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Environmental and Economic Analysis of an Anaerobic Co-Digestion Power Plant Integrated with a Compost Plant

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Abstract: Italian power generation through anaerobic digestion (AD) has grown significantly between 2009 and 2016, becoming an important renewable energy resource for the country, also thanks to the generous incentives for produced electricity available in the last years. This work focuses on the economic and environmental issues of AD technology and proposes a techno-economic analysis of investment profitability without government support. In particular, the analysis focuses on an AD power plant fed by zootechnical wastewater and agro-industrial residues coupled to a cogeneration (CHP) system and a digestate-composting plant that produces soil fertilizers. We aim to determine the economic profitability of such AD power plants fed by inner-farm biomass wastes, exploiting digestate as fertilizer, using the cogenerated heat and taking into account the externalities (environmental benefits). Environmental analysis was carried out via a life cycle analysis (LCA), and encompassing the production of biogas, heat/electricity and compost in the downstream process. The un-released environmental emissions were converted into economic benefits by means of a stepwise approach. The results indicate that integrating a compost plant with a biogas plant can significantly increase the carbon credits of the process. The results were evaluated by means of a sensitivity analysis, and they report an IRR in the range of 6%–9% according to the Italian legislative support mechanisms, and possibilities to increase revenues with the use of digestate as fertilizer. The results significantly improve when externalities are included.

Keywords: anaerobic digestion; life cycle assessment; global warming potential; externalities; compost

1. Introduction

Depletion of natural energy resources is compelling our planet to face crucial challenges. Hence, energy production from biowaste plays a critical role in this energy transition [1–8]. In waste management, anaerobic digestion (AD) is a widely implemented technology that has recently drawn attention due to its capability to produce sustainable energy [9–15]. Biogas from AD is a renewable energy-carrier that can substitute conventional fuels in terms of heat and power generation, in the transport sector as biomethane or even for production of biochemicals [16,17]. Despite recent progress in the exploitation of biomethane in the transport and heating sector, Italy's greatest use of biogas has been in the generation of power. Biogas power installed in Italy increased from 2009 to 2016 from 359 to 1352 MW, while electricity generated increased from 1665 to 8259 GWh [18]. In these years, power generation from biogas placed the third position in renewable energy after photovoltaic and wind power excluding hydroelectric power which is a conventional energy resource in Italy.

Biogas brings an added value in terms of circular economy in agriculture. The Italian Biomethane Decree introduces specific subsidies for the use of such fuel in gas networks and in transport [19,20]. In the last twelve years, feed-in-tariff incentive mechanisms to bioelectricity from biogas have been ruled by the Ministerial Decree 18/12/2008, the Ministerial Decree 06/07/2012, the Ministerial Decree 23/06/2016. Furthermore, one more option to incentivize renewable sources systems, until 2012, was the so called mechanism "Certificati Verdi (CV)" established by the Legislative Decree n. 79,16/03/99 20., which adopted the European Directive 96/92/CE.

A key advantage of AD plants is their flexibility for a broad range of output products, as well as their capability to provide programmable renewable electricity to the power system. Hence, they contribute to minimizing the challenges of high penetration of variable intermittent generation into the grid. The potential integration of programmable AD power generation and intermittent solar energy has been investigated in in the Argentinian rural sector [21], as well as in Southern Africa energy systems, with concentrating solar power integration [22]. The thermo-economic optimization and optimal sizing of other hybrid systems composed by biomass and natural gas [23,24] or biomass and concentrating solar [25,26] have been recently proposed in literature. Feedstock availability is another advantage of AD power plants, since biogas can be produced from a wide range of feedstocks. Traditionally, biogas is produced via dedicated herbaceous crops (maize or triticale silage). However, the use of dedicated crops raises concerns regarding food security and overall energetic and environmental balances. Therefore, the recovery of agro-industrial byproducts and zootechnical wastewater is undoubtedly a more sustainable and rational solution [27,28]. Many AD power plants are fed by different kinds of biowastes, such as wastewater [29–31], agricultural residues and food wastes [24,32–40]. On the other hand, development of AD power plants entails a large amount of digestate production as a byproduct. Although digestate—due to its macro and micronutrient content—can be utilized as an organic fertilizer for arable land in place of mineral fertilizer [41–43], its large volume and low dry matter content impose considerable costs for management, storage and spreading onto the soil [44]. Moreover, the storage, transport and application of a huge amount of digestate results in CH_4 and NH_3 emissions, contributing to global warming potential and soil acidification, respectively [45,46]. Therefore, the application of digestate as fertilizer without further treatment raises environmental concerns [47]. Hence, the integration of AD processes with a technology handling digestate is attractive. Among various technologies for digestate management, composting is one of the most reliable technologies, thanks to the enhanced quality of the end-product (compost) through reduction of moisture content, as well as reduction of volatile-compound concentration and phytotoxicity potential [48]. Integrating composting units with AD power plant presents more advantages, such as the improvement of energetic balances of the plant (the energy demand of compost production can be met by AD power plant), leading to the possibility to increase plant revenues and reduce environmental emissions.

