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The effects of incorporating renewable energy into the environmental footprint of beef production

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ABSTRACT

This study quantifies the influence of the on-farm implementation of different energy mitigation systems, anaerobic digestion (AD) for biogas production and rooftop photovoltaics (PV), and assesses the environmental and energy impact on beef cattle production. Data on technical aspects were collected and a cradle-to-farm gate life cycle assessment approach was adopted. Two baseline production scenarios, with conventional manure and slurry management (considering different slurry storage: open or covered), were compared with three alternatives: (i) with the implementation of AD plant only; (ii) with the implementation of a PV system only; and (iii) with both. Impacts on the infrastructure and operation of AD plant and PV systems were considered, as well as their influence on emissions and electricity generation. The latter was managed with a system expansion, considering an environmental credit. The results, expressed per 1 kg of live weight of beef cattle produced, showed widespread improvements across the impact categories assessed. The AD scenario presented larger mitigations than the PV system alone, but the best result is achieved when both energy systems are implemented, with global warming potential reduced by 12 % and fossil resource scarcity by 35 %. This work represents a benchmark for future life cycle analysis of renewable energy system implementation for livestock.

1. Introduction

Beef cattle production represents an environmental hotspot within the agricultural sector, in terms of carbon footprint, eutrophication, and acidification potential (LEAP, 2016), albeit with great internal variability. This is true when considering the direct comparison between product units (e.g. per kilogram of produced meat), when referring to its role within the average European diet [1], and when looking at the absolute emission profile of the agri-food production sectors [2].

In Italy, the sector is well structured, involves many stakeholders and is widespread throughout the country. In 2019, there were about 94.6 thousand farms specialising in this production, with a total of 2.635 million animals slaughtered per year. The number of animals reared is increasing (an increase of 8.6 % in the total beef-cattle population over the 5-year period 2015–2020), despite the fact that apparent per capita consumption of beef in Italy (16.8 kg in 2019) is observing a decreasing trend [3].

At an environmental level, it is known that manure management plays an important role in livestock production, especially impacting GHG emissions and the nitrogen cycle [4]. In this regard, the anaerobic digestion (AD) of livestock waste for biogas production is regarded as one of the most effective management techniques, from an environmental point of view [5]. EU member states' subsidies have been promoting electricity generation from bioenergy sources since 2009, following the Directive 2009/28/CE. Subsequently, the use of AD of agricultural biomass and combined heat and power (CHP) plants has become widespread. More and more livestock farms have implemented these plants, either privately owned or collectively, in agricultural consortiums [6], using livestock waste and, eventually, other agricultural biomass as feedstock due to its economic viability [[7,8]]. The AD of biomass from waste or by-products is now established as an important pillar of the circular bio-economy of the energy sector within the EU [9]. Given that the Circular Economy Action Plan (European Commission; COM/2020/98 final) states that circularity is a prerequisite for climate neutrality, it follows that waste management also plays an important role in the EU's climate goals [10], making the AD topic even more relevant.

Solar power systems, or photovoltaic (PV) systems, have also recently attracted interest in agriculture [11]. This can be implemented in different ways, by means of integrated PV or rooftop PV on farming structures such as stables, warehouses, and greenhouses, and even with

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List of acronyms and abbreviations

AD	Anaerobic Digestion
BS	Baseline Scenario
CH_4	methane
CHP	Combined Heat and Power
EEA	European Environment Agency
FEP	Freshwater Eutrophication
FRS	Fossil Resource Scarcity
FU	Functional Unit
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LW	Live Weight
MEP	Marine Eutrophication
MSR	Mineral Resource Scarcity
N_2O	Dinitrogen Monoxide
NH_3	Ammonia
ODP	Ozone Depletion Potential
PM	Particulate Matter Formation
PV	Photovoltaic
TAP	Terrestrial Acidification

land-based PV (referred to as agrivoltaic) [[12,13]]. Rooftop-based plants are more conventional and there are already several environmental and economic analyses in this regard [14], but the evidence in the literature of barns rooftop PV systems, however, is scarce. In a review of electricity use and generation in dairy farms [15], dealt with the energy potential of this technology. The authors also mention the important economic aspects regarding the uninterrupted fall in the costs of PV modules over the last decade, which makes the technology more and more competitive.

LCA is an approach regulated by ISO 14040 and 14044 to analyse products and processes from an environmental perspective along the entire life cycle, or part of it. The application of LCA to agri-food supply chains is increasingly adopted for environmental analysis and claims. Regarding the beef production sector, numerous studies have been published, in an international context [16] and an Italian context [[17, 18]]. At the same time, several studies have investigated the impact of the AD of agricultural waste biomass on biogas production, concluding that it is a practice that, under certain conditions, has the potential to (i) reduce the impact of traditional livestock waste management; (ii) generate generally more sustainable electricity than the current European mixes; (iii) generate an attractive source of income; and (iv) generate a further series of benefits, e.g., the reduction of treated waste odour [19]. Nevertheless, the focus of most of these studies was energy production, considering the plant as a stand-alone system and, therefore, considering only inputs and outputs directly connected to it [20].

