Development of a methodology for studying tunnel climate in long railway tunnels and for optimizing the
design process of cross-passage cooling systems

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Envisioning an Energy Performance Certificate for livestock houses: A general methodological development and a specific application to growing-finishing pig houses

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ABSTRACT

Climate control represents a significant energy use in livestock houses. Although energy-efficient solutions aimed at reducing this energy consumption are expanding, their spread in these facilities is hindered by the lack of standardized methodologies for assessing their impacts on the energy performance. An Energy Performance Certificate (*EPC*) for livestock houses represents a solid solution for assessing and rating the energy performance of these buildings accordingly to a standardized methodology. Unfortunately, specific *EPC*s for livestock houses are not present in literature. The aim of this work is to propose the first methodological framework for an *EPC* specifically developed for livestock houses which can be easily adapted to different types of livestock productions. An exemplificative adaptation and a practical application are provided for growing-finishing pig houses with the aim of clarifying the certification procedure, highlighting the potentialities of this approach, and providing and discussing some examples of results. The results show that the certified pig house has a low energy performance, labelled with the class E. By adopting the energy efficiency measures proposed in the framework of the *EPC*, the energy performance could remarkably improve and achieve a class-B rating. This *EPC* proposal represents a complete novelty in literature and an innovative and promising approach to the topic of energy efficiency in livestock sector by enhancing the comparison of the energy performance between existing livestock houses or design alternatives equipped with different energy-efficient technologies and solutions.

1. Introduction

1.1. Reducing the energy consumption in industrial livestock systems

One of the main consequences of the intensification of livestock production is the shift from extensive livestock systems -mainly based on traditional techniques- towards confined and industrialized systems in which automation is massively used -instead of labor- for routinary tasks (Fraser, 2005). Livestock is farmed in confined housing systems that are often equipped with mechanical climate control systems which use represents one of the main energy use in various types of livestock facilities. For example, the annual thermal energy consumption for heating can be up to around 140 kWh$_{th}$ m^{-2} in broiler houses which is almost the totality (96%) of the thermal energy consumption. Similarly, ventilation and local heating entail around 40 kWh$_{el}$ m^{-2} of electrical energy consumption in growing-finishing pig houses, accounting for around 50% of their annual electrical energy consumption (Costantino et al., 2016). According to Lammers et al. (2010), around 10 kWh$_{el}$ and between 58 and 64 kWh$_{th}$ are consumed for ventilation and heating -respectively- per pig space in growing-finishing pig houses in Iowa (USA).

This energy consumption can be reduced by increasing the energy efficiency of confined livestock housing systems. The Organization for Economic Co-operation and Development (OECD), in fact, estimated that the energy efficiency in agricultural sector has not significatively increased in the last 30 years in OECD countries, while major improvements were achieved in non-OECD countries (OECD, 2017). Thus, there is an untapped energy-efficiency potential that clashes with the policies of several OECD countries. Most of them, in fact, are pushing towards the improvement of the environmental sustainability of the livestock sector to achieve ambitious objectives, such as the ones defined by European Union (EU) in the Green Deal and in the Farm to Fork Strategy (European Commission, 2020).

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Nomenclature

$\mathbb{N}^+$	Set of natural positive numbers
$\mathscr{R}^+$	Set of positive real numbers
A	Regression coefficient of Gompertz function [kg]
A_{el}	Area of the building element [m^2]
A_{floor}	Useful floor area of the considered pig house [m^2]
a_{pig}	Pig age [days]
B	Regression coefficient of Gompertz function [days^{-1}]
b_{tr}	Temperature reduction factor [$-$]
C	Regression coefficient of Gompertz function [days]
E	Annual energy consumption for climate control referred to an energy carrier [kWh]
EEM	Energy Efficiency Measure
EP_{p_nren}	Non-renewable primary energy consumption for climate control [kWh$_p$ m^{-2} a^{-1}]
EP'_{p_nren}	Non-renewable primary energy consumption for climate control of notional pig house [kWh$_p$ m^{-2} a^{-1}]
EPB	Energy Performance of Buildings
$EPBD$	Energy Performance of Buildings Directive
EPC	Energy Performance Certificate
EPI	Energy Performance Indicator
f_{CO_2-eq}	*GHG* emission factor [kg$_{CO_2-eq}$ kWh^{-1}]
f_{p_nren}	Conversion factor for non-renewable primary energy [kWh$_p$ kWh^{-1}]
f_{p_ren}	Conversion factor for renewable primary energy [kWh$_p$ kWh^{-1}]
f_{p_tot}	Conversion factor for total (renewable *plus* non-renewable) primary energy [kWh$_p$ kWh^{-1}]
g	*g*-th building element of the envelope
GHG	Greenhouse Gas
H_T	Heat transfer coefficient of the pig house envelope [W K^{-1}]
IAQ	Indoor Air Quality
j	*j*-th energy carrier
k	*k*-th time step
k_{bs_0} - k_{bs_6}	Regression coefficients for base ventilation air flow rate calculation
k_{set_0} - k_{set_3}	Regression coefficients for set point temperature calculation
k_{SFP_0} - k_{SFP_2}	Regression coefficients for *SFP* calculation
m_{el}	Cardinality of the set of the elements of the envelope
m_{GHG}	Equivalent CO$_2$ emissions due to energy consumption for climate control [kg$_{CO_2-eq}$ m^{-2} a^{-1}]
m_{step}	Number of time step
n	Ordinal number of the considered class
n_{ach}	Number of air change per hour [h^{-1}]
n_{car}	Cardinality of the set of the considered energy carriers
n_{pig}	Number of pigs inside the house [pigs]
n_{ref}	Reference point
n_{class}	Cardinality of class set
RER	Renewable Energy Ratio of primary energy consumption for climate control [%]
SFP	Specific Fan Performance [m^3 Wh^{-1}]
U_{el}	Stationary thermal transmittance ($U-value$) [W m^{-2} K^{-1}]
$\dot{V}_{bs}$	Base air ventilation flow rate [m^3 h^{-1}]
w_{pig}	Pig live weight (body mass) [kg]
Y_n	Coefficient for defining the class lower boundary [$-$]
Δp_{st}	Static pressure difference between inside and outside [Pa]
$\Delta\tau$	Duration of the simulation time step [h]
θ_{air_i}	Indoor air temperature [°C]
θ_{set_C}	Cooling set point temperature [°C]
θ_{set_H}	Heating set point temperature [°C]
θ_{set_id}	Ideal set point temperature [°C]
Ω_{oH}	Overheating index of the enclosure [°*C* h]

To reach that goal, several efforts have been spent in the last years to investigate new solutions and technologies aimed at decreasing the energy consumption of livestock houses, with a focus especially on climate control. Some studies were focused on improving the energy performance of the building envelope. Axaopoulos et al. (2014) evaluated the optimum insulation thickness of the building envelope for piggeries in Greek climate conditions. They found that the optimum insulation thickness for a system composed of an inner layer of bricks and an outer layer of extruded polystyrene and plaster is 1.5 cm, considering the financial costs. When using polyurethane foam sandwich panels, the optimum insulation thickness increases up to 2.5 cm. The wall orientation was found not having a major effect on the optimum insulation thickness. Costantino et al. (2021a) evaluated the variation of the primary energy consumption of different envelope solutions for broiler houses in different climate conditions. The results suggested that a medium insulated envelope represents a reasonable trade-off between an acceptable energy performance and a sustainable global cost evaluated over 30 years. Moreover, Costantino et al. (2021a, b) highlighted the necessity of adopting the primary energy approach when evaluating the energy performance of livestock houses. Other studies have focused on reducing energy consumption for mechanical ventilation. Teitel et al. (2008) evaluated the potential energy saving achievable in poultry houses by adopting the variable-frequency drive in fan motors. The findings indicated that this type of control can reduce energy consumption by about 25% if compared to an on/off control. Shin et al. (2022) evaluated the applicability of a demand-controlled ventilation in pig houses for decreasing the energy consumption due to fan operation. They pointed out a significant potential for reducing energy consumption using this type of ventilation control. Finally, other studies were focused on the adoption of renewable energy sources coupled with climate control systems. Alberti et al. (2018) evaluated the potentialities of a geothermal heat pump coupled with an air handling unit in a pig house. The findings revealed a decrease by 46% in primary energy consumption and by 14% in the operating energy costs when compared to a traditional system relying on a fan gas burner. El Mogharbel et al. (2014) analyzed the potentialities of an innovative localized solar-assisted thermal system based on parabolic concentrators for heating in poultry houses. That innovative system was estimated to reduce the thermal energy consumption by around 70% when compared to a conventional system. The parabolic concentrator is estimated to cover 100% of the heating load during more than 50% of the time over the year.

As just shown, remarkable strides were recently made towards the reduction of the energy consumption of livestock houses. Energy-efficient solutions and technologies are currently present in literature and their adoption is strongly recommended by the Best Available Techniques for livestock farming set by EU (Giner Santonja et al., 2017). To boost the adoption of those solutions in commercial livestock houses, their actual impact on the energy performance must be clearly assessed. A robust and shared methodology for assessing, rating, and certifying the energy performance of livestock houses is needed by stakeholders (i. e., farmers and manufactures). In this way, the impacts of proposed Energy Efficiency Measures (*EEMs*) can be accurately evaluated and apples-to-apples comparisons between the energy performance of different buildings, design alternatives, or retrofit options can be possible.

1.2. Filling the gap of an energy performance certificate for livestock houses

In the given framework, an Energy Performance Certificate (*EPC*) for livestock houses represents a solid solution for facing this problem. In general terms, an *EPC* is a certificate which indicates the energy performance of the considered object calculated or measured according to specific methodologies (International Standard Organization (ISO), 2017a).

Currently, *EPCs* are one of the pillars of EU energy and climate policy, especially regarding buildings (Buildings Performance Institute Europe (BPIE), 2010). At the EU level, the *EPC* for buildings was introduced in 2002 by the Energy Performance of Buildings Directive (*EPBD*) 2002/91/EC (European Parliament and Council of European Union, 2002) and then improved and strengthened by the following *EPBD* recasts (Li et al., 2019). As highlighted by Volt et al. (2020), the introduction of the *EPC* can be seen as a reaction to the lack of information about building energy performance and the potential of the implementation of *EEMs*. The same lack of information concerns the livestock sector.

The benefits of the implementation of *EPCs* in the building sector are manifold, as noticeable by analyzing the scientific literature. According to Pasichnyi et al. (2019), the main idea behind *EPCs* is to influence the building market by informing the involved actors about the energy performance of buildings. Moreover, the *EPCs* represent a powerful tool for the assessment and comparison of the energy efficiency of buildings and for implementing adequate energy policies and requirements (Heidenthaler et al., 2022). Actually, *EPCs* could empower policymakers with better data for monitoring the impacts of policies and financial support schemes (Zuhaib et al., 2022). Another benefit is the collection of *EPC* data in national or local databases (Arcipowska et al., 2014) which can be used to provide a reliable overview about the energy performance of the national building stocks (Sesana and Salvalai, 2018). As found by Building Performance Institute Europe, in fact, data contained in *EPC* databases are currently among the most important sources of information on the energy performance of the EU's building stock (Arcipowska et al., 2014). This is also confirmed by Pasichnyi et al. (2019) who mapped the several applications that are enabled by *EPC* data, such as predicting future energy consumption and CO_2 emissions, mapping the building energy performance, and conducting investment analyses. One of the main critical aspects of *EPCs* is linked to quality assurance systems. The *EPC* certification process can be influenced by the certifier who can easily influence data (Hardy and Glew, 2019). Consequently, some concerns have been raised about the data quality provided by *EPCs* (Pasichnyi et al., 2019), especially considering that they are being used to define and evaluate energy policies.