However, beyond all above-mentioned benefits, the development of AD power plants requires a comprehensive assessment of environmental and economic benefits in order to indicate to what extent these systems improve sustainability. To date, many studies have addressed techno-economic [49–51] and environmental evaluations [52] of AD power plants. Moreover, technologies of digestate management were analyzed from an economic and environmental point of view [53]. To the best of our knowledge, no study assesses the overall environmental and economic performance of AD power plants, together with the downstream technologies required for their digestate management. This work also estimates external costs associated with production of electricity and compost. External costs or externalities are unaccounted costs arising from production or consumption of a business good or service. The monetization of externalities is based on the conversion of social and biophysical impacts into monetary values by weights mirroring social, ethical and political values. The energy sector and clean energy generation have utilized this economic concept [54–56]. The quantification of externalities into monetary values can complete this economic analysis. Therefore, this work aims to perform a comprehensive economic evaluation with the internalization of the monetized environmental benefits from a co-digestion plant, coupled with a downstream composting system.

The article is organized as follows: Section 2 describes the materials and methods including the LCA methodology, the simulation model, the main components and cost–benefit approach; Section 3 presents and discusses the main results of the work and Section 4 draws the conclusions.

2. Materials and Methods

2.1. LCA Methodology and Global Warming Potential

Life cycle assessment as a standard and comprehensive approach is used for environmental analysis of aa studied plant throughout its life cycle. The goal of this LCA study is to quantify the energy requirements and environmental impacts (in terms of global warming potential (GWP)) of a biogas production system—together with compost-production—starting from co-digestion of mixed solid and liquid biomass, followed by electricity and heat production from biogas in the CHP system, and finally, to production of compost known as organic fertilizer in a downstream process. In-line with LCA guidelines [57,58], this study quantifies all emissions relevant to greenhouse gases (GHG) derived from energy and material use in all above-mentioned phases, including carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). The functional unit considered for this study is the electricity produced (1 MWh_e) from biogas combustion, in a combined heat-and-power unit. This process is modeled in SimaPro 9.

Description of the Plant and Data Inventory

The case study refers to a wet-anaerobic fermentation plant coupled to an internal combustion engine and a digestate dehydration (or composting) plant located in the province of Bari. The flowchart of the conversion process is shown in Figure 1.

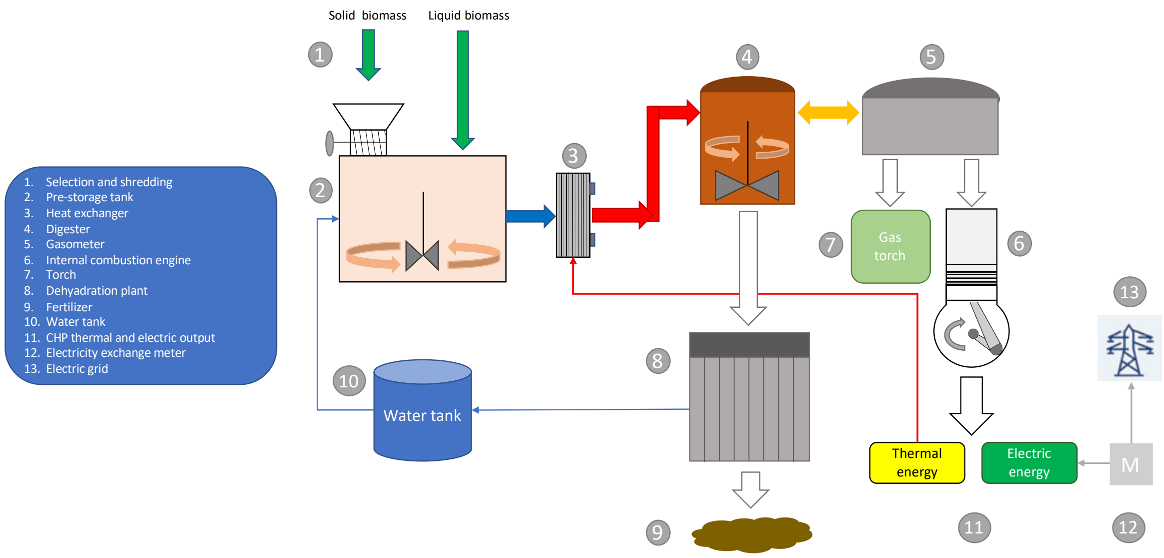

Figure 1. Overview of the production cycle of the plant.

