Science of the Total Environment 843 (2022) 157012

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Bioenergy from anaerobic digestion plants: Energy and environmental assessment of a wide sample of Italian plants

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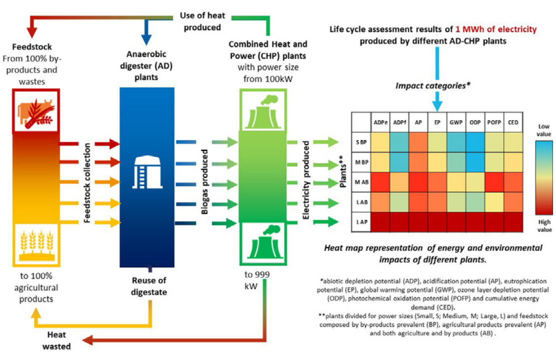
HIGHLIGHTS

- The electricity produced by biogas could help in reaching carbon neutrality.
- The study treats cogenerative biogas plants with different sizes and feedstocks.
- Impacts and hotspots are evaluated by a comparative life cycle assessment.
- Better environmental performances are obtained compared to the national grid.
- Best results are obtained for biogas small size plants fed by byproducts.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:
Biogas
Anaerobic digestion
Electricity
Heat
Life cycle assessment

ABSTRACT

This study assesses the energy and environmental performances of electricity produced from Italian anaerobic digestion coupled with combined heat and power plants. The Life Cycle Assessment methodology is applied to a set of plants characterised by different power sizes (from 100 to 999 kW) and feedstock compositions (variable rates of agricultural products and by-products). Then, the average eco-profile of the produced electricity is compared with electricity produced by the national grid and photovoltaic panels.
The analysis allows detection of the combinations of size and feedstock with the lowest impacts. They correspond to small and medium plants mainly fed by organic by-products.
In addition, compared to electricity from the grid, the average biogas electricity is characterised by the lowest contribution in impacts categories, such as abiotic depletion potential and ozone layer depletion potential, while largest in acidification and eutrophication. Focusing on global warming potential and cumulative energy demand fossil, the impacts of average biogas electricity (155 $kgCO_{2eq}$/MWh and 172 MJ/MWh) are about 35 % and 38 % of that generated by the grid. Furthermore, it could generate 47 % less of the impact in the abiotic depletion elements category of the solar system.
To enhance the farms' environmental and economic sustainability and balance the electric grid, these outcomes point out that biogas electricity produced from the agriculture and livestock sector can contribute to the decarbonisation and self-sufficiency of European countries.
The results strictly depend on the operative conditions and can aid policymakers at the global level in improving the energy supply security and sustainability. Further, they provide reliable information to stakeholders to select the most sustainable solution, according to the feedstock type, power supply, and management.

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http://dx.doi.org/10.1016/j.scitotenv.2022.157012
Received 11 April 2022; Received in revised form 12 June 2022; Accepted 23 June 2022
Available online 27 June 2022
0048-9697/

1. Introduction

Reducing greenhouse gas emissions represents a formidable global challenge, of which clean and affordable energy supply and effective circular economy strategies are the core issues (UNFCCC, 2015). Accordingly, within the energy context, the Directive (EU) 2018/2001 "RED II", replacing the Directive 2009/28/EC, sets the target of achieving an overall share of 32 % of energy from renewable energy sources (RESs) in the EU final consumption by 2030 (European Commission, 2018a). In the EU's 2030 Biodiversity Strategy, a core part of the European Green Deal, the Commission recognised sustainable bioenergy as an essential tool to fight climate change, identifying it as a priority.

Although wind and solar technologies represent the highest installed units and power rates among RESs technologies, they are characterised by high variability and unpredictability, with daily and monthly fluctuations in energy generation (Gielen et al., 2019). In order to reduce the intermittent production of energy and increase the use of RESs, bioenergy has gained a significant role in the energy transition allowing, for its nature, a stable and programmable production (International Energy Agency, 2020). IEA forecasts that bioenergy, identified as the 'overlooked' renewable, will show the highest growth among renewable resources in the following years at the world level, thus playing a pivotal role in achieving the Paris Agreement (Angelidaki et al., 2018; International Energy Agency, 2021).

Among all the different forms of biomass, biogas, including direct use and upgrading to biomethane, is used in Combined Heat and Power (CHP) plants of different power sizes for stable co-production of heat and electricity. Biogas is generally produced in Anaerobic Digestion (AD) plants, in which feedstocks are energy crops, livestock effluents (animal manure and sewage), and biowastes (e.g., wastewater, food waste and other organic urban waste). As reported in (Messineo et al., 2020), AD is a mature technology and, despite some criticalities that can be overcome by simultaneous treatment of different feedstocks and the inclusions of specific pre-treatments, can introduce technical and economic benefits due to the stability of the process and the possibility to recover energy and nutrients for the involved farms. Especially when different substrates are used, this technology allows contributing to the EU decarbonisation strategies (EBA, 2020; World Biogas Association, 2019). In a more comprehensive vision, bio-waste recovery for energy generation could be a sustainable waste management strategy to implement bio-circular economy actions (European Commission, 2018b, 2018c; Garcia-Garcia et al., 2019). Further, the AD plants produce digestate that, usable as fertilizer in the land, could replace energy-intensive chemical fertilizers and increase soil carbon storage (Kyttä et al., 2021). The agronomic use of digestate in Italy is regulated by a complex system of European, national and regional rules, on the one hand to enhance the nutrient content and on the other hand to protect the most vulnerable soils from an excessive spread of nitrates. Before operating, the farmers crop plans must be authorized by the offices in charge to use predetermined quantities of digestate in place of manure or fertilizers.

The feedstock used in most AD facilities operating in the EU is a mixture of manure, agricultural products, and agricultural residues. About 50–55 % of AD plants in Europe are fed with maize crops because of their higher energy yields (87–145 GJ) per hectare of cultivated land than other energy crops (Bacenetti et al., 2015; Nayal et al., 2016). In Italy, about 10 % of the agricultural area is dedicated to maize supply feedstock to AD plants (Selvaggi et al., 2018). Agricultural products are being replaced by mixes of agriculture and food industry waste and livestock effluents due to the growing environmental and economic concerns about the land used for agricultural cultivation without food purposes (Ingrao et al., 2019). This action may achieve a better nutrient balance in AD, optimum carbon-to-nitrogen ratios, and decrease the risk of ammonia inhibition (Vassilev et al., 2010; Ward et al., 2008). The selection of feedstock introduced in AD plants is more generally affected by the size of the combined heat and power (CHP) plant and its function (e.g. to deliver electricity or heat for farm's processes or district heating).

1.1. Aims of study

Sustainable energy sources have become relevant research topics in electricity generation. In this regard, Life Cycle Assessment (LCA) methodology, standardised at the international level by the series ISO 14040 (ISO, 2020a, 2020b), is the most comprehensive energy and environmental assessment tool.

