the broiler house. These costs are presented in Table 3 referring to the unit of useful floor area. Other costs, such as feeders and lighting system, are not considered since they negligibly affect the energy performance of the broiler house.

Table 3 – Costs of envelope and the climate control system elements and initial investment cost C_{I} referred to unit of useful floor area.

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
Pad pumps and pipelines	4.55	4.55	4.55
C_{I}	193.43	341.21	143.99

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

The considered annual costs C_{a} over the broiler house lifespan are due to energy and due to the replacement of the elements of climate control system. Other annual costs, such as insurances and ordinary maintenance, are considered out of the scope of this work. The annual cost of energy is estimated multiplying the yearly thermal and electrical energy consumptions obtained from the simulations by the cost of thermal C_{th} and electrical C_{el} energy for the considered country. The costs of energy adopted in this work were obtained from Eurostat (2020a, 2020b) and are reported in Table 4. The annual cost of element replacement for climate control system is estimated considering the initial costs presented in Table 3 and estimating a lifespan of 15 years for fans, gas air heaters and pumps and pipeline of the evaporative cooling system. 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} (Eq. (9)) is considered for envelope and climate control system elements.

Table 4 – Considered cost conversion factor γ_{PLI} and costs of thermal C_{th} and electrical C_{el} energy (including taxes).

Country	γ_{PLI} [−]	C_{th} [€ $\mathrm{kWh_{th}^{-1}}$]	C_{el} [€ $\mathrm{kWh_{el}^{-1}}$]
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

3 Results and discussion

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

3.1 Delivered energy approach

The delivered energy consumption is evaluated considering the thermal energy consumption for heating E_{th}, the electrical energy consumption for ventilation $E_{\mathrm{el\_ven}}$ and for evaporative cooling $E_{\mathrm{el\_ec}}$. 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.

3.1.1 Thermal and electrical energy consumption

In the bar charts of Fig. 5, 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} result 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 outdoor weather conditions and envelope type have in terms of thermal energy consumption of 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 the outdoor weather conditions characterized by the lowest $\bar{\theta}_{\mathrm{air\_o}}$. 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 broilers 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 per unit of useful floor area is 47 W in scenario ES-C. 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 sensible heat load from animals represents the major issue for cooling ventilation broiler houses, 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 non-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 favour the overheating of the enclosure. Consequently, higher electrical energy consumptions for ventilation $E_{\mathrm{el\_ven}}$ and evaporative cooling $E_{\mathrm{el\_ec}}$ are expected compared to 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 $\mathrm{kWh_{el}}$ m^{-2} y^{-1}) while the lowest one from United Kingdom (UK-C, 5.8 $\mathrm{kWh_{el}}$ m^{-2} y^{-1}). Even in this case, the higher $E_{\mathrm{el\_ven}}$ values come from the weather conditions characterized by the higher $\overline{\theta}_{\mathrm{air\_o}}$, 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 the $E_{\text{el\_ven}}$ is higher, such as Spain and Italy. The estimated $E_{\text{el\_ec}}$ values are considerably smaller than $E_{\text{el\_ven}}$, being 2.5 kWh$_{\text{el}}$ m^{-2} y^{-1}, or lower, for all the considered scenarios.

