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Effects of Energy Efficiency Measures in the Beef Cold Chain: A Life Cycle-based Study

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***Abstract* – Circular economy and industrial symbiosis represent a production and consumption model involving sharing, lending, reusing, and recycling existing materials and products in the most efficient way to increase sustainability and reduce or eliminate waste. Beef production has a high impact on the environment in different impact categories, especially those activities related to livestock breeding and feeding. In this study, a life cycle assessment and a life cycle cost evaluation are carried out investigating potential energy efficiency measures to promote industrial symbiosis scenarios referring to a proposed baseline scenario. Three main potential measures are evaluated: energy recovery from waste via anaerobic digestion, integration of renewable sources at warehouses, including solar PV panels, and the replacement of auxiliary equipment at the retailer. It was found that energy reconversion of food waste through anaerobic digestion and cogeneration provides the most valuable benefits to the supply chain. From the economic perspective, using a conventional life cycle cost assessment, the energy production from the use of wastes for anaerobic digestion proved to be the best potential option.**

Keywords: LCA; LCC; cold chain; beef; circular economy; industrial symbiosis; sustainability

Nomenclature

GHG	Greenhouse gases
SDG	Sustainable Development Goals
SETAC	Society of Environmental Toxicity and Chemistry
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
ISO	International Standard Organization
FU	Functional Unit
LCI	Life Cycle Inventory
EEM	Energy Efficiency Measure

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1. Introduction

The growing population and market conditions have increased per capita food demand mainly in developing countries [1]. Such boost in demand has created a rapid expansion in the livestock industry in developed and developing countries [2], [3], therefore also increasing the environmental toll associated with it, impacting greenhouse gases (GHG) emissions, deforestation, and land degradation [4].

The environmental impact of beef production shows a wide range of results mainly because of different methodological choices and fundamental cattle production systems that change among regions [1]. Moreover, beef meat farming is involved in several of the global Sustainable Development Goals (SDG) set by the United Nations. In particular, it contributes to SDG1 (zero hunger), SDG3 (good health and wellbeing), and SDG8 (decent work and economic growth) [5]. Nevertheless, meat production can also have an impact on other SDG, such as SDG13 (climate action) and SDG15 (life on land), as beef and sheep production has increased by 44 % and 56 % respectively from 1970 to 2018 worldwide [5].

The food supply chain (FSC) plays an essential role in ensuring the sustainability of meat production and distribution, as it is during the last stages of the FSC where most food is wasted [6]. According to [7], the produced but uneaten food represents almost 1.4 billion hectares of used land, which is equivalent to nearly 30 % of the world's total agricultural land. Furthermore, it has also been estimated that one ton of wasted food is responsible for the emissions of 4.5 CO_2 ton to the atmosphere contributing to methane formation once disposed of in a landfill.

Due to these reasons, the FSC has to be addressed from a sustainability and holistic point of view to optimize the agricultural sector's benefits and results [8]. By using a life cycle assessment (LCA) tool, it is possible to evaluate the overall sustainability of the food industry essentially related to the number of natural resources utilized, the human necessity for nourishment, and generally the dependence of communities on food for subsistence.

The need to use assessment tools for strengthening the food supply chain sustainability is also proposed in the study of M. Soysal *et al*. [9]. The authors emphasize the innate features in food products that require added efforts in logistics due to environmental and quality concerns. This finding also highlights the need for decision support tools that enable to incorporate the economic issue with food quality and environmental ones in the FSC, as the main challenges for sustainability managing.

This study has been conducted during the EU-funded H2020 project: 'Improving cold chain energy efficiency' (ICCEE) [10].