Several studies carried out an LCA applied to the bioenergy production system from agricultural and livestock biomass employing AD-CHP plants (Ingrao et al., 2018). However, the literature on biogas mainly focuses on climate change or a limited set of impacts. Bacenetti et al. (2016) highlighted that there had not been achieved general consensus in selecting the most proper functional unit, allocation method and system boundary and modelling the carbon cycle of biomass. Further, they pointed out that the assumptions made for goal and scope definition, inventory data, impact categories, feedstock and geographical regions by the LCA studies on biogas vary widely from one study to another. These assumptions involve quite different and often uncomparable results among the studies.

Generally, for developing an LCA study, the practitioner inevitably needs to use reliable inventory data collected on-field for the primary object and processes under study (the foreground system). Such data are integrated with those of the upstream and downstream life cycle phases (the background system), often taken from international databases and literature, in which data quality affects the study's overall results (Notarnicola et al., 2022).

Most existing studies do not apply primary data in foreground processes but are carried out using mainly secondary data derived from literature and international environmental databases (Pacetti et al., 2015; Ravina and Genon, 2015). Ingrao et al. (2019) highlighted the need for primary data to best model feedstock production. Primary data should be collected, taking into account the geographic and temporal variability of cultivation practices and biomass yields, and, when possible, secondary data should be used only for background processes.

Many studies show that plants supplied by agricultural wastes, instead of energy crops, achieve the best eco-profile and a small number of studies take into account AD-CHP plants with a size smaller than 500 kW (Lijó et al., 2017). For example, Fusi et al. (2016) assessed the life cycle environmental impacts of electricity generation from agricultural products and waste in five Italian AD-CHP plants. The results suggest that the most significant contribution to the impacts comes from the production step of the agricultural products, the anaerobic digestion process, and the open storage of digestate.

In this context, this paper aims to assess the energy and environmental performances of a sample AD-CHP plants located in North Italy. Such plants are appropriately selected depending on feeding mixes (predominance of silages or by-products), sizes and operative conditions.

In comparison with the existing literature studies, the paper's novelty is to provide detailed energy and environmental balances of some AD-CHP plants, characterised by various plant sizes and feedstock mix, and to highlight how these items can affect the environmental performances of the plants themselves. Further, starting from the eco-profile of the generated electricity from each plant, the average eco-profile of the electricity produced by the assessed AD-CHP plants is carried out and compared to the Italian electric grid and solar PV electric generation.

Literature reviews as Bacenetti et al. (2016) state that, concerning the foreground data, most of the assessed studies are carried out using mainly secondary data coming from literature and databases. The presented study is mainly based on primary data for the foreground system (site-specific feedstock composition, daily feedstock requirements, energy production and consumption, and plant operating conditions), collected on-field employing questionnaires and interviews with the plant managers and owners, except for the assessment of emissions related to digestate management.

The results could support the individuation of actions to be addressed in the future support schemes necessary for the evolution of existing biogas plants and the optimisation of the use of the available feedstocks by this technology, increasing the interest of stakeholders involved in the agri-food sector and policymakers. How the biogas industry will evolve by country essentially depends on feedstock availability, market conditions, and policy priorities and strategies.

2. Material and methods

2.1. Description of the system under study

The European biogas market is well established and mature. The EU-28 represents the most crucial biogas producer globally, reaching 16,670 ktoe in 2018 from 18,802 plants and a total installed electric capacity of 10,532 MW, with 62.5 TWh of produced electricity (EBA, 2020). In Italy, the biogas plants had a total installed power of 1448 MW in 2018 (agro-biogas plants represent about two-thirds of the total), generating a whole electricity production of 8.3 TWh and representing the 2.8 % of total annual electricity production (Gestore dei Servizi Energetici GSE S.p.A., 2019).

This paper focuses on AD-CHP plants in the large flat Italian northern land called Pianura Padana, where most of these systems are currently operating. In fact, about 70 % of the Italian agro-biogas plants are located in North Italy, thanks to the relevance of agricultural and livestock activities. The remaining 30 % of the Italian biogas plants are located in the central and southern regions (Gestore dei Servizi Energetici GSE S.p.A., 2019).

The plants analysed are located in rural areas of Piedmont and Lombardy. Data collected are referred to 128 biogas plants and the operation conditions of the year 2019, accounting for a total installed electric power of 66 MW. Taking into account only the agro-biogas category, despite the small size in terms of total electric power, the considered AD-CHP plants could be assumed as representative of the Northern Italy context and, more generally, of the national context, concerning feedstock, operative conditions of the AD plants, and features of the involved farms.

These AD-CHP plants are fed by agricultural and livestock feedstocks (energy crops, agricultural by-products, animal slurry and manure), which are produced in the agricultural and livestock farms close to plants, making the supply basin local and reducing costs, energy consumption, and environmental burdens, due to the limited transportation and storage.

Almost all adopt a co-digestion approach based on different percentages of energy crops (corn, triticale, and sorghum) and animal slurry and manure (from pigs and cows). The cereal silages represent the primary feedstock of the AD-CHP plants characterised by medium-large size (power > 300 kW), in co-digestion with other feedstock in less amount (agricultural by-products and zootechnical residues).

A comparative Life Cycle Assessment is implemented following ISO 14040 and ISO 14044 (ISO, 2020a, 2020b) to assess AD-CHP plants' energy and environmental impacts, identify the hot spots of the examined systems, and estimate the potential benefits achievable through the biogas production and recovery. This section presents the case study and the methodological choices for applying the LCA.

2.2. Definition of the AD-CHP sample

The main information about the plants was collected based on the available databases (ARPA, 2021; Consorzio Monviso Agroenergia, 2020; Fiper, 2018, 2021), and primary data on the operative features were collected or verified by surveys to farm owners and experts in the sector concerning the operation year 2019. These plants are characterised by expected flows of resources and energy, as reported in Fig. 1, where the dotted square represents the gate of farms.

In particular, the farm's feedstock used in AD plants includes agriculture products (silages) and by-products. The outputs of the AD process are the biogas and the digestate. The digestate, rich in nutrients substances, is used as a fertilizer by farms for agriculture products (Baştabak and Koçar, 2020). Biogas produced is conveyed as fuel to the CHP system for electricity and heat generation. The produced electricity is totally delivered to the national grid. The produced heat is mainly wasted, except for self-consumed low rates to heat digester, stables, chicken coops, greenhouses, laboratories, and homes within the farms. In some plants, a small fraction of the thermal energy generated by CHP is delivered to district heating networks close to the plant.

In order to account for different operating conditions of Italian plants, the Authors select a sample among the 128 to represent different feedstocks and power sizes. Since the operating conditions depend mainly on the type of feedstock and the size of the engine used for generating electricity in the CHP unit, proper classification of these plants must consider these factors.