The plant is fed by manure, cheese whey and green crop residues—biomass types widely available in the Bari district. In addition, wastewater from the composting process enters the biomass storage tank to produce biogas from residuals of composting.

The plant is characterized by the following phases:

1. Delivery, pre-treatment, storage: in this step, the raw materials enter into the system, namely semi-solid biomass (manure and green crop residues such as fruit and vegetable waste, foliage,

vegetable mowing, pruning residues, gardening waste) and liquid waste (cheese whey and composting plant wastewater). Liquid wastes are subject to screening and poured into pre-accumulation tanks, while the solid waste is sent to a storage tank where all materials are fluidized (with up to a maximum of 8% solid concentration) and sent to the digesters;

2. Flotation and anaerobic digestion of the serum: The serum from the pre-accumulation tanks is sent to the anaerobic digesters. The suspended solids and possible residues of fat are removed through flotation. Then, the serum remains in the digesters for an optimal period of 20 days. Meanwhile, continuous agitation of the sludge and the anaerobic fermentation produces biogas together with sludge, stabilized with a 95% water-percentage. Recirculation by centrifugal pumps ensures both suspension of the bacterial flora located in the lower part of the reactor and thickness restriction of the biologic layer that forms on the synthetic support of the upper part. The reactor heating is ensured by a heat exchanger.
3. Conventional anaerobic digestion of fluidized greenery: After fluidization of the semi-solid material, the cattle sewage and composting plant wastewater in the pre-accumulation tanks is directed to two digesters, where they are completely mixed with a high retention time. Each reactor is heated by a system with two spiral heat exchangers particularly suitable for sewage with high solid-content.
4. Common gas line, with gasometer and emergency thermal power plant: The treated product then passes from the digester to a third final storage tank, where the biogas is conveyed into two gasometers and subjected to a process of dehumidification and desulfurization in order to obtain a clean and functional chemical composition for the engines.
5. Production of electrical energy and heat with internal combustion engines powered by the biogas: The overall electrical and thermal efficiency is assumed to be 40% and 44%, respectively. The thermal energy (hot water at 80–90 °C) needed to heat up the biomass inside the digester is recycled from engine exhaust gas at 450 °C. The cogenerated heat largely exceeds the digestion process demand.
6. Dehydration, stripping and composting of digestate: For the sludge coming out of the digester reactor, the digested solid is dehydrated in a special centrifuge plant, stripping the ammonia in the dehydration with attached treatments like flocculation and coagulation, to recover the water in the storage tank in order to reuse it in future production cycles. The dehydrated sludge in this phase is deposited in a storage warehouse until it is subject to further stabilization by means of a composting process to obtain pure fertilizer. The refined material may be sent to bulk storage or used for bagging or pelleting, which are not considered in the study.
7. Aerobic biologic process (composting) and serum filtration: According to the stringent regulations in the region of Puglia, the biochemical parameters of BOD (biochemical oxygen demand) and COD (chemical oxygen demand) related to the sludge coming out of the serum digestate are still higher than values permissible for disposal. For this reason, it must undergo a series of purification operations, such as aerobic biologic processes and sand filtration of the various liquid flows for further reduction in the values of BOD and COD. The last processes are secondary flocculation and final disinfection of wastewater with UV rays.

The electricity consumed in the feeding operations accounts for 8% of the total electricity production. As regards the electricity consumption for the composting plant, it is assumed that 1 kWh_e is required per ton of wet organic waste as from literature data [59], and this electricity is withdrawn from the grid. Compost is a composition of N, P and K elements in different concentrations, also present in mineral fertilizers. Hence, the compost can substitute mineral fertilizers (e.g., ammonium nitrate, triple superphosphate and potassium sulfate) in terms of active ingredient contents [60,61]. Therefore, production of theses fertilizers is avoided as in other fields such as biochar application in soil as organic fertilizer [62]. Airborne and waterborne emissions (ammonia, nitrous oxide, nitrogen, nitrate and phosphate) arising from digestate application are excluded from this study as they are neutral in global warming potential. In the case of composting plant wastewater, a supply of about 100 days year^{-1} was considered. In addition, a storage with 20,000 m^3 capacity was assumed for green crop residues due to their seasonality. Cattle farms and dairy factories are within a 20-km radius of the AD power plant, while crop residues are transferred to the plant from a 30-km distance. Carbon dioxide emissions from biogas combustion in the CHP are also excluded from estimation owing to biogenic exemption [27,63,64]. Furthermore, greenhouse gas emissions deriving from the construction, operation and disposal of the plant was not taken into account. Excess heat from cogeneration on top of internal energy requirements was used to match local heat demand and substitute natural gas fuel. The mass and energy flow of the proposed system during 1 year of operation are illustrated in Figure 2. The overall list of energy and material used for 1 MWh electricity production from co-digestion plant is also presented in Table 1. The exploitable heat was not computed between the outputs of Table 1 because it is included among the avoided products as natural gas.