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

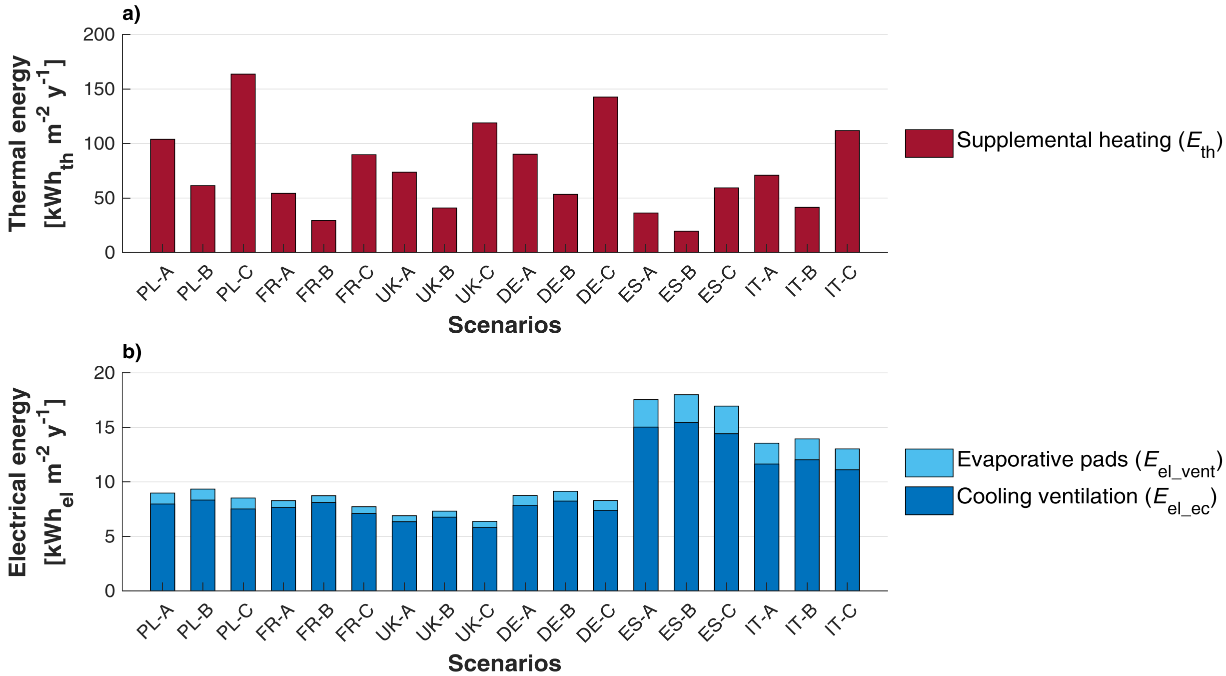

Fig. 5. Thermal (E_{th}, figure a), and electrical energy consumption (figure b) both for ventilation ($E_{\text{el\_ven}}$) and evaporative cooling ($E_{\text{el\_ec}}$) from the 18 scenarios.

3.1.2 Reference values of delivered energy consumption

The delivered energy consumption values are now used to provide 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 Costantino et al. (2016). Most of the existing reference values, 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. By contrast, the reference values present in this section were calculated 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 sensitivity analysis can better investigate the influence of each parameter on the final results. The results obtained from the simulated scenarios are normalized on the $\mathrm{kg_{meat}}$ and grouped to obtain ranges of 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 harvested broiler is estimated. The main limitation in the formulation of these reference values is the estimation of the broiler final live weight that does not consider eventual decrease of weight gain due to, for example, heat stress. This issue could be considered 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 $E_{\mathrm{meat\_el}}$ (sum of electrical energy consumption for 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 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 $\mathrm{Wh_{el}\ kg_{meat}^{-1}}$. The lowest $E_{\mathrm{meat\_el}}$ is the one from Great Britain (205 $\mathrm{Wh_{el}\ kg_{meat}^{-1}}$) while the greatest one is from Spain (577 $\mathrm{Wh_{el}\ kg_{meat}^{-1}}$). $E_{\mathrm{meat\_el}}$ of four countries (Poland, France, United Kingdom, and Germany) is between 205 and 299 $\mathrm{Wh_{el}\ kg_{meat}^{-1}}$. The $E_{\mathrm{meat\_el}}$ value from Italy is between 417 and 447 $\mathrm{Wh_{el}\ kg_{meat}^{-1}}$, while Spain has the wider $E_{\mathrm{meat\_el}}$ range (543 - 577 $\mathrm{Wh_{el}\ kg_{meat}^{-1}}$).

