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Life Cycle Environmental Assessment of Energy Valorization of the Residual Agro-Food Industry

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Abstract: This study assesses the potential environmental impacts related to the energy valorization of agro-food industry waste thought the Life Cycle Assessment methodology (ISO 14040). The system examined consists of a real anaerobic digester coupled with a combined anaerobic digester and heat and power plant (AD-CHP) operating in Sicily. The analysis accounts for all the impacts occurring from the delivery of the biomass to the AD-CHP plant up to the electricity generation in the CHP. The main outcomes of the study include the eco-profile of the energy system providing electricity and the assessment of the contribution of each life cycle phase aimed at identifying the potential improvement area. The obtained results highlight that the direct emissions associated with the biogas combustion process in the CHP account for 66% of the impact on climate change, and feedstock transport contributes 64% to the impact on mineral, fossil fuels, and renewable depletion. The contribution to the impacts caused by the electricity consumption is relevant in many of the environmental categories examined. It ranges from a minimum of about 22% for climate change up to 82% for freshwater ecotoxicity. Then actions aimed at reducing electricity consumption can significantly improve the environmental performances of the energy system examined.

Keywords: residual biomass; energy valorization; life cycle assessment; environmental sustainability

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1. Introduction

The energy valorization of biomass (bioenergy) has been recognized as an effective solution to improve the security and the environmental sustainability of the European Union's energy supply [1] and to achieve the EU's renewable energy targets for 2030 and beyond [2].

Besides energy crops specifically grown for the production of biomass for energy uses (rapeseed, corn, sorghum, etc.), an alternative source of biomass is represented by bio-wastes and residues, like slurry and manure from livestock farming, as well as waste such as olive pomace, vegetable residues, slaughter residues, and fruit processing wastes from the agri-food transformation industry.

The residual biomasses are particularly interesting as an economic and sustainable biomass source. The production of energy from bioenergy crops can present various environmental issues [3–5]. For example, bioenergy crops can have a significant impact due to the need for intensive agricultural practices that involve the use of fertilizers and pesticides, the consumption of a large amount of water, etc. In addition, growing bioenergy crops in an irrigated agriculture area may also result in increased competition for land and water resources with impacts on local food security of the Food and Agriculture Organization of the United Nations (FAO) [6]. In this context, residual biomasses are acquiring a key role in bioenergy production.

The energy valorization of biomasses through an anaerobic digestion process (AD) transforms the organic substance into biogas, a mixture consisting of 50–70% methane (CH_4), and for the remaining part, carbon dioxide (CO_2) and other components (hydrogen sulfide, ammonia, and hydrogen) [7].

The biogas produced in the anaerobic digester, after a purification treatment, can be used for the generation of electrical or thermal energy, or for the simultaneous generation of both forms of energy in cogeneration plants (CHP). Moreover, the upgrade of biogas increases the concentration of CH_4 in the mixture allowing one to obtain a gas with similar characteristics to natural gas (biomethane) compatible with the injection to the national gas grid [8–10].

Although the energy valorization of residual biomasses avoids the land and chemicals use issues associated with energy crops [11], other environmental issues are related to the biomass transport, and the operation phase of the AD and power plants requires deeper analysis of the environmental performance of these energy systems.

In order to assess the environmental impacts of biomass energy valorization chains, the Life Cycle Assessment (LCA) methodology has been applied in Europe and worldwide since it is widely recognized as the best framework for assessing the potential environmental impacts of products, processes, and systems [12–15]. LCA is a methodology based on a scientific approach, internationally standardized by the standards of the series ISO 14040 [16,17]. LCA allows for estimating the energy and environmental performance during the entire life cycle of a system under examination.

Two extensive literature reviews on LCA applied to energy valorization of the biomass supply chain have been carried out by Fantin et al. [18] and Bacenetti et al. [12]. The reviews highlighted that:

- Few studies model foreground processes using only primary data (such as [19–23]); in fact, most of them are mainly based on data from field reports and studies often integrated with data taken from environmental databases (such as [24–27]).
- Most of the studies reviewed focus on a CHP plant size of 500 kW and few below 100 kW;
- Most of them consider a limited number of impact categories (such as [20,28–30]).

In this context, the authors perform an LCA study in order to estimate the environmental impacts of the electricity generation in a real anaerobic digestion–combined heat and power plant (AD–CHP) and to identify the environmental hotspots. The AD is fueled with residual biomasses from the agro-industry sector and the produced biogas is injected in a 100 kW CHP.

In relation to the literature examined, the analysis is carried out by using mainly primary data collected by means of questionnaires and interviews with the plant owners and operators. The plant is modeled considering the real operating conditions. In addition, some strategies for improving the operating conditions are investigated in order to highlight the potential environmental benefits that can be obtained. Finally, a wide range of environmental impact categories are investigated.

The obtained results can represent a useful support for policy makers in the strategic planning of bio-waste management systems [23,31] and for the agro-industry sector stakeholders in the introduction of new technologies for bio-waste management and marketing purposes.

2. Materials and Methods: Life Cycle Assessment

The authors apply an attributional LCA approach in compliance with the international standards of series ISO 14040 [16,17]. The attributional LCA is based on a life cycle inventory (LCI) frame that inventories the input and output flows of all processes of the system examined as they occur [32].