About the feedstock mixes, the following clusters are identified (feedstock clusters):

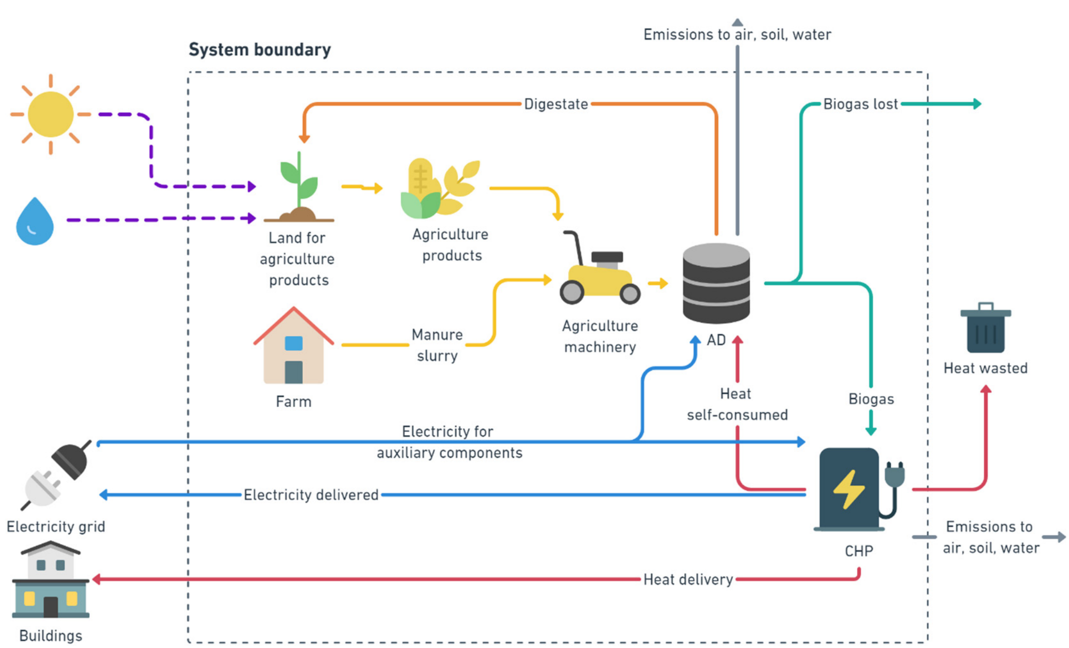

Fig. 1. Representation scheme of the investigated AD-CHP plants.

- Agricultural-Prevalent (AP) plants, if >75 % of the feedstock is based on agricultural products specifically cultivated for biogas production.
- By-product-Prevalent (BP) plants, if the feedstock includes <25 % agricultural products and >75 % animal slurry and manure from pig and cattle, and other farm by-products.
- Agricultural-By-products (AB) plants with a balanced supply chain (intermediate cases among the above feedstock compositions).

Concerning the installed power, according to the engine size of the CHP unit, the plants are further aggregated in the following clusters (power clusters):

- small plants (S), up to 150 kW of installed electric power;
- medium plants (M) between 151 and 500 kW of installed electric power;
- large plants (L), with >500 kW of electric power.

Fig. 2 shows the percentage of feedstock used for the power clusters. It highlights that the relative role between agricultural products, animal slurry, and manure depends mainly on plant size. In fact, while large plants are fed mainly by agricultural products, medium and small plants are mainly fed by agricultural by-products, animal slurry, and manure. According to the national statistics (Gestore dei Servizi Energetici GSE S. p.A., 2019), an average power of 380 kW for AD-CHP plants is mainly fed by slurry and manure and 722 kW for AD-CHP plants is mainly fed by agricultural products. The average powers are calculated as the ratio between the total power and the number of Italian plants fed by slurry, manure, and agricultural products.

The plants are divided into 9 CE-CHP clusters based on the two above characterisations. Starting from the size of CHP in terms of electric power, a cut-off threshold has been applied based on the feedstock category. After grouping the plants of the sample in the three power clusters (S, M, and L), the contribution of each feedstock cluster has been calculated. In the power cluster "S", most of the plants are "BP", most of the plants belonging to power cluster "M" are "AB" and "BP", while "AP" and "AB" are the prevalent feedstock cluster in the power cluster "L".

Only feedstock clusters that account for at least 10 % of the number of plants, electric power installed, and electricity produced have been considered within each power cluster. The values considered for calculation and application of the cut-off threshold are reported in supplementary materials (Table S1) in which details on the number of plants, total power, mean power, electricity production [MWh/year] and heat production [MWh/year] and their contribution are shown for each group of plants. As a result, only five combinations have been considered representative. These clusters are called S-BP, M-AB, M-BP, L-AP, and L-AB, while the others are neglected because they are considered not representative in this study. Since statistics reveal that the 5 clusters mentioned above are generally the most spread in Italy, the selected sample can be considered representative (Benato and Macor, 2019).

The authors select two plants for the above-mentioned 5 meaningful clusters to guarantee the sample's representativeness. As shown in Table 1, the selected systems are identified from P01 to P10, considering the two fundamental operative characteristics, i.e., the engine's size and the feedstock composition constituting the input to the AD.

These cases cover the entire range of the available electric power (size of the engine), from 100 kW to 999 kW, and the entire range of feedstock composition, from an input, totally based on by-products to another, totally constituted by agricultural products. In addition, the analysis of two cases of the same cluster allows for a better understanding of the effects deriving from operational features, even in similar contexts and sizes.

The selected plants are characterised by a high utilization factor (on average 96 %) and energy efficiency. The gross electric efficiency (ratio between the electricity produced and the primary energy input to the CHP unit as biogas) within the yearly operation of the plants is between 37 % and 42 %. Analogously, the gross thermal efficiency values (ratio between the heat produced and the primary energy input to the CHP unit as biogas) are consistently between 35 % and 47 %. The energy losses along the process refer to technological constraints and limits and the possibility of using cogenerated heat for additional purposes beyond self-consumption, even when small district heating networks use the available heat at users close to the plant site.

2.3. Goal and scope definition

The main goals of the study are:

- to assess the energy and environmental impacts of the sampled plants, considering the influence of the feedstocks type and the plant size;
- to quantify the contribution of each life cycle phase to the overall impacts;
- to compare the average eco-profile of power energy produced by different clusters with others providing the same function (i.e. electricity).

According to the above goals, electricity production represents a system-specific function. Therefore, 1 MWh of electricity produced is selected as a functional unit (FU).

The system boundaries considered for these systems is a "cradle to gate" approach that includes the following phases:

- Feedstock production.
- Anaerobic digestion process.