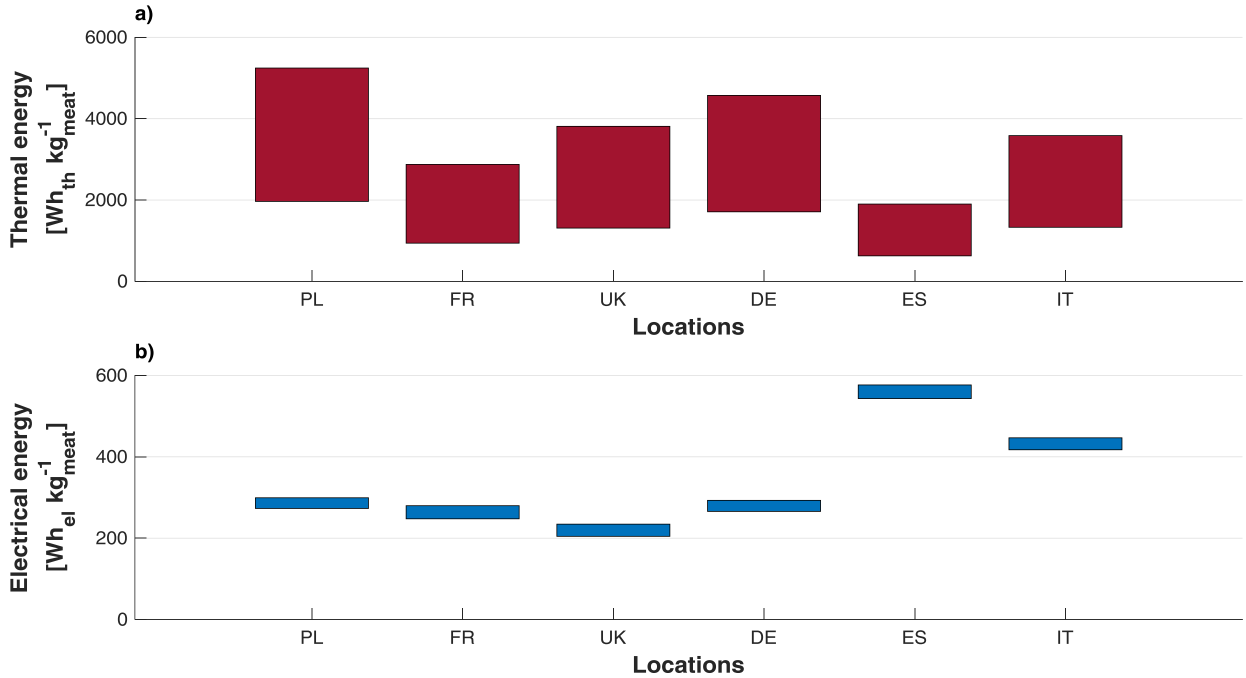

Fig. 6. Ranges of specific thermal ($E_{\mathrm{meat\_th}}$, figure a) and electrical energy consumption ($E_{\mathrm{meat\_el}}$, figure b) for the considered locations.

3.2 Primary energy approach

The previous analysis assessed the delivered energy consumption. Type-B envelope resulted the best solution to decrease E_{th}, while type-C envelope was the worst one by far in all the considered locations. On the contrary, type-C envelope was characterized by 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 best global solution, the primary energy performance is assessed for the 18 scenarios. In this way, the thermal and electrical energy consumption can be correctly weighted considering their respective energy overheads for extracting, refining, converting, and transporting energy.

3.2.1 Primary energy consumption

The conversion from delivered energy to primary energy can be performed according to Eqs. (1)-(3) using the total (renewable and non-renewable) primary energy consumption factors $f_{\mathrm{p\_th\_tot}}$ and $f_{\mathrm{p\_el\_tot}}$ reported in Table 5. The energy carriers that are considered are natural gas and electrical energy from the national grid. From Table 5, 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 difference 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 considered countries especially concerning $f_{\mathrm{p\_el\_tot}}$. These differences could be attributable to the different energy mixes proper of each country and, consequently, different energy overheads.

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

Country	$f_{\mathrm{p\_th\_tot}}$ (natural gas) [$\mathrm{kWh_p\ kWh_{th}^{-1}}$]	$f_{\mathrm{p\_el\_tot}}$ (electrical grid) [$\mathrm{kWh_p\ kWh_{el}^{-1}}$]	Source
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 $\mathrm{kWh_p\ kWh_{el}^{-1}}$.

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 $\mathrm{kWh_p\ m^{-2}\ y^{-1}}$). 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 $f_{\mathrm{p\_th\_tot}}$ that, for France, is equal to 1 $\mathrm{kWh_p\ kWh_{el}^{-1}}$. Furthermore, $\bar{\theta}_{\mathrm{air\_o}}$ (the highest one after ES and

IT), entails a reduced $E_{\mathrm{el\_vent}}$ (8.1 $\mathrm{kWh_{el}\ m^{-2}\ y^{-1}}$) that, converted in $E_{\mathrm{p\_el}}$, represents 43% of $E_{\mathrm{p\_glob}}$.

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%.