The implementation of *EPCs* has driven the energy efficiency in the building sector across EU and globally, in countries such as South Korea (Ji et al., 2022). A similar impact of *EPCs* may be expected also for the building sector. Many of the previously mentioned benefits of *EPCs* on the building sector could be easily transferred to the livestock sector, with positive impacts at both local and global levels. At local level, an *EPC* for livestock houses could be valuable for farmers. The *EPC*, in fact, enables the assessment of the energy performance of their livestock house using a solid and shared standardized methodology. Moreover, an apples-to-apples comparison with the energy performance of other livestock houses or design alternatives could be possible. At a global level, an *EPC* for livestock houses could contribute to provide a reliable overview about the energy performance of the national (or regional) building stock of livestock houses. Data from *EPC* databases could be used to provide periodic reports with aggregate results that show the evolution of the energy consumption of livestock houses. This information is of the utmost importance at national level for defining and evaluating the effectiveness energy policies, such as incentive schemes, energy regulations, and environmental taxes, as the ones proposed for pig farms by Mackenzie et al. (2017). National *EPC* databases could be used to establish reference values of energy consumption of livestock houses, that currently lack in literature, as highlighted by Costantino et al. (2016). Moreover, an *EPC* could create a demand-driven market for energy-efficient livestock houses and boost the implementation of *EEMs*.

To sum up, an *EPC* for livestock houses could act as a driver to foster the spread of energy-efficient solutions in industrial livestock systems and could contribute to improve the energy efficiency and the sustainability of the whole livestock sector. To the best of Authors' knowledge, an *EPC* specifically developed for livestock houses is not present in literature, even though the first *EPBD* (2002/91/EC) explicitly mentions the chance for each Member State to apply *EPCs* to non-residential agricultural buildings. So, an *EPC* for livestock houses represent an unexplored pathway toward the energy efficiency and the sustainability of the livestock sector. This represents a wide gap in literature that must be filled, especially considering the ambitious sustainability goals set by several countries.

The aim of this work is to propose the first methodological framework for an *EPC* specifically developed for livestock houses. The proposed methodological framework is adaptable to most types of livestock houses by defining specific aspects that characterize the considered livestock production. In this way, the proposed methodological framework becomes a flexible tool with a wide applicability that can be easily adapted depending on the type of livestock house, the geographical context, and the specific objectives of the energy policies. This adaptation process requires the definition of some parameters which regard the standard use of the livestock house and the energy rating. To clarify this process, an exemplificative adaptation of the proposed *EPC* methodological framework is performed for growing-finishing pig houses and is then applied to a real case study. In this way, the certification procedure is clarified, the potentialities of this approach are highlighted, and examples of results can be presented and discussed.

The present work represents a total novelty in scientific literature since proposes an innovative approach to the energy efficiency of industrialized livestock systems by blending, for the first time, the powerful and consolidated instrument of the *EPC* to a new context, the one of livestock systems.

The key contributions provided by this work are the following:

- The first proposal -according to Authors' knowledge– of an *EPC* methodology specifically developed for livestock houses. The methodological proposal contributes to increasing the current body of knowledge by defining for the first time the assessment type, the standard boundary conditions, the indicators, and the energy performance rating for this specific type of building.
- The exemplifying application of the developed methodology to a real case study which represents the first livestock house whose energy performance is certified in standardized conditions and energy labelled. Moreover, the impacts of the implementation of different *EEMs* on the energy performance are quantified and discussed.
- Proposing and exploring an innovative approach that broadens the scope of applications of *EPCs* to livestock houses and, more in general, to agricultural buildings. This contribution may represent a new research field straddling agricultural and building engineering areas.

The present work is structured as follows. After the motivations and the aim of the work (Section 1), the methodological proposal for the *EPC* for livestock houses is presented together with its exemplificative adaptation to growing-finishing pig houses (Section 2). Then, the results of the application of the adapted methodology to a real case study are presented (Section 3) and discussed (Section 4), with a specific focus on the impact of the *EEMs*. Finally, the concluding remarks are provided (Section 5).

2. Methodology

2.1. Methodology proposal: an EPC for livestock houses

The development of an *EPC* for livestock houses is a complex task and it should be based on a solid methodology. At international level, the major references for developing *EPCs* are ISO 52003–1 (International Standard Organization (ISO), 2017a) and ISO/TR 52003–2 (International Standard Organization (ISO), 2017b) standards. Both are part of a set of standards known as *EPB* (Energy Performance of Buildings) standards which aims at harmonizing the methodology for the energy performance assessment of buildings. At the EU level, the *EPB* standards represent the cornerstone in the *EPBD*. Specifically, ISO 52003–1 is considered one of the overarching *EPB* standards which are explicitly mentioned in the last recast of the *EPBD* 2018/844/EU (European Commission, 2018) as the basis of the calculation methodology for the energy performance assessment to be implemented in all Member States. The aim of ISO 52003–1 is to provide insights on the use of indicators for different purposes related to the building energy performance. This standard defines the different steps that should be taken for establishing the certification scheme, as well as some possible labels to adopt. ISO 52003–2 is the explanation and justification of ISO 52003–1. The former contains information for the correct understanding and use of the latter, such as details about the energy rating procedure.

In this work, ISO 52003–1 and 52003–2 are adopted to set the methodological framework at the basis of the proposed *EPC* and the following issues are addressed:

- Energy performance assessment;
- *EPC* indicators;
- Energy performance rating;
- *EPC* contents.

In the next subsections, each previously presented issue is deepened. The operative procedure to be followed by a certifier for issuing the *EPC* is also defined.

2.1.1. Energy performance assessment

The first step for setting up the methodological framework of the proposed *EPC* is the assessment of the livestock house energy performance. It means to quantify the energy consumed to meet the energy demand of the livestock house. The following points should be addressed:

- the energy uses to be considered in the assessment;
- the type of assessment.

The proposed *EPC* does not consider all the energy uses of livestock houses but is focused on the energy use for climate control only. Thus, the partial energy performance for climate control is assessed in the framework of the proposed *EPC*, in compliance with ISO 52003–1 (International Standard Organization (ISO), 2017a). The choice of focusing the energy performance assessment to climate control only is because this energy use is significant in various types of livestock houses, especially those for monogastric animals (Costantino et al., 2021a). Moreover, several solutions and strategies have been recently developed for improving climate control. Hence, an *EPC* focused on this specific energy use is considered convenient and with a wide applicability.

The type of energy performance assessment is defined in compliance with ISO 52000-1 standard (International Standard Organization, 2017) that outlines two types of assessment, namely asset and operational assessments. In Table 1, both asset and operational assessments are reported with their related subtypes and input data. As visible from the table, the energy performance is *calculated* in the asset assessment by modelling the energy use considering design, standard, or actual input data. By contrast, the energy performance is *measured* in the operational

Table 1

Types and subtypes of energy performance assessments of buildings according to ISO 52000–1 (International Standard Organization, 2017). The underlined type and subtypes are adopted in the proposed Energy Performance Certificate.

Type	Subtype	Input data		
		Livestock house	Climate	Use
Asset (calculated)	Design	Design	Standard	Standard
	As built	Actual	Standard	Standard
	Actual	Actual	Actual	Actual
	Tailored		Depending on purpose	
Operational (measured)	Actual	Actual	Actual	Actual
	Climate corrected	Actual	Corrected to standard	Actual
	Use corrected	Actual	Actual	Corrected to standard
	Standard	Actual	Corrected to standard	Corrected to standard

assessment considering actual, climate-corrected, use-corrected, or standard input data. The type of adopted input data depends on the aim of the assessment.

Even though both the asset and operational assessments are robust solutions, the asset assessment is usually preferred for the calculation of the standard energy performance in the framework of *EPCs*, as highlighted in the review of Wang et al. (2012). Cichowicz and Jerominko (2023) numerically evaluated the differences of those two types of assessment. Even though both the methods were considered reliable, they recommended the asset assessment. In the framework of this specific *EPC* proposal, different reasons pushed toward the adoption of the asset assessment and, specifically, to the "design" and "as built" subtypes. First, the asset assessment can always be performed because no measurements are needed. By contrast, the operational assessment can be performed only when measurements are available, and they should be long-term ones. Only with long-term measurements, the monitored energy performance can be considered independent from exceptional events, such as extreme weather conditions or system failures. Moreover, the asset assessment makes it possible to assess the energy performance even when measured data are not available, such as in new projects or refurbishments, as underlined by Goldstein and Eley (2014). In this way, different design alternatives can be compared, and the energy performance becomes a leading criterion that drives to the final decision between the alternatives. The asset assessment facilitates the apples-to-apples comparison of the energy performance of the livestock house under consideration with others (i.e., the energy rating, see subsection 2.1.3). This is because identical boundary conditions are considered when the energy performance is assessed. This apples-to-apples comparison would also be possible in the operational assessment by adopting the "standard" subtype, as visible in Table 1. In this case, the measured energy consumption should be normalized -i.e., corrected to standard- by considering the standard use and climate. For example, the degree-day method could be used to correct the weather conditions, as done by Lundström (2017) and Tam et al. (2021). Nevertheless, this normalization is an assumption itself -for example, of a linear correlation between degree days and energy consumption- that also affects the prediction of the energy performance. The asset assessment is preferred also because facilitates the energy rating. The energy performance calculated for the considered livestock house can be rated through a comparison with the energy performance calculated for a notional livestock house, as better explained in subsection 2.1.3. Thus, the energy rating can be performed considering the specificities of the analyzed livestock house, even when benchmark values of energy consumption are not available, which is often the case for livestock houses (Costantino et al., 2016).

As visible from Table 1, each subtype of assessment needs different input data regarding the livestock house, the climate, and the use. All the

input data should be defined for the proposed *EPC* methodology. The input data regarding the livestock house (e.g., geometrical dimensions and thermophysical properties) are either the design or the actual ones, depending on the subtype of the assessment. If the *EPC* is performed for a livestock house project ("design" subtype), the building data will be the design ones. If the *EPC* regards an existing livestock house ("as built" subtype), the actual data should be used. As reported in Table 1, standard climate conditions are required to assess the energy performance of the livestock house under consideration. In the framework of the proposed *EPC* methodology, the data from the Typical Meteorological Year (TMY) are adopted. In this way, extreme events that regard meteorological variables, such as outdoor air temperature and solar radiation, are excluded. Moreover, the robustness of the comparison between the energy performance of livestock houses in different climates increases.