2. Methodology

The term life cycle assessment (LCA) was coined in 1990 during the SETAC (Society of Environmental Toxicity and Chemistry) congress held in Vermont (USA). The definition given at that time, and still widely accepted today, describes LCA as 'an objective process of evaluating the environmental burdens associated with a product, process, or activity, conducted through the identification and quantification of energy and materials used and wastes released into the environment, to assess the impact of these energy and material uses and releases on the environment, and to evaluate and implement opportunities for environmental improvement. The assessment encompasses the entire life cycle of the product, process, or activity, including extraction and treatment of raw materials, manufacturing, transportation and distribution, use, reuse, maintenance, recycling, and final disposal' [11].

In this study, the authors propose an LCA model for the beef cold chain. Specifically, the authors compare a baseline scenario and scenarios with a hypothetical scenario implementing energy efficiency measures from the circular economy and industrial symbiosis solution. The study aims to assess the environmental impacts in the regional and local supply chain in a European context.

Specifically, this study was carried out with the ISO 14040 and 14044:2006 standards [12] implementing the LCA methodology in a four-stage standardized procedure. *SimaPro 9.0* [13] software developed by Pré Consultants and *Ecoinvent 3.0* [14] were used for the creation of the LCA model and the overall environmental impact was evaluated using the IMPACT 2002+ method [18].

2.1. Goal and scope definition

2.1.1. Goal

This study aims to evaluate the environmental impacts of a regional and local beef cold chain in a European context. The beef cold chain is very complex and may include several actors, an undefined number of stages such as processes of slaughtering, processing, storage, and transport activities in different geographical areas.

In this LCA study, the performance of four scenarios (including the baseline scenario) are compared and analyzed, namely:

1. Baseline scenario;
2. Energy recovery scenario through the transformation of biowaste into biogas with subsequent cogeneration of heat and power (CHP) – EEM1 scenario;
3. Renewable energy use (photovoltaic solar energy) – EEM2 scenario;
4. Efficient compressors replacement – EEM3 scenario.

2.1.2. Scope

The supply chains under study were modeled without considering the end consumer step. This stage can be very flexible and unpredictable, in fact depending on the type of consumers, their needs, living conditions, energy consumption, geographical area, social conditions, political, economic, and environmental constraints, and finally, the type of end consumer (e.g., household, restaurant, hotel, canteen, etc.).

The processing stage for the regional beef cold chain contains a larger, more articulated, and highly diversified production process that accommodates more products than the local one's processing stage. In both scenarios, the processing phase also includes the post-processing storage of the beef. Transportation was considered from farm to slaughterhouse, from slaughterhouse to processing, from processing to a central distributor, and from a central distributor to wholesale and retail.

The main differences considered between the regional and local supply chain are the size and energy consumption of the processing and storage phase, different product demands in the processing and storage phase, transport distances, especially from the processing and storage phase to the distribution center, and the geographical contextualization in which the two (i.e., local and regional) supply chains work. These activities are shown in Fig. 1.

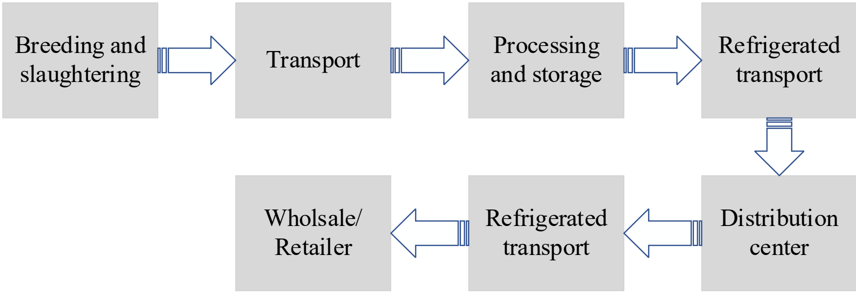

Fig. 1. Modeled supply chain.

2.1.3. Functional unit

In this study, the functional unit (FU) is represented by 1 kg of beef delivered at the wholesaler or retailer, so all the reported values (such as energy consumption, packaging, waste, water, transport, etc.) across the life cycle have been normalized on 1kg of product.