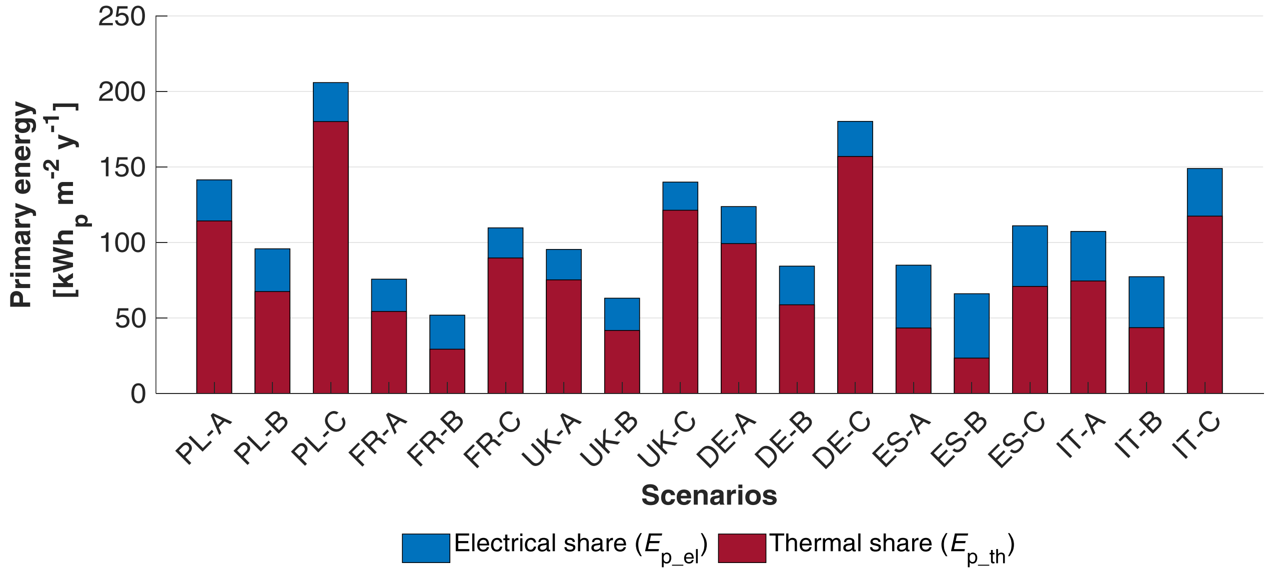

Fig. 7. Primary energy consumption $E_{\mathrm{p\_glob}}$ of each scenario. In addition, the energy shares due to electrical ($E_{\mathrm{p\_el}}$) and thermal ($E_{\mathrm{p\_th}}$) energy consumptions are shown.

The values of $E_{\mathrm{p\_glob}}$ 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 $E_{\mathrm{p\_glob}}$ 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 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 $\mathrm{kWh_p\ m^{-2}\ cycle^{-1}}$ (around

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 6.4 $\text{kWh}_\text{p}\ \text{m}^{-2}\ \text{cycle}^{-1}$ (35% due to $E_{\text{cycle\_p\_th}}$ and 65% due to $E_{\text{cycle\_p\_el}}$).

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

Looking at the shares of $E_{\text{cycle\_p\_glob}}$, in 1st, 2nd, 5th and 6th production cycles in PL-C scenario, $E_{\text{cycle\_p\_th}}$ is always higher than 80% of the total, with a maximum value of 98% during the 1st production cycle. In 3rd and 4th production cycles (during the warm season), $E_{\text{cycle\_p\_th}}$ 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, $E_{\text{cycle\_p\_glob}}$ is quite constant during all the year being the minimum and the maximum values 3.9 and 8.7 $\text{kWh}_\text{p}\ \text{m}^{-2}\ \text{cycle}^{-1}$, respectively. Another difference 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-C scenario $E_{\text{cycle\_p\_el}}$ is the lowest one in all the production cycles with the only exception of the 4th one. In ES-B scenario, $E_{\text{cycle\_p\_el}}$ is the highest share during warm season production cycles (3rd, 4th, and 5th), reaching the maximum relative value of 97% during the 4th production cycle.