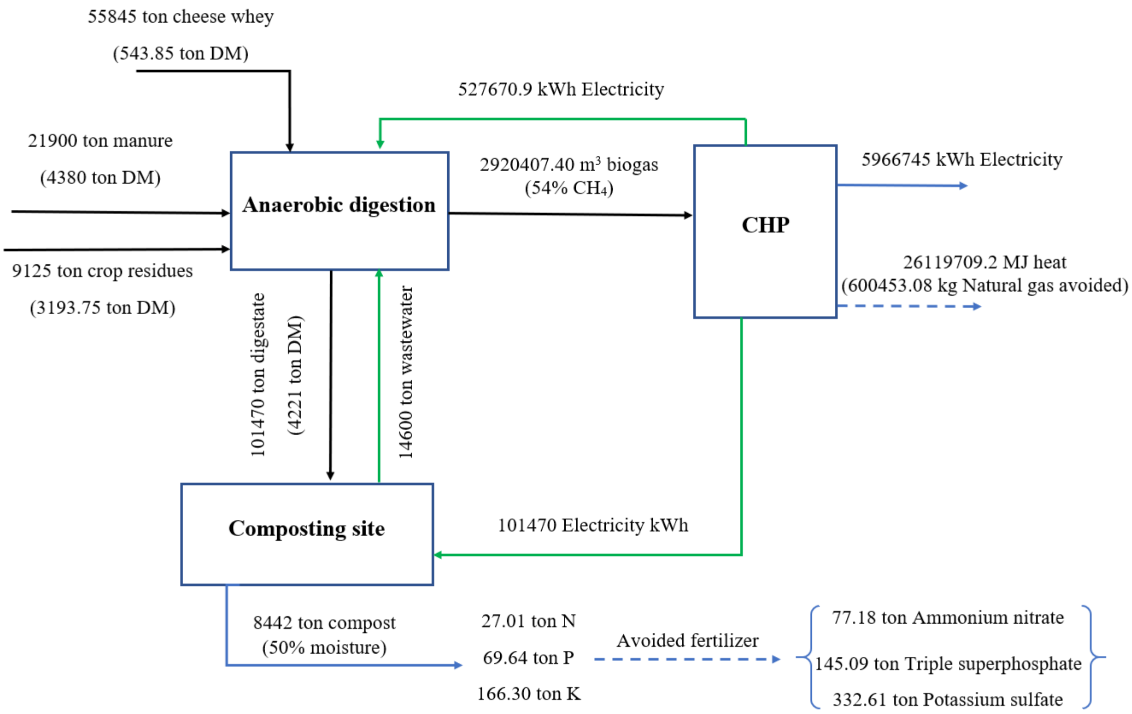

Figure 2. System layout and mass and energy balances referred to 1 year of operation.

Table 1. Global inventory data per 1 MWh$_e$.

Inputs		Outputs	
Manure	3.67 ton	Electricity	1 MWh
Whey from cheese factories	9.36 ton	Compost	1.41 ton
Green crop residues	1.53 ton		
Composting plant wastewater	2.44 ton	Avoided products	
Transport	306.5 tkm *	Natural gas (heat)	50.31 kg
		Ammonium nitrate	12.93 kg
		Triple superphosphate	24.31 kg
		Potassium sulfate	55.74 kg

* tkm = ton-kilometer (unit of transportation measurement).

2.2. Economic Analysis

A cost–benefit approach was applied to assess the investment profitability. The investment cost of the plant and its associated operating expenditures with raw materials and energy consumption were considered. Revenues generated by sales of electricity, heat and compost as well as biophysical sources including externalities were taken into account.

This analysis ignored potentially available incentives (in the form of capital grants, or incentives for avoided primary energy consumption, which could be available in the Italian framework) in order to understand if, and to what extent, the investment was profitable without specific subsidies.

The economic evaluation converted environmental impact to external costs [62,65]. Among different approaches for monetary valuation, budget constraint approach has been recommended by [66] for LCA applications due to its simplicity and its capacity to minimize uncertainty of the monetary value of a human life–year. The used unit is QALY that is a Quality-Adjusted-Life_Year. It represents the monetary value of a life year with high quality. The average annual income is the maximum that a person can purchase an additional life–year and a quality-adjusted life–year (QALY) defines a life–year lived at full wellbeing, then an upper limit for the monetary value of a QALY is provided [67]. The Stepwise 2006 method developed on budget constraint approaches—and specifically designed for life cycle impact assessment—is adapted in this study [68].

Therefore, environmental impact estimated into GWP (kg CO_2) was converted to monetary values in order to internalize social, ethical and political cost of this bioenergy system within economic analysis. Global warming potential GWP was converted to a monetary value by weighting factor of 0.08 Euro/kg CO_2 [62]. Since this factor refers to Eur 2003, it was necessary to use inflation rate to estimate cost in current year.