Finally, the standard use of the livestock house under assessment should be defined, specifically the farming conditions and the settings of the climate control system. The standard use of the livestock house depends on the considered type. This is since different types of livestock houses are characterized by a different use. For this reason, the proposed *EPC* methodology defines the items that should be standardized when the *EPC* methodology itself is adapted to a specific livestock production.

The farming conditions that should be standardized depending on the type of livestock house are the following:

- the animal stocking density;
- the animal liveweight at the beginning and the end of the production cycle;
- the dates of beginning and end of the production cycles;

The following settings of the climate control system should be standardized too:

- the ideal set point temperature and its dead band;
- the base ventilation flow rate during the production cycles;
- the minimum air changes during empty periods.

Once defined the type of energy performance assessment and the input data, the energy simulation method for estimating the energy consumption should be defined. Energy simulation models, in fact, represent the core pillar for any *EPC* since they make it possible the simulation-based estimation of the building energy performance, once defined the standardized boundary conditions. Until few years ago, few reliable energy simulation models for livestock houses were present in literature (Costantino et al., 2022). The recent rising interest in the sustainability of livestock production boosted investigations on the energy modelling of livestock houses that has become a thriving research field in the last years. Consequently, robust energy simulation models for livestock houses are now present. For example, validated dynamic models for energy simulations were recently developed by Lee et al. (2020) for duck houses, and by Xie et al. (2019) and Costantino et al. (2022) for pig houses.

In this *EPC* methodology proposal, the adoption of dynamic energy simulation methods with short simulation time steps is strongly recommended to properly consider the sudden variation of boundary conditions typical of livestock houses and precisely estimate their energy consumption. The expected outputs of the simulation should be the thermal and electrical energy consumption for heating, cooling, and ventilation. The lumped hourly values of indoor air temperature and relative humidity are also required. For this purpose, both customized energy models or Building Energy Simulation (BES) tools, such as EnergyPlus and TRNSYS, could be adopted.

2.1.2. EPC indicators

Indicators are essential in any *EPC* since they represent a quantitative approach to concisely provide details about the energy performance of the livestock house. Moreover, further aspects, such as Greenhouse Gas

(*GHG*) emissions or the indoor environmental quality could be evaluated to provide additional information to stakeholders.

The indicators adopted in the framework of this *EPC* proposal are presented in Table 2, along with their respective units of measurement and their areas of focus. As visible from the table, five different indicators are adopted. They are focused on the energy performance, the energy system, the envelope thermal insulation, the *GHG* emissions, and the animal welfare.

The first indicator presented in Table 2 is an Energy Performance Indicator (*EPI*). In general terms, an *EPI* can be defined as the ratio between the energy input and the factor related to the energy using component (Abu Bakar et al., 2015). In buildings, the *EPI* is usually the ratio between the building energy consumption and the building gross floor area (Abu Bakar et al., 2015). In the proposed *EPC*, EP_{p_nren} is adopted as the indicator for the annual energy performance and reads

$$EP_{p\_nren} = \frac{\sum_{j=1}^{n_{car}} \left(E_j \bullet f_{p\_nren,j} \right)}{A_{floor}} \left[\frac{kWh_p}{m^2 \, a} \right] \tag{1}$$

where E_j is the annual energy consumption for climate control referred to the *j*-th energy carrier [kWh], $f_{p\_nren,j}$ is the non-renewable primary energy factor for the *j*-th energy carrier [kWh$_p$ kWh^{-1}], and n_{car} is the cardinality of the set of the considered energy carriers. The term A_{floor} is the useful floor area [m^2] of the livestock house under consideration.

The proposed EP_{p_nren} can be classified as an aggregate *EPI* (Martínez-de-Alegría et al., 2021). This is because the different energy end-uses for climate control (i.e., heating, cooling, and ventilation) are aggregated in the same indicator (Kim et al., 2019). This aggregation is possible by using primary energy that represents a major metric for the energy assessment at the European level (European Parliament and Council of European Union, 2018). Primary energy accounts for all forms of direct energy that are supplied to the livestock house, including the share of energy that is lost and/or embedded along the entire energy supply chain. The potentialities of the adoption of primary energy approach was previously demonstrated by its application to evaluate industrial processes (Dunkelberg et al., 2018), district heating scenarios (Bilardo et al., 2021), and the energy performance of office buildings (Krstić-Furundžić et al., 2019). The primary energy approach is becoming more and more used also in livestock sector, as highlighted by previous works in literature at Greek (Baxevanou et al., 2017), Spanish (Costantino et al., 2020), and European levels (Costantino et al., 2021a). The use of primary energy enhances an in-depth assessment of the global energy performance of the livestock house by weighting different renewable and non-renewable energy carriers and by considering the specific energy mix of the considered country. As reported in Eq. (1), EP_{p_nren} accounts only for non-renewable primary energy, a choice that is in accordance with the energy policies of EU (European Parliament and Council of European Union, 2018).

The second indicator reported in Table 2 is the Renewable Energy Ratio (*RER*). This indicator was proposed by Kurnitski (2013) and

Table 2
Indicators adopted in the proposed Energy Performance Certificate and their respective areas of focus.

Indicator		Area of focus
Non-renewable primary energy consumption for climate control	EP_{p_nren} $\left[\frac{kWh_p}{m^2 \, a} \right]$	Energy performance
Renewable Energy Ratio referred to primary energy consumption for climate control	RER [%]	Energy system
Total transmission heat coefficient of the envelope	H_T $\left[\frac{W}{K} \right]$	Envelope thermal insulation
Equivalent CO$_2$ emissions due to energy consumption for climate control	m_{GHG} $\left[\frac{kg_{CO_2-eq}}{m^2 \, a} \right]$	Greenhouse gas emissions
Overheating index	Ω_{oH} [$^\circ C$ h]	Animal welfare

accounts for the actual fraction of the primary renewable energy consumption over the total primary energy consumption. This metric was developed following the distinction between renewable and non-renewable primary energy and is becoming widespread at the international level. This is because several countries -especially in EU- sets minimum values of *RER* as legislative requirements for buildings. The potential of this indicator were highlighted by Musall and Voss (2014) that analyzed different energy technologies and by Bilardo et al. (2020) with a specific focus on solar cooling. The equation provided by Kurnitski (2013) is adapted for the aim of this work and limited only to the energy use for climate control. Thus, it reads

$$RER = \frac{\sum_{j=1}^{n_{car}}\left(E_j \bullet f_{p\_ren,j}\right)}{\sum_{j=1}^{n_{car}}\left(E_j \bullet f_{p\_tot,j}\right)} \quad [\%] \tag{2}$$

where E_j is the annual energy consumption for climate control referred to the *j*-th energy carrier [kWh], $f_{p\_ren,j}$ is the renewable primary energy factor for the *j*-th energy carrier [kWh$_p$ kWh^{-1}], $f_{p\_tot,j}$ is the total (renewable *plus* non-renewable) primary energy factor for the *j*-th energy carrier [kWh$_p$ kWh^{-1}]. The term n_{car} is the cardinality of the set of the considered energy carriers.

The third indicator is the heat transfer coefficient of the envelope (H_T) that quantifies its thermal insulation. The formulation of H_T is reported in ISO 52016–1 (International Standard Organization (ISO), 2017c) standard and reads

$$H_T = \sum_{g=1}^{m_{el}}\left(b_{tr,g} \bullet U_{el,g} \bullet A_{el,g}\right) \quad \left[\frac{W}{K}\right] \tag{3}$$

where $b_{tr,g}$ is the dimensionless temperature reduction factor [−] for the *g*-th element of the envelope, $U_{el,g}$ is the stationary thermal transmittance ($U - value$, [W m^{-2} K^{-1}]) for the *g*-th element of the envelope, and $A_{el,g}$ is the area of the *g*-th element of the envelope. The term m_{el} is the cardinality of the elements of the envelope, both opaque and glazed. More details for the definition of $b_{tr,g}$ can be found in ISO 52016-1 standard (International Standard Organization (ISO), 2017c).

The proposed *EPC* also considers the annual *GHG* emissions due to the energy use for climate control from the livestock house under consideration. For this purpose, the indicator m_{GHG} is introduced and reads

$$m_{GHG} = \frac{\sum_{j=1}^{n_{car}}\left(E_j \bullet f_{CO_2-eq,j}\right)}{A_{floor}} \quad \left[\frac{kgCO_2-eq}{m^2\,a}\right] \tag{4}$$

where E_j is the annual energy consumption for climate control referred to the *j*-th energy carrier [kWh], A_{floor} is the useful floor area [m^2] of the livestock house under consideration, and n_{car} is the cardinality of the set of the considered energy carriers. The term $f_{CO_2-eq,j}$ is the *GHG* emission factor for the *j*-th energy carrier [kg$_{CO_2-eq}$ kWh^{-1}] calculated according the standard *IPCC* (Intergovernmental Panel on Climate Change) procedure (IPCC, 2007). The f_{CO_2-eq} factors used in this work are the ones provided by Koffi et al. (2017).

The last indicator reported in Table 2 is the overheating index (Ω_{oH}) and is related to animal welfare. Animals' productive and reproductive performances, in fact, can be seriously affected by heat stress. Hence, overheating problems should be avoided. The indicator Ω_{oH} was proposed by Panagakis and Axaopoulos (2008) and the following alternative formulation proposed by Costantino et al. (2021a) is adopted in the proposed *EPC*.

$$\Omega_{oH} = \sum_{k=1}^{m_{step}}\left(\Omega_{oH,k} \bullet \Delta\tau_k\right) [^{\circ}C\,h] \tag{5}$$

with

$$\Omega_{oH,k} \in \mathscr{R}^+ \tag{6}$$

and

$$\Omega_{oH,k} = \theta_{air\_i,k} - \theta_{set\_C,k} \quad [^{\circ}C] \tag{7}$$

where $\Omega_{oH,k}$ is the overheating index calculated at the *k*-th time step, $\Delta\tau$ is the duration of the calculation time step [h], and m_{step} is the number of time step. Considering an hourly time step, $\Delta\tau$ is constant and equal to 1 h. The terms $\theta_{air\_i,k}$ and $\theta_{set\_C,k}$ are the indoor air temperature and the cooling set point temperature at the *k*-th time step, respectively.

The indicator Ω_{oH} is adopted in the proposed *EPC* for a dual purpose. The first purpose is to provide a measure of possible overheating problems inside the livestock house. This information is valuable for stakeholders since animal welfare considerably affects productivity and is a topic which is gaining more and more importance within public opinion. The second purpose is technical. The sizing of climate control systems of livestock houses is not performed according to a standardized procedure, as it happens for other building types (e.g., residential and office buildings). It means that slight differences in terms of indoor climate conditions may exist between different livestock houses. Hence, it is essential to ensure that good energy performances are not due to excessively poor indoor climate conditions that would negatively affect animal welfare. The introduction of additional indicators for evaluating the energy performance of buildings when differences exist in building system is a principle called "presence of system principle" that is in compliance with ISO 52000 standard (International Standard Organization, 2017). Nevertheless, the differences in terms of sizing of climate control system that may exist between livestock houses could negatively affect the comparison between their energy performances. This issue represents a limitation of this work and, in general, a problem that has to be further addressed in the perspective of developing *EPCs* for livestock houses. A possible solution is to develop a standardized procedure for sizing the climate control systems of livestock houses.