This study, on the other hand, aims to evaluate the environmental impact of beef cattle production by using the LCA approach, when combined with anaerobic digestion plants fed with the resulting livestock waste (manure and slurry) in an overall perspective. By using this approach [21], analysed the influence of integrated pig farming and anaerobic mono-digestion [22]; explored the implementation of anaerobic digestion in a cow dairy system; and [23] studied buffalo dairy systems. This study explores the implementation of PV systems on barn rooftops and any additional energy or environmental benefits derived from it [24]. measured the combination of PV systems with animal production in a life cycle perspective, but that study was concerned with agrivoltaics on rabbit pastures. An overview of these studies is provided in Table 1.The novelty of this study is that, to the authors' knowledge, it is the first environmental analysis that deals with the effects of integrating the above-mentioned renewable energy production systems with beef cattle production.

2. Materials and methods

2.1. Goal and scope definition and scenario modelling

This study aims to quantify the mitigation potential of two renewable energy production systems widely implemented in livestock farms, namely AD for biogas production and PV systems. This undertaking considers the integration of renewable electricity generation from these two sources into a beef system, by using the LCA approach. For this purpose, this work focuses on the environmental analysis of a beef cattle farm in northern Italy, equipped with an operating plant for the AD of livestock waste and subsequent conversion of biogas into electricity and a PV system that includes multi-crystalline Si panels integrated into cattle barn roofs. The farm practices an intensive open-cycle cattle farming system, that covers only a part of the rearing cycle. Weaned calves are bought externally from pasture-based systems, mainly in France, and are directly managed through the fattening part of the process, where animals are fed a mixed diet of self-produced fodder and commercial feed, with supplements purchased externally. This production system is particularly widespread in the north of the country, its incidence on national beef production is around 44–48 % [3], and it has been extensively described in the literature [[17,18]. The farm produces maize silage, which it uses to partially satisfy its animal feed requirements. Part of the silage is also fed to AD along with livestock waste, as it is a very common practice to use it as an energy crop in

Table 1
Overview of the literature on LCA environmental analysis of livestock system mitigation through renewable energy production systems.

Reference	Country	Livestock system	Mitigation system analysed	LCA Approach	Main results compared to the reference conventional farming system
[21]	Not specified, EU average data	Pig	Anaerobic digestion of pig slurry	FU: 1 t live weight SB: Cradle-to-farm gate System expansion	Savings in GWP, ozone depletion, acidification, PM formation and fossil depletion. Trade-offs in eutrophication and toxicity
[22]	IT	Dairy cattle	Anaerobic digestion of cattle slurry	FU: 1 kg FPCM SB: Cradle-to-farm gate System expansion	Saving of 22 % for GWP, 29 % for acidification and 18 % for eutrophication
[23]	IT	Dairy buffalo	Anaerobic digestion of buffalo slurry	FU: 1 kg ECM SB: Cradle-to-farm gate System expansion	Savings between 10 % and 40 % for GWP
[24]	US	Rabbit	Pasture-based agrivoltaic system	Multiple-output functional unit SB: Cradle-to-farm gate	Saving of 98.5 % for GWP and 92.9 % for fossil energy demand

co-digestion with livestock waste in agricultural biomass plants [25].

In this work, different productive scenarios (two baseline scenarios and three alternative ones) are developed for comparative purposes:

- the two Baseline Scenarios (BS) represent the standard beef cattle production system without implementing any on-farm renewable energy generation system. The difference between the two lies in slurry management: in the first scenario (BS-open) this is stored in uncovered tanks while, in the second (BS-cover), it is stored in covered tanks. This is to represent existing farms that have not implemented livestock waste AD and are managing it, either by following best practices or not;
- the AD scenario comprises the on-farm implementation of the anaerobic digestion plant;
- the PV scenario comprises the on-farm implementation of the photovoltaic system. Since this technology does not affect maintenance management, this alternative scenario is split into two, depending on whether the system is implemented on a BS-open or BS-cover;
- the AD and PV scenario comprises the implementation of both.

All scenarios share the same crop cultivation and livestock management data but differ in the modelling of manure management. In the baseline scenarios, livestock waste is handled in the form of manure and slurry, as cattle are partially housed on straw bedding and partially slatted floor structures. More specifically, manure is handled with deep bedding and subsequent solid storage, while slurry is collected in open tanks (for BS-open) or covered tanks (for BS-cover). In the scenarios where the AD plant is implemented instead, both slurry and manure are managed as a feedstock for the AD plant, and all the other inputs and output flows related to the AD plant are also included. In this scenario, the digestate resulting from the waste treatment is stored in covered tanks. In fact, according to the most recent regulations, newly implemented AD plants require covered post-treatment storage. In the scenarios where a PV system is implemented, all input and output flows related to the solar power system are considered.

The outcomes of this study are aimed at researchers and stakeholders involved in the agri-food industry, to understand and quantify the potential impact caused by the implementation of anaerobic digestion plants and PV systems within a beef production system. The results can also be useful for policy makers working with agro-environmental regulations, e.g. to support decision making phases and direct price rewards or incentives for actions aimed at the mitigation of environmental impacts of agricultural activities.

2.2. Functional unit and system boundaries

This study was carried out with a cradle-to-farm gate perspective, as it focused on the agricultural phase of beef production, which is known to be the main hotspot of the whole beef life cycle impacts. The selected Functional Unit (FU) is 1 kg of live weight (LW) produced, intended as to mean the mass of cattle leaving the farm to the slaughterhouse. This FU is widely adopted in LCA literature related to the livestock agricultural phase and is also suggested by the LEAP guidelines [26]. All of the input and output inventory data and, consequently, the functional unit, refer to a specific period, i.e. 2021.