The internal rate of return (IRR), net present value (NPV) and payback period (PBP) were calculated for a 15-year timeframe.

The investment costs of the plant were estimated through market analysis of plants with similar configurations and also communications with suppliers of technologies similar to those proposed in the study. The costs are summarized in Table 2. The costs assumed for dehydration, stripping and composting treatments of the digestate produced by green residues and manure to obtain fertilizer, as well as those for biologic finishing, ultrafiltration and clariflocculation of serum and plant wastewater to obtain water for fertigation were indicative, achieved from market research and confirmed in literature. The total investment cost of the 1-MW_e system is 4 k€/kW_e, in agreement with previous results [69]. The annual electricity production is 6595 MWh_e, assuming average operating hours in AD powerplants in Italy (GSE statistics, 2020). Costs and revenues of the investment are estimated based on these operating hours.

Biomass costs were determined by the cost of a minority part of biomass consumed respect to the total amount because the project is based on preponderant use of on site available bio-wastes at no cost. The global service costs represent the service cost including maintenance of the system and were determined on the basis of the specific cost of 0.032 €/kWh_e [70]. Staff costs are based on the involvement of 4 employees and overhead expenses are considered on top of the other operating costs. The discount rate—or weighted average cost of capital (WACC)—was set to 8% according to the relevant literature [14,71–74].

Revenues were generated by physical sources, namely sale of electricity, heat and compost as well as externalities. Electricity price was fixed according to a power purchase agreement. External benefit regarding carbon offsets was estimated 13.22 €/MWh_e, assuming a weighting factor 0.08 eur/kg CO_2. The monetary valuation can be applied to LCA results in order to weigh environmental benefits against environmental costs through different approaches. In the present study, the Stepwise 2006 approach was used. Nevertheless, in Section 3, sensitivity analysis of economic parameters respect to variation of the approach was shown. To that end, in addition to the Stepwise 2006 method, ecotax and ecovalue approaches were considered.

Table 2. Operating and investment costs for the plant under study.

Investment Costs	
Cost item	Value (kEur)
Cost of civil works	700
Cost of digesters, tanks and biogas treatment	1150
Cost of electrical system group and cogeneration plant	600
Dewatering, stripping and composting plant cost	750
Cost of filtration and clariflocculation	650
Engineering and development costs	150
Total amount	4000
Operating Costs kEur/year	
Biomass	47
Global service	211
Staff	140
Overhead expenses	60
Total amount	458
Additional Parameters	
Plant useful life	15 years
Discount rate	8%
Heat exploitation	50%
External benefit (Stepwise 2006 method)	13.22 €M Wh_e^{-1}
Electricity selling price	120 €M Wh_e^{-1}
Price of natural gas	75 €M Wh_{th}^{-1}
Price of compost	10 €*t*-[1]

3. Result and Discussion

3.1. Environmental Analysis

Global warming potential (GWP) was quantified by IPCC 2013 method converting GHG emissions to kilograms of CO_2. For the studied system, the global warming potential was found to be −167.52 kg $CO_{2,}$ representing an outstanding carbon offset (Figure 3). Negative values reflect environmental benefits achieved by avoidance of product uses [62]. These benefits were primarily associated with avoided mineral fertilizers consumption.