2.1.3. Energy performance rating

The EP_{p_nren} indicator provides a quantitative datum about the energy performance of the livestock house. However, it does not automatically provide information about its quality, an essential aspect, especially for non-technical stakeholders. To evaluate if the analyzed livestock house has a high or low energy performance, it should be rated. It means that the previously calculated EP_{p_nren} should be compared to reference values.

The first step for rating the energy performance is to define the reference values for EP_{p_nren}. For this aim, ISO 52003–1 (International Standard Organization (ISO), 2017a) proposes two different approaches, namely the "formula" and the "notional reference building" approaches that are in-depth described in ISO/TR 52003–2 (International Standard Organization (ISO), 2017b). In the formula approach, the reference values are calculated through a formula which is statistically or analytically derived from the energy simulation method by setting a set of hypotheses based on the variation of building geometry. In the notional reference building approach, the reference value is directly obtained through the energy simulation method considering the notional building. According to the definition of Foroushani et al. (2022), the notional building is a hypothetical building of the same design as the one under consideration whose envelope and energy system specifications meet a set of minimum requirements. This second approach is currently used in various standards, such as the ASHRAE 90.1 (American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), 2019) and 90.2 (American Society of Heating Refrigerating and Air-Conditioning Engineers (ASHRAE), 2018)), and energy building codes, such as the ones of Italy (Italian Ministry of Economic Development, 2015) and United Kingdom (HM Government,

2021). The notional building approach is adopted in the framework of the proposed *EPC* methodology. In this *EPC* proposal, the notional livestock house is derived from the real livestock house by setting the standardized values for both the envelope and the climate control system. Specifically, the standardized values for the envelope regard the $U - value$ of each building component and are defined to set the thermal insulation level of the notional livestock house. The standardized values for the climate control system mainly regard the efficiency of the systems, such as the heating and ventilation systems.

Once numerically defined the reference values for the energy performance of the actual livestock house, the classes for rating and classify the energy performance can be defined. For this purpose, the default energy rating method with a single reference point (n_{ref}) in compliance with ISO 52003–1 (International Standard Organization (ISO), 2017a) is adopted. This method enhances the definition of the classes by setting their number, the reference point, the shape of the scale, and their boundaries. First, the cardinality of class set (n_{class}) is defined. In the proposed *EPC*, seven classes are used ($n_{\text{class}} = 7$), from class one (best energy performance) to class seven (worst energy performance). Each class is labelled with a letter, from A (class one) to G (class seven). Second, n_{ref} has to be set. The term n_{ref} determines the position of the notional livestock house on the scale and, contemporary, represents the boundary between that class and the previous one. Third, the shape of the scale is defined using the geometric series proposed by ISO/TR 52003–2 (International Standard Organization (ISO), 2017b) that reads

$$Y_n = \sqrt{2}^{\left(n-n_{\text{ref}}\right)} \quad [-] \tag{8}$$

that is defined in the interval $[1, n_{\text{class}}[$, with the following constraints

$$1 \leq n < n_{\text{class}} \wedge n \in \mathbb{N}^+ \tag{9}$$

In Eq. (8), the term n is the number of the considered class and Y_n is a dimensionless coefficient used to define the class lower boundary.

Finally, the boundaries of the classes are defined as a function of Y_n and $EP'_{\text{p\_nren}}$, that is the $EP_{\text{p\_nren}}$ calculated for the notional livestock house. For a generic n class, the boundaries read as

$$Y_{n-1} \bullet EP'_{\text{p\_nren}} < \text{Class } n \leq Y_n \bullet EP'_{\text{p\_nren}} \quad \left[\frac{\text{kWh}_p}{\text{m}^2}\right] \tag{10}$$

Please note that for the first ($n = 1$) and last class ($n = n_{\text{class}}$) the boundaries are different and read

$$\text{Class } 1 \leq Y_n \bullet EP'_{\text{p\_nren}} \quad \left[\frac{\text{kWh}_p}{\text{m}^2}\right] \tag{11}$$

$$\text{Class } n_{\text{class}} \geq Y_{n_{\text{class}}-1} \bullet EP'_{\text{p\_nren}} \quad \left[\frac{\text{kWh}_p}{\text{m}^2}\right] \tag{12}$$

Once defined the boundaries of all the classes (Eq. (10)–(12)), the energy performance of the actual livestock house can be rated by comparing $EP_{\text{p\_nren}}$ to the calculated boundaries of classes.

2.1.4. EPC contents

The information contained in the *EPC* should be a concise report about the inputs, the method, and the outputs of the certification (International Standard Organization (ISO), 2017a), with the aim of guaranteeing the replicability of the entire procedure and improving the communication of the energy performance.

The contents of the *EPC* developed following the proposed methodology are resumed in Table 3 and are identified according to the recommendations of ISO/TR 52003–2 (International Standard Organization (ISO), 2017b) standard. As visible from the table, four content categories are present, namely administrative data, technical data, recommendations, and graphical representations of the results.

The administrative data are necessary to uniquely identify both the certified livestock house and the certifier who is the practitioner that has

Table 3
Contents included in the proposed Energy Performance Certificate methodology.

Content category	Content
Administrative data	Livestock house location
	Name and contacts of the certifier
	Date of issue and validity of the *EPC*
Technical data	Geometrical data
	Thermophysical data
	Type and subtype of assessment
	Considered energy use
	Calculated indicators
	Energy rating
Recommendations	Modernization
	Management
Graphical representations of the results	Energy rating
	Indicators

issued the *EPC*. The livestock house location can be identified by referring to its address, geographical coordinates, and reference number on national databases. The validity of the *EPC* is set equal to five years. This time span is considered appropriate to consider potential system renovations resulting from the intensive use of equipment in dusty and aggressive environments, such as livestock houses. The technical data include the main inputs for assessing the energy performance of the livestock house, the type and subtype of the assessment, and the considered energy uses. Technical data also include the results of the calculation of the indicators and the energy rating. Recommendations are essential for improving the energy performance of the certified livestock house and they are *EEMs* suggested by the certifier. They may regard both the modernization and the management of the livestock house, as visible in Table 3. Modernization regards both building fabric and systems. For example, increasing the envelope thermal insulation is a modernization that regards the building fabric. The implementation of renewable energy technologies is a modernization that regards the energy system. The recommendations regarding the management are aimed at improving the operation and control of the livestock house. These improvements could be achieved by adopting Precision Livestock Farming (PLF) technologies that represent a significant technological advancement in livestock sector (Tzanidakis et al., 2021) and they can contribute to the improvement of the energy performance. The last category of content reported in Table 3 is the graphical representation aimed at providing qualitative information about the energy performance in an eye-catching way. In this way, the communication of the details about the energy performance is significatively improved, also among non-technical stakeholders. In the proposed *EPC*, the graphical representation of the energy rating is developed in compliance with the energy label models provided by ISO/TR 52003–2 (International Standard Organization (ISO), 2017b).

2.1.5. The EPC operative procedure

The operative procedure for the application of the proposed *EPC* methodology to a livestock house is schematized in Fig. 1. The procedure is divided into five different stages which represent the consecutive steps that the certifier should follow to issue the *EPC* for the livestock house under consideration. First, data regarding the livestock house are retrieved from technical drawings and documentation, and through an on-site survey (stage 1). Next, the energy performance and the indicators are assessed for both the real and notional livestock houses (stage 2). Then, the energy rating is performed (stage 3) and recommendations to improve the energy performance of the certified livestock house are defined (stage 4). In the last step, the *EPC* document is issued (stage 5) and uploaded to national *EPC* databases, once established.
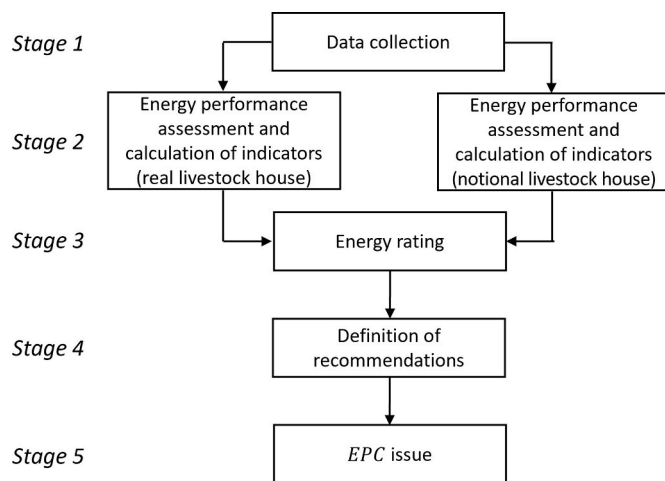
Fig. 1. Schematic of the operative procedure for the Energy Performance Certificate application.

2.2. Methodology adaptation: an EPC for growing-finishing pig houses

2.2.1. A focus on growing-finishing pig houses

In the previous section, the general *EPC* methodology for livestock houses was defined to be adaptable to different types of livestock houses by defining the standard use of the livestock house and the notional livestock house. Broilers, laying hens, piglets, and growing-finishing pigs are considered the animal productions that could be the main targets for the adaptation of the proposed *EPC* methodology. This is because these livestock productions are usually carried out in totally enclosed buildings where climate control represents a remarkable share of the overall energy consumption (Costantino et al., 2016). Moreover, the target livestock productions are very spread at the global level (OECD/FAO, 2019). However, the proposed methodology is suitable to be adapted to further animal productions that are specific of some geographical contexts, such as ducks in South Korea (S.-Y. Lee et al., 2020), or are characterized by different building features, such as partially enclosed systems for ruminants.

To adapt the proposed *EPC* methodology, the standard use of the livestock house and the notional livestock house should be defined. To illustrate this adaptation process, the general *EPC* methodology developed in section 2.1 is now adapted to growing-finishing pig houses equipped with mechanical ventilation. An *EPC* for growing-finishing pig houses is considered of a relevant interest in contributing to decrease the energy consumption of livestock sector because:

- pork is the second greatest meat production worldwide. In 2020, it represented around 33% of the total meat produced at a global level (FAO, 2022).
- in 2011, around 55% of the produced pork come from industrialized growing-finishing pig houses (FAO, 2011). This share is expected to be higher nowadays. In many countries, in fact, pig breeding is changing from traditional extensive systems to large-scale pig farms. For example, large-scale pig facilities in China have grown from 20% up to 80% of the total farms since 2011 (Hu et al., 2023).
- climate control represents up to 50% of the total electrical energy and up to 70% of the total thermal energy that is used in mechanically ventilated growing-finishing pig houses (Costantino et al., 2016).

The proposed adaptation of the *EPC* focuses on mechanically ventilated livestock houses because are characterized by higher energy consumption than naturally ventilated ones. It is worth mentioning that, currently, natural ventilation is also a strategy adopted in pig houses. At first glance, this issue may limit the application of the proposed *EPC*.