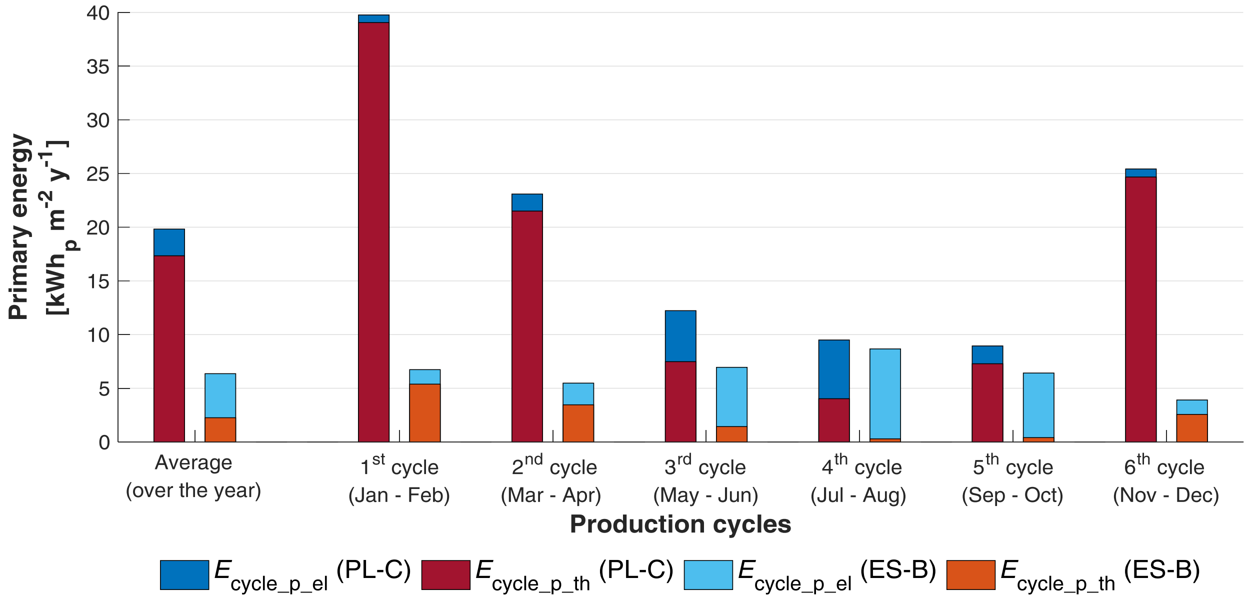

Fig. 8. Primary energy consumption for each production cycle ($E_{\mathrm{cycle\_p\_glob}}$) and shares due and electrical ($E_{\mathrm{cycle\_p\_el}}$) and thermal ($E_{\mathrm{cycle\_p\_th}}$) energy from PL-C and ES-B scenario.

3.2.2 Reference values of primary energy consumption

Reference values are provided for primary energy consumption, considering the global energy performance of the broiler houses. In Table 6, the primary energy consumption for climate control needed to produce a unit of mass of broiler 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-insulated envelopes.

Table 6 – Primary energy consumption embedded in a unit of mass (kg) of broiler meat ($E_{\mathrm{meat\_p\_glob}}$) 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 evaluation

The previously presented scenarios are analysed from the financial point of view to understand the differences in terms of cost-benefit analysis. The global cost C_{G} of each scenario was estimated according to the methodology described in section 2.5.

In Fig. 9, the shares of C_{G} due to envelope, climate control system and energy of each considered scenario are presented in 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 4 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 € $\mathrm{kWh}_{\mathrm{th}}^{-1}$ and 0.15 € $\mathrm{kWh}_{\mathrm{el}}^{-1}$, respectively), while Germany is characterized by the highest C_{el}.

The results of the global cost analysis presented in Fig. 9 show 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 considerably 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 from the financial point of view. In this sense, type-A envelope could represent a good compromise since it is a solution that guarantee a favourable 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.