1. The LCA methodology operates with four separate phases [16,17]: Goal and scope definition. The goal sets the decision context and the intended application of the study. During the scope definition, the object of the LCA study is identified and described in detail and all methodological aspects of the LCA study are set (such as functional unit, system boundaries, data quality, etc.);
2. Life cycle inventory (LCI). During this phase, information about the physical flows in terms of input of resources, materials, products, and the output of emissions, waste, and valuable products for the product system are collected. The result of the PCI

phase is the inventory table that lists the inputs and the outputs of elementary flows of the product system;
3. Life cycle impact assessment (LCIA). In this phase, the elementary flows that have been assessed in the inventory analysis are translated into impacts on the environment;
4. Life cycle interpretation. In this phase, the findings of either the LCI or LCIA are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

2.1. Goal and Scope Definition

The main goals of the study are:

- To estimate the potential environmental impacts and benefits related to the energy valorization of residual biomass derived from the agro-food industry through an anaerobic digester (AD)–combined heat and power plant (CHP) system (AD–CHP);
- To assess the contribution of each life cycle phase to the overall impacts.

The examined AD-CHP is a real system operating in Sicily (Italy) since 2016. The average operational time is 7920 h per year (330 days per year). The anaerobic digestion occurs in a continuous stirred-tank reactor through a single-stage process and under mesophilic conditions (40 °C). The plant utilizes several residual biomasses available in situ and at short-to-medium distance. The feedstocks are pre-mixed in a feeding tank in order to obtain a homogeneous mixture entering the AD. In the AD, the feedstock is mechanically mixed, and it is heated through a heat exchanger that recovers the thermal energy generated by the CHP. The outputs of the anaerobic digestion process are biogas and digestate (that can be used as fertilizer [33]). The volume of digestate is around 90–95% of that fed into the digester.

The biogas produced is stored in the gasholder dome placed on the top of the digester. Before being fed into the CHP, the biogas is desulfurized, filtered, and dehumidified in a chiller. The purified biogas is fed into the CHP to generate electrical and thermal energy. The electricity generated is partially fed into the national grid and partially used by the product system investigated. The heat is partially recirculated to fulfil the requirement of the digester and the surplus is wasted into the atmosphere.

The main technical characteristics of the AD and CHP plants are recapped in Table 1.

Table 1. Main technical characteristics of the AD and CHP plants.

AD Parameter	**Value**
Net volume (m^3)	1300 *
CHP parameter	**Value**
Electric power (kW)	100 **
Electrical efficiency (%)	37.3 **
Thermal power (kW)	138 **
Thermal efficiency (%)	51.5 **

* Plant owner's data; ** CHP data sheet available at www.mtmenergia.com (accessed on 25 August 2021).

The functional unit (FU) is 1 kWh of electricity generated by the energy system under investigation. The system boundaries include the transport of the feedstocks that are not locally available to the plant; the "sulla" silage production; the anaerobic digestion process; the combustion of biogas in the CHP unit, and the production processes of the materials employed in the infrastructures. The flow chart of the examined energy system and the unit processes included within system boundaries are illustrated in Figure 1.

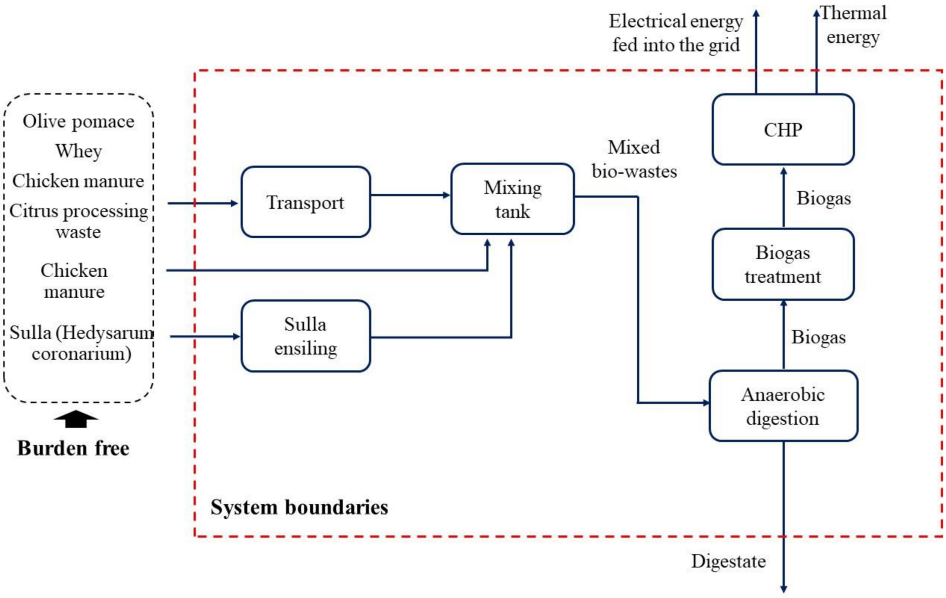

Figure 1. Energy system flowchart and system boundaries.

The environmental burdens are entirely allocated to electrical energy as the surplus thermal energy and the digestate are discharged as waste [34].

The production processes of olive pomace, whey, citrus processing waste, chicken, and bovine manure are not included within the system boundaries. In fact, since they are the waste of other production processes, a zero-burden approach is assumed and then only the impact related to their transportation is accounted for in the examined system [22]. Concerning "sulla", it is assumed that it grows spontaneously, and only the impact related to the silage production process is considered.

Other assumptions concern the AD and CHP lifetimes. The useful lifetime of the AD plant is assumed to be 20 years [34,35], while for the CHP plant, a lifetime of 10 years is assumed [34].

The impact assessment is based on the ILCD 2011 midpoint method and impact categories recommended by the European Commission [36]. The selected impact categories are listed in Table 2.

Table 2. Impact categories.