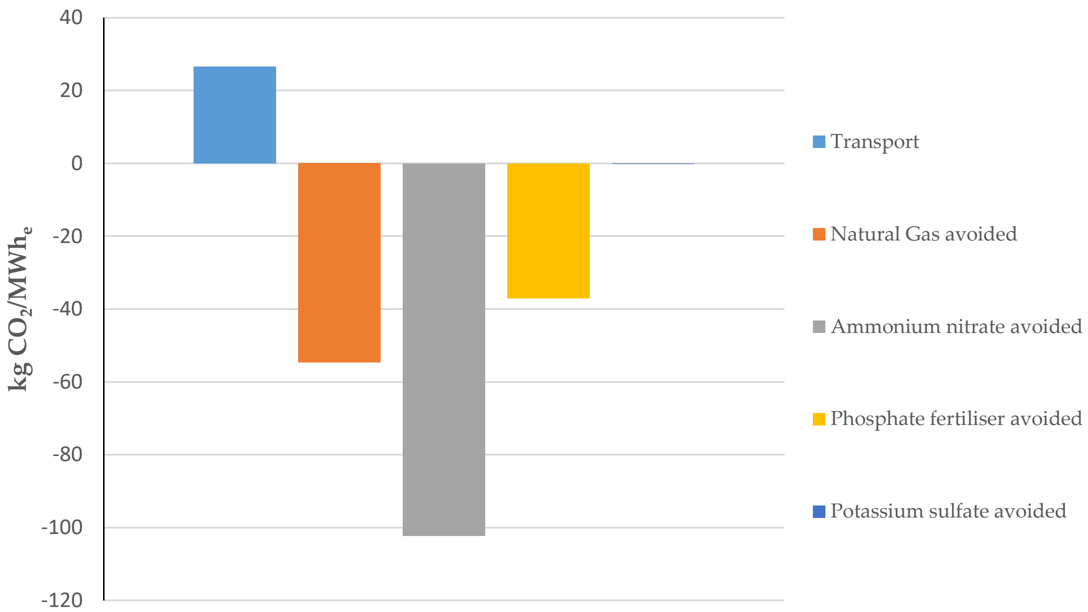

Figure 3. Global warming potential of processes in the studied system.

3.2. Economic Analysis

The main economic results are shown in Table 3. In addition, Figures 4–6 represent results of sensitivity analysis. The investment profitability is obviously lower than in the previous years, when generous incentives for electricity generation were available. This reduction was however partially mitigated by the reduction of the investment costs for the learning curves of well-established technologies and the possibility to purchase biomass at very low cost.

Table 3. Results of the cost-effectiveness analysis.

Economic Index	With Externalities	Without Externalities	Unit of Measurement
Payback time (PBT)	8	10	years
Net present value (NPV)	312	−323	kEur
Internal rate of return (IRR)	9.36	6.54	%

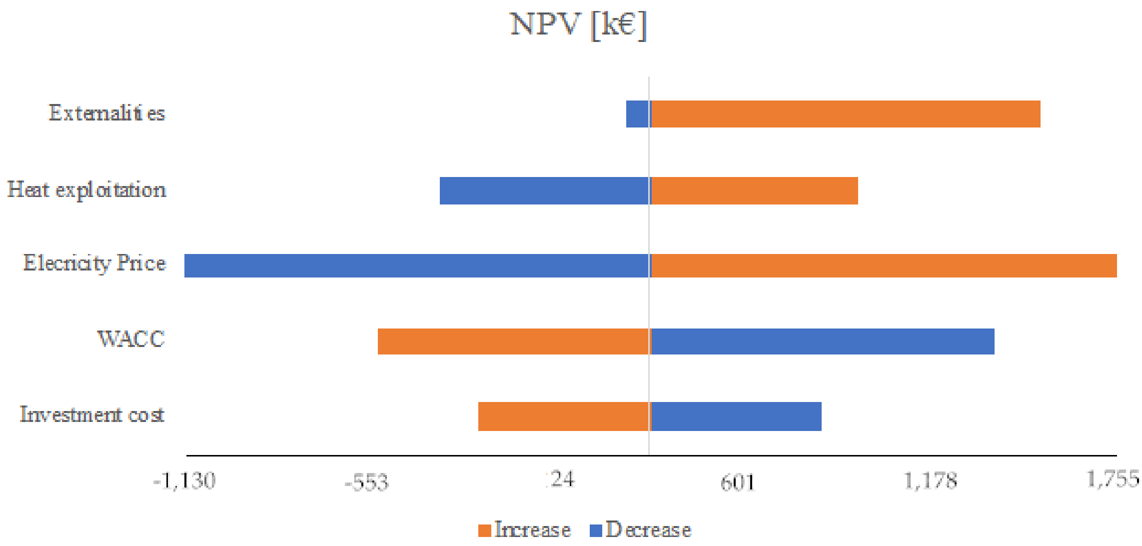

Figure 4. Tornado diagram for representation of sensitivity analysis of net present value (NPV).