The system boundaries are schematised in Fig. 1, where the subsystems of the alternative scenarios and the system expansions linked to them are also highlighted. Manufacture (including the extraction of raw materials), supply and use of all raw input materials consumed for crop cultivation (such as seeds, fuels, fertilisers and pesticides) are included, as well as all the derived field application emissions. The indirect environmental burdens of virtual consumption of tractors and other machinery, including maintenance and final disposal, were also considered. In contrast, the indirect impact of the farm's capital goods (buildings, warehouses) was not taken into account, as it was considered to be scarcely influential due to their long life span. As for livestock, the boundaries include the whole rearing cycle, thus considering inputs

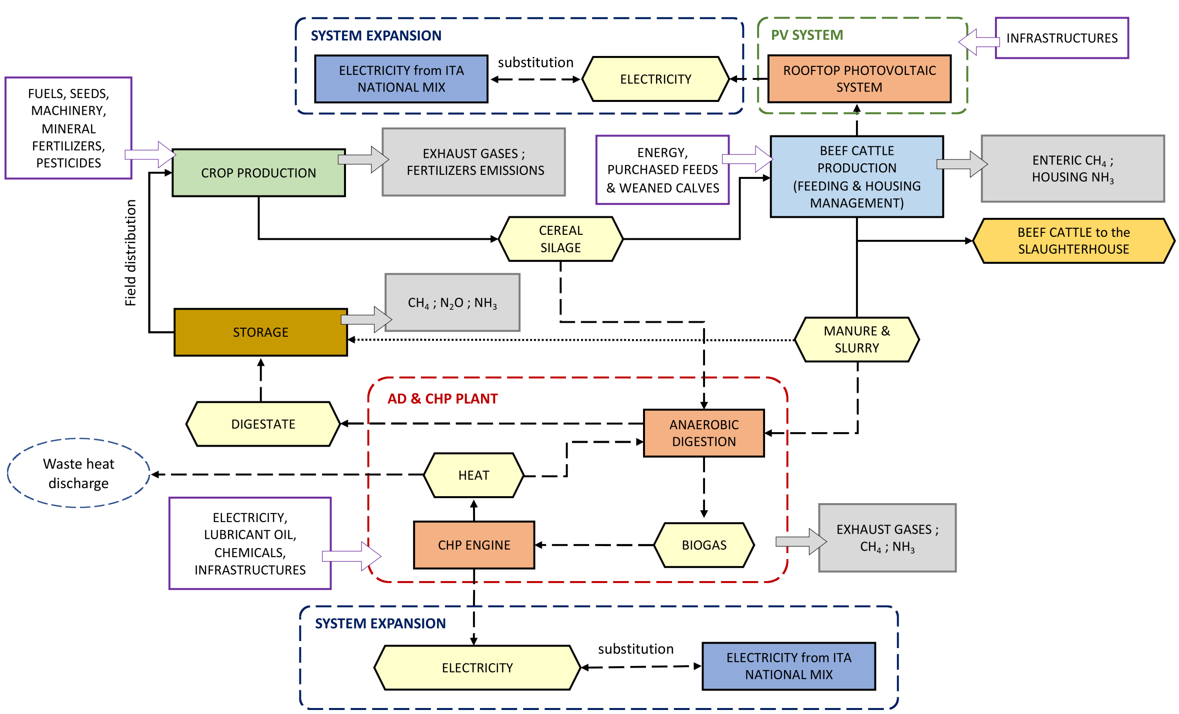

Fig. 1. Schematic representation of the system boundaries of the study. The main processes and inputs (white boxes), outputs (yellow boxes) and emissions (grey boxes) are reported. The boundaries of the mitigation systems implemented in the alternative scenarios are shown with dashed boxes (PV system in green and AD & CHP plant in red) and the respective flows with dashed arrows. The manure management flow follows the dotted line in the baseline and PV scenarios, being directly stored and subsequently used as organic fertilizer. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(weaned calves, raw materials, energy and fuels) and outputs such as animal-related emissions (i.e. enteric fermentations and manure-related emissions). Impacts associated with the production and usage of veterinary medicines and cleaning products were not included. Impacts resulting from post-production transport, processing, distribution, consumption and all related waste disposal were excluded from the assessment. Regarding the AD scenario, the boundaries were virtually extended to include the production and supply of crops used as feedstock; construction and decommissioning of AD plants and CHP engines; biogas production and conversion and related inputs (consumption of raw materials) and outputs (emissions and Ee); and digestate management. Similarly, all components for the installation of the photovoltaic plant and energy use for the mounting, as well as decommissioning, were included in the PV scenario.

In all scenarios except the baseline one, where the system involves co-production of electricity, multifunctionality was solved by system expansion, it being the first hierarchical choice among the options to manage it according to the ISO standards. Therefore, an environmental credit was considered for the avoided production of electricity, taking the Italian national mix as a reference, substituted by the electricity produced from biogas conversion in the co-generator and from the solar power system.

A sensitivity analysis related to multifunctionality was also performed. This focused on the AD scenario, testing the economic allocation between co-products. The impact of the system was, thus, divided between cattle live weight and electricity produced, based on their relative economic value. The calculations and results of this analysis are reported in the supplementary materials.