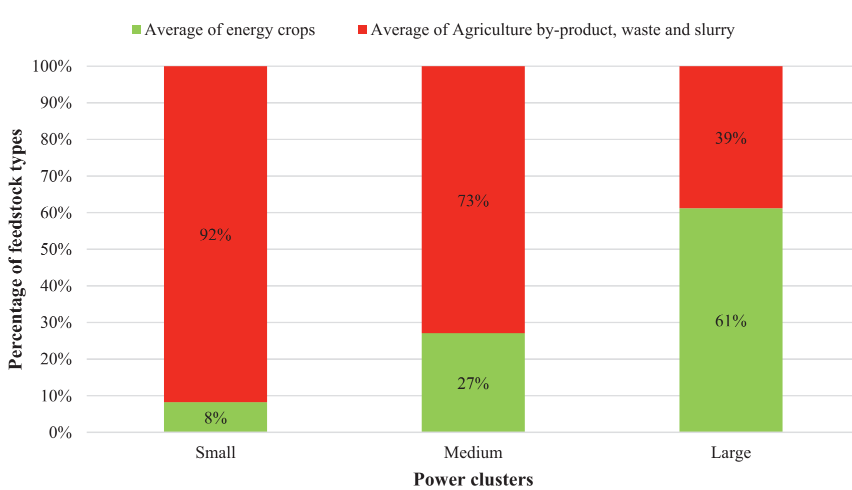

Fig. 2. Composition of feedstock (in % of weight) for the three power clusters.

Table 1
Sample selected for the analysis.

ID	Power cluster	Feedstock cluster	Electric power [kW]	Feedstock composition (% weight)		Electricity production [MWh/year]	Heat production [MWh/year]
				Agricultural products	By-products		
P01	S	BP	100	0 %	100 %	776	903
P02	S	BP	100	12 %	88 %	853	903
P03	M	AB	249	33 %	67 %	2027	2312
P04	M	AB	250	36 %	64 %	2122	2258
P05	M	BP	300	19 %	81 %	2611	2234
P06	M	BP	400	14 %	86 %	2995	3612
P07	L	AB	526	46 %	54 %	4516	4410
P08	L	AB	998	25 %	75 %	8458	8811
P09	L	AP	635	90 %	10 %	5469	5644
P10	L	AP	999	100 %	0 %	8639	9021

- Digestate management.
- Power and heat cogeneration in the CHP unit.

The AD-CHP plants are inside the farm sites. Thus, the feedstocks are available in situ. The agricultural production of biogas is considered, while animal slurry and manure are considered a waste of livestock activities without resource depletion and impacts. Fuels consumed by agriculture activities are considered, while the electricity lost during transmission and distribution is excluded from the system boundary.

Electricity produced by the CHP plants is exported to the grid. Electricity consumed in the biogas plants is imported from the grid, allowing plants operability during even CHP maintenance or malfunctioning.

The environmental profiles of plants are estimated by using the characterisation factors reported by the CML 2 baseline 2000 method (CML - Department of Industrial Ecology, 2016) for six impact categories: abiotic depletion potential (ADP), acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP) and photochemical oxidation potential (POFP). Energy consumption is assessed by applying the Cumulative Energy Demand (CED) method. The CED represents the total primary energy requirement, which arises from the entire global life cycle (Frischknecht et al., 2007), and it is considered an additional impact category. It is divided into six contributions: Non-renewable, fossil ($CED_{nr,f}$), Non-renewable, Biomass ($CED_{nr,b}$), Non-renewable, nuclear ($CED_{nr,n}$), Renewable, Biomass ($CED_{r,b}$), Renewable, water ($CED_{r,wat}$), Renewable, wind, solar, geothermal ($CED_{r,others}$), These indicators are selected according to (Lijó et al., 2014).

2.4. Life cycle inventory

Life Cycle Inventory (LCI) is carried out to develop the energy and mass balances of the selected ten AD-CHP plants, including the inputs in terms of material and resource consumption, and outputs in terms of air emissions, wastes, products, and co-products.

In this context, foreground processes are modelled through primary and site-specific data on feedstock production, anaerobic digestion process, electricity and heat consumption and generation. Through questionnaires and interviews, farmers, managers, and owners of the AD-CHP plants provide such data. Data collected are referred to the year 2019.

Regarding the background processes, secondary data on plant production and decommissioning, agriculture crops, and electricity from the Italian grid are taken from Ecoinvent (Wernet et al., 2016).

In addition to electricity, additional outputs, which yield quantifiable benefits (heat and digestate), are produced. This study avoids allocation by adopting the system expansion method or substitution approach to include the additional functions related to heat and digestate, following ISO standards.

The AD process produces biogas and digestate. Biogas is considered the main product, while the digestate is used as organic fertilizer, involving a reduction of mineral fertilizer (urea) in closed farms. An avoided product perspective is applied, assuming the application of the digestate without any previous treatment and calculating the related emissions. The environmental impacts of the avoided fertilizer can be subtracted and considered as credits.

In CHP plants, most of the generated heat is wasted. In plants P03 and P07, it is totally wasted. However, >25 % of the generated heat is recirculated to the digesters for AD heating demand at the selected sample level, and <20 % is delivered to near district heating networks. In these cases, heat is used in such a way that it avoids the production of heat by a conventional source (natural gas boiler as a reference system, because the natural gas grid reaches the site where the analysed plants are located), and the environmental loads of the avoided heat production (credits) may be subtracted. The eco-profile of natural gas is taken from Ecoinvent (Wernet et al., 2016).

Table 2 reports the detailed inventory data per FU; additional details are reported in the following paragraphs.

2.4.1. Feedstock production

Feedstock production includes the following steps: cultivation and harvest of the agriculture products, by-products recovery, and their collection and transport to the anaerobic digesters. The average composition of feedstocks consumed is primary data. The background data for agricultural products are inferred from Ecoinvent datasets (Wernet et al., 2016), while the foreground ones are collected as primary data using a survey from farm owners.

2.4.2. AD process

Biogas is the main product of the AD operation. Its composition is quite similar across the plants, and the Authors assume an average methane content equal to 52 % of the biogas volume (Caputo, 2018). According to (Giuntoli et al., 2017), the rest of the biogas is assumed to be composed only of CO_2.

A small percentage of biogas produced is not captured and thus released into the atmosphere.

In particular, according to the plant owners' estimates and to the higher technological levels that characterised large plants, uncontrolled emissions account for 2 % in P08 and P10 plants and 4 % in the others for yield biogas.

In addition to biogas, digestate is also co-produced in AD plants. It is extracted from the bottom of the digester, stored, and then applied as organic fertilizer without further processing (Cusenza et al., 2021). Nitrous oxide (N_2O) and methane (CH_4) emissions occur during the open storage of digestate due to the residual organic matter. Such emissions are calculated according to literature (Fusi et al., 2016; Reichhalter et al., 2011). The system is expanded to include the credits derived from the avoided production and application of the mineral fertilizer (urea), quantifying the amounts of mineral fertilizers substituted as a function of the nutrients contained within the digestate (Lijó et al., 2014). Further, according to (Reichhalter et al., 2011; Sedorovich et al., 2007), it is assumed that the avoided emissions from 1 ton of manure and slurry are the following: 4.10 kg of CH_4 and 0.10 kg of N_2O per m^3 in a year.