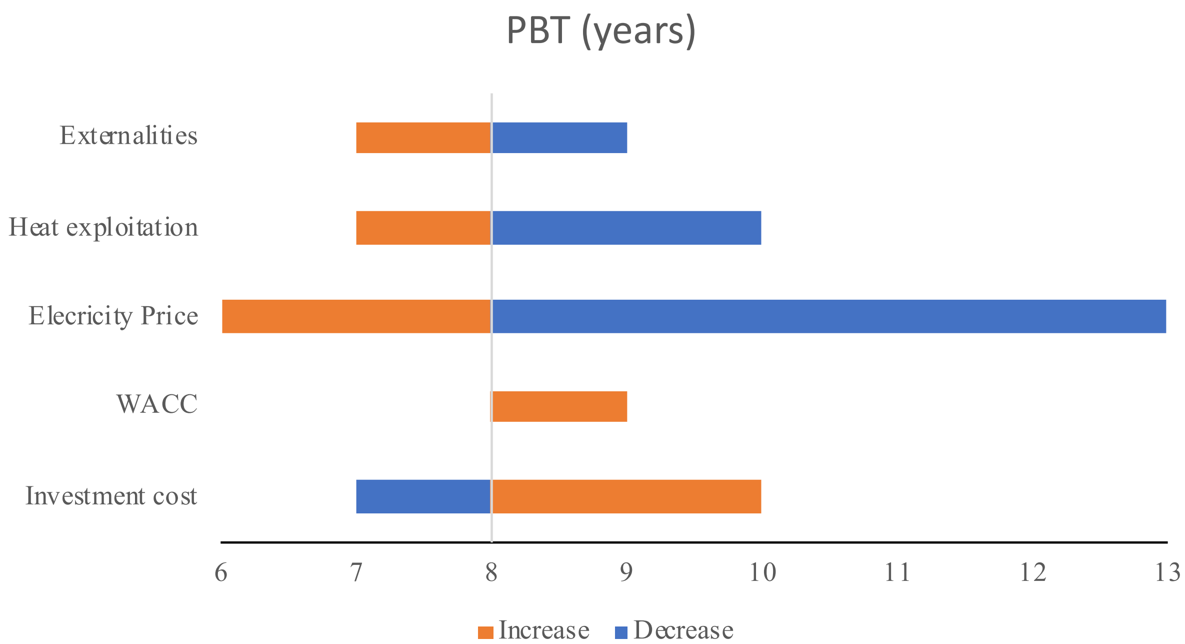

Figure 5. Tornado diagram for representation of sensitivity analysis of payback time (PBT).

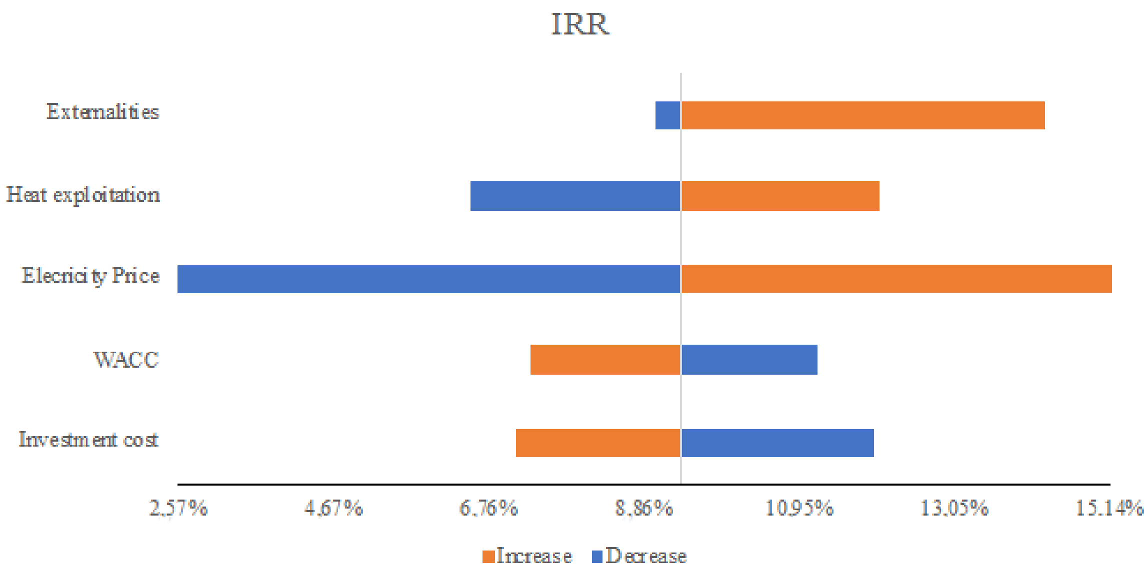

Figure 6. Tornado diagram for representation of sensitivity analysis of internal rate of return (IRR).

Based on Table 3, it was possible to appreciate the different results with and without the economic benefits from environmental evaluation.

Furthermore, a sensitivity analysis aimed to appreciate the response of the economic model to variation of the most impactful parameters was developed and represented by means of a tornado diagram in Figures 4–6 for NPV, PBP and IRR, respectively. Parameters were varied within the following realistic and interesting ranges. Percentages of variation of each considerable parameter were: ± 10% for the investment cost, ± 25% for the WACC, ± 25% for the electricity price, ± 30% for the thermal energy exploitation, while the externalities were varied between the minimum value attainable by the ecotax method corresponding with 11.58 €/MWh$_e$ and the maximum value attainable by the ecovalue method corresponding with 38.37 €/MWh. The tornado diagrams are centered on the values shown in Table 2.

Considering the three tornado diagrams, the range of variation of the most influencing parameter—electricity price—was extended, both in decrease and increase. This parameter had a remarkable impact on all three considered parameters. Its increase allowed reaching the best economic configuration of the project represented by 15.14% IRR, 1.75 M€ NPV and 6 years PBT. The sensitivity of the externalities method was especially relevant to the ecovalue approach, which enables to achieve 14.25% IRR, 1.52 M€ NPV and 7 years PBT. In general, PBT varied between 6 and 10 with the exception of the case of electricity price whose decrease considerably affected PBT: it grew until 13 years. As in several CHP projects, the exploitation of heat produced by the internal combustion engine was important to the good outcome. The sensitivity analysis shows that disadvantageous scenarios are not so far from the base configuration.