2.1.4. Geographical boundaries

A distinction between regional and local supply chains is made as follows: the regional cold chain begins with the breeding in Villareal (Spain), moving to the slaughter in Tarragona (Spain) with a transport distance of 200 km, and then arrives in Lleida (Spain), for the meat processing and storage phase (100 km of distance); from Lleida, the beef is transported to Italy to reach the distribution center located in Florence with a distance of 1240 km, and finally, within Florence, the beef is transported to the city's supermarkets with a further transport of 20 km.

The local beef cold chain begins with the breeding in Tolmezzo (Italy), moving to slaughter in Castelfranco Veneto (Italy) with a transport of 200 km, and then the raw beef is transported to Verona (Italy) for processing (100 km). From Verona, the beef products are transported to the Rome distribution center (Italy) for 500 km and finally, in Rome, the food product is distributed in the supermarkets of the city with a further transport of 20 km.

2.2. Life cycle inventory

Life cycle inventory (LCI) represents the LCA phase for the collection of data to be implemented in each scenario necessary for the assessment of the potential environmental impacts from the regional and local beef cold chain. In the LCI, data are referred and normalized to the functional unit of 1kg of beef delivered. For the implementation of the inventory data, the following databases related to the inventory processes in SimaPro were used:

– *Ecoinvent 3*. The *Ecoinvent v3.6* database [14] contains LCI data from various sectors such as energy production, transport, building materials, production of chemicals, metal production, and fruit and vegetables;
– Agri-footprint [15]. This database includes linked unit process inventories of crop cultivation, crop processing, animal production systems, and processing of animal products for multi-impact life cycle assessments.

In this study, data from two different processing companies in Italy was obtained, both conducting activities such as cutting, freezing, and packaging of beef [16]. For data related to water and electricity consumption, packaging, and industrial area in the processing phase, the company with the higher annual production (i.e., 3000 t/year) was considered for the regional chain, while the one with smaller capacity was considered for the local supply chain (i.e., 1200 t/year). The same amount of electricity consumption in the breeding and slaughtering phase for the regional and local beef cold chain was considered. The companies providing such information were partners of the ICCEE project or companies interviewed within the ICCEE project implementation.

Electricity consumption is one of the recurrent inflows in most of the process as it is used for slaughtering, production and refrigeration activities, in both the regional and local cold chains. Thermal energy is used in the slaughtering and processing step to supply hot water and hot air, for hygiene, and space heating in several other stages of the beef cold chain. Water consumption is used for refrigeration, slaughtering, processing, storage and transport. In the transport activities, it is assumed the truck engine drives the refrigeration system.

The transport activity (from the slaughterhouse to the processor) is modeled as waste-free, assuming 1.66 kg of meat per functional unit (FU) as input and output in the process. The only unit process considered in this step is the vehicle operation for 100 km (Freight lorry > 32 metric ton, EURO 5) for both regional and local supply chains.

The processing stage in the supply chain is performed considering data available from an existing warehouse. Refrigerant type R134a and the average occupation of the storage room of 90 % were assumed. All other relevant data for this activity are presented in Table 1. The activities performed in this stage include cutting, freezing, packaging, and later storage of previous transport to the distribution center.

TABLE 1. LCI FOR PROCESSING STAGE (NORMALIZED TO FU)

Material	Regional	Local
Output – Frozen meat (beef), kg	**1.0**	**1.0**
Output - Meat organic waste, kg	**0.66**	**0.66**
Input – Raw meat, kg	1.66	1.66
Thermal energy, MJ	2.391	2.391
Electricity, kWh	0.14742	0.12346
Tap water, kg	0.013	0.0042
Packaging material - polyethylene, low density, granulate, kg	0.000056	0.000066
Packaging film, low density polyethylene, kg	0.0046	0.00583
Occupation industrial area, m^2	0.000221833	0.00031

After the processing unit, the next stage of the cold chain is transport to the distribution center, using a freight lorry 7.5–16 ton capacity with a refrigeration unit driven by the main truck engine using R134a as a refrigerant. This unit process is taken directly from the Ecoinvent database and adjusted to a transport distance of 1240 km for the regional cold chain and 500 km for the local one. Softened water is used in this stage and just as in the previous transport activity, this stage is considered waste-free. The inventory for the storage activity is presented in Table 2.