Impact Category	Acronym
Global Warming Potential ($kgCO_{2eq}$)	GWP
Ozone Depletion potential ($kgCFC\text{-}11_{eq}$)	ODP
Human toxicity–cancer effect (CTUh)	HT-nce
Human toxicity–cancer effect (CTUh)	HT-ce
Particulate Matter ($kg\ PM2.5_{eq}$)	PM
Ionizing Radiation–human health ($kBqU^{235}{}_{eq}$)	IR-hh
Ionizing Radiation–ecosystem (CTUe)	IR-e
Photochemical Ozone Formation Potential ($kgNMVOC_{eq}$)	POFP
Acidification Potential ($molH^{+}{}_{eq}$)	AP
Terrestrial Eutrophication ($molN_{eq}$)	EU_T
Freshwater Eutrophication (kgP_{eq})	EU_F
Marina Eutrophication (kgN_{eq})	EUM
Freshwater Ecotoxicity (CTUe)	E_{FW}
Land use ($kg\ C_{deficit}$)	LU
Water resource depletion ($m^3{}_{water}$)	WRD
Mineral Fossil and Renewable Resource Depletion ($kgSb_{eq}$)	MFRRD

To evaluate how the methodological choices relate to the multifunctionality management, the impact assessment method, and the uncertainty of the LCI data, and how this affects the life cycle impact assessment results, a sensitivity analysis is carried out. Concerning the multifunctionality management, the substitution approach by system expansion is applied according to the ISO 14044 hierarchy. In detail, it is hypothesized that the surplus of thermal energy can be used, avoiding the production of an equivalent amount of thermal energy from an alternative energy system producing thermal energy. Concerning the digestate, it is assumed that it can be used as fertilizer, avoiding the production of a functional equivalent amount of mineral fertilizer. Moreover, to assess how the impact assessment method affects the results of the LCA, further evaluation is carried out applying the EF 3.0 method (adapted) developed within the environmental footprint initiative [37]. Finally, Monte Carlo simulation is applied to estimate the uncertainties in the LCIA results introduced by the statistical variability or temporal, geographical, or technological gaps in the LCI data [38–40]. Moreover, a sensitivity analysis is carried out to assess how the most contributing processes affect the obtained results, increasing/decreasing the related values by 30%.

2.2. *Life Cycle Inventory (LCI) Analysis*

The following paragraphs illustrate data collection and elaboration for obtaining the inventory of the examined system. The energy system is modelled by using primary data collected via questionnaires and interviews with the plant managers and operators and through assumption based on the scientific literature in this area. In addition, secondary data from the Ecoinvent 3.6 database are employed [35] for modelling materials and energy sources (background processes) used in the examined energy system. The recycled content, or cut-off, approach is used to compile the LCI.

Unless otherwise specified, the system's energy consumption is estimated based on the rated power and the operation hours declared by the plant managers and operators. It is assumed that the electrical energy required for plant operation is partially satisfied by the CHP plant. The remaining electricity requirements are satisfied by purchasing electricity from the grid. According to the literature, it is assumed that a percentage equal to 8% of the electricity generated by the CHP is consumed within the product system [22,41].

2.2.1. Feedstock Supply

The feedstocks employed consist of olive pomace, whey, chicken manure, citrus processing waste, bovine manure, and "sulla" (Hedysarum coronarium) silage. The unit process "feedstock supply" involves the "sulla" silage production, the mixing process, and the mixing tank construction.

According to the recycled content approach, only the burdens associated with the sulla ensiling and to the residual biomass transportation processes are considered within the feedstock supply life cycle phase.

The "sulla" silage production is modelled according to Bacenetti and Fusi [42] assuming maize silage production as a proxy for "sulla" silage production. The feedstocks not locally available are transported to the plant by truck. The construction process of the mixing tank is modelled based on the technical design report of the plant. The useful lifetime of the mixing tank is assumed to be 20 years. Within the mixing tank, the feedstock is homogenized through a 11 kW mechanical stirrer operating 20 h/day.

Table 3 shows the types of substrates used in the AD plant and the transport distance for each feedstock. These data are based on plant owner's primary data.

2.2.2. Anaerobic Digestion

The anaerobic digestion unit process involves the anaerobic digestion plant and the necessary treatments before feeding the biogas into the CHP.

The feedstock is fed into the AD by means of a centrifugal pump. The daily biomass entering the digester is about 17 tons (Table 4). The biomass within the AD is mixed by

3 mechanical stirrers. Two have a rated power of 9 kW and work 20 h/day, while one has a rated power of 11 kW and works 4 h/day.

Table 3. Feedstock supply.

Feedstock	Amount (ton/Day)	Transport Distance (km)
Olive pomace	0.7	25
Whey	8.4	60
Chicken manure	1.9	100
Citrus processing waste	4.0	200
Bovine manure	0.9	Local
Sulla (Hedysarum coronarium) silage	1	Local

Table 4. Data collection and elaboration results.