The CHP unit satisfies the AD's heat demand which ranges from 25 to 50 % of heat generation, while the grid provides electricity.

Table 2
Inventory data for feedstock composition, AD and CHP operation.

Plants	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10
Feedstock supply[a]										
Input										
Maize [t]	–	0.86	1.62	1.47	0.60	0.67	1.43	1.80	1.56	2.14
Triticale [t]	–	–	–	–	0.22	0.30	–	0.04	0.21	–
Sorghum [t]	–	–	–	–	0.33	–	–	0.02	0.43	–
Barley [t]	–	–	0.11	–	0.55	–	–	–	–	0.02
Wastewater [t]	–	–	–	–	–	0.69	–	–	–	–
Bovine slurry [t]	13.40	5.76	2.38	2.29	–	3.96	–	3.04	–	–
Pig slurry [t]	–	–	–	0.17	8.30	–	–	–	–	–
Bovine Manure [t]	0.73	0.42	0.13	0.11	0.03	1.06	1.71	0.84	0.13	–
Output										
Substrate [t]	14.12	7.03	4.23	4.05	10.03	6.68	3.14	5.74	2.33	2.16
AD plants										
Input[a]										
Electricity-grid [MWh]	0.14	0.13	0.12	0.10	0.11	0.11	0.10	0.06	0.11	0.10
Heat-CHP [MWh]	0.29	0.26	0.32	0.27	0.43	0.30	0.24	0.30	0.26	0.26
Output[a]										
Biogas [m^3]	458.43	455.76	511.85	455.31	476.49	467.12	480.01	479.45	491.28	462.96
Digestate [m^3]	12.35	6.70	3.64	3.73	9.42	6.92	1.99	4.67	1.69	1.89
Air emissions from biogas release[b]										
CH_4 due to biogas release [kg]	9.54	9.48	10.65	9.47	9.91	9.72	9.98	9.97	10.22	9.63
CO_2 due to biogas release [kg]	8.62	8.57	9.62	8.56	8.96	8.78	9.02	9.01	9.24	8.70
Air emissions from digestate management[c]										
CH_4 (digestate storage) [kg]	16.61	9.01	4.90	5.01	12.67	9.31	2.68	6.28	2.28	2.55
CH_4 (manure and slurry storage) [kg]	−46.92	−20.61	−8.31	−8.54	−27.36	−17.32	−7.00	−13.41	−0.53	–
N_2O (digestate storage) [kg]	0.38	0.21	0.11	0.12	0.29	0.21	0.06	0.14	0.05	0.06
N_2O (manure and slurry storage) [kg]	−2.75	−1.21	−0.49	−0.50	−1.60	−1.01	−0.41	−0.79	−0.03	–
CHP plants[a]										
Input										
Electricity [10^{-3} MWh]	14.18	10.55	4.93	9.43	3.83	9.68	2.21	1.18	1.83	7.52
Output										
Electricity [MWh]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Net heat produced [MWh]	0.87	0.80	0.82	0.80	0.43	0.90	0.73	0.75	0.77	0.78
Heat wasted [MWh]	0.74	0.76	0.82	0.64	0.34	0.67	0.73	0.69	0.76	0.57
Heat delivered [MWh]	0.13	0.04	–	0.16	0.09	0.23	–	0.06	0.01	0.21
Air emissions from operation										
NO_x [kg]	1.86	1.69	1.69	1.95	1.90	2.21	2.44	1.67	1.65	1.64
CH_4 [kg]	1.16	1.06	1.08	1.22	1.19	1.38	1.56	1.11	1.10	1.10

[a] Data sourced from farm/plant owners.
[b] Calculations based on farm/plant owner's data.
[c] Reichhalter et al. (2011), Sedorovich et al. (2007).

Construction and decommissioning of AD plants are considered, assuming a useful life of 20 years. The background data on the construction materials are sourced from the Ecoinvent database v3.8 (Wernet et al., 2016). Since the data for the construction of AD plants in Ecoinvent depends on the plant sizes, the related manufacture's environmental impacts are estimated by scaling up or down their capacity to match the sizes of the plants considered in this study.[1]

2.4.3. Combined heat and power (CHP) generation process

The thermal and electric energy generated in the plants and the detailed inventory data for the CHP plants are considered. A detailed breakdown of the final use of energy produced is reported in supplementary materials (Fig. S1).

Due to the combustion processes, the CHP plant emissions are accounted for and are based on primary data. In particular, the following macro-pollutants will be considered in the elaboration: nitrogen oxides and methane.

3. Results

3.1. Life Cycle Impact Assessment results

The Life Cycle Impact Assessment (LCIA) is presented in Table 3. All the impacts are expressed per FU. For every impact category, the first row shows the contribution of the plants without environmental credits, while the second one shows such contributions taking into account the environmental credits.

The results suggest that the electricity generated by plant P01 is the best energy and environmental option when all the impact categories are assessed. This result is primarily due to the feedstock composition (100 % by-products and no agricultural products) and the highest environmental credits. The plant P06 shows the best performances after P01, except for AP and EP impacts. Plants P02 and P07 present the lowest contribution to AP and EP because of the lowest methane emissions from the digestate open storage. Despite the significant biogas production for the functional unit (see Table 2), plant P09 presents the lowest performance across all the impact categories, essentially attributable to the agricultural phase.

[1] The AD plants are scaled applying the following formula as suggested in Ecoinvent: $U_i = U_0 \times (C_i/C_0)^{0.7}$, where U_i represents the number of infrastructure units for the i^{th} reference case, U_0 is the number of the referenced infrastructure assumed as 1 unit characterised by an annual biogas production of 350,000 [m^3/year] (C_0), and C_i is the annual biogas production for the reference case i^{th}, in m^3/year.

The environmental credits are particularly significant for P01 and P05 due to the digestate recovery.

It is worthy of note that plants of the same power size and feedstock clusters present different eco-profiles, involving different contributions to the impact categories due to the feedstock type and the plant management. This effect is evident when comparing P03 to P04 (AB, M) and P05 to P06 (BP, M).

Fig. 3 shows the results of the hotspot analysis, which identifies the different contributions to the assessed impact categories, as defined in subsection 2.3, from life cycle phases gathering the different inputs and outputs as follows:

- Feedstock, which includes the production of agricultural products.
- Infrastructures, which consider construction and decommissioning of the AD and CHP units.
- Electricity, which considers the grid electricity consumed in AD and CHP plants.
- Emissions, which include the air emissions from CHP and AD.
- Net emissions from digestate storage, which are estimated as the difference between the emissions arising from digestate open storage and the avoided emissions from slurry and manure utilization.
- Avoided urea, which includes the avoided impacts for fertilizer production.
- Delivered heat, which considers the avoided impacts from heat valorisation in small district heating networks.