The last transport activity, from the distribution center to the retailer or wholesale place, is modeled using the unit process found in Ecoinvent as 'Freight lorry 3.5–7.5 ton with refrigeration machine, R134a refrigerant, EURO5', for a total distance of 20 km in the regional and local supply chain models. Again, this stage is considered waste-free. The last stage in the supply chain is the retailer facilities' storage as presented iin Table 3.

TABLE 2. LCI FOR STORAGE AT THE DISTRIBUTION CENTER (NORMALIZED TO FU)

Material	Regional	Local
Output – Frozen meat (beef), kg	**1.0**	**1.0**
Input – Frozen meat, kg	1.0	1.0
Electricity, kWh	0.01957	0.01957
Tap water, kg	0.034463	0.0282
Occupation industrial area, m^2	0.000002712	0.000002712

TABLE 3. LCI FOR STORAGE AT RETAILER/WHOLESALER (NORMALIZED TO FU)

Material	Regional	Local
Output – Frozen meat (beef), kg	**1.0**	**1.0**
Input – Frozen meat, kg	1.0	1.0
Electricity, kWh	0.04	0.04
Occupation industrial area, m^2	0.000042462	0.000042462

2.3. Energy Efficiency Measures

In this study, three different types of energy efficiency measures (EEM) are evaluated in terms of renewable energy and energy recovery intervention and intervention on auxiliary technologies. The scenarios are described in detail in the following subsections.

2.3.1. Energy Recovery (EEM-1)

This measure is considered applied at the first and third stages of the supply chain, at the slaughterhouse and processor's facility. The transformation of biowaste generated from the standard activities conducted in these facilities into biogas by anaerobic digestion and subsequent cogeneration of heat and power (CHP) is modeled considering the study conducted by [17]. The authors of the study assume that meat biowaste can be processed in bioreactors to produce biogas through anaerobic digestion.

In the present study, it is assumed that biogas is used to generate electricity and thermal energy, with an industrial cogeneration unit, to re-use them in the slaughtering and processing stages. This scenario is in line with the application of both circular economy principles (i.e., valorization, recycling, and reuse of meat biowaste) and industrial symbiosis (i.e., sharing of bioresource within a synergic and efficient network). Nonetheless, electricity and heat can be shared with other networks integrating them in other supply chains, companies, or even communities boosting industrial symbiosis.

In the stages under consideration for implementing the EEM-1, it is assumed that 90 % of the biowaste fraction can be converted effectively into biogas [17], and further injected into a 90 % efficiency CHP plant.

Calculated potential new consumptions or energy outputs to the grid are displayed in Table 4 for both supply chain scenarios. Whenever the produced energy is higher than the facility's demand and extra energy is available to be sold, a positive number is expressed, while a negative value means the energy internally produced is not enough and consumption from the grid is still required in the displayed amount. Values are referred to as the functional unit.

TABLE 4. NEW ENERGY CONSUMPTIONS AFTER IMPLEMENTING EEM-1

		At Slaughtering, MWh	At Processing, MWh
Regional supply chain	Electricity consumption (-) /prosumption (+)	0.000110824	0.000257912
	Heat consumption (-) /prosumption (+)	0.000278743	0.000179739
Local supply chain	Electricity consumption (-) /prosumption (+)	0.000110824	0.000281877
	Heat consumption (-) /prosumption (+)	0.000278743	-0.000179739

2.3.2. Renewable Energy Production and use (EEM-2)

The second EEM scenario evaluates the production of renewable energy at the storage stage in the distribution center. Aiming to reduce fossil fuel usage, refrigeration driven by solar energy has become one of the promising approaches to reduce or partially replace conventional refrigeration systems. The technology is almost mature to compete with conventional cooling equipment but remains highly dependent on climatic conditions.

