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Research paper

Framework to assess eco-efficiency improvement: Case study of a meat production industry

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ABSTRACT

The industry sector accounts for nearly a quarter of the total global final energy and heat makes up two-thirds of that parcel. Sectors such as food & drinks, steel, cement, ceramic and glass, among others represent a considerable part of the energy consumption thought their predominant electric consumption and thermal processes. The meat production industry corresponds to the food & drink industry one of the most representative manufacturing industry in terms of sales turnover and energy use in the European Union. Such is associated to considerable environmental impacts, namely on emissions of equivalent carbon dioxide (CO_{2eq}). Within this sector, the main energy demanding systems are refrigeration systems and steam boilers, with the former being responsible for a great electric energy use within a meat production plant. In order to reduce the CO_{2eq} emissions in an industrial plan and so to contribute to the promotion of industrial eco-efficiency, several improvement measures are proposed, which for instance include energy efficiency improvement measures (waste heat recovery technologies and strategies and cooling improvements), renewable energy integration (solar water heating systems and concentrated solar power) and alternative fuel integration (biomass and biogas fuel integration). The paper presents the development of a framework for the assessment of eco-efficiency improvements widely applicable, namely to manufacturing industries. It has been applied to a case study — meat processing industry and the results have shown an increase of the eco-efficiency indicator up to 8.1% for the energy efficiency measures, up to 22.7% for the renewable energy integration and 10.3% for alternative fuel integration. The research progresses subsist on characterisation of energy key performance indicators (KPI), improvement barriers, improvement of electric energy use in refrigeration components, optimisation of carcass chilling processes, waste heat recovery and integration of renewable energy, alternative fuels and waste-to-energy technologies. A still existing gap is identified in respect to the benefits and correlation of the main improvement measures for manufacturing industries in the improvement of the eco-efficiency indicator.

1. Introduction

The sustainability within the manufacturing industry is an issue relevant in the context of energy and environmental policies around the globe (Posinasetti, 2018). In a worldwide perspective, the Paris Agreement emerged with the aim to promote sustainable development and mitigate the impacts of climate change, considering the specific objectives to limit global warming below 2 °C and preferably 1.5 °C (Horowitz, 2016). In the context of industrial processes, the assessment of sustainability involves the analysis of the energy performance, operational performance and environmental impact associated to these processes (Tonelli et al., 2013). Nonetheless, to classify a process as sustainable and unsustainable is not immediate and it does not rely on the observation of the energy or the environmental impact aspect separately, requiring the adoption of an adequate framework to analyse all parameters simultaneously. In this prospect, authors have been studying the application of the concept of eco-efficiency, which is based on the same notion adopted by global policies which is to create more economic value with less environmental impacts (The Global Development Research Center, 2021). The eco-efficiency for industrial processes may be defined as the ratio between the techno-economic performance associated to a process and the environmental burden associated to its operation (Umezawa et al., 2007). Within the manufacturing industry, the promotion of eco-efficiency has been framed on the scope of several sectors such as the food industry and the meat production industry (Asia-Pacific Economic Cooperation, 1998; Maxime et al., 2006; Meat and Livestock Australia Ltd,

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Nomenclature

CO_2	Carbon dioxide emissions (ton/year)
CO_{2eq}	Equivalent carbon dioxide emissions (ton/year)
$EB_{Resource}$	Environmental Burden associated to resource (ton/year)
EB_{Total}	Total Environmental Burden (ton/year)
$Eco-efficiency$	Eco-efficiency indicator (%)
FE	Final Energy (GJ/year)
GDP	Gross Domestic Product (€/year)
$Material$	Quantity of material (ton/year)
PE	Primary Energy (GJ/year)
$Performance$	Techno-economic performance (ton/year)
$Product$	Quantity of product (ton/year)
$Resource$	Quantity of resource (ton/year)
$Revenue$	Revenue (€/year)
UE	Useful Energy (GJ/year))

Abbreviations

BAT	Best Available Technologies
CSP	Concentrated Solar Power
GHG	Greenhouse gases
LCA	Life-cycle assessment
PV	Photovoltaic
RS	Refrigeration system
RC	Refrigeration cycle
TES	Thermal Energy Storage
VSD	Variable Speed Drives
WHR	Waste Heat Recovery

2002; Risku-Norja et al., 2004). According to the International Energy Agency, the industrial sector is responsible for 29% of the global energy consumption (IEA - International Energy Agency, 2019), corresponding to approximately 20% of greenhouse gas emissions in the EU-28 (European Environment Agency, 2019). The food industry in particular, represents 10.1% of the total energy consumption of the European industrial sector (Nunes et al., 2016a), which itself represents 25.3% of the total energy consumption within the EU (Eurostat Statistics Explained, 2017). The meat production industry, one of the most representative sub-sectors within the food industry, is responsible for a high part of the total carbon footprint associated to its encompassing sector (Petrovic et al., 2015). Within the most relevant issues related to the operations of meat production plants are the high level of energy consumption and the environmental impacts of the meat production processes (Alcázar-Ortega et al., 2012; Cesari et al., 2018; Nunes et al., 2016a). Such justifies the research on improvement measures which for instance encompass the requirement to improve energy efficiency, promote waste heat recovery, promote the use of renewable energy resources, the production and use of alternative fuels and overall promote eco-efficiency (Chantasiriwan, 2020; Froome et al., 2015; Gomaa et al., 2020; Herrero et al., 2013; Jouhara et al., 2018; Liu et al., 2020; Oliveira, 2018; Oliveira et al., 2021; Pathare et al., 2019; Pollock and Mason, 2015; United Nations Environment and Development Division, 2009).

In the prospect to improve the energy use and mitigate the environmental impacts within the meat production industry, several authors studied the implementation of technologies and strategies to reduce fuel consumption, electric energy use and CO_2 emissions (Fritzson and Berntsson, 2006a,b). Studies have been performed on eco-efficiency promotion within the meat production industry through the use of life-cycle assessment (LCA) methodology (Martinelli et al., 2020) and by overall incorporating the use of energy and its improvement within the context of eco-efficiency (Meat and Livestock Australia Ltd, 2002). The progresses regarding the improvement of energy use and environmental impact mitigation in the context of meat production industry may be overall grouped into:

- Energy use in food industry, namely the characterisation of key performance indicators (KPI), implementation of measures and barriers to energy efficiency improvement (Barba et al., 2019; Bhadbhade and Patel, 2020; Bühler et al., 2016; Castro Oliveira and Iten, 2021; De Corato and Cancellara, 2019; Fluch et al., 2017; Menon et al., 2020; Nunes et al., 2016a; Oliveira et al., 2019; Ramírez et al., 2006a; Sheppard and Rahimifard, 2019; Vellini et al., 2020);
- Promotion of eco-efficiency and contributions to the low carbon economy within the scope of the meat production industry, related to the improvement of energy efficiency (Kanaly et al., 2010; Meat and Livestock Australia Ltd, 2002; Pollock and Mason, 2015; Rijsberman, 2017; Silva et al., 2016; Tang and Jones, 2013);
- Improvement of the operation of refrigeration components (compressors, condensers and cooling towers), namely through optimising of the electric energy use (ABB Group, 2020, 2019; AgInnovators, 2021; Al-Bahadly, 2007; Ashrafi et al., 2015; Eskom, 2015; Lick and Hackel, 2019; Qureshi and Tassou, 1996; Robinson and Scepaniak, 2007; Rowland, 1982; Tang and Horwood, 2015; Wu et al., 2017; Yang et al., 2020);
- Measures directly triggering the production processes such as of carcass chilling, slow/fast, spray and multistep chilling and superchilling (Banach et al., 2020; Brown et al., 1993; Carciofi and Laurindo, 2010; Cetin et al., 2012; Ec, 2021; Evans, 2009; Huff-Lonergan and Page, 2006; Institute, 2021; James et al., 2006; Kuffi et al., 2013; McGinnis et al., 1994; Mielnik et al., 1999; Savell et al., 2005; The Pig Site, 2008);
- Technologies and strategies making use of the plant waste heat streams to reduce the fuel consumption of combustion-based processes (steam boilers) and to produce electric energy (containing turbines) (Formánek et al., 2016; Fritzson and Berntsson, 2006a,b; IEA - International Energy Agency, 2010; Kvalsvik, 2015; Seck et al., 2013; SWEP, 2019; Teixeira et al., 2020; Walmsley et al., 2015; Zajac, 2019);
- Integration of renewable energy resources, with focus on solar energy and analysing the potential associated to other resources (Cotrado et al., 2014; Fartaria, 2016; Froome et al., 2015; Gad et al., 2020; García et al., 2019; González-González et al., 2014; IRENA - International Renewable Energy Agency, 2020, 2015; Kumar et al., 2019; Mandi et al., 2019; Reviewing the Solar Photovoltaic Assessment Tool for the Chicken Meat Industry, 2019; Sanni et al., 2019; Sobrosa Neto et al., 2018);
- Integration of alternative fuels in meat production industry, with focus on the implementation of biogas and biomass systems (Green Warmth, 2007; Hamawand, 2015; Herrero et al., 2013; IRENA - International Renewable Energy Agency, 2012; Vilvert et al., 2020; Virmond et al., 2011);
- Implementation of waste-to-energy technologies to valorise the waste streams from the meat production plant with focus on the production of alternative fuels (biogas and biomass) (Assemany et al., 2016; de Sena et al., 2008; León-Becerril et al., 2016; Lu et al., 2015; Marcos et al., 2010; McCabe et al., 2014; Okoro et al., 2017; Onwosi et al., 2020; Rahman et al., 2014).

In the context of industrial sustainability research, the promotion of eco-efficiency is regarded, however a gap is still observed in respect to the benefits and correlation of the main improvement measures for manufacturing industries, such as energy efficiency, renewable energy and alternative fuel integration in the improvement of the eco-efficiency indicator. In this prospect, this paper establishes a framework for the promotion of eco-efficiency in industries. The potential of such measures is to be studied by adopting an innovative approach considering the potential on the mitigation of GHG emissions, thus also establishing indirectly an energy efficiency-oriented assessment method to analyse potential improvements to reduce overall environmental impacts.

2. Methodology framework for eco-efficiency in the meat production industry

In the previous study by the authors in Castro Oliveira et al. (2020), the potential of waste heat recovery (WHR) systems in the ceramic sector has been identified for the energy efficiency improvement. In this study, the following main areas have been identified:

- Waste heat recovery (crucial approach of the study);
- Renewable energy integration (mainly encompassing solar energy and biomass-based energy);
- Alternative fuel integration (including biofuels and hydrogen energy).

The same study (Castro Oliveira et al., 2020), has been conceived in the prospect of the most recent energy and environmental policies, including the 2030 climate & energy framework (European Commission, 2020a), the European Green Deal (European Commission, 2019a) and the 2050 long-term strategy (European Commission, 2020b). These policies have been established with the overall view to promote circular economy of industrial processes and contribute to the Paris Agreement aim to reach climate neutrality (Horowitz, 2016). In particular, the European Green Deal and 2050 long-term strategy jointly dwelled with the need to promote energy system integration across multiple sectors of the EU (European Commission-Press Release, 2020), namely through:

- Increase of the circularity of the energy systems (with a special focus on waste heat recovery);
- Promotion of the direct electrification of end-use sectors;
- Promotion of the use of clean fuels (with focus on renewable hydrogen, sustainable biofuels and biogas).

The industrial eco-efficiency may be handled through the application of several improvement measures and its relation with the use of energy resources at different levels (e.g. energy efficiency improvement and renewable energy integration) is admitted in several technical reports, as for the meat production industry (Meat and Livestock Australia Ltd, 2002) and scientific publications (Chen and Lin, 2020; Martinelli et al., 2020). Nonetheless, the methodology framework proposed in this paper is set to directly correlate the benefits of such improvement measures (for instance, energy savings) with overall reduction of GHG emissions in the targeted sector and so, with the improvement of the eco-efficiency indicator. In practice, it is set to establish a direct mathematical correlation between the impacts of energy improvement-based measures and the promotion of eco-efficiency. In order to assess how energy efficiency may imply an eco-efficiency improvement, it is essential to formulate the study concept. Such is initiated by analysing the significance of eco-efficiency (Umezawa et al., 2007), which may be translated by Eq. (1).

$$\textit{Eco-efficiency} = \frac{\textit{Performance}}{\textit{Product}} \times \frac{\textit{Product}}{\textit{Material}} \times \frac{\textit{Material}}{\textit{Resource}} \times \frac{\textit{Resource}}{EB_{resource}} \times \frac{EB_{resource}}{EB_{Total}} \tag{1}$$

Through its simplification and considering the final factors: *Performance* and EB_{Total}, Eq. (1) may be re-edited to

$$\textit{Eco-efficiency} = \frac{\textit{Performance}}{EB_{Total}} \tag{2}$$

While the *Performance* is related to the technical and economic productivity of the production process (in the case of the manufacturing), the EB_{Total} is related to the overall environmental impact of the plant operation (Science Direct, 2021). The correlation between the performance improvement and the reduction of GHG emissions (by the direct consequence of the application of the Kaya identity), enables to determine the overall eco-efficiency. The factor CO_{2eq} is accounted in the factor EB_{Total}, which in its turn represents the total environmental burden associated to a determinate operation. Nonetheless, the total environmental impacts caused by industrial operation also encompass the emissions of other greenhouse gases. For a more accurate analysis, the Kaya identity Eq. (3) can account for the emissions of other GHG and the equivalent CO_2 metric (CO_{2eq}) may thus be accounted. Such has been considered by Hwang et al. (2020) and a modified Kaya identity equation may be enunciated as Eq. (3).

$$CO_{2eq} = \frac{CO_{2eq}}{PE} \times \frac{PE}{FE} \times \frac{FE}{UE} \times \frac{UE}{GDP} \times GDP \tag{3}$$

Attending to Eq. (3), the following factors are established for the analysis:

- The $\frac{CO_{2eq}}{PE}$ (ton/GJ) factor, related to the decarbonisation process, decreased by renewable energy and alternative fuel integration.
- The $\frac{PE}{FE}$ (%) and $\frac{FE}{UE}$ (%) factors, related to the efficiency of each energy transformation process phase (primary energy to final energy and final energy to useful energy), decreased thought energy efficiency improvement measures;
- The $\frac{UE}{GDP}$ (GJ/€) factor, corresponding to the useful energy intensity, normally considered as a constant value as not presenting a considerable variation (Serrenho et al., 2016, 2014);
- The *GDP* (Gross Domestic Product) factor, tendentially a growing factor over a determinate time frame (years) (Serrenho et al., 2016).