2.3. Inventory analysis and impact assessment

Primary data relating to both crop systems, cattle rearing, and renewable energy plants were collected by means of interviews with farmers and technicians. For the crop production subsystem, data was collected for each crop, including yields, quantities and types of productive factors used, the sequences of field mechanised operations, the agricultural machinery used and their fuel consumption. With regards to cattle, primary data included the number of animals bought and sold per year and their respective live weight, the division of the breeding cycle into feeding phases and their duration, feed consumption (both self produced forages and purchased mineral supplements and feeds) and productive parameters. For the biogas plant, data concerned the installed power, the hours of operation, the energy produced, the biomass ration fed daily, and the type of post-treatment storage. For the PV system, data concerned the technology used, power, the surface area and number of modules installed, and the energy produced.

Inventory data regarding the farm's structure, inputs and outputs are reported in Table 2; Table 3 presents the data regarding the AD & CHP plant and Table 4 gives data regarding the PV system. More details on crop production inventories and feed compositions are reported in the supplementary materials.

Secondary data mainly concern pollutant emissions from (i) crop cultivation, (ii) cattle rearing and (iii) the AD and CHP plant. These were estimated through models and literature data. On-field nitrogen compound emissions due to fertiliser application were computed based on the model proposed by Ref. [27], considering climatic data, soil conditions and fertiliser characteristics, which was digestate for the AD scenario. Phosphate (PO_4^{3-}) emissions were calculated following [28,29]. Finally, based on [30], a loss of chopped product (maize whole plant) during ensiling was assumed to be equal to 10 %.

As for the emissions from the cattle rearing subsystem, the Tier 2 approach from the IPCC guidelines [[31,32]] was used to estimate methane (CH_4) and dinitrogen monoxide (N_2O) emissions from enteric fermentations and manure management. Ammonia (NH_3) emissions from animal housing and manure management, as well as particulate emissions from housing, were estimated based on the EEA air pollutant emission inventory Guidebook instead [33]. Regarding methane emissions from manure management in the AD scenario, the emission factors for an anaerobic digester were considered under conditions of low leakage, high quality gastight storage, and best complete industrial technology [32]. Where relevant in the models, the 'warm temperate, moist' IPCC climate zone was considered. Further details of the emission estimation process are reported in the supplementary materials.

With regard to the NH_3 emissions from the AD plants, the estimates were made following the EEA air pollutant emission inventory Guidebook [34], taking into consideration the amount of nitrogen input (both from livestock waste and from other biomass), and pre-treatment storage losses. Emissions from CHP, in the form of the average amount of pollutant emissions per MWh produced, were retrieved from Ref. [35]. Some information regarding the modelling of biogas plant infrastructures, such as the lifespan of digesters and CHP, was recovered from Ref. [36], who analysed 10 AD plants in Northern Italy and integrated the inventory of biogas plants.

In the scenarios with the PV system, on the other hand, no changes to beef production or manure management processes were considered. For the PV system infrastructures and all the impacts related to their supply and assembly, a 30-year lifespan was considered, as a standard duration reported in the Ecoinvent® database [[37,38]].

Background data were retrieved from the established Ecoinvent® database v. 3.8 [[37,38]] (Table S7 in SM). These refer to crop seeds, fertilisers, chemicals, diesel fuel and lubricating oil, agricultural machinery, weaned calves, purchased feed, digester infrastructure, CHP engines, solar power systems and the Italian electricity mix.

Table 2
Main inventory inputs and outputs data relating to the cattle rearing subsystem.

Parameter	Unit of measure	Value
Weaned calves - average live weight	kg/head	399.4
Total weaned calves purchased	t/year	963.9
Beef cattle sold – average live weight	kg/head	649.2
Total beef cattle sold	t/year	1811
Share of animal whose waste is handled as slurry	%	71
Share of animal whose waste is handled as manure	%	29
Electricity consumption	MWh/year	81.5
Natural gas consumption	m^3/year	2445
On-farm diesel consumption (excluding field operations)	t/year	19.63

Table 3
Design and operating data for the AD & CHP plant considered.

Parameter		Unit of measure	Value
Digesters/Postdigester		N	1 + 1
Total digesters' volume		m^3	1800 + 2000
Biomass supply	Cattle manure	t/day	22
	Cattle slurry	t/day	35
	Maize silage	t/day	1.4
Sodium hydroxide		kg/year	134
Electrical capacity		kW	299
Specific volume		m^3/kW	13.3
Process temperature		°C	40.5
Operating time		h/year	7345
Annual Electricity generation		MWh	2196
Electricity self-consumption		%	9.98
Lubricating oil		kg/year	600

Table 4
Design and operating data for the PV plant considered.

Parameter	Unit of measure	Value
Peak electrical power	kWp	949.4
Total modules area	m^2	6640
Number of modules	–	4040
Annual Electricity generation	MWh	1080

All of the collected inventory data were processed and converted into indicators that reflect environmental pressures, as well as resource scarcity. The dataset was characterised by means of the ReCiPe 2016 Midpoint (H) method, version 1.04/World [39], considering eight impact categories (Annex II in the Supplementary Materials). The analysis was performed using SimaPro® LCA software v 9.2 [40].

3. Results

Table 5 shows the absolute results of the baseline and AD scenarios, as well as the relative comparisons for the assessed impact categories. For the impact categories affected by the emissions of greenhouse gases and ammonia, a clear difference between BS-open and BS-cover and the AD scenario appeared, indicating the benefit given by the implementation of the AD plant.