For the particular case, a photovoltaic slater-roof installation of crystalline silicon panels with a total peak power of 2378.33 kW_p was modeled based on calculations considering a PV farm with 793 panels installed at the distribution center facilities in Florence and Rome, Italy. The total electricity production was calculated for both scenarios taking into account the two different geographical locations, reducing the electricity consumption from the national grid by 1.12 % and 1.02 % in the regional and local supply chain scenarios, respectively.

2.3.3. Efficient compressor replacement (EMM-3)

The third EEM measure applied in the life cycle model is the replacement of efficient compressors in the wholesale/retail stage (supermarket) of the meat cold chain. This energy efficiency measure consists of installing new compressors that are virtually capable of covering a larger portion of the cold load. The switching of compressors may result in a significant reduction in electricity consumption and CO_2 savings. It can also improve working conditions and safety due to an ammonia leakage detection system that can be installed with the new system. Other significant benefits are the increased lifespan, lower maintenance costs, and improved control system.

It was further assumed that replacing all old compressors with new ones, including new inverters (7.5 kW), can save up to 20 % of electricity per year at the retailer stage in the supply chain. The equipment replacement was included in the inventory for both supply chains and electricity consumption adjusted accordingly to a 20 % of electricity savings.

3. LCA RESULTS

From a first analysis, no differences in the results were observed from one scenario to the other, despite the modeled changes considering different EEMs. This is explained as the breeding and slaughtering phase are the main driver in the overall environmental impact in the supply chain, with more than 95 % of the total impact allocated to this stage. Hence, it was considered to exclude it from the cold supply chain to distinguish the effects of the EEM scenarios more clearly in the remaining stages.

The baseline scenario weighted results for the regional supply chain are shown in Fig. 2, including the total single score representation per stage and the disaggregated impact per each area of concern.

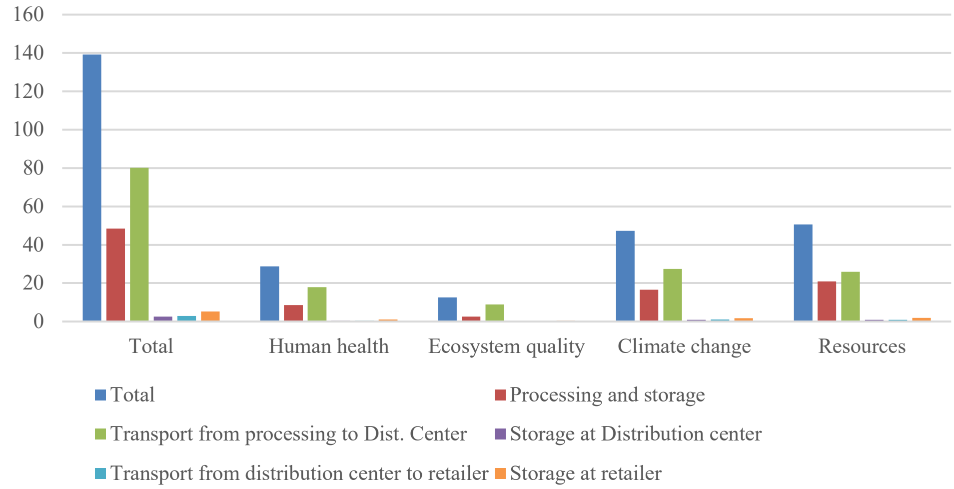

Fig. 2. Weighted results per stage for the baseline scenario in the regional supply chain.

A total environmental impact of 140 mPt was found for the regional supply chain scenario. The most relevant stages are transport from the processing facility to the distribution center followed by the processing phase.