Although not directly established in this work, according to Eq. (3), for the CO_{2eq} mitigation, the reduction of the $\frac{PE}{FE}$, $\frac{FE}{UE}$ and $\frac{CO_{2eq}}{PE}$ factors must surpass the increase of gross domestic product (expected in developed countries and holding most of the manufacturing industries) over a studied time frame. The energy consumed by end-users such as industry, corresponds to final energy (*FE*), which is converted from primary energy (*PE*) Eurostat (2018). As such, the terms $\frac{CO_{2eq}}{PE}$ and $\frac{PE}{FE}$ may be aggregated into one term: $\frac{CO_{2eq}}{FE}$, thus simplifying Kaya identity in Eq. (5),

$$CO_{2eq} = \frac{CO_{2eq}}{FE} \times \frac{FE}{UE} \times \frac{UE}{GDP} \times GDP \tag{4}$$

As such, the Kaya identity Eq. (5) considers two terms which may be used to translate potential improvements at the level of single plants, which are the decarbonisation term ($\frac{CO_{2eq}}{FE}$) and the energy efficiency term ($\frac{FE}{UE}$). The CO_{2eq} term considered as the outcome of Eq. (5), may be calculated considering the energy consumption of each source and the correspondent emission ratios, corresponding in an aggregated indicator for the total environmental burden (EB_{Total}) considered in Eq. (2). The *Performance* indicator of Eq. (2) may be in its turn be correlated to the economic outcome of the production process of an industrial plant, being translated by the revenue generated within a plant (Verfaillie and Bidwell, 2000). As such, the eco-efficiency calculation translated by Eq. (2) may be reformulated as Eq. (5).

$$Eco\text{-}efficiency = \frac{Revenue}{CO_{2eq}} \tag{5}$$

3. Case study description and characterisation — meat production industry

The meat production industry is considered the largest sector within Food & Drink industry (Feliciano et al., 2014). Therefore, its characterisation must be performed in the light of the encompassing sector. Within the EU, the Food & Drink industry is represented by the non-profit confederation FoodDrinkEurope (FoodDrinkEurope, 2021). According to the data provided by the confederation (electrical4u, 2020). It generates a turnover of 1.2 trillion euro and a value added of 266 billion euro and has a total of 286 thousand companies, being considered the most representative sector within the European manufacturing industry (representativeness of about 14.6%) (FoodDrinkEurope, 2020). Consistently, the European food industry has also a great representativeness within the manufacturing industry, with the energy use within this sector being responsible for 10.1% of the total energy consumption of the European manufacturing industry (Eurostat, 2015).

The meat industry in particular, represents 12.3% of the overall sales turnover of the food industry and has associated 1159 companies (Nunes et al., 2016b). The sector has a prominent consumption of electricity and thermal energy (fuels), although electric energy is consistently the most relevant parcel of total energy consumption (Meyers et al., 2016). Within the distribution of electric energy use, the refrigeration systems generally represent the most significant part (Okos et al., 1998; Pagan et al., 2004; Ramírez et al., 2006b). Fig. 1 presents a set of illustrative figures associated to the energy use in the European meat production industry, gathering data different studies (Nunes et al., 2016b; SGCIE - Sistema de Gestão dos Consumos Intensivos de Energia, 2018).

3.1. Description of the production process

The meat production process is constituted by several phases. In respect to thermal energy requirements (heat and cold energy), the energy needs within a meat production plant may be disaggregated as follows:

- Refrigeration of refrigerated chambers for meat storage, rapid cooling tunnels and building rooms;
- Heating for the scalding, smoking, cooking, sterilisation and pasteurisation processes.

In Fig. 2, the flowsheets for the whole processes involved in for instance in a slaughterhouse and a meat production plant are presented. In Table 1, the processes requirements of heat and cold energy are characterised considering the data and aspects described by Burton and Tinker (2008), Spyrou et al. (2019), Swart et al. (2003) and Zhang et al. (2019).

3.2. Refrigeration systems and steam boiler

The use of energy within the meat production industry may be decoupled into thermal energy and electric energy. The steam generation process is accountable for the intensive thermal energy use (Ramírez et al., 2006c). On the other hand, the refrigeration systems in charge for the cooling of carcasses and operation rooms are accountable for the high electric energy consumption (Feliciano et al., 2014). The assessment of energy efficiency improvement measures (and considerably measures for renewable energy and alternative fuel integration) must be performed for the existing equipment in the industrial plants. For the meat production industry, the most relevant systems or components are the refrigeration cycles (installed for carcass cooling) and the steam boilers (for steam generation) (Nunes et al., 2016b). In order to proceed with the assessment of these two types of systems, it is necessary to analyse the objective of their installation:

- Refrigeration cycles are commonly installed to cool down refrigerated chambers for meat storage, rapid cooling tunnels and building rooms (Meat and Livestock Australia, 2008);
- Steam boilers are commonly installed to produce steam to be used in vertical scald, epilator, hot water tank (for sanitation), fat melting tank, kilns, dryers, ballast washing machines and by-product treatment machines (ThermoDyne Engineering Systems, 2018).

The refrigeration cycle corresponds to a thermodynamic cycle composed by a condenser, evaporator, compressor and expansion valve (Pal et al., 2018). Depending on the type of the condenser, the refrigeration cycle may be coupled with a secondary circuit encompassing a cooling tower (Edmondson, 2014), which is installed in the condenser side to serve as a heat sink. While steam boiler corresponds to a combustion-based process composed by a combustion chamber and a heat exchanging structure, in which the heat from the combustion gases is supplied to a water stream (electrical4u, 2020). A simplistic representation of their operation is displayed in Fig. 3.

Table 2 presents details related to the energy use in each equipment of the refrigeration systems and the steam boiler.

4. Application of the eco-efficiency framework in the meat production industry

The framework presented in Section 2 allows the assessment of eco-efficiency of the processes and energy systems in manufacturing industries. The objective is to perform such assessment with base on the reduction of the total environmental burden (EB_{Total}). As explained in Section 2, the total environmental burden encompasses the emissions of greenhouse gases (GHG), correlated as the CO_{2eq}. The approach considered in this paper is energy efficiency-oriented rather than LCA-oriented. Such analysis is suitable to achieve the aims of the overall research work, in which the promotion of eco-efficiency is attained by the assessment of the of energy efficiency improvement measures (Section 4.1) and renewable energy and alternative fuel integration measures (Section 4.2).

4.1. Measures for energy efficiency

With the scope of improving industrial eco-efficiency, the energy efficiency measures, as above-mentioned, directly improves the $\frac{FE}{UE}$ factor of Kaya identity and translated by Eq. (4). While the renewable energy and alternative fuel integration impact directly the plant's energy inputs (Castro Oliveira et al. 2020), the