Life Cycle Phase	Amount	Type of Data	Ecoinvent 3.6 Dataset Selected for LCI Modelling
Feedstock supply			
Feedstock (t/d)	1.7×10^{1}	Own calculations based on plant owner's data	Burden free
Sulla ensiled	1.0×10^{0}	Literature data [42]	(See Table 3)
Transport (tkm/d)	1.5×10^{3}	Own calculations based on plant owner's data	Transport, freight, lorry 16–32 metric ton (EURO 6)
Operational phase			
Electricity–mixing tank (kWh/d)	2.2×10^{2}	Own calculations based on plant owner's data	92% Electricity low voltage (IT), 8% self-consumption from CHP
Electricity–AD (kWh/d)	5.2×10^{2}	Own calculations based on plant owner's data	92% Electricity low voltage (IT), 8% self-consumption from CHP
Electricity–Biogas treatment (kWh/d)	1.2×10^{2}	Own calculations based on plant owner's data	92% Electricity low voltage (IT), 8% self-consumption from CHP
Electricity–CHP (kWh/d)	3.6×10^{1}	Own calculations based on plant owner's data	100% Electricity low voltage (IT)
Thermal energy–CHP (kWh/d)	8.8×10^{2} [a]	Own calculations based on plant owner's data	Self-consumption (AD process)
Lubricant oil–CHP (kg/d)	2.3×10^{0}	Own calculations based on plant owner's data	Lubricating oil production
Direct emissions			
Carbon dioxide biogenic–AD (kg/d)	1.2×10^{1}	Own calculations based on plant owner's data and literature data	Elementary flows
Carbon dioxide biogenic–Biogas treat. (kg/d)	6.0×10^{0}	Own calculations based on energy system owner's and literature data	Elementary flows
Carbon dioxidebiogenic–CHP (kg/d)	1.57×10^{3}	Literature data [35]	Elementary flows
Carbon monoxidebiogenic–CHP (kg/d)	9.1×10^{-1}	Literature data [35]	Elementary flows
Nitrous oxide–CHP (kg/d)	4.7×10^{-1}	Literature data [35]	Elementary flows
Methane, biogenic–AD (kg/d)	4.5×10^{0}	Own calculations based on plant owner's data	Elementary flows
Methane, biogenic–Biogas treat. (kg/d)	2.2×10^{0}	Own calculations based on plant owner's data	Elementary flows
Methane, biogenic–CHP (kg/d)	4.3×10^{-1}	Literature data [35]	Elementary flows
NMVOC–CHP (kg/d)	3.8×10^{-2}	Literature data [35]	Elementary flows
Platinum–CHP (kg/d)	1.3×10^{-7}	Literature data [35]	Elementary flows
Sulfur dioxide–CHP (kg/d)	4.7×10^{-1}	Literature data [35]	Elementary flows
Capital good			
Cement–mixing tank (tons)	2.8	Own calculations based on plant owner's data	Concrete block, production
Cement–AD (tons)	4.8×10^{2}	Own calculations based on plant owner's data	Concrete block, production
Polystyrene–AD (tons)	1.1×10^{0}	Own calculations based on plant owner's data	Polystyrene foam slab for perimeter insulation, production
Steel–AD (tons)	2.4×10^{1}	Own calculations based on plant owner's data	Reinforced steel, production

Table 4. *Cont.*

Life Cycle Phase	Amount	Type of Data	Ecoinvent 3.6 Dataset Selected for LCI Modelling
Output			
Electrical energy (kWh/d)	$2.2 \times 10^{3\,b}$	Own calculations based on plant owner's data	-
Thermal energy (kWh/d)	$2.5 \times 10^{3\,c}$	Own calculations based on plant owner's data	-
Digestate (tons/d)	1.5×10^{1}	Own calculations based on plant owner's data	-

[a] Average value calculated on an annual basis; [b] Net value, excluded the electrical energy self-consumed; [c] Net value, excluded the thermal energy self-consumed.

The process temperature is maintained at 40 °C (mesophilic conditions) by means of the thermal energy recovered from the CHP through the heat recovery circuit consisting of two pumps of 4 and 0.25 kW rated power operating 24 h/day. The thermal energy required is estimated based on the amount of biomass introduced in the AD and its specific heat capacity, the difference between the temperature inside the digester and the average local temperature, and the dispersion of heat from the digester walls, foundation, and gasholder dome. The estimated thermal energy demand ranges from 499.06 kWh/day in the summer season to 1189.75 kWh/day in the winter season. The thermal energy demand is entirely satisfied by the CHP.

The AD is made of reinforced concrete and has a polystyrene external insulation. Data about the amount of construction materials are inferred from the technical design report of the AD-CHP plant. The useful lifetime of the AD plant is assumed to be 20 years [34,35].

The biogas is stored within the gasholder dome that reaches a maximum height of 5 m from the base of the digester and it is maintained at maximum volume thanks to the injection of air by means of a pumping unit (0.5 kW, operating 24 h/day) with a pressure switch control. The daily biogas production is 1341 m^3/day. Methane content represents about 50% of the biogas volume. According to the literature, biogas leakages from AD plants are considered equal to 1% of biogas produced [21,28,43]. The biogas leakages are modelled as direct emissions associated with the anaerobic digestion process. The amount of digestate produced in the AD is equal to 15.33 tons/day.

Before being fed in the CHP, the biogas is desulfurized, filtered, and dehumidified. The desulfurization process takes place inside the AD and consists of biological desulphurization by air injection into the gasholder [43]. The insufflation occurs by means of a 0.7 kW pump operating 24 h/day. The biogas dehumidification takes place in a 5 kW chiller. It is hypothesized that biogas leakage equal to 0.5% of the volume treated occurs during the biogas purification processes [44]. Biogas leakages are modelled as direct emissions associated to the biogas treatment process.

2.2.3. CHP

Biogas is burnt in the CHP internal combustion engine. It is injected into the CHP though a 1.5 kW pump operating 24 h/day. The thermal and electrical energy generated are calculated based on the thermal and electrical efficiency of the engine (Table 1), the biogas entering the CHP daily (1321 m^3/day) with a low heating value of about 17.64 MJ/m^3. The thermal and electrical energy generated are, respectively, 3333.51 kWh/day and 2407.89 kWh/day. Considering an operational time of 330 days per year (see Paragraph 2.1), the electrical energy potentially generated in a timeframe of 20 years is 1.6×10^7 kWh.

Biogas leakages from the CHP engine are considered equal to 0.5% of the biogas combusted, while the emissions related to the combustion process are based on the Ecoinvent 3.6 database [35].

The Life Cycle Inventory (LCI) for the CHP plant construction and disposal are inferred from the Ecoinvent 3.6 database. Due to a lack of primary data, the emissions into the air (direct emissions) associated with the biogas combustion within CHP (operational phase) are assumed equal to those reported in Ecoinvent 3.6 for the process "Electricity, high voltage {IT}∣ heat and power co-generation, biogas”. The useful lifetime of the CHP plant is assumed to be 10 years [34].