When looking at the areas of concern, the environmental burden is mainly in the area of climate change, resource consumption, and slightly less on human health, leaving the ecosystem quality only mildly affected. For the local beef supply chain, the results are similar since most activities require similar energy consumption and are performed very similarly. Nevertheless, the shorter distance for transport activities, especially for reaching the distribution center after processing, makes this supply chain less environmentally intense, with a total score of 90 mPt.

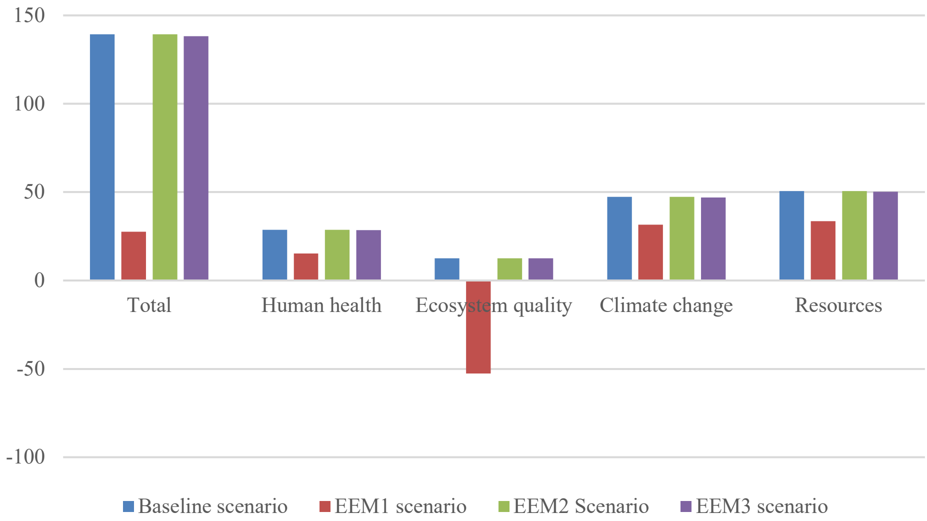

Fig. 3. Weighted results comparison for the regional supply chain.

The comparison graph displayed in Fig. 3, shows how EEM-1 is the one that brings the most environmental benefits in every single area of concern, while the other EEM scenarios barely show any difference when compared with the baseline. The EEM-1 scenario might also potentially deliver environmental credits to the ecosystem quality area, due to avoiding electricity consumption from the country mix, which is mainly linked to the use of fossil fuels and land use for hydropower production [18].

Since the local supply chain has lower impact due to lower transportation distances, the savings created by the EEM-1 scenario make a bigger impact on its overall result, showing even a negative value (environmental benefit) for the entire food supply chain.

As for the regional supply chain, the local scene is not affected by implementing the energy efficiency measures 2 and 3, as shown in Fig. 4.