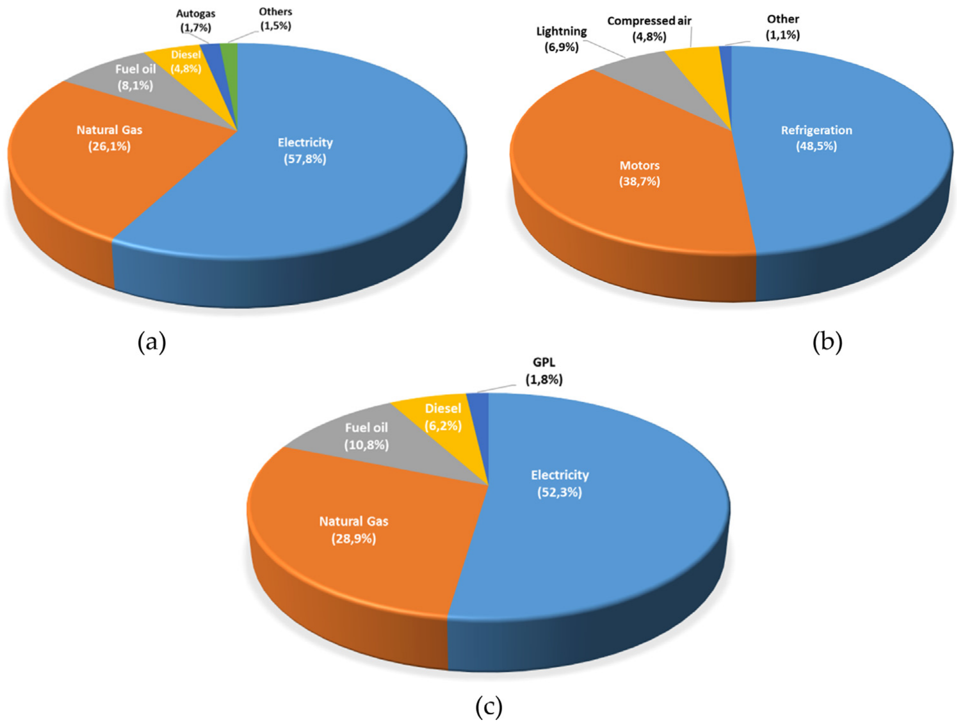

Fig. 1. Representation of the share (a) each energy form over total energy consumption, (b) electric energy use by each system over total electric energy consumption, (c) equivalent CO_2 emissions associated to each energy form.
Source: Data gathered from Nunes et al. (2016b) and SGCIE - Sistema de Gestão dos Consumos Intensivos de Energia (2018)

Table 1
Processes characterisation of the meat production industry and operation conditions requirements.
Source: Adapted from Burton and Tinker (2008).

Process	Brief Description	Operational conditions
Heat Energy Requirements		
Scalding	Process of treating carcass with hot water or steam for efficient removal of the bristles or feathers.	Water temperature 58 to 62 °C
Smoking	Process of preserving meat through long exposure to heat and smoke, dehydrating it and imparting its antibacterial properties.	Steam temperature 65 to 100 °C
Cooking	Process in which meat is roasted, grilled, fried or cooked with steam to destroy microorganisms and enzymes with potentially harmful consequences.	Water/steam temperature 80 to 100 °C
Sterilisation	Process in which a highly efficient thermal treatment is applied to the meat.	Temperature > 100 °C
Pasteurisation	Process in which thermal treatment is applied to the meat within simple cooking vats.	Temperature < 60 °C
Cold Energy Requirements		
Slow Chilling	Chilling is performed with air circulation through a forced draught cooling unit and followed by the passage of carcasses in a chilling room. Similar to a traditional chilling procedure.	Temperature 0–4°C
Fast Chilling	Chilling process in which meat is chilled to −1 °C/ 5 h post-mortem.	Temperature of −20 to −15 °C
Spray Chilling	Process of hot carcasses or carcass sides intermittent spraying using water or another cooling fluid during the early stages of cooling.	Temperature of 2 °C
Multistep Chilling	Process in which carcasses are chilled for varying periods in more than two stages.	Temperature varies with the stage
Superchilling	Process in which the carcass is cooled to its initial freezing point and in which then 5% to 30% of the water is kept frozen (removing the latent heat of crystallisation).	Temperature of −4 to 0.3 °C

measures for energy efficiency improvement, applicable to a certain equipment or strategy, aim better operations performance, indirectly improving the plant's energy input. The best available technologies (BAT) for industrial plants and applicable to the food and meat production plant (European Commission, 2019b, 2015; Santonja et al., 2019), in general, include:

- Periodic maintenance and the implementation of a balanced planning of the plant;
- Equipment inspection;
- Calibration of measuring instruments;
- Assurance of the thermal insulation of pipes, valves, fittings, vessels and building walls;
- Displacement of vapour lines and refrigeration lines;

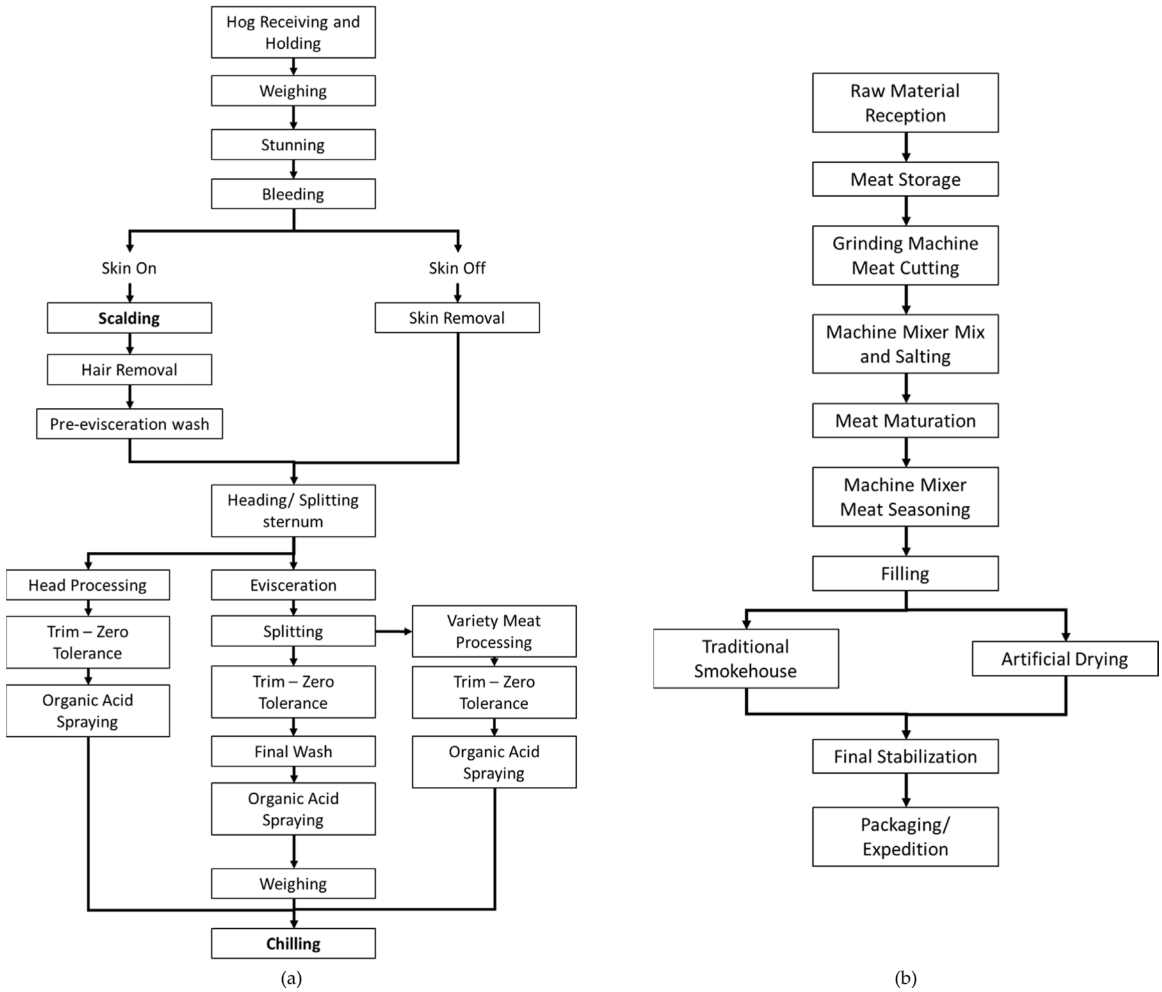

Fig. 2. Flowsheet for (a) processes in a slaughterhouse and (b) overall processes in a meat production industry plant.
Source: Adapted from Rosenthal Meat Science and Technology Center (2000) and Environmental Handbook (1995).