Data collection and elaboration results are recapped in Table 4.

Figure 2 synthetizes the quantified input and output for each unit process included in the analysis.

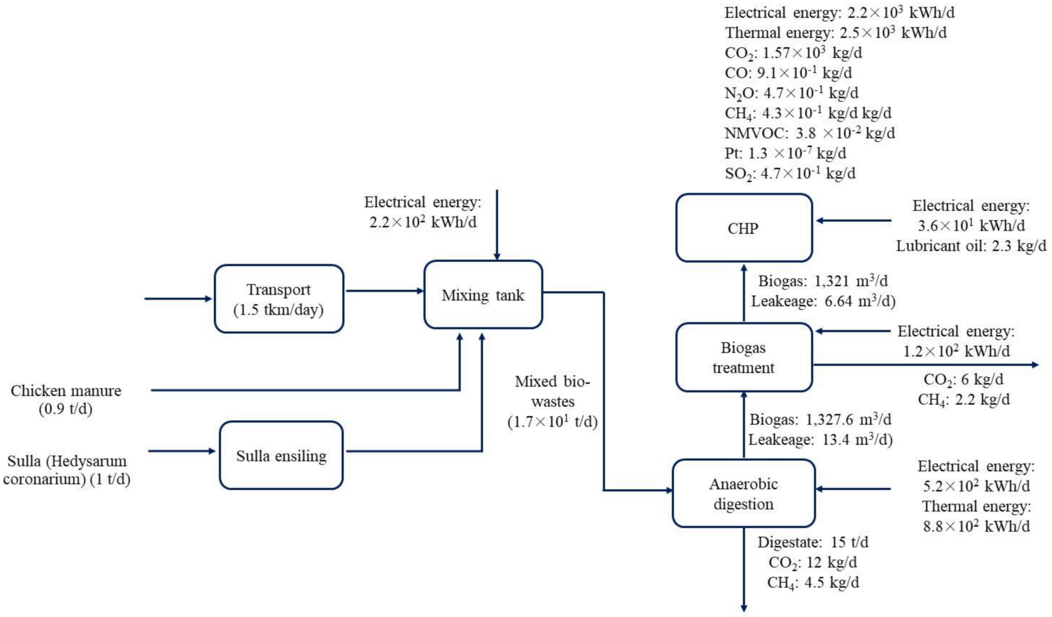

Figure 2. Input and output of the energy system unit processes.

3. Results and Discussion

3.1. Life Cycle Impact Assessment and Interpretation

The life cycle impact assessment results of the selected FU are illustrated in Table 5. The contribution of the feedstock supply, operational phase (electrical energy and lubricant oil consumption), direct emissions, and capital good to the overall impact is detailed in Figure 3.

Table 5. Life cycle impact assessment results referring to the FU (1 kWh of electricity generated by the energy system).

Impact Category	Total
GWP ($kgCO_{2eq}$)	1.06×10^{0}
ODP ($kgCFC\text{-}11_{eq}$)	3.85×10^{-8}
HT–nce (CTUh)	5.71×10^{-8}
HT–ce (CTUh)	1.12×10^{-8}
PM (kg $PM2.5_{eq}$)	1.13×10^{-4}
IR–hh ($kBqU^{235}{}_{eq}$)	2.59×10^{-2}
IR–e (CTUe)	9.79×10^{-8}
POFP ($kgNMVOC_{eq}$)	8.21×10^{-4}
AP ($molH^{+}{}_{eq}$)	1.54×10^{-3}
EU_T ($molN_{eq}$)	3.05×10^{-3}
EU_F (kgP_{eq})	4.98×10^{-5}
EU_M (kgN_{eq})	2.29×10^{-4}
E_{Fw} (CTUe)	5.44×10^{0}
LU ($kgC_{deficit}$)	7.81×10^{-1}
WRD ($m^3{}_{water}$)	1.41×10^{-3}
MFRRD ($kgSb_{eq}$)	5.46×10^{-6}

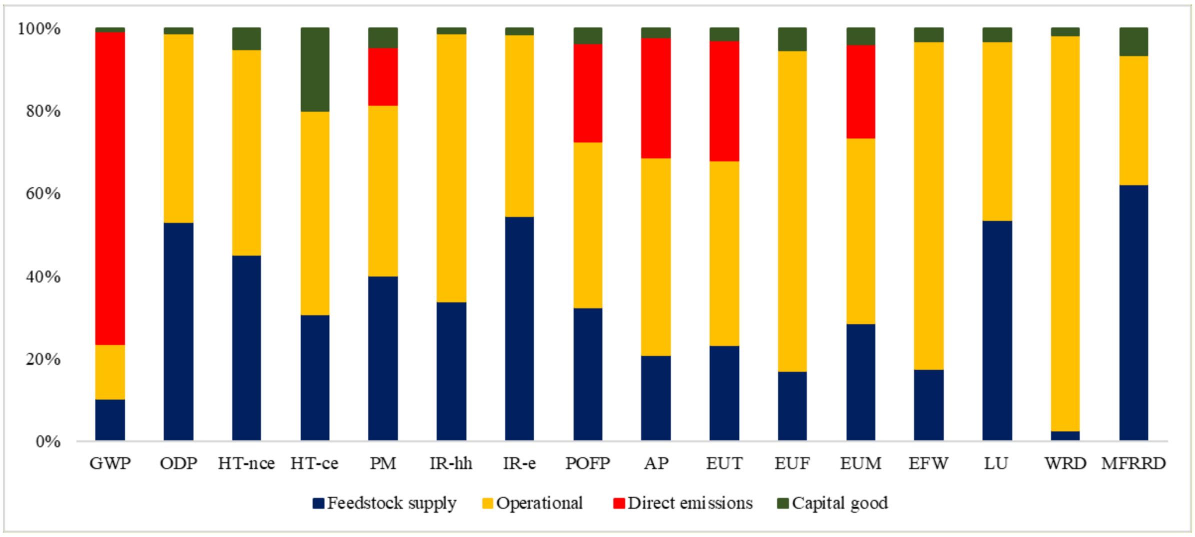

Figure 3. Contribution of feedstock supply, operational phase, direct emissions, and capital good.