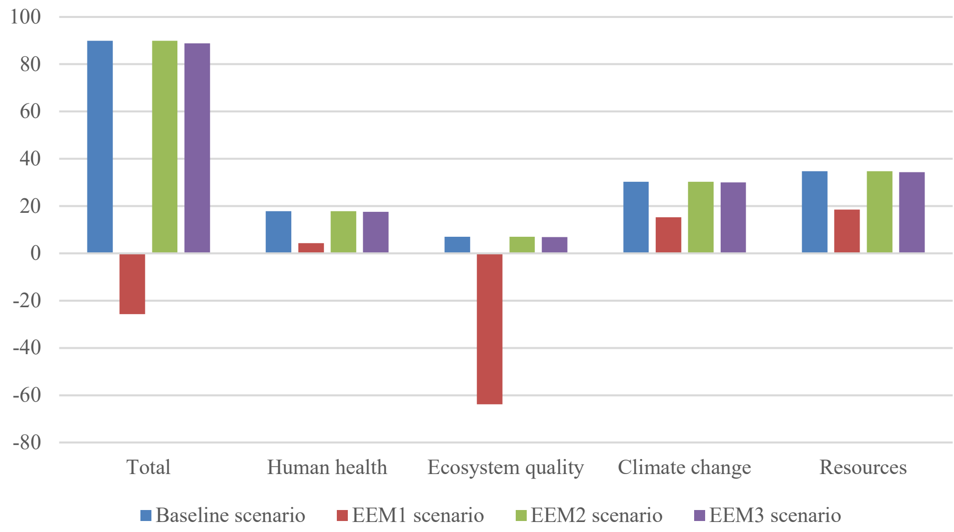

Fig. 4. Weighted results comparison for the local supply chain.

4. Life Cycle Cost

Life cycle cost (LCC) is a versatile technique that can be applied for various purposes and at different stages of a project's life cycle to support decision-making. It might be undertaken both as an absolute analysis (e.g., to support the process of budgeting) and as a relative analysis (e.g., to compare alternative technologies). Three variants of LCC can be distinguished: Conventional LCC, Environmental LCC, and Societal LCC.

The conventional LCC, also called financial LCC can be considered synonymous with Total Cost of Ownership [19].

In this work, a comparative and conventional approach was undertaken between the baseline and different energy efficiency measures scenarios. This task was achieved by analyzing the required investments from different beef cold chain actors for each scenario evaluating each investment's economic convenience.

As changes between the modeled regional and local supply chain mainly distinguish from each other only at the transport activities, and EEM scenarios in this study are only implemented at the level of the processing or storage stages, only the regional supply chain is considered for the LCC evaluation.

The baseline scenario's cost structure for comparison with the EEM-1 is presented in Annex 1, and the investment required for the construction of anaerobic digestion and cogeneration of heat and power plants was estimated at 26 878 EUR. Potential new running costs after EEM-1 are implemented are shown in Annex 2 and include a reduction in electricity and heat consumption as well as an increase in labour costs due to new equipment operation. The financial scheme consists of an annual interest loan rate of 10 %, a required rate of return of 20 %, and a share of investment supported by equity of 30 %. The inflation was taken from the Italian average value in the last 5 years (0.6 %).

For the comparison between the baseline scenario and EEM-2, the warehouse's running costs are presented in Annex 3, and the total costs for investment were estimated at 3 567 495 EUR. For this case, the financial conditions considered were a required rate of return of 14 %, an interest rate on the loan of 6.0 %, and an inflation of 0.6 %. Similarly, the EEM-3 running costs comparative scenario is presented in Annex 4, considering an electricity reduction of 20 %. The compressor replacement cost was estimated at 6800 EUR and the same financial conditions as in EEM-2 were considered.

For the economic evaluation, budget and market prices were used, referring to the specific regions' market conditions where activities are modeled.

After a sensitivity analysis, it was found that the changes in market prices for beef could either positively or negatively affect the internal rate of return or the profit index of the evaluated projects if the production capacity of the plants remains constant in time. Net Present Value (NPV) analysis shows that the EEM-1 is the most attractive one from the economic perspective.

5. CONCLUSIONS

The study provides an insight on the environmental and economic sustainability towards the cold supply of beef meat. From a holistic perspective implemented with an LCA and conventional LCC, this study highlights the potential effects of specific EEMs within a local and regional context.

The study considered four different scenarios implemented within the regional and local context, taking into a baseline scenario and three types of EEM scenarios implementing both energy efficiency solutions, circular economy and industrial symbiosis, and integrating renewable energy technologies.

The study shows that the breeding and slaughtering phase of the beef cold chain is the environmental hotspot overtaking most of the overall potential impacts in the supply chain. This is due to the land use required for the livestock, methane emissions from ruminants, and its food production cycle.