Table 2
Energy use in the refrigeration systems and steam boiler.
Source: Adapted from Herrero et al. (2013), Horowitz (2016) and Huff-Lonergan and Page (2006).

Component	Type of Energy Use	Energy Use
Compressor	Electric	Operation of the electric generator connected to the compressor
Condenser		Air cooled condenser: operation of fans; Water cooled condenser: operation of the fan of a cooling tower encompassed in a secondary water circuit); Evaporative condenser: operation of fans
Cooling Tower		Operation of fans
Steam Boiler	Thermal (Fuel)	Vaporisation of a water stream

- Installation of automatic doors in buildings to prevent thermal.

Furthermore, specific measures range from coupling of variable speed drives (VSD's) to reduce electric energy consumption in electric motors (pump motors, fans), optimisation of cooling in processes to waste heat recovery (WHR) technologies and strategies. Table 3 summarises several measures applicable to meat production plant and Fig. 4 presents a flowsheet example presenting WHR opportunities. Regarding the steam boilers, energy efficiency measures for industrial boilers have been presented by the author's in Castro Oliveira et al. (2020), hence not being presented in this paper. Details on such measures are accessible in Castro Oliveira et al. (2020) and may be applicable in the context of the meat production industry steam boilers.

4.2. Measures for renewable energy and alternative fuel integration

The integration of renewable energy resources is pointed as a potential set of measures for decarbonisation within the meat production industry, allowing the reduction of fossil fuel consumption. On the scope to improve industrial eco-efficiency, these measures overall improve the $\frac{CO_{2eq}}{FE}$ factor of Kaya identity translated by Eq. (4). Within the context of meat production plants, solar energy technologies have most prominently been applied, although other renewable resources such as wind energy, hydro energy and geothermal energy have been conceptually explored (Froome et al., 2015). In addition, decarbonisation may be attained by the use of alternative fuels. Although some authors consider some alternative fuels as renewable energy resources (Herrero et al., 2013), this paper establishes a distinction between

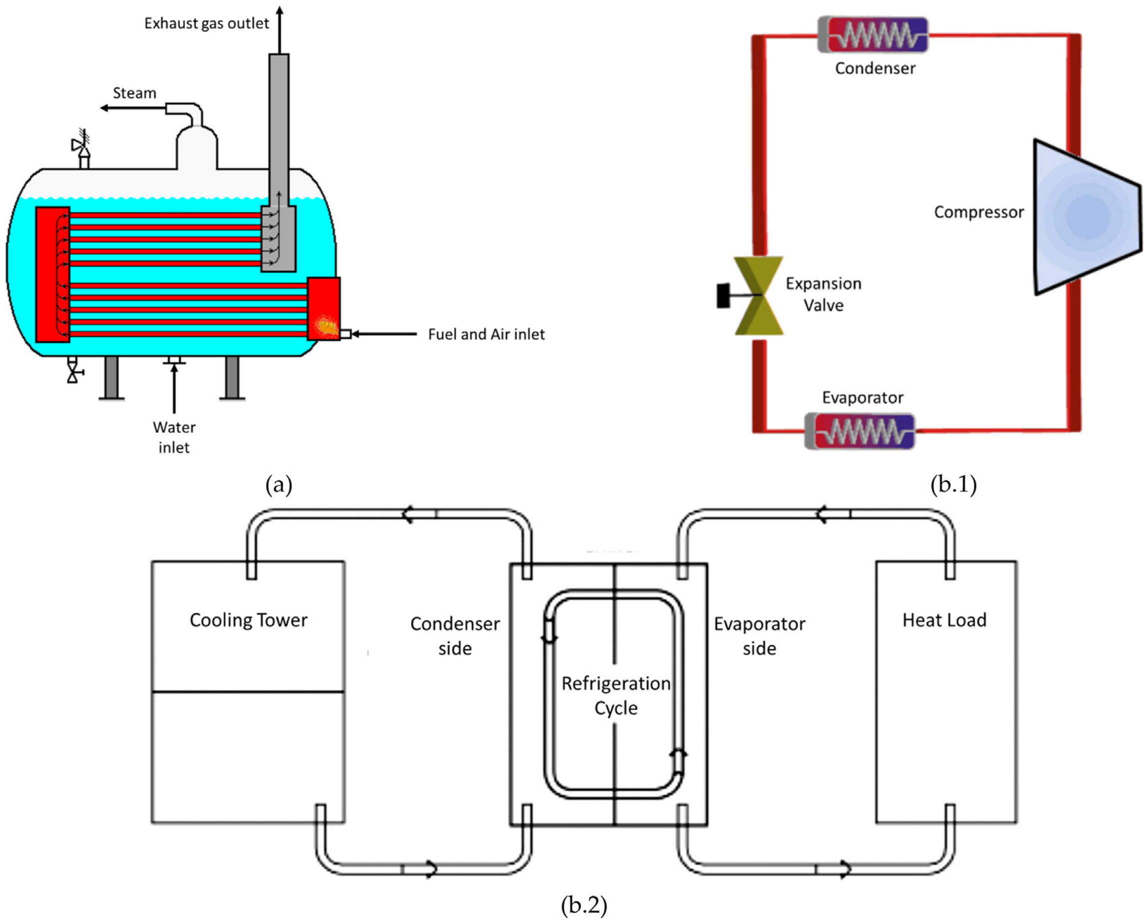

Fig. 3. Scheme of (a) steam boiler, (b.1) refrigeration cycle, (b.2) refrigeration cycle with coupled cooling tower and heat load.
Source: Adapted from Araner (2021), Pinterest (2021) and Weifang Heng An Imp & Exp Co. (2014).

these two sets of measures (hence, biofuels that may be considered renewable energy are in here assumed as alternative fuels). In the context of the meat production industry, the alternative fuels used in the plants may be generated by using waste-to-energy technologies such as anaerobic digestion and flotation process (Vilvert et al., 2020). Table 4 lists several measures for renewable energy and alternative fuel integration. In Fig. 5, a flowsheet for the implementation of a renewable energy integration system is presented.

4.3. Assessment of the eco-efficiency improvement for a Portuguese meat production industry

This section presents the assessment of the Eco-efficiency improvement by applying the framework presented in Section 2 to a case study — Portuguese meat production industry. It is to note that the methodology framework is set to be generalist, applicable to different countries as well as to manufacturing industries. A Portuguese meat production sector has been selected as an example for its applicability. The assessment is related to specific improvement measures (presented in Tables 4 and 5) and so to analyse their impact in the overall eco-efficiency enhancement. The significance of such measures is analysed by the determination of the Eco-Efficiency translated in Eq. (5), considering the assessment of the influence of the variation of the Kaya identity factors as translated by Eq. (4) on the reduction of the equivalent CO_{2eq}. For such analysis, the following assumptions have been made:

- The food industry average energy consumption has been considered due to inexistence of specific values for the Portuguese meat production sub-sector (Eurostat, 2021; INE, 2018);
- Owing that meat production corresponds to the most representative sub-sector within the encompassing Food & Drink Industry sector (Feliciano et al., 2014), the average energy consumption of the food industry has been considered in the assessment and calculations;
- The considered values for the share of reduction are based the improvement measures presented in Tables 3 and 4;
- The use of electric energy by refrigeration and motor operation has been determined considering the relative share of energy use presented in Fig. 1(b);
- Data on CO_{2eq} emission ratio has been gathered from literature and reference documents (Covenant of Mayors et al., 2017; Kumar and Randa, 2014);
- The revenue for a single plant has been calculated considering a sales turnover of the Portuguese food industry and its dimension at the national context, available in FIPA (INE, 2018).