With regard to ADP_e and ADP_f, P01 reaches the highest performance, while P09 the lowest. Fig. 3.a and b show that the agricultural step and the use of grid electricity represent the most relevant hotspots.

Considering the environmental credits, primarily due to the avoided urea from digestate utilization as fertilizer, plant P01 has the highest performance, followed by plants P05 and P06, while P09 performs the worst. As Fig. 3.a shows, with regards to ADP_e, infrastructures represent the most relevant hotspot in almost all the plants, except for P08, P09, and P10, in which feedstock production is the most predominant contribution to the impact category. A similar trend is identified in ADP_f, to which the contribution of electricity from the grid is not negligible.

In plant P01, the contribution to ADP_e arises mainly from the AD and CHP infrastructures, respectively 29 and 19 % of the total impacts. The environmental credits reduce ADP_e from 13 % (P09) to 84 % (P01). Regarding ADP_f, the environmental credits involve a negative contribution in plants P01, P05, P06, and P08.

About AP, the global value is around 3 kg SO_{2eq}/MWh in all the assessed plants, ranging from 2.97 (plant P06) to 3.67 (plant P02). Considering EP, the variation range is a little wider, going from about 0.9 (plant P01) to 2.1 $kgPO_{4eq}$/MWh (P09 and P10) (Fig. 3. c and d).

In plants P01 and P02, the highest contribution to AP is attributable to infrastructure (62 % and 51 %, respectively), while in plants P08, P09 and P10, the most contribution comes from feedstock production and the emissions from AD plants. Regarding EP, except for P01(where infrastructure accounts for about 60 %), the feedstock production mainly affects this impact indicator in all the other plants. In P09 and P10, it accounts for about 77 %.

The environmental credits significantly reduce AP and EP, more distinctly in P01, P05, and P06. Fig. 3.e shows that CED varies from 6500 to 16,200 MJ/MWh. P01 involves a minor contribution to the impact. The highest value occurs in P09, followed by P10, P03, P05, and P08. Except for P01, feedstock production is the most affecting step, accounting for >50 % in almost the assessed plants. In P09 and P10, feedstock accounts for about 80 %. Except for P01 and P02, in all the other plants, CED from non-renewable fossil sources accounts for <25 %, while >70 % of CED is renewable from biomass.

As described in Fig. 3.f, GWP ranges from 378 (P08) to 571 kg CO_{2eq}/MWh (P09). Due to the not captured biogas, which reduces production yield, GHG emissions from the AD process are directly affected by uncontrolled methane emissions. They result in the most relevant hotspot for this impact category for all the assessed plants, varying from 265 to 300 $kgCO_{2eq}$/MWh. Feedstock production primarily affects plants P08, P09, and P10.

Except for plants P09 and P10, where slurry and manure are not included in the AD feedstock, in all the other plants, the negative contributions to GWP arise mainly from methane credits for avoiding the spreading on the fields of slurry and manure.

Table 3
Life cycle energy and environmental impacts per FU.

Impact categories	Contributes	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10
ADPe kg Sb_{eq}	Without credits	6.81E-03	7.99E-03	7.68E-03	6.84E-03	7.15E-03	5.85E-03	6.03E-03	6.37E-03	7.35E-03	6.88E-03
	With credits	1.07E-03	5.05E-03	5.85E-03	5.10E-03	3.02E-03	3.41E-03	4.53E-03	4.03E-03	6.29E-03	6.01E-03
ADPf MJ	Without credits	3.10E+03	3.15E+03	2.60E+03	2.33E+03	2.41E+03	2.24E+03	2.03E+03	1.86E+03	2.34E+03	2.16E+03
	With credits	-2.68E+03	2.96E+02	9.10E+02	1.27E+02	-1.73E+03	-8.90E+02	6.40E+02	-5.31E+02	1.31E+03	5.74E+02
AP kg SO_{2eq}	Without credits	3.23E+00	3.67E+00	3.38E+00	3.21E+00	3.36E+00	2.97E+00	3.18E+00	3.02E+00	3.43E+00	3.32E+00
	With credits	1.66E+00	2.87E+00	2.88E+00	2.71E+00	2.23E+00	2.28E+00	2.77E+00	2.38E+00	3.14E+00	3.06E+00
EP kg $PO_4^{3-}{}_{eq}$	Without credits	8.65E-01	1.45E+00	1.91E+00	1.71E+00	1.88E+00	1.38E+00	1.68E+00	1.87E+00	2.17E+00	2.11E+00
	With credits	-1.21E-01	9.99E-01	1.69E+00	1.50E+00	1.27E+00	9.19E-01	1.50E+00	1.55E+00	2.11E+00	2.06E+00
GWP kg CO_{2eq}	Without credits	5.75E+02	5.93E+02	5.97E+02	5.39E+02	5.62E+02	5.31E+02	5.35E+02	3.78E+02	5.71E+02	4.03E+02
	With credits	-1.24E+03	-1.63E+02	3.03E+02	2.06E+02	-4.41E+02	-3.17E+02	2.40E+02	-1.32E+02	5.66E+02	3.94E+02
ODP kg CFC-11_{eq}	Without credits	2.31E-05	2.39E-05	2.12E-05	1.89E-05	1.98E-05	1.80E-05	1.67E-05	1.53E-05	1.98E-05	1.83E-05
	With credits	-3.10E-05	-2.92E-06	5.22E-06	-9.69E-07	-1.90E-05	-1.02E-05	3.55E-06	-7.03E-06	1.02E-05	4.65E-06
POFP kg C_2H_{4eq}	Without credits	1.88E-01	1.85E-01	1.55E-01	1.41E-01	1.44E-01	1.40E-01	1.33E-01	9.61E-02	1.38E-01	9.99E-02
	With credits	-5.22E-02	8.65E-02	1.16E-01	1.00E-01	1.42E-02	3.62E-02	9.19E-02	2.95E-02	1.38E-01	1.04E-01
CED MJ	Without credits	6.54E+03	1.10E+04	1.46E+04	1.27E+04	1.39E+04	9.79E+03	1.17E+04	1.35E+04	1.62E+04	1.55E+04
	With credits	-1.63E+02	7.73E+03	1.26E+04	1.01E+04	9.13E+03	6.19E+03	1.01E+04	1.07E+04	1.50E+04	1.37E+04

The worst outcome is coloured in red for each row, while the best option is in white—the different shades of light red to pink show intermediate outcomes.

Fig. 3. Hotspot analysis for the AD-CHP plants: a) ADP_e; b) ADP_f; c) AP; d) EP; e) CED; f) GWP; g) ODP; and h) POFP).

Looking at Fig. 3, the environmental credits associated with the digestate utilization as fertilizer reduce the contribution to ODP impact in all the plants sensibly, inducing a negative impact in most of the assessed plants, except for P09 and P010 P03, and P07.