The mitigation offered by the installation of the solar power system was minor (Table 6): in the PV scenario, the two categories with the greatest reductions were FEP and FSR (−4.5 % and −12.7 %, respectively); the others showed limited reductions of less than 2 %.

Finally, the results of the AD and PV scenario, and the relative comparisons with the baselines, are shown in Table 7. As expected, this is the scenario where the impact reductions obtained were greater. The trends for this alternative scenario reflected the scenarios where the single mitigation strategy was implemented, with a marked reduction in the improved impact categories, and a marked trade-off for the others (MEP and MSR).

In general, most of the impact categories had an improved environmental performance across the mitigation scenarios, except for marine eutrophication and mineral resource scarcity, which increased in all three alternative scenarios (even if only slightly), with a maximum increase of +1.1 %.

Detailed results of the contribution analysis can be found in the supplementary materials. A focussed analysis of the AD and PV scenario is graphically shown in Fig. 2. The contribution analysis showed that the mitigation of the GWP impact, due to the AD implementation, occurred because of the combined effect of strongly reducing GHG emissions with respect to conventional manure management and the environmental credit given by electricity co-production. The same drivers were responsible for ODP reduction but to a lesser extent.

In some cases, the environmental credit given by system expansion was greater than the impact given by the inputs and outputs (emissions) of the infrastructure and operation of the AD plant and the PV system, thus generating an overall credit; in other cases, the credit did not offset the impacts so the related contribution appears positive in the graph. Notably, fossil resource scarcity obtained the greatest benefit in all the alternative scenarios, down to −34.5 % of the absolute results per FU in the AD & PV scenario.

The contribution analysis revealed the supply of weaned calves and feeding during fattening as the two main hotspots for beef cattle production. In the baseline scenarios (Tables S1 and **S2**), the former dominated the contribution of GWP, ODP, PMF, TAP and MEP; while the latter dominated FEP, MSR and FSR. These impacts remained unchanged in absolute terms in the alternative scenarios, as the plants had no influence on the rearing cycle. For GWP, an average contribution of enteric emissions of about 13 % was observed in the baseline scenarios, still unchanged in absolute terms in the alternative ones. GHG emissions from manure management (including N_2O and CH_4) had a share of 8 % in BS-open, already reduced to 6 % due to the storage coverage in BS-cover and, finally, greatly reduced to less than 1 % with the implementation of the AD (its contribution is almost negligible in Fig. 2). Ammonia and particulate emissions contribute up to 35 % to PMF and 36 % to TAP in BS-open; reduced to 18 % and 22 % in the AD scenario, respectively. For these two impact categories a great reduction was already observable, depending on the management of the slurry in the baseline. The consumption of energy and fuels on the farm during fattening, on the other hand, played a minor role, reaching a maximum of 7 % of the share for FRS in the AD & PV scenario. The results in the baseline scenario were in line with other LCA studies carried out in the Italian context: for this production system [18] observed a value of 17.62 ± 1.78 kg CO_2 eq./kg LW [17]; reported a lower value of 13.1 ± 0.8 kg CO_2 eq./kg LW. However, since the contribution analysis of the latter is comparable to the present study, the observed differences were likely to have been dependent on the impact assessment method: it should be noted that the one used in this study also included climate-feedback, attributing a characterisation factor of 34 kg CO_2 eq. to biogenic methane emissions.

To test the robustness of the results obtained when comparing the different scenarios, a quantitative uncertainty analysis was performed using the Monte Carlo technique (1000 iterations and 95 % confidence interval) as a sampling method. For parameters of the inventory where the distribution was not known, this was estimated based on the data quality pedigree approach, according to Ref. [41]. The results are shown in Fig. 3. The bars represent the probability that the environmental impact of the baseline was greater than, or equal to, the alternatives, while those on the left represent the opposite probability. The results show that there are some trends in the comparison between the PV scenario and the BS-cover scenario, but the only significant difference between the two concerns fossil resource scarcity. On the other hand, when comparing the AD scenario with the BS cover scenario, the results show that the differences are significant for 5 out of 8 impact categories, except for ODP, MEP and MSC. This confirms the environmental benefits of the AD installation previously presented and that these are not affected by the uncertainty due to data selection from databases, partial model adequacy and data variability.

4. Discussion

In comparison with previous studies, which analysed the influence of anaerobic digestion implementation in livestock farms, the mitigations observed in the present study were minor. In fact, in Ref. [22], reductions of −22 % in GWP, −29 % in acidification potential and −18 % in eutrophication potential per kg of fat and protein corrected milk were observed for a dairy system with an implemented 300 kW AD plant fed exclusively by livestock waste. The minor reduction observed in the present study suggests that, since the life cycle of beef production generally has a higher carbon footprint than that of milk per product

Table 5
Environmental results of baseline and AD scenarios for the assessed impact categories, with relative variations of the mitigation scenario compared to the baseline ones. Results are expressed per 1 kg of live weight leaving the farm to the slaughterhouse.