The process contribution analysis highlights that the feedstock supply, including the transport of the different feedstocks to the plant and the "sulla" ensiling process, represents a significant share in almost all the investigated impact categories (Figure 1). Specifically, it contributes more than 50% to mineral fossil fuels and renewable depletion (64%), ozone depletion potential (53%), and land use (53%). The feedstock transport is responsible for the highest contribution. In detail, it contributes to the impact with percentages ranging from a minimum value of 2.5% (for water resource depletion) to a maximum value of 62% (for mineral fossil fuels and renewable depletion). The "Sulla" ensiling process represents a percentage lower than 0.5% in all the examined impact categories.

Concerning the transport process, deeper analysis shows that the lead and zinc used for lorry construction and maintenance phases are responsible for the highest contribution to mineral fossil fuels and renewable depletion.

This outcome is consistent with previous LCA studies on energy valorization of residual biomass [12]. Then, reducing the transport distance for residual biomass supply chain can significantly improve the environmental performance of the examined energy system. The comparison of the energy valorization of bio-wastes through an AD-CHP system with other systems is complex because of differing assumptions, in terms of both the method (e.g., functional unit, system boundary, impact categories assessment, credits for co-products, accounting for biogenic carbon contribution on GWP, etc.), feedstock in input (energy crops, residual biomasses or a mix of them), and obtained products (biogas, bio-char [45], syngas [46]). The comparison with LCA studies on an AD-CHP plant fueled with bio-wastes is carried out referring only to the GWP impact category since this is the only environmental category investigated in all the studies analyzed. The comparison highlights that the impact on GWP from the literature (about 2.10×10^{-1} kg CO_{2eq} [3,34,47] is lower than the value obtained in this study (1.06 kg CO_{2eq}). However, contrary to this study, the cited LCAs [3,34,47] do not account for CO_2 emissions associated with biogas combustion in the CHP since they are considered carbon neutral. There is no consensus in the scientific community on this aspect [44,48]. Considering the importance of the valorization of residual biomasses in the transition to a circular economy, the issue of climate neutrality of biogenic carbon must be investigated and regulated.

The plant operational phase includes the electrical energy consumed for mixing the biomass, and during the anaerobic digestion, biogas treatment, and energy generation (CHP) processes, and the lubricant oil consumption. The contribution of the electricity consumption to the different impact categories is relevant. It ranges from a minimum of about 13% for climate change up to 95% for water resource depletion. Moreover, it contributes percentages higher than 60% to freshwater ecotoxicity (about 80%), freshwater eutrophication (77%), and ionizing radiation on human health (63%). The highest contributions are related to the electricity consumed during the anaerobic digestion process (more than 50%). Then the transition towards an electricity mix with a high share of renewable energy source can significantly improve the environmental performance of the system examined [49].

The lubricant oil represents a contribution lower than 2% to all the examined impact categories.

Direct emissions are responsible for the highest impact in climate change (76%). In addition, they contribute about 30% to acidification potential and terrestrial eutrophication, about 25% to photochemical ozone formation potential and marine eutrophication, and 15% to particulate matter. To climate change, the larger contribution (90%) is represented by the emissions of biogenic carbon dioxide during the biogas combustion in the CHP. Biogenic CO_2 emissions are not considered climate neutral in the ILCD 2011 midpoint method. There is no clear consensus among scientists on the “neutrality” of biogenic carbon [48,50]. In order to highlight how this assumption affects the obtained results, in the sensitivity analysis, the impacts are evaluated with the EF 3.0 method (adapted) in which the contribution to climate change of the CO_2 biogenic emissions is assumed zero.

Finally, the impact of capital goods to the different impact categories is generally low, with the exception of the human toxicity–cancer effect impact category in which they contribute 20%.

Biomass transport distance and electricity consumed during the plant’s operational phase are the most contributing processes to the overall life cycle impact then they are relevant parameters in the sensitivity analysis.

The LCIA results are elaborated to obtain a single score representing synthetic information of the environmental impact of the energy system examined. The normalization and weighting of the impacts are based on the EC-JRC Global, equal weighting of the ILCD 2011 Midpoint method. The environmental score in reference to the FU is 208.9 µPt. The contribution of each impact category is detailed in Table 6.

Table 6. Normalized life cycle impact assessment results referred to the FU (1 kWh of electricity generated by the energy system).

Impact Category	Unit	Total
GWP	µPt	$1.00 \times 10^{+1}$
ODP	µPt	2.10×10^{-1}
HT–nce	µPt	$2.45 \times 10^{+1}$
HT–ce	µPt	$6.00 \times 10^{+1}$
PM	µPt	1.48×10^{0}
IR–hh	µPt	7.15×10^{0}
POFP	µPt	1.21×10^{0}
AP	µPt	1.83×10^{0}
EU_T	µPt	1.24×10^{0}
EU_F	µPt	5.08×10^{-1}
EU_M	µPt	5.01×10^{-1}
E_{FW}	µPt	$9.69 \times 10^{+1}$
LU	µPt	1.00×10^{-2}
WRD	µPt	1.36×10^{0}
MFRRD	µPt	1.89×10^{0}

Data analysis highlights that the highest contribution to the environmental score is associated with the freshwater ecotoxicity (about 50%), followed by the human toxicity–cancer effect (about 29%) and the human toxicity–no cancer effect (12%).