Concerning POFP (Fig. 3.h), it is mainly affected by methane emissions from the AD plants (34–52 %) and infrastructure (30–60 %). The environmental reduction credits reduce this impact in all the plants, involving a negative contribution in plant P01.

3.2. Electricity eco-profile of biogas from the AD-CHP plants and comparison with alternative sources

The above LCIA results are aggregated scales to assess the energy and environmental performance of the electricity production at the cluster level. According to Section 3.1, the following clusters are considered according to power size and feedstock reported in Table S1: S-BP, M-BP, M-AB, L-AB, and L-AP.

Table 4
Energy and environmental impacts of 1 MWh of biogas electricity and comparison with electricity from the Italian grid and PV plants.

Impact categories		Electricity by clusters						Electricity by	
		S-BP	M-AB	M-BP	L-AB	L-AP	Average profile	Grid	PV
ADPe	kg Sb_{eq}	3.16E-03	5.47E-03	3.23E-03	4.20E-03	6.12E-03	4.99E-03	4.86E-04	9.41E-03
ADPf	MJ	-1.12E+03	5.10E+02	-1.28E+03	-1.23E+02	8.61E+02	1.97E+02	5.65E+03	9.07E+02
AP	kg SO_{2eq}	2.29E+00	2.80E+00	2.26E+00	2.52E+00	3.09E+00	2.75E+00	1.87E+00	5.38E-01
EP	kg $PO_4^{3-}{}_{eq}$	4.65E-01	1.59E+00	1.08E+00	1.53E+00	2.08E+00	1.69E+00	4.89E-01	2.38E-01
GWP	kg CO_{2eq}	-6.76E+02	2.53E+02	-3.74E+02	-2.68E+00	4.61E+02	1.55E+02	4.38E+02	8.07E+01
ODP	kg CFC-11_{eq}	-1.63E-05	2.06E-06	-1.43E-05	-3.34E-06	6.80E-06	-1.29E-07	5.74E-05	7.53E-06
POFP	kg C_2H_{4eq}	2.04E-02	1.08E-01	2.60E-02	5.12E-02	1.17E-01	8.04E-02	8.29E-02	2.71E-02
CED	MJ	3.97E+03	1.14E+04	7.56E+03	1.05E+04	1.42E+04	1.17E+04	8.72E+03	1.24E+03
$CED_{nr,f}$	MJ	-1.29E+03	5.10E+02	-1.45E+03	-1.71E+02	8.95E+02	1.72E+02	6.16E+03	9.76E+02
$CED_{nr,b}$	MJ	1.49E-01	1.46E-01	1.25E-01	1.16E-01	1.31E-01	1.27E-01	3.56E-02	3.21E-02
$CED_{nr,n}$	MJ	2.40E+02	2.25E+02	1.55E+02	1.38E+02	2.20E+02	1.85E+02	9.63E+02	1.18E+02
$CED_{r,b}$	MJ	4.74E+03	1.04E+04	8.65E+03	1.04E+04	1.29E+04	1.11E+04	3.00E+02	2.78E+01
$CED_{r,wat}$	MJ	2.03E+02	1.72E+02	1.51E+02	1.16E+02	1.60E+02	1.46E+02	8.59E+02	1.23E+02
$CED_{r,others}$	MJ	7.59E+01	6.17E+01	5.58E+01	4.00E+01	5.95E+01	5.30E+01	4.34E+02	3.87E+03

The energy and environmental performances of biogas electricity are strictly connected to the type of feedstock, which also affects the entity of the environmental credits. This result is highlighted in the graphical representation reported in supplementary materials (Fig. S2), which recalls the impact categories shown in Table 4 in percentage. In fact, despite the highest production of electricity, the cluster L-AP performs the worst eco-profile across all the assessed impact categories, essentially due to the silages production.

On the other hand, the best option is represented by the cluster S-BP, followed by M-BP, as it emerges for the impact categories analysed, with remarkable differences to the other three assessed clusters. This outcome highlights that biogas production from manure and slurry involves both the valorisation of zero-burden by-products and the remarkable environmental credits from avoiding manure and slurry storage emissions. However, such plants involve a higher impact associated with infrastructure per functional unit than the large ones.

The other assessed clusters (M-AB, L-AB), characterised by using agricultural products and by-products, present intermediate eco-profiles between small and large plants.

Only about AP and EP indicators, all the assessed cluster presents relatively slight differences. These results derive from the contributions of infrastructure, feedstock, and AD emissions.

Further, the average eco-profile, weighing the energy and environmental impacts on the electricity produced by each cluster, is carried out. Fig. 4 highlights the incidence of the different steps. This analysis confirms the relevance of agricultural feedstock production and AD emissions in affecting almost all the energy and environmental impacts. As the percentage of agricultural products increases in the AD feedstock, the contribution to the impact categories increases.

Without considering environmental credits, it can be observed that CED non-renewable (CED_{nr}) accounts only for 19 % of the total CED, while the remaining 81 % is essentially due to renewable biomass.

Table 4 shows the average eco-profiles of the five clusters understudy, weighing the energy and environmental impacts on the electricity produced by each clustered plant and considering the environmental credits. In addition, an average eco-profile is added, weighing the energy and environmental impacts on the electricity produced by each sampled plant. Table 4 includes the impacts of 1 MWh of electricity produced by the national mix (electricity from the national grid) and solar PV compared with other electricity generation systems (Muteri et al., 2020). The worst outcome is coloured in red for each row, while the best option is in white —the different shades of light red to pink show intermediate outcomes.

As can be deduced from Table 4, electricity from the national grid presents the worst performance in the most impact indicators (ADP_f,

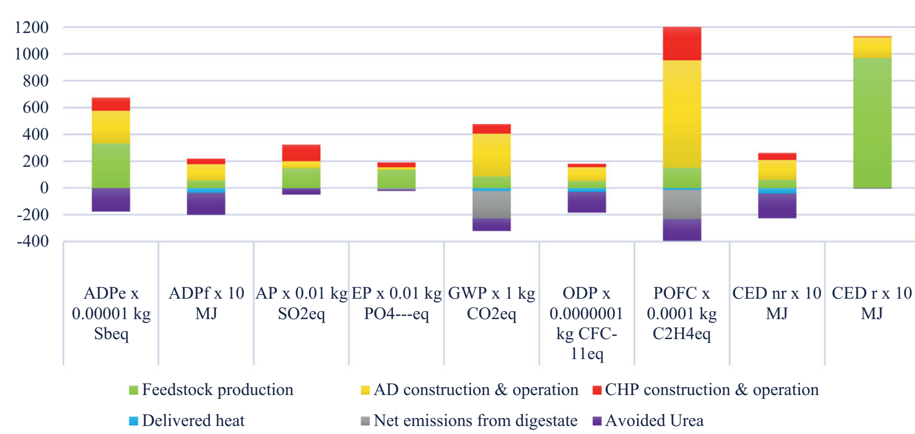

Fig. 4. Life-cycle impact steps contribution of the average eco-profile.