Impact category	Unit	BS-open	BS-cover	AD Scenario	Relative comparison	Delta BS-open vs AD	Delta BS-cover vs AD
Global warming potential (GWP)	kg CO_2 eq	15.16	14.81	13.57	%	−10.5	−8.4
Ozone depletion potential (ODP)	g CFC11 eq	0.120	0.121	0.117	%	−2.5	−3.3
Particulate matter formation (PMF)	g PM2.5 eq	11.95	11.17	9.91	%	−17.1	−11.3
Terrestrial acidification (TAP)	g SO_2 eq	74.50	68.14	59.86	%	−19.7	−12.2
Freshwater eutrophication (FEP)	g P eq	1.10	1.09	0.99	%	−10.0	−9.2
Marine eutrophication (MEP)	g N eq	23.70	23.70	23.93	%	+1.0	+1.0
Mineral resource scarcity (MSR)	g CU eq	15.14	15.14	15.24	%	+0.7	+0.7
Fossil resource scarcity (FRS)	kg oil eq	0.55	0.55	0.42	%	−23.6	−23.6

Table 6
Environmental results of baseline and PV scenarios for the assessed impact categories, with relative variations of the mitigation scenario compared to the baseline ones. Results are expressed per 1 kg of live weight leaving the farm to the slaughterhouse.

Impact category	Unit	BS-open	BS-cover	BS-open & PV	BS-cover & PV	Relative comparison	Delta BS-open vs PV	Delta BS-cover vs PV
Global warming potential (GWP)	kg CO_2 eq	15.16	14.81	14.96	14.62	%	−1.3	−1.3
Ozone depletion potential (ODP)	g CFC11 eq	0.120	0.121	0.120	0.121	%	−0.1	−0.1
Particulate matter formation (PMF)	g PM2.5 eq	11.95	11.17	11.77	10.99	%	−1.5	−1.6
Terrestrial acidification (TAP)	g SO_2 eq	74.50	68.14	73.89	67.53	%	−0.8	−0.9
Freshwater eutrophication (FEP)	g P eq	1.10	1.09	1.05	1.05	%	−4.5	−3.7
Marine eutrophication (MEP)	g N eq	23.70	23.70	23.70	23.70	%	0.0	0.0
Mineral resource scarcity (MSR)	g CU eq	15.14	15.14	15.20	15.20	%	+0.4	+0.4
Fossil resource scarcity (FRS)	kg oil eq	0.55	0.55	0.48	0.48	%	−12.7	−12.7

Table 7
Environmental results of baseline and AD & PV scenarios for the assessed impact categories, with relative variations of the mitigation scenario compared to the baseline ones. Results are expressed per 1 kg of live weight leaving the farm to the slaughterhouse.

Impact category	Unit	BS-open	BS-cover	AD & PV Scenario	Relative comparison	Delta BS-open vs AD & PV	Delta BS-cover vs AD & PV
Global warming potential (GWP)	kg CO_2 eq	15.16	14.81	13.37	%	−11.8	−9.7
Ozone depletion potential (ODP)	g CFC11 eq	0.120	0.121	0.116	%	−3.3	−4.1
Particulate matter formation (PMF)	g PM2.5 eq	11.95	11.17	9.73	%	−18.6	−12.9
Terrestrial acidification (TAP)	g SO_2 eq	74.50	68.14	59.2	%	−20.5	−13.1
Freshwater eutrophication (FEP)	g P eq	1.10	1.09	0.94	%	−14.5	−13.8
Marine eutrophication (MEP)	g N eq	23.70	23.70	23.92	%	+0.9	+0.9
Mineral resource scarcity (MSR)	g CU eq	15.14	15.14	15.31	%	+1.1	+1.1
Fossil resource scarcity (FRS)	kg oil eq	0.55	0.55	0.36	%	−34.5	−34.5