Firstly, the eco-efficiency indicator for the baseline scenario has been determined in which any improvement measure has yet to been applied: corresponding to the ratio between the plant's revenue and the total equivalent CO_{2eq} emissions of the manufacturing plant. The energy consumption and related CO_{2eq} emissions associated to a typical Portuguese food industry listed in Table 5 has been considered. Such has been followed by

Table 3
Characterisation of energy efficiency measures.

Measure	Main Findings	Potential
Improvement of Refrigeration Systems		
Installation of VSD's	It is set to reduce the electric energy consumption of electric motor devices; may be applied to adapt flow demands to different cooling needs of the heat load, such as in refrigeration cycle circuit pumps (adapt working fluid flow demands) and air cooled/evaporative condenser and cooling tower fans (adapt airflow demands); Theoretically, energy savings are calculated according to the affinity laws of pump motors and fans.	25%–40% energy savings
	Ref.: ABB Group (2020, 2019), AgInnovators (2021), Al-Bahadly (2007), Eskom (2015), Lick and Hackel (2019), Qureshi and Tassou (1996), Robinson and Scepaniak (2007) and Rowland (1982)	
Supply of lubricating oil to compressors	The application of oil in a compressor of refrigeration cycle in order to lubricate bearings, sealing and leakage paths, as well as cooling refrigerant gas and regulating capacity; It allows the improvement of the compressor performance compared to standard oil injection; Testing the parameters associated to the oil flow, allows to analyse the influence of lubricating oil on the decrease of pressure pulsations.	3.9% total efficiency improvement
	Ref.: ABB Group (2020, 2019), AgInnovators (2021), Al-Bahadly (2007), Eskom (2015), Lick and Hackel (2019), Qureshi and Tassou (1996), Robinson and Scepaniak (2007), Rowland (1982), Wu et al. (2017) and Yang et al. (2020)	
Improvement of Refrigeration in Processes (e.g. Carcass Chilling)		
Evaporative cooling of carcasses	Alternate process to the conventional chilling processes; Carcases are moistened with a water spray and transported through a cooling tunnel (being brought into contact with cold dry air) while the moisture at the surface evaporates (heat is drawn from the carcass); The process is repeated until the cooling reaches the operational requirements.	Payback time of 7 years 50% electric energy savings for chilling
	Ref.: ABB Group (2020, 2019), AgInnovators (2021), Al-Bahadly (2007), Brown et al. (1993), Carciofi and Laurindo (2010), Eskom (2015), Lick and Hackel (2019), Mielnik et al. (1999), Qureshi and Tassou (1996), Robinson and Scepaniak (2007) and Rowland (1982)	
Electrical stimulation for carcass chilling	Applying electric current to hot carcass immediately after slaughtering; It is set be an alternate measure to the change from slow to fast chilling (which produces considerable energy savings), being a non-invasive method; Its implementation depends on plant production efficiency, mechanisation of production processes and the use of processing power and surfaces.	15%–45% energy savings
	Ref.: Banach et al. (2020), Cetin et al. (2012) and The Pig Site (2008)	
Air cooling for carcass chilling	Optimisation of the airflow distribution in carcass cool rooms; Performed by analysing the influence of parameters such as room temperature, humidity, air velocity and turbulence.	15%–45% energy savings
	Ref.: Evans (2009), Kuffi et al. (2013) and McGinnis et al. (1994)	
Waste Heat Recovery and Electricity Generation		
Installation of Desuperheaters	Installation of a heat exchanger between the compressor and condenser in order to use the heat from the superheated refrigerant gas; Desuperheating is commonly applied for water heating, being potentially useful as capable of heating a water stream to a higher temperature than with the use of a condenser; May be coupled with the installation of two oil coolers (cold water is preheated in the desuperheater and then transported to the oil cooler zone, from which the outlet hot water may be stored in a water thermal tank);	10%–34% electric energy savings
	Ref.: Formánek et al. (2016), Kvalsvik (2015), SWEP (2019), Teixeira et al. (2020) and Zajac (2019)	
Installation of heat exchanger networks	Implementation of a complex WHR strategy in which several heat exchangers are installed to overall improve the operation of both refrigeration systems and steam boilers; In practice, several authors studying such type of implementation within the meat production plant made use of the pinch technology.	Up to 15% energy savings
	Ref.: Fritzson and Berntsson (2006a,b) and Walmsley et al. (2015)	
Steam and gas turbine Cogeneration	Combined heat and power (CHP) systems may be used to produce electric energy to refrigeration cycles and thermal energy to be used in steam boilers; Performed by using either steam or gas turbines to produce electric energy and also by including micro-turbines and Organic Rankine cycles (ORC's) in the design of the system.	Biogas: 2 years payback time. Natural gas: 5 years Payback (investment cost of 1020 €/kW)
	Ref.: Bianchi et al. (2006), Colley (2010), IEA - International Energy Agency (2010) and Patrascu and Minciuc (2013)	

considering a set of improvement measures (improvement of refrigeration systems and processes; waste heat recovery and electricity generation; renewable and alternative fuel Integration) leading to CO_{2eq} emissions reduction as listed in Table 6.

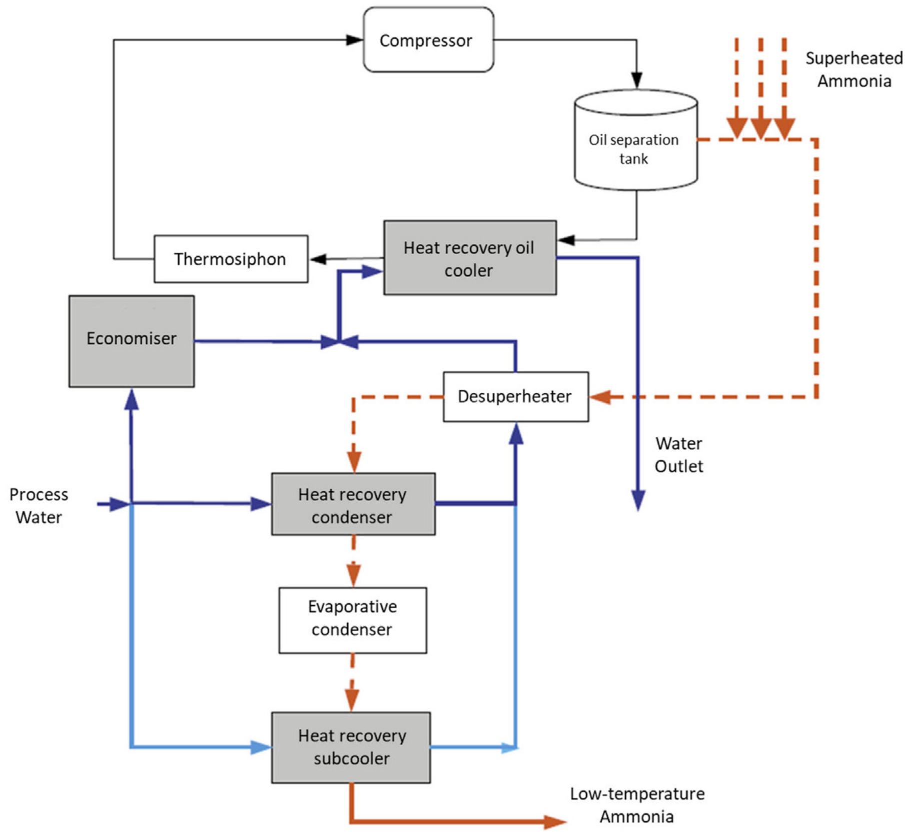

Fig. 4. Flowsheet of a WHR strategy implemented to improve the operation of refrigeration systems.
Source: Adapted from Ashrafi et al. (2015)

Table 4
Characterisation of measures for renewable energy and alternative fuel integration.