3.2. Sensitivity and Uncertainty Analysis

This section illustrates and discusses the results of the sensitivity analysis performed to assess how the methodological choices related to the multifunctionality management approach and how the selected impact assessment method affects the obtained LCIA results. Moreover, the results of Monte Carlo simulation for the uncertainty analysis of increasing/decreasing the transport distance and the electricity consumed during the operational phase by 30% is illustrated and discussed.

With reference to the LCIA method, Table 7 shows the LCIA results calculated with the EF 3.0 method (adapted) and the percentage variations with respect to those calculated with the ILCD 2011 method. Only the impact categories expressed in the same unit of measure in both EF 3.0 and ILCD 2011 methods are included in the analysis.

Table 7. Sensitivity analysis results—Life cycle impact assessment results in reference to the FU (EF 3.0 method/percentage variations compared to the LCIA results calculated with the ILCD 2011 method).

Impact Category EF/ILCD	EF	Percentage Variation (EF-ILCD)/ILCD
CC ($kgCO_{2eq}$)	3.72×10^{-1}	−65.0%
ODP ($kgCFC\text{-}11_{eq}$)	4.51×10^{-8}	17.2%
IR/IR–hh ($kBqU^{235}{}_{eq}$)	2.59×10^{-2}	0.%
POFP ($kgNMVOC_{eq}$)	8.37×10^{-4}	2.0%
HT–nce (CTUh)	3.55×10^{-9}	−93.8%
HT–ce (CTUh)	1.06×10^{-10}	−99.0%
AP ($molH^{+}{}_{eq}$)	1.54×10^{-3}	0.%
EU_F (kgP_{eq})	4.96×10^{-5}	−0.5%
EU_M (kgN_{eq})	2.29×10^{-4}	0.%
EU_T ($molN_{eq}$)	3.05×10^{-3}	−0.1%
E_{FW} (CTUe)	4.12×10^{0}	−24.2%
WRD (m^3 water)	8.57×10^{-2}	5995.1%
MFRRD/$RU_{m\&m}$ ($kgSb_{eq}$)	4.59×10^{-6}	−15.9%

The impact on climate change associated with the selected FU decreases by 65% if calculated with the EF 3.0 method. In contrast to the ILCD 2011 method, EF 3.0 assumes that biogenic CO_2 emissions are climate neutral, so the impact on climate change decreases. The percentage variations are significant for human toxicity impact categories (higher than 90%) and not negligible for freshwater ecotoxicity (24%). The impact on resource consumption calculated with the EF 3.0 method decreases by about 16%, and this reduction is related to the fact that in contrast to the EF 3.0 method, the ILCD 2011 method includes the consumption of renewable energy resources (not considered within EF 3.0 method) and non-renewable energy resources (calculated with a specific indicator in the EF 3.0 method). The impact on water resource depletion is not comparable since, contrary to the EF 3.0 method, the ILCD 2011 method does not account for the water available after deducing current demand [51].

These results confirm the importance of comparing product systems providing the same function based on the LCIA results calculated with the same impact assessment method and the importance of transparency in the LCA to avoid misleading and wrong conclusions.

Concerning the multifunctionality management, Table 8 shows the environmental credits arising from avoiding the production of the mineral fertilizer displaced by the digestate and the thermal energy substituted by the surplus from the energy system examined, and the percentage reductions of the impact obtained in the expanded system compared to the reference one. The environmental credits for the avoided thermal energy and mineral fertilized production allow a reduction of the impact ranging from 10.7% (for WU) to 100% (for ODP). These results demonstrate the importance of a fully circular management of the co-products generated by productive processes. Moreover, they can be a useful support in planning sustainable agriculture practices [52].

Table 8. Sensitivity analysis results—Life cycle impact assessment results referred to the FU (EF 3.0 method/percentage variations compared with the LCIA results calculated with the ILCD 2011 method).

Impact Category EF/ILCD	Environmental Credits for Avoided Mineral Fertilizer	Environmental Credits for Avoided Thermal Energy Production	LCIA–ExS *	Percentage Variation (RS **-ExS)/ExS
CC ($kgCO_{2eq}$)	-8.41×10^{-2}	-3.96×10^{-1}	5.85×10^{-1}	−45%
ODP ($kgCFC\text{-}11_{eq}$)	-3.59×10^{-9}	-3.49×10^{-8}	-3.38×10^{-11}	−100%
IR/IR–hh ($kBqU^{235}{}_{eq}$)	-2.47×10^{-8}	-1.39×10^{-8}	1.85×10^{-8}	−68%
POFP ($kgNMVOC_{eq}$)	-2.36×10^{-9}	-3.93×10^{-9}	4.87×10^{-9}	−56%
HT–nce (CTUh)	-2.94×10^{-5}	-2.69×10^{-5}	5.64×10^{-5}	−50%
HT-ce (CTUh)	-2.12×10^{-3}	-4.94×10^{-3}	1.88×10^{-2}	−27%
AP ($molH^{+}{}_{eq}$)	-8.43×10^{-9}	-1.55×10^{-8}	7.40×10^{-8}	−24%
EU_F (kgP_{eq})	-1.84×10^{-4}	-3.96×10^{-4}	2.40×10^{-4}	−71%
EU_M (kgN_{eq})	-4.65×10^{-4}	-4.54×10^{-4}	6.23×10^{-4}	−60%
EU_T ($molN_{eq}$)	-1.41×10^{-3}	-8.85×10^{-4}	7.54×10^{-4}	−75%
E_{FW} (CTUe)	-1.19×10^{-5}	-1.27×10^{-5}	2.53×10^{-5}	−49%
WRD ($m^3{}_{water}$)	-6.78×10^{-5}	-8.34×10^{-5}	7.73×10^{-5}	−66%
MFRRD/$RU_{m\&m}$ ($kgSb_{eq}$)	-1.92×10^{0}	-1.05×10^{0}	2.47×10^{0}	−55%

* Expanded scenario including environmental credits from avoiding mineral fertilizer and thermal energy production; ** Reference scenario without environmental credits.