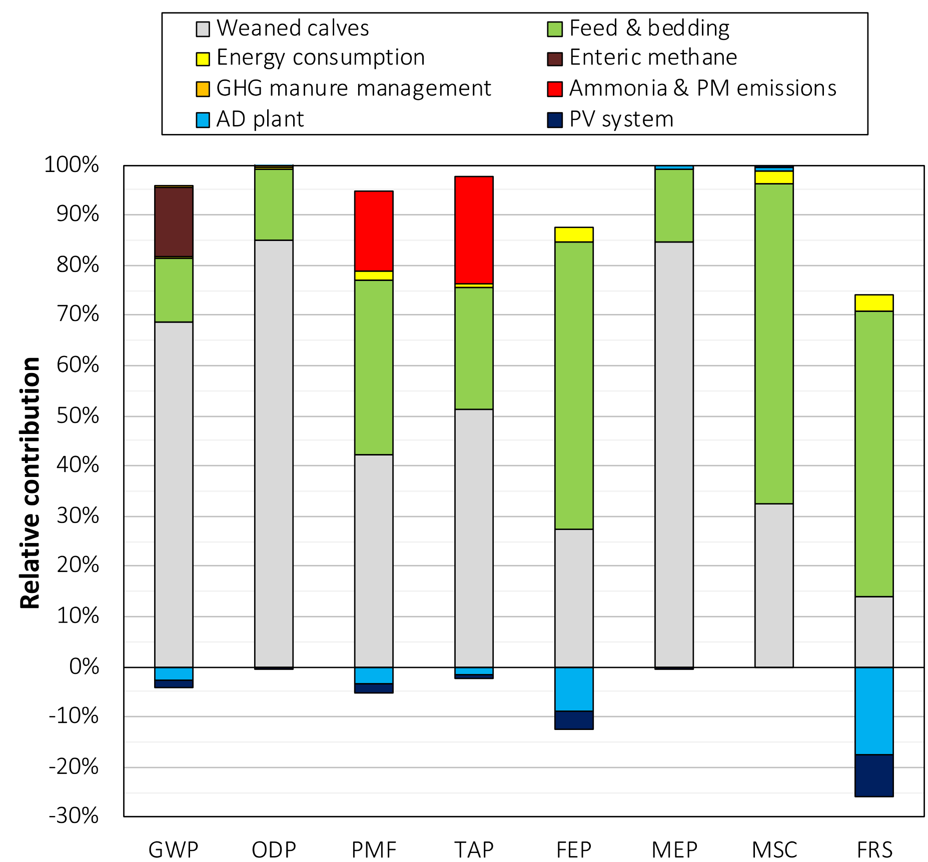

Fig. 2. Contribution analysis for the AD & PV scenario. (Note: AD – Anaerobic Digestion; PV – Photovoltaic; GWP – Global Warming Potential; ODP – Ozone Depletion Potential; PMF – Particalate Matter Formation; TAP – Terrestrial Acidification; FEP – Freshwater Eutrophication; MEP – Marine Eutrophication; MSR – Mineral Resource Scarcity; FRS – Fossil Resource Scarcity).

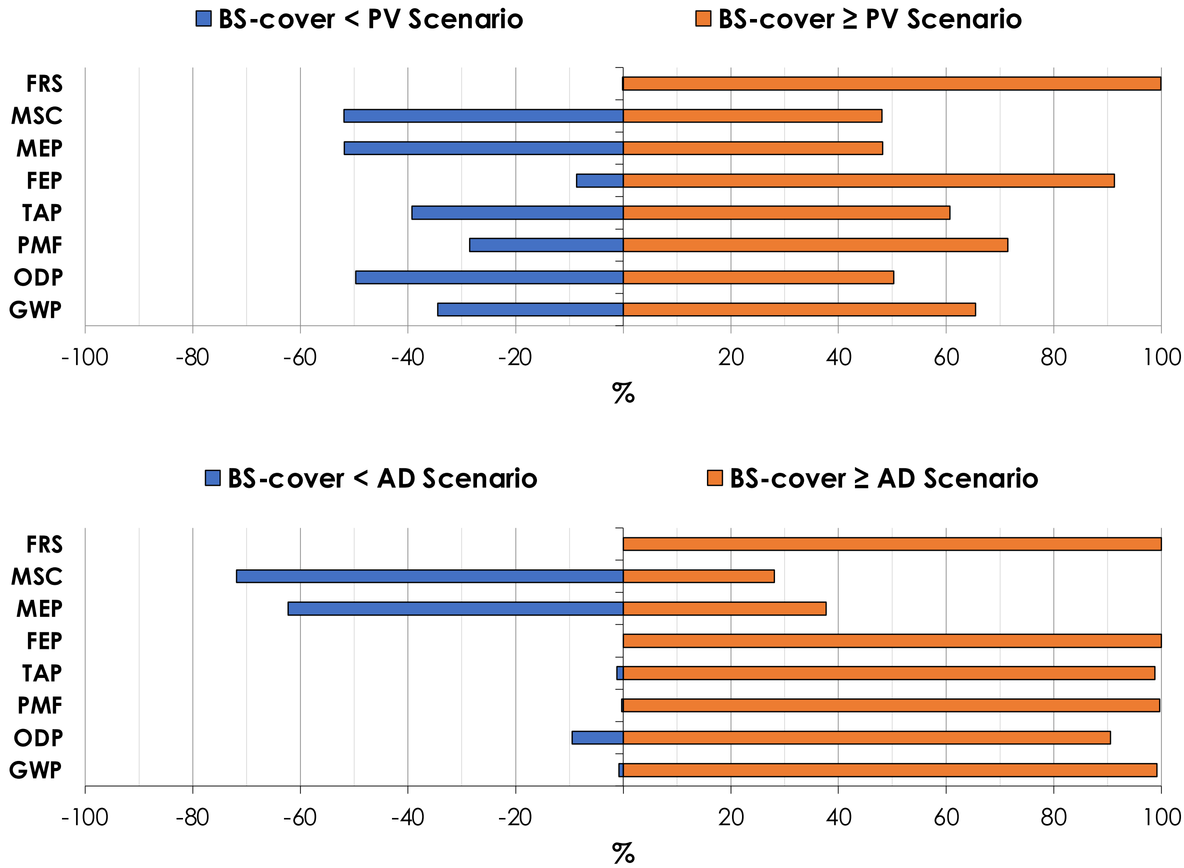

Fig. 3. Uncertainty analysis results regarding the comparison between Baseline Scenario and Alternative ones. Orange bars represent the probability that the environmental impact of the baseline is greater than or equal to the alternative scenarios, blue bars on the left represent the opposite probability. *(Note: AD – Anaerobic Digestion; PV – Photovoltaic; GWP – Global Warming Potential; ODP – Ozone Depletion Potential; PMF – Particalate Matter Formation; TAP – Terrestrial Acidification; FEP – Freshwater Eutrophication; MEP – Marine Eutrophication; MSR – Mineral Resource Scarcity; FRS – Fossil Resource Scarcity)*. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

unit, the benefit obtainable due to the implementation of AD is lower in relative terms. The same applies to the comparison with the savings obtained in the buffalo and pig systems (see Table 1). Furthermore, this study among all those cited is the only one in which the digester installed on farm is not only fed with livestock waste as feedstock but also, albeit to a lesser extent, with agricultural biomass, which is known to limit for the positive environmental effects of this energy system [36].