GWP, ODP, POFP, CED), essentially attributable to the enormous contribution of fossil fuels in the Italian electricity mix.

PV electricity presents the best in AP, EP, GWP, POFP, and CED, while the worst in ADP_e.

At least, taking into account the performances of the considered plants, biogas electricity shows the lowest contribution to ADP_f, and ODP, while affecting to a more significant extent AP and EP. Electricity from the grid has lower AP and EP than biogas electricity, respectively, by 32 % and 70 %.

Concerning GWP, the PV electricity eco-profile shows the lowest contribution to such an impact (about 81 $kgCO_{2eq}$/MWh), and the contribution from biogas electricity (155 $kgCO_{2eq}$/MWh) is about 35 % of the national grid.

Concerning the biogas electricity, taking into account the credits arising from avoiding mineral fertilizers use and from delivering surplus heat, the contribution in CED is at an average higher than the national grid and solar PV, except for S BP and M BP cluster, where the contribution to CED is, respectively, 46 % and 87 % of the grid one.

However, the contribution to the overall CED is affected by CED renewable from biomass ($CED_{r,b}$) for 95 %.

About CED non-renewable fossil demand ($CED_{nr,f}$), in the Italian electric grid $CED_{nr,f}$ accounts for about 70 % of the total CED.

Without considering the environmental credits, all the assessed plants involve a reduction in non-renewable fossil energy from 44 % to 67 % of the Italian grid, translated into an average value of 62 % for the average profile.

This result underlines the influential role of biogas, as a renewable energy source from biomass, in reducing fossil fuels for electricity generation and, consequently, mitigating climate change. Even at the European level, using biomass for energy purposes could satisfy energy requirements, implying lower dependency on fossil fuels for many EU countries where biomass is a local resource.

4. Discussion of results

The outcomes reported in Table 4 highlight that the average biogas electricity could reduce non-renewable fossil energy demand by at least 62 % compared to grid electricity.

The cluster assessment points out that the energy and environmental performances of biogas electricity, including the related credits, are essentially affected by feedstock. In the case of agricultural products, impacts depend on agricultural procedures and cultivation management. In the case of by-products from livestock, such as manure and slurry, impacts depend on the correspondent handling conditions. Comparing the results to previous literature studies, it is worth noting that calculated emissions align with them. For example, focusing on GWP, the contribution of average biogas electricity (155 kg of CO_2/MWh) is less than that calculated by Ingrao et al. (2015), that focused only on one large plant of 1MWe fed by both agricultural products and by-products (43 % animal sewage, 20 % manure, 25 % silages and finally 12 % milling co-products, such as "tritello") and estimated that 1 MWh of electricity produced via cogeneration could emit 209 kg of CO_2 eq. The differences in results can be due to the plants' characteristics and yearly operation hours.

As highlighted by the life-cycle assessment results, relevant hotspots in biogas electricity are the uncontrolled emissions of anaerobic digestion due to the not captured biogas. These emissions affect GWP and reduce the biogas production yield. Thus, improvement efforts should be managed to reduce such uncontrolled releases through maintenance operations and further technological development.

Further, as shown by the hotspot analysis, the contribution of infrastructure to the environmental impact indicators is not negligible, particularly in the small AD-CHP plants, where their impact is relevant, as confirmed by literature (Bacenetti et al., 2016; Fantin et al., 2015).

Another critical issue is the digestate stored in open tanks before being applied as fertilizer on the farms close to the AD plants. The consideration of digestate as a valuable co-product in organic fertilization involves environmental benefits since it avoids the production of mineral fertilizers, involving a positive effect in almost all the impact categories due to the environmental credits arising not only from avoiding conventional urea but also animal slurry, being the emissions from digestate lower than from slurry. Therefore, the plants fed with livestock by-products present the best performances, thanks to the environmental credits arising from the digestate that replaces the conventional urea and slurry.

Conversely, the plants fed mainly with agricultural products have the worst energy and environmental performances.

Concerning the size of the AD-CHP plants, larger capacity involves worse energy and environmental performances in electricity production, even if they are the most efficient. The study shows that the large ones (> 500 kW), although they have higher energy production, are the worst-performing. This is since, to be operable, they have to be fed chiefly with agricultural feedstock, which has higher biogas yield than livestock by-products but involves more relevant impacts.

As highlighted by the study outcomes, small and medium plants fed with by-products have better eco-profiles. In this case, focusing on GWP, they represent the less impacting options compared to the national grid. This consideration can be extended to other impact categories (ADPf, ODP, and POFP).

5. Conclusions

LCA methodology was applied to anaerobic digestion – combined heat and power plants located in northern Italy and fuelled by different mixes of agricultural products and by-products from livestock.

The study mainly used primary data for the foreground system, collected on-field and site-specific feedstock composition, daily feedstock requirements, energy production and consumption, and plant operating conditions. Such data were integrated with secondary data to assess emissions related to digestate open storage and to evaluate environmental credits arising from digestate use as organic fertilizer, avoided slurry management and heat recovery.

The study outcomes provide a broad set of energy and environmental indicators and highlight the most significant hotspots in generating electricity from biogas.

Compared to electricity from the Italian grid, AD-CHP technology can reduce climate change, replace fossil fuels, and enhance energy self-sufficiency in the Italian context.

The above issues point out the need for future deepening to investigate different strategies of management in order to optimize the energy and environmental performance of the electricity generation from biogas, considering that the optimal performance is those related to small or medium plants mainly based on by-products. However, this option is not always possible, and often the available supporting mechanisms entail the construction of large plants to get the highest remuneration from the electricity sale to the grid. In this framework, sustainable agricultural and livestock activities could represent an excellent opportunity for regeneration in rural-urban areas (Caputo et al., 2020).

In conclusion, additional improvements could involve avoiding open storage tanks for digestate, exploiting the surplus heat, reducing agriculture products, and increasing waste, by-products, and cogenerated heat valorisation.

The potential impacts and benefits linked to other types of energy conversion should be evaluated depending on the particular context, e.g., the upgrading to biomethane and the production of hydrogen can be considered to reduce the impacts of the fossil fuel consumed for agriculture or other machines.

CRediT authorship contribution statement

Marina Mistretta: Conceptualization, Methodology, Data collection and curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Teresa Maria Gulotta**: Conceptualization, Methodology, Data collection and curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Paola Caputo**: Conceptualization, Methodology, Data collection and curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. **Maurizio Cellura**: Conceptualization, Methodology, Data collection and curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing.

All authors certify that they have participated equally in the work to take public responsibility for the content, including participation in the concept, methodology definition, data collection, analysis, manuscript writing and revision.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157012.

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