Nevertheless, it has to be considered that natural ventilation is usually adopted in cool climate conditions -like European ones- that avoid an excessive overheating of the enclosure and consequent heat stress for pigs. Unfortunately, not all geographical regions have such suitable climate conditions. For example, the warm climate that characterizes some regions of China, makes it preferable the adoption of mechanical cooling systems, as highlighted by Hu et al. (2023). Moreover, it has to be considered that, in the next years, different drivers may cause an increase in the number of growing-finishing pig houses equipped with mechanical ventilation. First, fully-mechanically controlled livestock houses are considered agricultural practices resilient to climate changes (Rötter and Van De Geijn, 1999) due to their capacity for facing extreme weather events, such as heat waves. Second, mechanically ventilated houses can be associated with better environmental conditions for growing finishing pigs. The use of natural ventilation, in fact, is associated with worse thermal and gaseous environment and to a higher daily prevalence of respiratory disease cases, as highlighted by Chantziaras et al. (2020). Third, the use of mechanical ventilation leads to the improvement of productive parameters (i.e., feed conversion ratio and average daily gain) and animal welfare (Chantziaras et al., 2020). Hence, considering the general concern regarding the impacts of climate change on agriculture, the constant push toward the increase of farm productivity, and the rising demand for an improved animal welfare, the number of growing-finishing pig houses equipped with mechanical ventilation, or even mechanical cooling, is expected to rise in the coming years, also in those geographical areas where they are not currently spread. Given this picture, the proposed *EPC* tries to forecast the needs of the pig sector in the coming future.

2.2.2. Definition of the standard use of growing-finishing pig houses

To adapt the general *EPC* methodology to the specific case of growing-finishing pig houses, the standard use has to be defined. The standard use regards both the standardized farming conditions and the settings of the climate control system, as previously mentioned in subsection 2.1.1. In other sectors where *EPCs* were previously developed, most of the features regarding the standard use of buildings are well known, making easier the definition of the standardized boundary conditions. For example, the indoor set point temperatures, internal heat gains, and minimum air changes for residential buildings are defined and harmonized by normative and legislation. This harmonization is still not present in the livestock sector, making the definitions of the standard use of livestock houses a complex challenge that is first faced in this work.

To define the standard use of growing-finishing pig houses, values from literature are adopted. In Table 4, the standard input data related to pig farming conditions and settings of climate control systems are presented. The standard input data related to pig farming conditions are aimed to define the pig stocking density, the liveweight, and the periods of the year in which production cycles are performed. The pig stocking density is fixed at 1.00 pig m^{-2} of useful floor area. This value is considered typical of pork production since is in compliance with European Directive 2008/120/CE (European Commission, 2008). To obtain the pig liveweight and the duration of the production cycle, data from the European Commission are used because they are considered representative of the typical pig farming conditions, at least at EU level. In the methodology for the calculation of pork statistics, the EU Meat Market Observatory considers the pig liveweight to be 25.00 kg at the beginning of the production cycle and 121.00 kg at the end of it. The duration of the production cycle is considered equal to 120 days, with an average daily gain of 0.8 kg day^{-1} (European Commission, n.d.). To simulate the trend of pig liveweight (w_{pig}) as a function of the age (a_{pig}), Gompertz function (Gompertz, 1825) is recommended. Previous studies (Sabbioni et al., 2009; Wellock et al., 2004) demonstrated that it best describes the trend of pig liveweight and protein retention (Green and Whittemore, 2005). It reads

Table 4
Standard input data for pig farming conditions and settings of climate control system for the energy performance assessment of the proposed Energy Performance Certificate for growing-finishing pig houses.

Parameter	Standard input data	Standardized value	Source
Pig farming conditions	Pig stocking density	1.00 pig m^{-2}	European Commission (n.d.)
	Initial pig liveweight	25.00 kg	
	Final pig liveweight	121.00 kg	
	Duration of the production cycle	120 days	
	Duration of the sanitary empty period	10 days	De Lorenzi et al. (2020)
	Beginning of the 1st production cycle	January 1st	Costantino et al. (2021a), Jackson et al. (2018), Tyris et al. (2023)
Settings of climate control system	Ideal set point temperature of indoor air (θ_{set_id})	Eq. (15)	PIC North America (2014)
	Dead band	±2 °C	Costantino et al. (2022), Schauberger et al. (2000)
	Base ventilation flow rate ($\dot{V}_{bs}$)	Eq. (16)	PIC North America (2014)
	Infiltration rate during sanitary empty periods (n_{ach})	0.5 h^{-1}	Jackson et al. (2017)

$$w_{pig} = A \bullet e^{-e^{\left(B \bullet \left(a_{pig} - C\right)\right)}} \quad [\text{kg}] \tag{14}$$

where a_{pig} is the pig age (in days) and *A*, *B*, and *C* are regression coefficients that can be calculated fitting the Gompertz function on data present in literature. Considering the previously defined initial and final w_{pig} as well as the duration of the production cycle, the coefficients *A*, *B*, and *C* are assumed equal to 208.3 kg, 0.01166 days^{-1}, and 112.0 days, respectively. These factors were obtained by fitting the function on growth data provided by PIC North America (2014).

The dates of the production cycles are set chronologically during the year, starting from January 1st. This is a common approach generally adopted in literature. For example, Tyris et al. (2023) adopted this approach for estimating the thermal loads of a broiler house and the dynamic operation of three heat pumps. Costantino et al. (2021a) adopted the same approach for estimating the energy consumption of broiler houses across Europe. Jackson et al. (2018) simulated various pig production cycles starting from January 1st to evaluate the impact of a passive technology on the resource efficiency and the pig welfare. Thus, this approach is considered solid and the shift of production dates over the year is estimated to have a minor impact on energy performance. Moreover, the adoption of the same production dates for both the real and notional pig houses causes a minimum impact on the energy rating.

The production cycles are carried out using the "all in/all out" system and are followed by a 10-day sanitary empty period for the cleaning and disinfection procedures, as recommended in a scientific review focused on commercial pig holdings (De Lorenzi et al., 2020). A 10-day sanitary empty period, in fact, is adequate to prevent the spread of diseases, including the recent epidemic of African swine fever. The same time duration of the sanitary empty period was adopted by Mikovits et al. (2019) in their simulations. Hence, the production cycles are carried out between January 1st and April 30th (2880 hours), May 11th and September 7th (2880 hours), and September 18th and December 31st (2520 hours). In this way, 2.88 production cycles are completed each year. So, m_{step} (Eq. (5)) is equal to 8280 h, that is the total duration of the production cycles over a year.

The standard input data regarding the settings of climate control system are also provided in Table 4. The ideal set point temperature (θ_{set_id}) was defined as a function of w_{pig} using the data reported in a rearing manual for pig farming (PIC North America, 2014). The provided data are the recommended values obtained from the company's research and represent generally accepted industry standards. The following piecewise-defined function determines θ_{set_id}.

$$\theta_{set\_id}\left(w_{pig}\right) = \begin{cases} \sum_{i=0}^{3}\left(k_{set\_(i)} \bullet w_{pig}^{i}\right) & w_{pig} < 90 \\ 14.4 & w_{pig} \geq 90 \end{cases} \quad [°C] \tag{15}$$

Where w_{pig} is the pig liveweight [kg] and k_{set_3} - k_{set_0} are polynomial regression coefficients obtained from PIC North America (2014) and reported in Appendix (Table A1). A dead band of ±2 °C from θ_{set_id} is considered for defining the heating (θ_{set_H}) and cooling (θ_{set_C}) set point temperatures, as done in previous works such as in Schauberger et al. (2000) and the following works based on the same model (Mikovits et al., 2019a; Scherllin-Pirscher et al., 2022). The same width of dead band was also used in the simulations performed by Costantino et al. (2022).

In a similar way, the base ventilation air flow rate for Indoor Air Quality (*IAQ*) control ($\dot{V}_{bs}$) was set considering the data reported in PIC North America (2014). The following piecewise-defined function is adopted

$$\dot{V}_{bs} = \begin{cases} \sum_{i=0}^{6}\left(k_{bs\_(i)} \bullet w_{pig}^{i}\right) \bullet n_{pig} \bullet w_{pig} & w_{pig} < 50 \\ 0.17 \bullet w_{pig} \bullet n_{pig} & w_{pig} \geq 50 \end{cases} \left[\frac{m^3}{h \, pig}\right] \tag{16}$$

where n_{pig} is the number of farmed pigs calculated considering the standard input data of stocking density (Table 4) and the useful floor area of the pig house. The terms k_{bs_6} - k_{bs_0} are regression coefficients obtained from PIC North America (2014) and reported in Appendix (Table A2). The considered values of $\dot{V}_{bs}$ are considered adequate to maintain the concentrations of contaminants (e.g., noxious gases and dust) below acceptable thresholds.

The last standardized value that is defined in Table 4 is the infiltration rate (n_{ach}) during the sanitary empty periods. In this work, n_{ach} is set equal to 0.5 h^{-1}. This value is the arithmetic mean between the maximum and minimum infiltration rates considered by Jackson et al. (2017).

2.2.3. Definition of the notional growing-finishing pig house

To define the notional growing-finishing pig house, the standardized values for both the envelope and the climate control system are set. The standardized values for the envelope regarding the *U − value* of each building component are defined to set the thermal insulation level of the notional pig house. Defining these standardized *U − values* is a challenging task. Few works, in fact, were focused on this specific topic and detailed information about the typical *U − values* adopted in commercial livestock facilities lack in literature. An analysis of the impact of envelope thermal insulation on the energy consumption of broiler houses was performed by Costantino et al. (2021a) whom evaluated a range of *U − values* from 2.90 to 0.27 W m^{-2} K^{-1} for the walls, and from 0.64 to 0.27 W m^{-2} K^{-1} for the roof in different European climate conditions. Axaopoulos et al. (2014) evaluated the optimum insulation thickness for different types of growing-finishing pig house in Greece by considering *U − value* ranges from 2.50 to 0.12 W m^{-2} K^{-1} for brick walls and from 5.88 to 0.16 W m^{-2} K^{-1} for sandwich panel walls. Minimum recommended overall *U − values* are provided in the S401.2 standard of the ASABE (ASABE, 2012) for the United States of America context. The provided values are used as standardized *U − value* for the notional livestock house and they are specified in Table 5. The selected overall *U − values* are 0.91 W m^{-2} K^{-1} for the walls and 0.33 W m^{-2} K^{-1} for the ceiling. The *U − value* for the floor is set equal to the walls, when in

Table 5
Standardized values of the notional growing-finishing pig house.