The contribution analysis highlighted the important role of weaned calves within the life cycle impact. This translates into the fact that only a minority share of the impact is directly linked to the Italian fattening farms for most of the impact categories, which reduces their possibilities of intervention in the supply chain for technical-productive and environmental improvements; this is in line with the findings in Refs. [17, 18]. Linked with this, it is interesting to note that the on-farm energy consumption, despite being equal to an average of 58.4 kWh and 14.07 kg of diesel per head on a farm per year, did not remarkably affected any of the impacts.

Another factor to consider is the continuous increase in the renewables share of the national energy mix, which tends to reduce the impact per kWh for most of the impact categories year by year. In fact [42], reported that, by 2030, the carbon footprint of 1 kWh of electricity of the Italian mix could be reduced from the current 0.42 kg CO_2 eq down to 0.36–0.23 kg CO_2 eq, according to different energy and technological transition scenarios and mix evolutions. In an analysis carried out within the setting of this study, this would result in an increasingly reduced environmental credit in the future, as the energy produced replaces an electricity mix that emits between 14 % and 45 % less CO_2 eq. Indeed, this is a reason to look for further improvements in the management of the AD plant and keep its environmental benefit high. In this sense, one of the energy and environmental improvements overlooked by both policies and plant managers is the recovery and enhancement of the surplus heat generated by the biogas conversion process [43]. Greenhouses, dryers, domestic heating, ORC turbines [[36,44]] and absorption groups are some possible uses of the surplus heat from AD plants. Another innovation in this sector, on which the EU has focussed on recently, is the upgrading of biogas into biomethane, to favour a growing diffusion of this biofuel (European Commission; COM/2022/230 final), which would also be a scenario to be explored, in environmental terms, for agri-food waste-fed AD plants. The strategic planning of AD plants in this direction is required in the coming years, as well as the need for further research [[45,46]].

At the same time, it must be kept in mind that anaerobic digestion treatment alone does not make manure management sustainable. The best management practices must be applied, starting with the removal of animal housing structures and through to the field distribution, passing through storage and treatments [[9,47]]. Field distribution is extremely important, in order not to invalidate all the efforts made upstream to avoid GHG and NH_3 emissions [48]. The technique, modality, and timing of manure application can lead to important variations within application impacts. Future studies could expand this comparative analysis by also adding different manure application scenarios.

Regarding the PV system, even if the environmental and energy potential for the farm was lower, compared to the AD system, barns are perfect for placing solar panels. Such investments will be more and more prioritised under future CAP Strategic Plans (European Commission; COM/2020/381 final). Future studies should investigate the influence of the possible design and operational variables when implementing this on-farm technology.

Finally, it is important to emphasize that relying solely on the LCA method for environmental analysis has limitations. This method provides valuable insights into the direct environmental impacts of a system, but especially for energy systems (such as biofuels or more broadly renewables) it is also crucial to develop in parallel emergy, energy and exergy analyses [49]. Integrated assessments with complementary approaches are therefore needed to identify the most efficient and sustainable solutions, as well potential trade-offs and unintended consequences [50], and future research should focus on an increasingly comprehensive approach.

5. Conclusions and prospects

This work reported the impact of the integration of renewable energy generation systems, namely the anaerobic digestion (AD) of agricultural biomass and waste and photovoltaic (PV) systems installed on barn roofs, on beef cattle farming. The results showed that the on-farm implementation of anaerobic digestion systems generally leads to significant improvements in the environmental and energy impact of beef production. GWP was reduced by 10.5 % in the AD scenario, compared to a baseline scenario of conventional manure management and slurry open storage (BS-open), and by 8.4 % when compared to an improved baseline scenario with slurry cover storage (BS-cover). These are noticeable reductions, given the high absolute impact of this supply chain when compared with other agri-food products, between 14.81 and 15.16 kg CO_2 eq. per kg of live weight produced in the baseline production scenarios. The mitigation provided by the PV system was more contained, above all for the GWP, but still a further improvement. The most improved impact category concerned the replacement of the use of energy from fossil fuels: fossil resource scarcity is reduced by −35 % in the scenarios with both the AD plant and the PV system. Mineral resource scarcity and marine eutrophication potential are the only categories in which trade-offs have been highlighted, albeit very limited.

The main methodological assumption of practicing system expansion, and considering an environmental credit for avoided electricity production, was evaluated with an economic-based sensitivity analysis that showed similar trends in the results. In conclusion, this study quantified the positive environmental effects on the whole beef farming system given by electricity produced by livestock waste anaerobic digestion and photovoltaics, showing good results for both. The limitations of the present study open up opportunities to deepen and broaden our understanding of the topic in future studies: many technical-productive parameters and their combination with different farming systems need to be explored. With regard to AD plants, this study provided some interesting insights into the influence of the plant on the entire farming system; however, the possible variability given by factors, such as the power of the plant and its feeding, need to be better explored. Regarding PV systems on barn rooftops, future studies could provide a deeper comparison between farms at different locations, in terms of irradiance, a factor that strongly influences their energy and, consequently, mitigation potential.

CRediT authorship contribution statement

Michele Costantini: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Visualization, Writing - original draft, Writing - review & editing. **Giorgio Provolo:** Methodology, Writing - review & editing. **Jacopo Bacenetti:** Conceptualization, Data curation, Methodology, Supervision, Writing - review & editing.

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

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.129960.

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