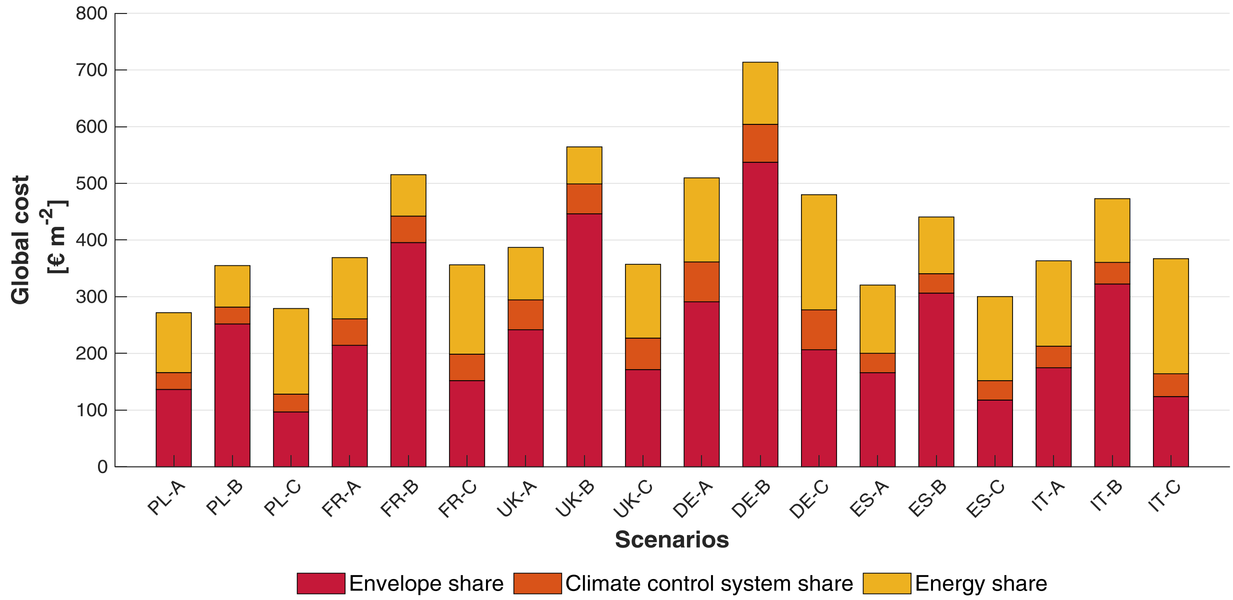

Fig. 9. Global cost C_G and shares due to envelope, climate control system and energy for each of the analysed scenarios.

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 θ_{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 considering the indoor climate conditions to assure that low energy consumptions are not related to excessively poor indoor climate 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 with the outdoor weather conditions of Spain and Italy, while the other scenarios are characterized by low Ω_{oH}. The minimum Ω_{oH} value is from UK-C scenario.

Through the bar chart of Fig. 10, the differences between the three types of envelope in the same outdoor weather conditions in terms of Ω_{oH} can be assessed. In the same outdoor weather conditions, the maximum Ω_{oH} 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 θ_{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.

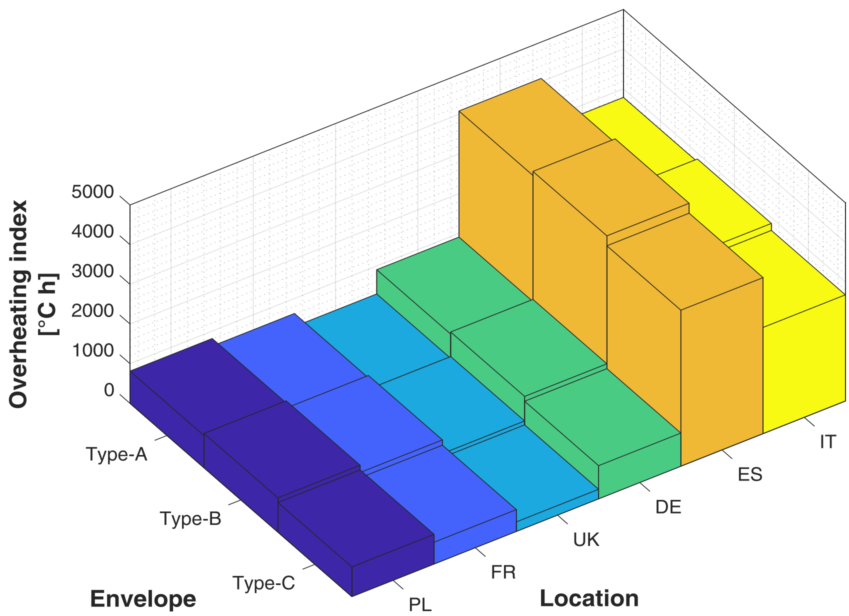

Fig. 10. Overheating index (Ω_{oH}) of the analysed scenarios.

4 Conclusions

In the present work, the best energy-efficient solution in terms of envelope for a typical broiler house in the European context was identified in different scenarios. This identification was performed through the assessment of the delivered energy consumption (state of the art) and the primary energy consumption (new proposed approach). The results 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. By contrast, a medium insulated envelope could be interesting since is a compromise between a good energy performance and a sustainable cost without increasing considerably the overheating of the enclosure.

The previous analyses lay the groundwork for future research into the energy efficiency of livestock house through two main contributions. First, this work shows the importance of a case-by-case 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 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 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 of the considered energy carrier and different energy mixes proper of the country. This last aspect is essential to evaluate 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. In addition, primary energy approach could represent the core of a new energy certification scheme *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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