	Parameter	Standardized value	Source
Envelope	$U-value$ for walls	0.91 W m^{-2} K^{-1}	ASABE (2012)
	$U-value$ for ceiling	0.33 W m^{-2} K^{-1}	
	$U-value$ for floor[a]	0.91 W m^{-2} K^{-1}	
	$U-value$ for glazed elements	2.10 W m^{-2} K^{-1}	Costantino et al. (2021a)
Climate control system	Heating system efficiency Specific Fan Performance in free delivery conditions (0 Pa)	100% $\leq$ 1 hp[b]	Commercial products
		> 1 hp[b]	

[a] Only for floor in contact with the ground. For slatted or partially slatted floors, the floor $U-value$ is the same of the real pig house.
[b] 1 hp = 0.75 kW.

direct contact with the ground. If slatted or partially slatted floors with ventilated pits below are considered, the $U-value$ of the floor is the same of the livestock house under consideration. The transmission heat losses through glazed elements in livestock houses are usually negligible because, in many cases, glazed elements are not present or represent a minor share of the envelope. Nevertheless, a standardized $U-value$ of 2.10 W m^{-2} K^{-1} was set to widen the applicability of the proposed *EPC* methodology. The proposed value was adapted by Costantino et al. (2021a) and is representative for polycarbonate hollow panels, a glazing solution typical in livestock buildings.

To obtain the notional pig house, some features of the climate control system should be set, as reported in Table 5. The efficiency of the heating system is set equal to 100%. This is since a common solution for providing heat to pigs is to place air heaters directly inside the enclosure. In this way, the generated heat is released inside the enclosure and heat losses are avoided.

The last specification of the notional pig house regards the efficiency of the ventilation system. Fans are characterized by the Specific Fan Performance (*SFP*), a parameter that expresses the volume [m^3] of air impelled/expelled by the fan referred to the unit of energy [Wh]. The *SFP* can be expressed as a function of the static pressure difference (Δp_{st}) between upstream and downstream of the fan as

$$SFP = \sum_{i=0}^{2} \left(k_{\text{SFP}\_(i)} \bullet \Delta p_{st}^{i} \right) \quad \left[\frac{\text{m}^3}{\text{Wh}} \right] \qquad (17)$$

where $k_{\text{SFP}\_2} - k_{\text{SFP}\_0}$ are regression coefficients obtainable from the technical datasheet of the fan model.

To obtain the ventilation system of the notional pig house, the fans of the pig house under consideration are simulated considering the *SFP* calculated using in Eq. (17) the regressions coefficients reported in Table A3. The reported coefficients depend on the mechanical power of the fan -higher or lower than 1 hp- and they were obtained from the technical datasheets of commercial products (Munters, n.d., n.d.).

Once defined the standardized values of the notional growing-finishing pig house, the value of n_{ref} should be defined. As previously mentioned in sub-section 2.1.3, n_{ref} determines the position of the notional pig house on the scale. In the framework of this *EPC*, n_{ref} is set equal to three ($n_{ref} = 3$). It means that the notional pig house occupies the third class on the scale (class C). This value is because the notional pig house is considered an energy-efficient building due to its low $U-$values and energy-efficient climate control system. Nevertheless, further room for improvement exists. Pig houses equipped with climate control systems based on renewable energy technologies are considered more

efficient than the notional pig house. Thus, they would occupy higher classes on the scale (classes A and B).

In Fig. 2, the values of Y_n calculated as a function of n using Eq. (8) and considering n_{ref} equal to 3 are displayed. The obtained values of Y_n represent the boundaries of the classes and their labels are also displayed in Fig. 2.

Please note that the standardized values of the notional pig house are not necessarily representative of the current state of the art. The notional pig house, in fact, represents the basis of the comparison with the real pig house to perform the energy rating and, hence, evaluate the energy performance. In the actual practice, the features of the notional pig house and the value of n_{ref} should be defined by policy makers and technical actors with the aim of pushing the pig sector toward the objectives and targets set by energy-efficiency policies.

3. Results: methodology application to a case study in Northwestern Italy

In this section, the adapted methodology for growing-finishing pig houses is applied to a real case study. This practical application is performed with the aim of clarifying the entire certification process, showing some result examples, and highlighting the potentialities of the proposed *EPC*. This application is performed following the procedure defined in the flowchart of Fig. 1. Thus, the following subsections are organized accordingly to follow the same stages.

3.1. Stage 1: data collection

The first stage is data collection. The selected case study is the existing growing-finishing pig house presented in Fig. 3 and is located in Northwestern Italy. Since the energy certification regards an existing pig house, an "as built" assessment (see Table 1) should be performed. The actual features of the analyzed pig house were collected through field measurements performed during a site survey and through the analyses of as-built technical drawings. The collected data regard the geometrical dimensions, the construction of the building components to estimate their thermophysical properties, and the features of climate control systems.

As visible from Fig. 3, the analyzed pig house has a structure that integrates beams and pillars made of prefabricated reinforced concrete. The walls are made of hollow concrete blocks and the roof is made using sandwich panels. The $U-values$ of the walls and the roof are estimated to be 2.18 and 0.64 W m^{-2} K^{-1}, respectively. Inside, the pig house is divided into pens and a partially slatted floor separates the rearing area from the pit where manure is collected. The useful floor area is approximately 280 m^2 (17.80 m × 15.68 m) and the volume is roughly 1030 m^3. Three exhaust fans of 0.58 hp (0.43 kW) provide pit ventilation to control both *IAQ* and θ_{air_i}. During the cool season, supplemental
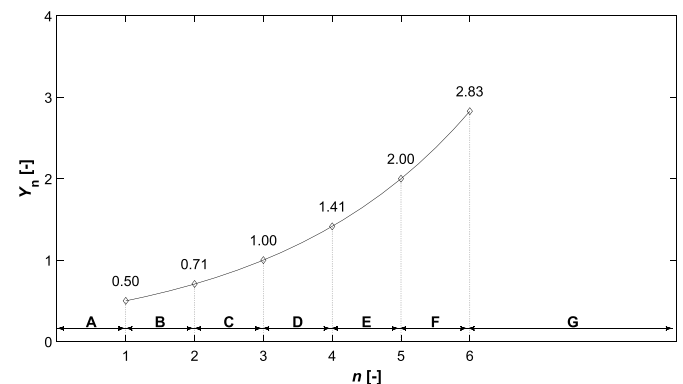

Fig. 2. Values of the Y_n coefficients as a function of the considered n class. The chart also shows the class labels.

a)

b)

Fig. 3. External (a) and internal (b) views of the analyzed pig house.

heating is provided by portable air heaters fueled by diesel oil that are placed inside the enclosure. More details about the selected case study can be found in Costantino et al. (2022).

3.2. Stage 2: energy performance assessment and calculation of indicators

The collected data and the standardized ones (subsection 2.1.1) are now used to assess the energy performance for both the real and notional pig houses. In this work, the energy performance assessment is performed using the dynamic energy simulation model developed by Costantino et al. (2022) in compliance with ISO 13790 standard (European Committee for Standardisation and EN ISO, 2008). The reliability and robustness of the adopted simulation model was previously assessed through a validation against experimental data acquired in the pig house under consideration (Costantino et al., 2022).

At this stage, the indicators established in subsection 2.1.2 are calculated for both the real and notional pig houses. The primary energy factors (f_{p_tot}, f_{p_ren}, and the non-renewable factor f_{p_nren}) and the *GHG* emission factors ($f_{CO_2-eq,j}$) for diesel oil and electrical energy from the grid are reported in Table 6 and refer to Italian context. As visible from the table, diesel oil is considered totally non-renewable. By contrast, a share of the electricity from the grid is considered renewable because the Italian energy mix adopts renewable energy sources for the national power generation. Thus, the results of an *EPC* may vary considerably depending on the considered country due to differences in the national energy mixes and the primary energy factors. For the application of the proposed *EPC* methodology to other European countries, updated primary energy factors can be retrieved from Bilardo et al. (2022). Similarly, the *GHG* emission factors regarding electricity vary on a national basis and they can be retrieved from Koffi et al. (2017).

The obtained indicators are reported on the axes of the spider plot of

Table 6
Total, non-renewable, and renewable primary emission factors (f_{p_tot}, f_{p_nren}, and f_{p_ren}) and greenhouse gas emission factors ($f_{CO_2-eq,j}$) of the energy carriers for the considered case study.

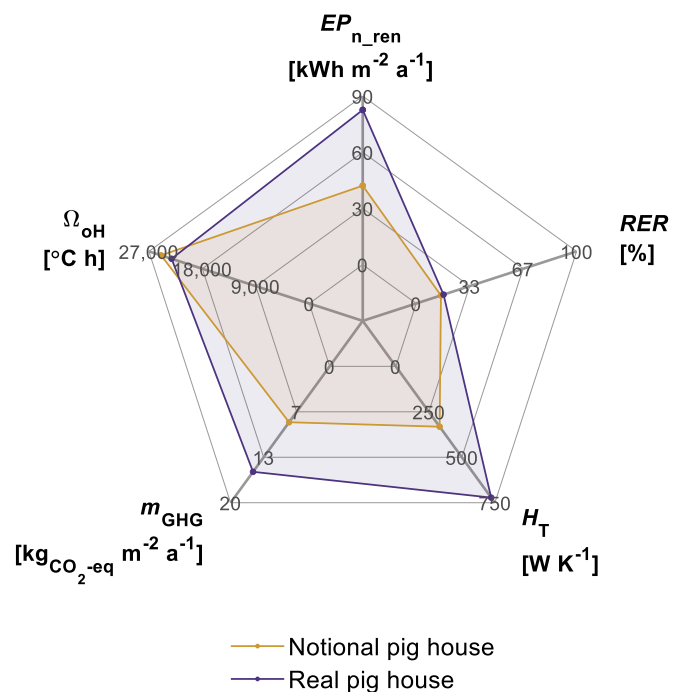| Energy carrier	Factor	Values	Unit of measurement	Source
Diesel oil	f_{p_tot}	1.07	$kWh_p\ kWh^{-1}$	Italian Ministry of Economic Development (2015)
	f_{p_nren}	1.07		
	f_{p_ren}	0.00		
	$f_{CO_2-eq,j}$	0.268	$kg_{CO_2-eq}\ kWh^{-1}$	Koffi et al. (2017)
Electricity from the grid	f_{p_tot}	2.42	$kWh_p\ kWh^{-1}$	Italian Ministry of Economic Development (2015)
	f_{p_nren}	1.95		
	f_{p_ren}	0.47		
	$f_{CO_2-eq,j}$	0.344	$kg_{CO_2-eq}\ kWh^{-1}$	Koffi et al. (2017)

Fig. 4. Indicators of the Energy Performance Certificate for the notional and real pig houses.

Fig. 4, for both the real and notional pig houses. As visible from the chart, EP_{p_nren}, H_T, and m_{GHG} differ remarkably between the real and the notional pig houses. Slighter differences regard *RER* and Ω_{oH}. For the real pig house, EP_{p_nren} is 82.6 kWh$_p$ m^{-2} a^{-1}, while, in the notional one, the value of this indicator is lower by almost 50% (42.2 kWh$_p$ m^{-2} a^{-1}). This difference is attributable to two main factors. The first one is a reduced thermal energy consumption due to heating, that is 11.3 kWh$_{th}$ m^{-2} a^{-1} in the real pig house and 9.6 kWh$_{th}$ m^{-2} a^{-1} in the notional one. The thermal energy consumption due to heating decreases since the thermal insulation of the notional pig house is higher than the real one, as visible by comparing the H_T indicator. The second reason is that the real pig house is equipped with outdated and low-energy-performance fans that entail an electrical energy consumption due to ventilation (36.2 kWh$_{el}$ m^{-2} a^{-1}) that is more than twice than the one of the notional pig house (16.4 kWh$_{el}$ m^{-2} a^{-1}). This remarkable difference in terms of EP_{p_nren} will considerably affect the energy rating, as shown in the next subsection.