Measure	Main Findings	Potential
Renewable energy integration		
Photovoltaic systems	Implementation of photovoltaic (PV) technologies may be processed in order to supply electric energy; The power generation may be processed by the application of hybridised technologies encompassing the use of PV and biofuels.	Payback time of 2–7 years (investment cost of about 4750 €/kW)
	Ref.: Fartaria (2016), González-González et al. (2014), IRENA - International Renewable Energy Agency (2020), Reviewing the Solar Photovoltaic Assessment Tool for the Chicken Meat Industry (2019) and Sanni et al. (2019)	
Solar Water Heating Systems	Application of solar thermal energy to heat up plant water streams, such as the inlet water at a steam boiler; Several technologies may be applied for the purpose, such as concentrated solar power (CSP) and thermal energy storage (TES) through the use of a water thermal tank.	Payback time of 5–7 years (investment cost of 250–1000 €/kW)
	Ref.: Cotrado et al. (2014), Froome et al. (2015), Gad et al. (2020), García et al. (2019), IRENA - International Renewable Energy Agency (2015), Kumar et al. (2019), Mandi et al. (2019) and Sobrosa Neto et al. (2018)	
Alternative fuel integration		
Biomass as an alternative fuel	Biomass may be used as an alternative fuel for steam generation; The production of biomass may be performed by a flotation process for wastewater treatment.	Payback time of 3 years (investment cost of about 1540 €/kW)
	Ref.: de Sena et al. (2008), Green Warmth (2007), Herrero et al. (2013), IRENA - International Renewable Energy Agency (2012), León-Becerril et al. (2016), Lu et al. (2015), Onwosi et al. (2020), Rahman et al. (2014) and Virmond et al. (2011)	
Biogas as an alternative fuel	Biogas may be used for power generation; The production of biogas may be processed by installing an anaerobic digestion unit for wastewater treatment.	16% electric energy savings and payback time of 6 years
	Ref.: (Assemany et al., 2016; Hamawand, 2015; Okoro et al., 2017; Vilvert et al., 2020)	

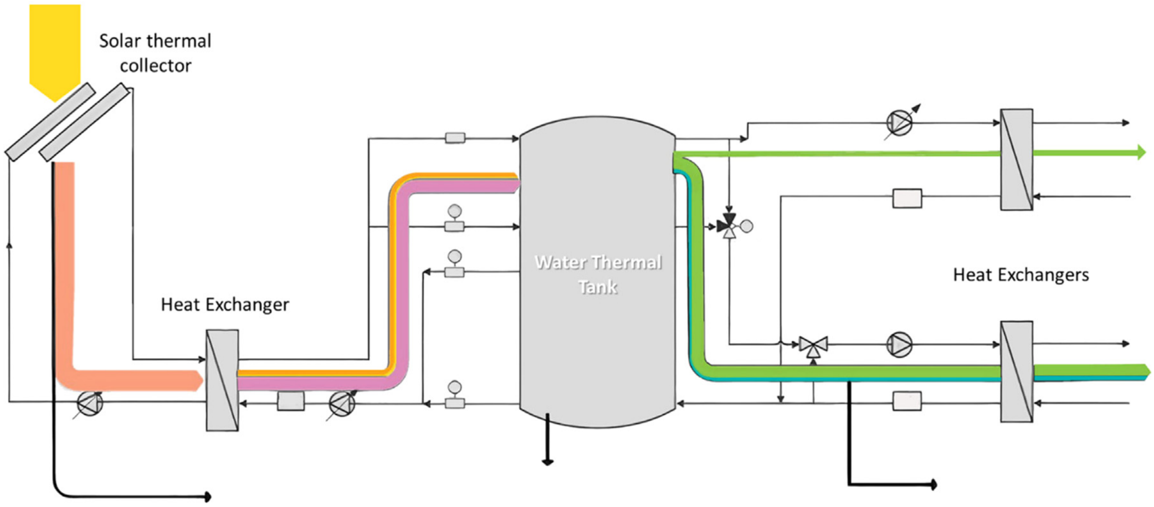

Fig. 5. Flowsheet of a solar water heating systems installed in a meat production plant.
Source: Adapted from (Cotrado et al., 2014)

Table 5
Energy Consumption and CO_{2eq} emission data associated to typical Portuguese food industry.

Energy Source		Average Energy Consumption (MWh/year) (Eurostat, 2021; INE, 2018)	CO_{2eq} Emission Ratio ($tonCO_{2eq}$/MWh) (The Pig Site, 2008; ThermoDyne Engineering Systems, 2018)	CO_{2eq} Emissions ($tonCO_{2eq}$/year) (Covenant of Mayors et al., 2017; Kumar and Randa, 2014)
Electric Energy	Total	189.8	0.369	70.0
	Electric Energy for Refrigeration	92.0		33.9
	Electric Energy for Motors	73.4		27.1
Natural Gas		104.9	0.202	21.2
Solar Photovoltaic			0.050	
Solar Thermal			0.000	
Biomass			0.002	
Biogas			0.251	
Total		328.4		133.9

Table 6
CO_{2eq} emissions reduction and eco-efficiency improvement associated to the measures described for the meat production industry.

Measure	Correspondent Energy Source	Share of the reduction of the correspondent factor	Mitigation on CO_{2eq} Emissions ($tonCO_{2eq}$/year)
Improvement of Refrigeration Systems			
Installation of VSD's	Electric Energy for Motors	5.1%	6.8
Supply of lubricating oil to compressors		0.8%	1.1
Improvement of Refrigeration in Processes (e.g. Carcass Chilling)			
Evaporative cooling of carcasses	Electric Energy for Refrigeration	12.7%	17.0
Electrical stimulation for carcass chilling		3.8%	5.1
Air cooling for carcass chilling			
Waste Heat Recovery and Electricity Generation			
Installation of Desuperheaters	Natural Gas	1.6%	2.1
Installation of heat exchanger networks		2.4%	3.2
Steam and gas turbine Cogeneration		2.7%	3.6
Renewable Energy Integration			
Application of Photovoltaic systems	Electric Energy	29.5%	39.5
Application of Solar Water Heating Systems	Natural Gas	7.4%	10.0
Alternative Fuel Integration			
Biomass as an alternative fuel	Natural Gas	10.1%	13.5
Biogas as an alternative fuel	Electric Energy	8.4%	11.2

Table 7 presents an estimation of the improved eco-efficiency. It was determined for each identity Kaya (energy efficiency improvement, renewable energy integration and alternative fuel integration) considering an average value of the CO_{2eq} emission mitigation.