Table 9 presents the main results of the Monte Carlo analysis, describing the mean value, standard deviation, coefficient of variation, and 95% confidence interval (the 2.5th percentile and the 97.5th percentile).

Table 9. Uncertainty analysis results.

Categoria D'impatto	Mean Value	Standard Deviation	Coefficient of Variation (%)	2.5th Percentile	97.5th Percentile
GWP ($kgCO_{2eq}$)	1.07×10^{0}	2.09×10^{-2}	2.0	1.03×10^{0}	1.11×10^{0}
ODP ($kgCFC\text{-}11_{eq}$)	3.83×10^{-8}	9.83×10^{-9}	25.7	2.37×10^{-8}	6.40×10^{-8}
HT–nce (CTUh)	5.63×10^{-8}	4.47×10^{-8}	79.4	-2.78×10^{-8}	1.49×10^{-7}
HT–ce (CTUh)	1.05×10^{-8}	5.04×10^{-9}	47.9	5.48×10^{-9}	2.39×10^{-8}
PM (kg $PM2.5_{eq}$)	1.14×10^{-4}	1.14×10^{-5}	10.0	9.62×10^{-5}	1.38×10^{-4}
IR–hh ($kBqU^{235}{}_{eq}$)	2.56×10^{-2}	1.85×10^{-2}	72.0	1.06×10^{-2}	7.02×10^{-2}
IR–e (CTUe)	9.76×10^{-8}	2.80×10^{-8}	28.6	5.60×10^{-8}	1.63×10^{-7}
POFP ($kgNMVOC_{eq}$)	8.23×10^{-4}	8.43×10^{-5}	10.2	6.94×10^{-4}	1.02×10^{-3}
AP ($molH^{+}{}_{eq}$)	1.54×10^{-3}	1.21×10^{-4}	7.8	1.34×10^{-3}	1.80×10^{-3}
EU_T ($molN_{eq}$)	3.06×10^{-3}	2.96×10^{-4}	9.7	2.54×10^{-3}	3.70×10^{-3}
EU_F (kgP_{eq})	5.13×10^{-5}	2.77×10^{-5}	53.9	2.18×10^{-5}	1.24×10^{-4}
EU_M (kgN_{eq})	2.29×10^{-4}	2.48×10^{-5}	10.8	1.88×10^{-4}	2.87×10^{-4}
E_{FW} (CTUe)	5.48×10^{0}	1.35×10^{0}	24.7	3.53×10^{0}	8.66×10^{0}
LU ($kgC_{deficit}$)	7.85×10^{-1}	2.26×10^{-1}	28.8	4.63×10^{-1}	1.31×10^{0}
WRD ($m^3{}_{water}$)	5.70×10^{-3}	1.31×10^{-1}	2298.7	-2.76×10^{-1}	2.19×10^{-1}
MFRRD ($kgSb_{eq}$)	5.44×10^{-6}	1.48×10^{-6}	27.2	3.44×10^{-6}	8.90×10^{-6}

The results suggest that a large degree of uncertainty is introduced into WDR, HT-nce, IR-hh, EU_T, and HT-ce. Thus, the life cycle impact assessment results for the above categories are characterized by high dispersion and are strongly influenced by the variability of the input data. Concerning the other impact categories, the coefficients of variation are lower than 50%, indicating that the distribution of the results is correctly represented by the mean value and that the results are characterized by a low dispersion.

The sensitivity analysis of the electricity consumed during the operational phase shows that the environmental impacts increase/decrease at percentages ranging from ±4% (for CC) to ±29% (for WRD). Finally, the sensitivity analysis shows that if the transport distance is increased/decreased by 30%, the environmental impacts increase/decrease at percentages ranging from ±1% (for WRD) to ±20% (for MFRRD). So, both parameters are of high interest towards a more sustainable pathway for residual biomasses valorization.

4. Conclusions

In the context of increasing interest in residual biomasses in bioenergy production, the authors perform an LCA study of an anaerobic digestion-combined heat and power plant fueled with residual biomass derived from the agro-food industry sector. The energy system in analyzed considering the real operational condition of the plant in which both the surplus of thermal energy and the digestate are wasted. Moreover, an improvement scenario is analyzed in which both thermal energy and digestate are valorized as valuable products.

The study provides a wide set of environmental outcomes and identifies the hot spots of the examined technology that must be carefully considered to improve its environmental sustainability.

In particular, the LCA highlights that the feedstock transport, the electrical energy consumption, and the direct emissions occurring during the operational phase are responsible for a significant contribution to different impact categories. Specifically, feedstock transport contributes 64% to mineral fossil fuels and renewable depletion and 50% to ozone depletion potential. Then, reducing transport distance could improve the environmental performance of the examined energy system in these impact categories. The contribution of the electricity consumption to the different impact categories is generally relevant. Then, measures aimed at improving the environmental performance of the electrical energy consumed and reducing the amount required can decrease the impact in almost all the examined impact categories. Direct emissions are responsible for the highest impact in climate change (66%). In considering the relevance of this impact category to society and policy, it is paramount to implement strategies preventing the greenhouse gas from entering the atmosphere.

The study highlights that the valorization of all co-products of the energy system examined can allow significant reduction of the impacts, so in order to increase the environmental benefits related to residual biomasses valorization systems, a fully circular management approach should be implemented.

The sensitivity and uncertainty analysis shows that high variability is associated with both the impact assessment method selected and the LCI data used to model the background system, so LCA transparency is key to avoiding misleading conclusions and recommendations.

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