The previously mentioned differences in terms of energy consumption have a great impact on m_{GHG}. The *GHG* emissions due to energy use are estimated to be around 15.5 kg$_{CO_2-eq}$ m^{-2} a^{-1} for the real pig house

and only 8.2 kg_{CO_2-eq} m^{-2} a^{-1} for the notional one. As visible from Fig. 4, the value of *RER* is 17.1% for the real pig house and 15.4% for the notional one. Both the *RER* values are low since the adopted energy system is mostly based on non-renewable energy carriers. Only the renewable energy share of the grid electricity is accounted in the calculation of *RER*, as visible from Table 6.

The last indicator that is showed in Fig. 4 is Ω_{oH}. The obtained values are 23,180 $°C$ h for the real pig house and 24,948 $°C$ h for the notional pig house. The difference between Ω_{oH} of the real and the notional pig house is around 8%, meaning that no remarkable differences exist in terms of overheating. The higher value of Ω_{oH} in the notional pig house is mainly due to the increased thermal insulation of the envelope.

3.3. Stage 3: energy rating

After the assessment of the energy performance and the calculation of the indicators, the energy performance of the real pig house is rated through a comparison with the energy performance of the notional pig house. For this aim, the boundaries of the classes for the considered case study are created as a function of the EP'_{p_nren} indicator, as specified in Eqs. (10)–(12) and reported in Table 7. The table shows that the analyzed pig house should be characterized by a EP_{p_nren} equal or lower than 21.1 kWh$_p$ m^{-2} a^{-1} to be rated with class A. By contrast, if the EP_{p_nren} is higher than 119.3 kWh$_p$ m^{-2} a^{-1}, the pig house will be rated with class G. The comparison of the EP_{p_nren} of the real pig house (82.6 kWh$_p$ m^{-2} a^{-1}) with the boundaries reported in Table 7 shows that the real pig house is rated with class E.

3.4. Stage 4: definition of recommendations

After rating the energy performance, some *EEMs* are rcommended for improving the energy performance of the pig house and achieving a better energy rating. These *EEMs* are provided by the certifier based on the results of the energy performance assessment and the site survey.

For the investigated case study, the following *EEMs* could be recommended:

EEM1. The increasing of the envelope thermal insulation;
EEM2. The adoption of more energy-efficient fans;
EEM3. The increasing of the use of renewable energy sources.

Even though the proposed *EEMs* are provided at the end of the certification process, they are fundamental for two main reasons. On the one hand, the proposed *EEMs* show to the farmers the main shortcomings that are affecting the energy performance of the livestock house and possible solutions to overcome them. On the other hand, the provided recommendations represent a solid starting point for technicians who are asked to intervene to improve the energy performance of the

considered livestock house. For example, the provided recommendations could channel energy audits aimed at evaluating the energy performance in real conditions and to improve it. The proposed recommendations and their possible impacts are later discussed in subsection 4.2.

3.5. Stage 5: EPC issue

In this last stage, the *EPC* is issued. The certifier resumes all the collected data, the inputs, and results in a concise report for communicating the obtained information and guaranteeing the replicability of the certification process. A graphical representation of the energy rating is also issued for increasing the understandability especially among non-technical stakeholders. An example of this graphical representation is reported in Fig. 5. The proposed representation summarizes the main results of the *EPC*, such as the assessed energy performance (EP_{p_nren}), the energy rating (the energy class), and the boundaries of the various classes.

Ideally, the *EPC* is uploaded to a national or regional *EPC* database. As previously highlighted, collecting *EPC* data in such databases is essential to create datasets for providing a reliable overview about the livestock house building stock.

4. Discussion

4.1. Beyond the EPC: improving the energy performance and the indoor climate

The *EEMs* proposed in the framework of the *EPC* (subsection 3.4) could be implemented to improve the energy performance of the analyzed pig house. The first proposed recommendation (*EEM1*) is increasing the thermal insulation of the pig house envelope. The H_T of the real pig house (722 W K^{-1}) is considerably lower than the one of the notional pig house (332 W K^{-1}), resulting in higher transmission heat losses. The difference between the considered H_T is explained by analyzing the $U-values$ of the envelope components. In the notional pig house, the $U-values$ of the ceiling and the walls are 0.33 and 0.91 W m^{-2} K^{-1}, respectively, while in the real pig house they are almost twice (0.64 and 2.18 W m^{-2} K^{-1}). The $U-values$ of the real pig house seem excessively high, as also demonstrated by comparing these $U-values$ with the ones reported in Table 8 that were retrieved from literature. As visible from the table, the wall $U-values$ retrieved from literature range from 0.30 to 0.91 W m^{-2} K^{-1}, while the ceiling $U-values$ range from 0.19 to 0.52 W m^{-2} K^{-1}. This remarkable difference is due to the lack of thermal insulation in the masonry walls, a typical

Table 7
Boundaries of energy classes for the considered case study. All the boundaries are expressed in kWh$_p$ m^{-2} a^{-1}.

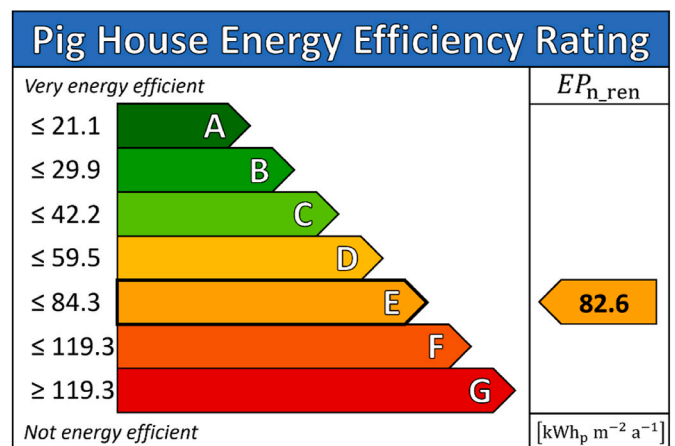| Boundary		Class label		Boundary	
–		A	$\leq$	21.1	
21.1	<	B	$\leq$	29.9	
29.9	<	C	$\leq$	42.2	Class of the notional pig house
42.2	<	D	$\leq$	59.5	
59.5	<	E	$\leq$	84.3	Class of the real pig house
84.3	<	F	$\leq$	119.3	
–		G	>	119.3	

Fig. 5. Example of graphical representation of the energy rating attached to the issued Energy Performance Certificate.

Table 8
Comparison between the envelope $U - values$ of the analyzed pig house and $U-$ *values* from literature for the same building type.

$U - values$ [W m^{-2} K^{-1}]		Reference
Walls	Ceiling	
2.18	0.64	Analyzed pig house
0.91	0.33	Notional pig house (ASABE, 2012)
0.41[a]	0.41[a]	Mikovits et al. (2019b)
0.49	0.52	(Jackson et al., 2017, 2018)
0.74	0.30	Van Wagenberg et al. (2003)
0.30	0.19	Lambert et al. (2001)

[a] Average of the entire envelope.

configuration of outdated pig houses in the considered geographical area. To implement the *EEM1*, it is feasible to add a layer of external thermal insulation to the existing walls. To this aim, a layer of 0.06 m of extruded polystyrene -thermal conductivity of 0.04 W m K^{-1}- is considered. The wall $U - value$ would decrease to 0.51 W m^{-2} K^{-1}.

The second *EEM* (*EEM2*) is the adoption of more energy-efficient fans. A modernization of the ventilation system is considered necessary after the on-site survey which highlighted that the exhaust fans are outdated. In Fig. 6, this aspect is investigated numerically by comparing the *SFP* of the fans of the real and notional pig houses as a function of Δp_{st} in the range between 0 and 60 Pa. The comparison enhanced by this graph highlights how the *SFP* of the fans of the real pig house is considerably worse than the fans of the notional pig house. In free delivery conditions ($\Delta p_{st} = 0$ Pa), the fans of the real pig house can impel around 11 m^3 per each Wh. By contrast, the fans considered in the notional pig house can impel up to 25 m^3 per each Wh. To practically implement the *EEM2*, the existing fans are considered to be replaced by fans of the same model of the one considered for the notional pig house.

The last recommendation (*EEM3*) is increasing the use of renewable energy sources considering that the *RER* of the analyzed pig house is around 17%. In this way, EP_{p_nren} would reduce with a direct improvement on the energy rating. Additional benefits would be the improvement of the *RER* and the m_{GHG} indicators, which would increase and decrease respectively.

A feasible solution for the analyzed pig house could be the installation of a photovoltaic array on the roof of the facility. This choice is
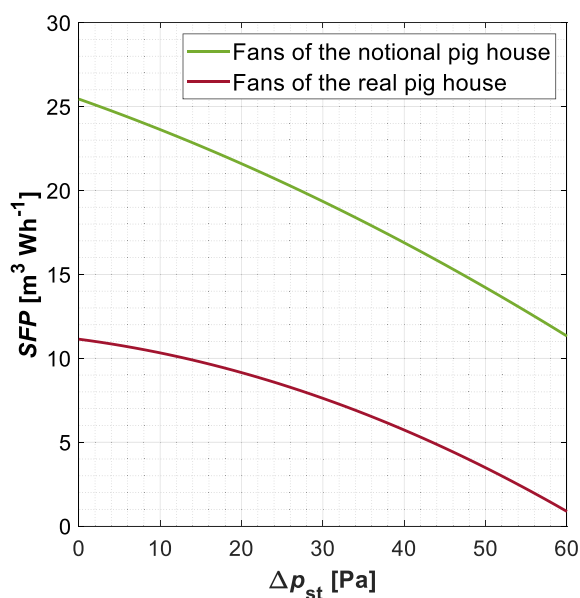

Fig. 6. Comparison between the Specific Fan Performances (*SFPs*) of the fans of the real and notional pig houses. The comparison is shown as a function of the static pressure difference (Δp_{st}).

driven by the fact that the peak of power demand for ventilation is during the warmest hours of the day, when the solar radiation is high as it is photovoltaic power generation (Costantino et al., 2023). In this way, the self-sufficiency of the system -degree of autonomy of the system in terms of power absorption from the external grid (Amato et al., 2021)- could be high. Moreover, this *EEM* is facilitated by the availability of the roof surface for the photovoltaic panel installation. Please note that additional analyses are neededfor sizing the system, estimating the photovoltaic power generation and the match between power supply and demand. Since these analyses are out of the scope of this work, *EEM3* is assumed to consist in the installation of a photovoltaic array which production covers 40% of the electrical energy demand for climate control of the facility on an annual basis. This value agrees with the one estimated by Kwak et al. (2021) -35%- for a piglet house.