From Tables 6 and 7, it is possible to observe several aspects for the selected improvements. Moreover, for the framework presented in this paper, the improvements related to the energy use are proportional to the reductions of CO_{2eq} emissions and these are, in its turn, proportional to the increase of the eco-efficiency indicator. Thus, referring an improvement at one end implies an improvement at the other ends. Within the energy efficiency improvement level (encompassing the refrigeration systems, refrigeration of processes, waste heat recovery and electricity generation), it is possible to observe considerable discrepancies in terms of improvement potential. This is observable at the final of CO_{2eq} emissions values. Such suggests that in a context of energy planning, at a single plant level, some measures are preferred over others. In the case of a meat production industry, the ones related to the improvement of electric energy efficiency (refrigeration systems and refrigeration in processes) are potentially favoured over measures based on the rationalisation of thermal energy (such as waste heat recovery). Such is due to the predominance of electricity consumption in this sector over the natural gas (second most representative parcel- Fig. 1) and which justifies the higher CO_{2eq} emissions reduction associated to the former. Within the overall of energy efficiency improvement measures, the ones related to carcass chilling are the ones with the highest associated potential, which may be attributed to the fact that these measures consist in the direct improvement of the process rather than to an electric system such as the optimisation of the refrigeration systems.

In respect to renewable energy integration, a similar remark may be established, as the potential of PV integration is considerably higher than solar thermal integration (e.g. the production of additional electricity in industrial plants is favoured over additional thermal energy). And as such, measures related to improvement of electric energy use are overall associated to a higher potential for the promotion of eco-efficiency in the context of the meat production industry. For the alternative fuel integration, the former observation is not verified, although the considerable (but not significant) higher potential is associated to biomass use over biogas and this may be attributed to route for the utilisation of each of these energy sources. While estimated efficiencies of biogas for electricity production are o 8%–54% (Hakawati et al., 2017), steam production from biomass is associated to 58.25% efficiencies (Prasit and Maneechot, 2014). This may be considered roughly proportional to the potentials presented in Table 6. In a generalist view, by direct observation of Table 7, it is observed that while energy efficiency improvement and alternative fuel integration measures have a considerable impact in respect to the promotion of eco-efficiency of meat production plants, the implementation of most commonly renewable energy systems are associated to the highest potential for the improvement of the eco-efficiency indicator. Such may be effectively attributed to PV systems integration, which is a measure with a rather high estimated potential.

The framework methodology described in this paper was developed to be universally applicable, namely in the context of individual industrial case-studies set on all sectors of the manufacturing industry and also several countries. For instance, any case-study subsisting on the implementation of decarbonisation measures may be studied on the scope of the improvement of the eco-efficiency indicator, achieved by maintaining constant (or relatively increasing) the *Revenue* factor and decreasing the CO_{2eq} factor of Eq. (5). In the context of this paper, the meat production industry was selected as the case-study in which several state-of-the-art measures were identified and described in terms of improvement potential and numerical estimations for the eco-efficiency indicator for the initial and improved cases were determined.

5. Further work

Further work is to consider in respect to:

- The potential of the implementation of the proposed framework to other case-studies (industrial sectors/processes and countries);
- The further development of the framework by encompassing other relevant environmental impacts to addition to the equivalent carbon dioxide metric, such as the ones related to use of freshwater resources, discharge of pollutants contained in wastewater streams and the overall impacts associated to industrial solid wastes;
- The assessment of the mitigation of the abovementioned impacts by considering these as part of the total environmental burden encompassed by the definition of the eco-efficiency indicator (whose mitigation being possible to be assessed through the application of other type of improvement measures).

6. Conclusions

In this paper, a framework for the eco-efficiency assessment is proposed for industrial processes and the meat production industry, an energy intensive industry, has been considered as case-study. Its application required a review on improvement measures applicable for this sector, mainly assessing the potential of energy efficiency, renewable energy integration and alternative fuels strategies. The methodology framework presented in Section 2 has been developed to be applicable to industrial/manufacturing processes. Nonetheless, a meat production industry in Portugal has been selected for convenience of data, though the methodology if effectively applicable to any other country and industry.

The eco-efficiency assessment of the energy systems in meat production plants is performed through the assessment of the potential associated to several measures (e.g. energy savings; payback time) which have direct impact on the mitigation of equivalent carbon dioxide (CO_{2eq}) emissions, and as such on the reduction of the environmental burden. The framework thus performs the proposed assessment by considering the variation of the factors of the Kaya identity: energy efficiency ($\frac{FE}{UE}$) and decarbonisation factor ($\frac{CO_{2eq}}{FE}$) on the decrease of CO_{2eq} emissions. The overall conclusions of the proposed framework to the proposed case study in respect to benefits at the level of energy use are as follow:

- At the energy efficiency level, several measures are applicable for the improvement of refrigeration systems (such as installation of variable speed device (VSD) in refrigeration components and installation of desuperheaters); improvement of process chilling (e.g. carcass chilling) and waste heat recovery technologies and strategies. At this level, the carcass chilling presents the highest potential as it consists in the direct improvement of the process rather than to the energy systems (e.g. optimisation of the refrigeration systems);

Table 7
Estimation of Eco-efficiency improvement.

	Average mitigation on CO_{2eq} Emissions ($tonCO_{2eq}$/year)	Initial Case Eco-Efficiency Indicator (€/$kgCO_2eq$)	Improved Eco-efficiency Indicator (€/$kgCO_2eq$)
Energy efficiency improvement	10.0		9.2
Renewable energy integration	24.7	8.5	10.4
Alternative fuel integration	12.5		9.4

- At the renewable energy level, several measures are applicable to promote decarbonisation of the whole energy system such as the application of photovoltaic systems (payback time of 2–7 years) and the use of biogas (payback time of 6 years). At this level the photovoltaic systems play the major role, with a share of the reduction of the correspondent factor by 29.5% and consequently a reduction of 39.5 $tonCO_{2eq}$/year).

For the alternative fuel integration level, the biomass and biogas as alternative fuels have been analysed corresponding to a share of the reduction of the correspondent factor of 10.2% and 8.4%, respectively. The analysed measures have been assessed for the promotion of eco-efficiency of a Portuguese meat production plant. Overall, an increase up to 8,1% of the eco-efficiency indicator has been observed for the selected energy efficiency improvement measures. While the highest improvement of the eco-efficiency factor (22.7%) has been observed for the renewable energy integration (application of photovoltaic systems and application of solar water heating systems) The alternative fuel integration presented a similar improvement of the eco-efficiency factor as the energy efficiency level (10.3%)Nonetheless, several study gaps and further work have been identified, such as:

- Study of the impact of different working fluids on the refrigeration cycles at meat production plants, in order to assess the most adequate fluids in a perspective of energy efficiency improvement;
- Analysis of other renewable energy resources integration in addition to solar energy, such as wind, hydro energy and thermal energy through the use of geothermal energy;
- Investigation of the alternative fuels to analyse the benefits of its use within the operation of plants, disaggregating from the study of the application of waste-to-energy technologies for the production of these fuels.

CRediT authorship contribution statement

Muriel Iten: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – original draft, Writing – review & editing. **Ulisses Fernandes:** Conception and design of study. **Miguel Castro Oliveira:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – original draft.

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.

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