Within an internal and deeper analysis, the weighted results at mid-point impact categories show that categories such as 'Non-carcinogens', 'Terrestrial ecotoxicity' and 'Land occupation' are the most affected for the four scenarios considered in the global beef cold chain. In the local supply chain, the same categories as in the regional supply chain are found to be the most impacted ones. Among the mid-point categories, the 'Non-carcinogens' impact category represents about 18 % of the total impact, 'Terrestrial ecotoxicity' contributes with near 70 %, and 'Land occupation' covers about 9 %, mainly from the breeding and slaughtering activities.

At the end-point level, the ecosystem quality category represents near 80 % of the total impact, while the human health category represents about 22 % in the four scenarios, both for regional and local supply chains.

It was also found that long transport distances can negatively affect the beef supply chain due to the fuel consumption invested in the trip and required for running the refrigeration units. The processing stage is a key contributor to the cumulative environmental load across the supply chain due to the different activities in the facilities such as meat cutting, internal transport, packaging, handling waste, and storage of previous waste. This finding is disregarding the length of the supply chain. To these intrinsic sub-processes, the administration activities requiring personnel in the building might increase the whole process energy expenditure to ensure a comfortable environment that comes with the use of either air conditioners or heaters, depending on the season.

When the breeding and slaughtering phase is excluded from the LCA, results show that the most affected areas are climate change and the use of resources, followed by human health. By evaluating the three alternatives considered in this study, it is found that the production of energy from waste via anaerobic digestion and a cogeneration plant (EEM-1), is the one that delivers more benefits to the environmental performance of the supply chain.

The EEM-2 does not bring environmental benefits to the supply chains under evaluation as the energy savings are barely in the order of 1 % and still require installing a large PV system. On the other hand, EEM-3 could save up to 20 % of electricity consumption from the electricity mix but requires installing new devices, the environmental burden of which is related to its manufacturing process and overlaps the potential benefits.

The study emphasizes the need to move towards evaluating energy efficiency interventions towards the food cold supply chain to find the optimal condition (both environmental and economic) for the entire actors involved in the whole supply chain rather than the single actor.

Further research will be necessary to evaluate the effect of quality losses on the considered supply chain.

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Annexes

Annex 1. Cost Structure for EEM–1(Baseline)

	Project costs		Unit	Baseline
Running costs/Cost Categories	Operation and maintenance	Electricity	€/year	52 875
		Labour costs	€/year	340 000
		Water	€/year	88
		Refrigerants	€/year	375.6
		Thermal energy	€/year	97 633
	Production costs	Raw material – Beef	€/year	8 070 000
		Packaging material 1	€/year	166.6
		Packaging material 2	€/year	43 400

Annex 2. Running Costs Structure for the Implemented EEM–1 at the Processing Stage

	Project costs		Unit	Baseline	EEM1
Running costs/ Cost Categories	Operation and maintenance	Electricity	€/year	52 875	–
		Labour costs	€/year	340 000	493 000
		Water	€/year	88	88
		Refrigerants	€/year	375.6	375.6
		Thermal energy	€/year	97 633	26 422
	Production costs	Raw material – Beef	€/year	8 070 000	8 070 000
		Packaging material 1	€/year	166.6	166.6
		Packaging material 2	€/year	43 400	43 400

ANNEX 3. COST STRUCTURE FOR BASELINE VS EMM–2 IMPLEMENT SCENARIO (AT WAREHOUSE STAGE)

	Project costs		**Unit**	**Baseline**	**EEM2**
Running costs/Cost Categories	Operation and maintenance	Electricity	€/year	41 182 200	40 770 378
		Labour costs	€/year	400 000	560 000
		Water	€/year	849 170	849 170
		Refrigerants	€/year	238 944	238 944

ANNEX 4. COST STRUCTURE FOR BASELINE VS EMM–3 IMPLEMENTED SCENARIO (AT A RETAILER)

	Project costs		Units	Baseline	EEM3
Running costs/Cost Categories	Operation and maintenance	Electricity	€/year	3006	2405
		Labour costs	€/year	300 000	300 000
		Refrigerants	€/year	500.8	500.8