4.2. Beyond the EPC: the impact of the proposed EEMs on the energy performance and rating

To evaluate the impacts of the implementation of the proposed *EEMs* (*EEM1*, *EEM2*, and *EEM3*) on the energy performance of the analyzed pig house, the energy certification procedure is carried out again, considering the implementation of each single *EEM* and the possible combinations of them. To perform this assessment the f_{p_tot} and f_{p_ren} for photovoltaic power generation are considered equal to 1, while f_{p_nren} equal to 0 (Italian Ministry of Economic Development, 2015). The related f_{CO_2-eq} is also considered equal to 0 kg$_{CO_2-eq}$ kWh^{-1}, in accordance to Koffi et al. (2017).

In Table 9, the impact comparison of the considered combinations of *EEMs* is presented. As visible from the table, the contemporary implementation of all the three proposed *EEMs* cuts down significantly the EP_{p_nren} which decreases from 82.6 to 29.4 kWh$_p$ m^{-2} a^{-1}. Likewise, the energy rating improves remarkably, and an energy class B is assigned to the analyzed pig house. A significant decrease also regards m_{GHG}. The adopted *EEMs* cuts down the *GHG* emissions related to the energy consumption by around 60% if compared to the current situation (from 15.5 to 6 kg$_{CO_2-eq}$ m^{-2} a^{-1}). This estimated reduction highlights the untapped potential in decreasing the *GHG* emissions from livestock houses by adopting adequate *EEM* s, especially based on renewable energy sources.

It is worth to be mentioned that the implementation of *EEMs* requires financial investments that are estimated to return in a certain payback period due to the reduced operative costs related to energy use. Hence, financial analyses are recommended before implementing any *EEMs*. Implementing all three *EEMs* would represent a significant investment for the farmer and the payback period should be carefully evaluated because could be excessively long, making the investment not financially sustainable. This type of techno-economic analyses is out of the scope of the present work but represents a relevant investigation opportunity for future works. A robust alternative to reduce the investment and the payback period could be the implementation of *EEM2* and *EEM3*, without *EEM1*. The results reported in Table 9 show that the differences between this configuration and the one including all three *EEMs* are slight. Their EP_{p_nren}, in fact, are very similar. The only difference is the energy rating that is one energy class lower (C) for the configuration including *EEM2* and *EEM3* only.

Another relevant element that stands out from Table 9 is that, for this specific case, the increasing of wall thermal insulation (*EEM1*) is not an effective *EEM* when implemented alone. Increasing the wall thermal insulation, in fact, slightly reduces the thermal energy consumption for supplemental heating (from 11.3 to 9.7 kWh m^{-2} a^{-1}). By contrast, it slightly increases the electrical energy consumption due to ventilation (from 36.2 to 38.6 kWh m^{-2} a^{-1}). Considering that the f_{p_nren} for electrical energy from the grid is significantly higher than the one for diesel oil (Table 6), the EP_{p_nren} slightly increases. This issue confirms two findings that were previously highlighted by Costantino et al. (2021a). First, increasing thermal insulation of livestock houses may not always

Table 9

Impact comparison of the considered Energy Efficiency Measures (*EEMs*) on the indicators and energy class. *EEM1* consists in the increase of the thermal insulation of the walls, *EEM2* consists in the adoption of energy-efficient fans, and *EEM3* consists in the installation of a photovoltaic array that can cover 40% of the electrical energy demand for climate control on an annual basis.

			EEM1			EEM1	EEM1		EEM1
	Pig house			EEM2		EEM2		EEM2	EEM2
	Real	Notional			EEM3		EEM3	EEM3	EEM3
EP_{p_nren} [kWh$_p$ m^{-2} a^{-1}]	82.6	42.2	85.5	42.0	57.1	42.2	55.4	30.0	29.4
RER [%]	17.1	15.4	17.5	14.7	31.5	15.4	32.2	25.9	27.5
H_T [W K^{-1}]	722	332	355	722	722	355	355	722	355
m_{GHG} [kg$_{CO_2-eq}$ m^{-2} a^{-1}]	15.5	8.2	15.8	8.3	11.0	8.2	10.5	6.2	6.0
Ω_{oH} [°C h]	23,180	24,948	24,927	23,180	23,180	24,927	24,927	23,180	24,927
Energy class	E	C	F	C	D	C	D	C	B

EP_{p_nren}: non-renewable primary energy consumption, *RER*: Renewable Energy Ratio, H_T: Heat transfer coefficient of the envelope, m_{GHG}: Equivalent CO_2 emissions due to energy consumption, Ω_{oH}: Overheating index.

be beneficial from both the primary energy and financial points of view. Thus, designing the thermal envelope of livestock houses should be a process that needs to be performed through optimization processes -as done by Axaopoulos et al. (2014)- and with a multi-objective approach. Second, the performed analysis points out the importance of evaluating the energy performance of livestock houses through the primary energy approach. Only through this approach, in fact, the weight of each energy carrier can be considered in a reliable way and the global energy performance of the livestock house is properly assessed.

Analyzing the results reported in Table 9 a question arises: how the analyzed pig house could reach the maximum energy rating (class A)? A possible solution could be increasing even more the energy use from renewable energy sources. Photovoltaic power generation could be further increased. The temporal mismatching between the power demand and supply should be further analyzed in future works also considering the presence of electrical storages to increase the self-sufficiency of the system. Another possible solution is to decrease the amount of non-renewable energy used for supplemental heating. At the current state, diesel oil is used as the energy carrier for the air heaters. A possible alternative could be the use of biogas. This energy carrier could be produced on site and used to generate both electrical and thermal energy through Combined Heat Power units integrated in micro grids, as done in previous works for broiler (Omar et al., 2020; Tan et al., 2022) and dairy houses (Teymoori Hamzehkolaei and Amjady, 2018). Alternatively, the adoption of innovative systems such as heat pumps could be fruitful because they could be used either for heating and cooling. This solution has been evaluated in different types of livestock houses and seems promising, as highlighted by the results of the works of Alberti et al. (2018) in a piglet house, and Manolakos et al. (2019) and Tyris et al. (2023) for broiler houses. Nevertheless, further investigations are needed to better understand the impacts of this solution and the proper system integration with pig houses.

5. Conclusions

In this work, the first methodological framework for an Energy Performance Certificate (*EPC*) specifically developed for livestock houses is proposed. The proposed methodology can be easily adapted to different types of livestock productions, by defining some parameters regarding the standard use of the livestock house and the energy rating. An exemplificative adaptation and a practical application are provided for growing-finishing pig houses. By following the proposed methodology, a selected case study was certified and rated with the energy class E. The *EPC* results highlight a remarkable non-renewable primary energy consumption and significant greenhouse gas emissions. The implementation of Energy Efficient Measures (*EEMs*) can remarkably improve the energy performance of the analyzed pig house and the energy rating can rise up to class B.

The main findings of this work are the followings:

- An *EPC* for livestock houses can be actually developed following the ISO 52003–1 and ISO 52003-2 standards. However, the most complex task is the definition of the standard input data and the standardized values of the notional livestock house. Further analyses are needed to evaluate the current state of the art about the technologies and equipment typically used in livestock houses.
- The *EPC* provides information about the energy performance and on other aspects of the livestock houses, such as greenhouse gas emissions. The energy rating remarkably facilitates the comparison between different buildings or design alternatives also for non-technical stakeholders.
- The comparative analysis among the *EEMs* proposed within the framework of the *EPC* has pointed out that the increase of the thermal insulation does not reduce the non-renewable primary energy consumption and does not improve the energy rating of the analyzed pig house. In the analyzed context, the improvement of the climate control system and the implementation of renewable energy technology are *EEMs* that should be preferred.

This work has some limitations. The first limitation is that the proposed *EPC* was adapted for only one type of animal production and applied to one exemplificative case study. A large-scale application involving more types of livestock houses and several case studies is needed for testing and stressing the methodology in different contexts. Large-scale applications will provide the needed data for fine-tuning the standard input data on the current state of the livestock building stock. The second limitation is due to the adoption of ISO 52003–1 and ISO 52003–2 for proposing the *EPC* methodology. On the one hand, those standards provide solidity to the proposed *EPC*. On the other hand, those standards were developed for "civil" buildings. Thus, they may not properly consider the specificities of buildings for livestock production.

CRediT authorship contribution statement

Andrea Costantino: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Enrico Fabrizio:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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This research was performed in the framework of the contract

Appendix

Table A1
Regression coefficients for the definition of the ideal set point temperature (θ_{set_id}, Eq. (15)).

Coefficient	Value	Unit of measurement
k_{set_3}	$-6.43424 \bullet 10^{-5}$	$^\circ C\,kg^{-3}$
k_{set_2}	$+1.12127 \bullet 10^{-2}$	$^\circ C\,kg^{-2}$
k_{set_1}	$-6.99575 \bullet 10^{-1}$	$^\circ C\,kg^{-1}$
k_{set_0}	$+32.55571$	$^\circ C$

Table A2
Regression coefficients for the definition of the base ventilation air flow rate for Indoor Air Quality control ($\dot{V}_{bs}$, Eq. (16)).

k_{bs_6}	$+2.60378 \bullet 10^{-9}$	$m^3\,h^{-1}\,kg^{-6}$
k_{bs_5}	$-4.87602 \bullet 10^{-7}$	$m^3\,h^{-1}\,kg^{-5}$
k_{bs_4}	$+3.65480 \bullet 10^{-5}$	$m^3\,h^{-1}\,kg^{-4}$
k_{bs_3}	$-1.40279 \bullet 10^{-3}$	$m^3\,h^{-1}\,kg^{-3}$
k_{bs_2}	$+2.92192 \bullet 10^{-2}$	$m^3\,h^{-1}\,kg^{-2}$
k_{bs_1}	$-3.18979 \bullet 10^{-1}$	$m^3\,h^{-1}\,kg^{-1}$
k_{bs_0}	$+1.69046$	$m^3\,h^{-1}$

Table A3
Regression coefficients for the definition of the Specific Fan Performance (*SFP*, Eq. (17)) of the fans of the notional pig house.

Fan mechanical power	Coefficient	Value	Unit of measurement
≤ 1 hp*	k_{SFP_2}	$-1.06844 \bullet 10^{-3}$	$m^3\,Wh^{-1}\,Pa^{-2}$
	k_{SFP_1}	$-1.71318 \bullet 10^{-1}$	$m^3\,Wh^{-1}\,Pa^{-1}$
	k_{SFP_0}	25.45	$m^3\,Wh^{-1}$
> 1 hp*	k_{SFP_2}	$-1.47703 \bullet 10^{-4}$	$m^3\,Wh^{-1}\,Pa^{-2}$
	k_{SFP_1}	$-1.34018 \bullet 10^{-1}$	$m^3\,Wh^{-1}\,Pa^{-1}$
	k_{SFP_0}	25.92	$m^3\,Wh^{-1}$

*1 hp = 0.75 kW.

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