4. Conclusions

After a remarkable growth between 2009 and 2016, biogas-sourced electricity generation slowed down significantly, due to the lack of subsidies available. This article describes an economic and environmental analysis of electricity generation from an anaerobic co-digestion plant coupled to a downstream process producing compost from digestate. The aim was to mark out some of the key aspects which could increase the sustainability of this technological application such as the use of low cost biomasses on site available and exploitation of digestate as fertilizer to the soil. A life-cycle assessment was applied to count the global warming potential of the system. Furthermore, the economic concept of externalities expressing environmental and socioeconomic impacts in monetary values was included in this study. The novelty of this work was to consider externalities and to internalize them in the economic assessment. Therefore, economic analysis encompasses not only physical and private costs, e.g., the operating and investment costs of a plant (digestion plant, cogeneration system and compost plant), the incentives available in the Italian legislative scenario, the raw material costs and the sale price of compost, but also biophysical costs as externalities. Results demonstrate economic and environmental profitability of this plant which mainly arises from bioelectricity production. In particular, sustainable economic performance were demonstrated independently of the presence of incentives regarding the electric production. Incidentally, the work was aimed to the evaluation of the system without incentives in order to understand if the system can face the market without any external support. Outstanding environmental benefits were represented by means of the −167.52 kg CO_2 global warming potential. Acceptable economic results were attained in terms of NPV, PBT and IRR, respectively 0.31 M€, eight years and 9.36% for base configuration and a propitious variation of parameters can be crucial for the improvement of economic performance as shown by the sensitivity analysis. These results were much more important if the lack of incentives recognized to the electricity produced by the system was considered. For Externalities contribute propitiously to the project evaluation and this contribution was much more important in case of ecovalue approach. From the sensitivity analysis exigency to choose the controllable expedient conditions ensues. Consequently, these findings make the investment on this type of plants encouraging on condition that parameters are duly selected.

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References

1. Achinas, S.; Achinas, V.; Euverink, G.J.W. A Technological Overview of Biogas Production from Biowaste. *Engineering* **2017**, *3*, 299–307. [CrossRef]
2. Carlini, M.; Castellucci, S.; Mennuni, A. Thermal and fluid dynamic analysis within a batch micro-reactor for biodiesel production fromwaste vegetable oil. *Sustainability* **2017**, *9*, 2308. [CrossRef]
3. Malinauskaite, J.; Jouhara, H. The trilemma of waste-to-energy: A multi-purpose solution. *Energy Policy* **2019**, *129*, 636–645. [CrossRef]
4. Pallozzi, V.; Di Carlo, A.; Bocci, E.; Villarini, M.; Foscolo, P.U.; Carlini, M. Performance evaluation at different process parameters of an innovative prototype of biomass gasification system aimed to hydrogen production. *Energy Convers. Manag.* **2016**, *130*, 34–43. [CrossRef]
5. Carlini, M.; Castellucci, S.; Cocchi, S.; Manzo, A. Waste wood biomass arising from pruning of urban green in viterbo town: Energy characterization and potential uses. In *International Conference on Computational Science and Its Applications*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 242–255.
6. Pantaleo, A.; Villarini, M.; Colantoni, A.; Carlini, M.; Santoro, F.; Hamedani, S.R. Techno-economic modeling of biomass pellet routes: Feasibility in Italy. *Energies* **2020**, *13*, 1636. [CrossRef]
7. Villarini, M.; Bocci, E.; Di Carlo, A.; Savuto, E.; Pallozzi, V. The case study of an innovative small scale biomass waste gasification heat and power plant contextualized in a farm. *Energy Procedia* **2015**, *82*, 335–342. [CrossRef]
8. Rajabi Hamedani, S.; Bocc, E.; Villarini, M.; Di Carlo, A.; Naso, V. Techno-economic Analysis of Hydrogen Production Using Biomass Gasification -A Small Scale Power Plant Study. *Energy Procedia* **2016**, *101*, 806–813. [CrossRef]

9. Oreggioni, G.D.; Gowreesunker, B.L.; Tassou, S.A.; Bianchi, G.; Reilly, M.; Kirby, M.E.; Toop, T.A.; Theodorou, M.K. Potential for energy production from farm wastes using anaerobic digestion in the UK: An economic comparison of different size plants. *Energies* **2017**, *10*, 1396. [CrossRef]
10. Browne, J.; Allen, E.; Murphy, J. Assessing the variability in biomethane production from the organic fraction of municipal solid waste in batch and continuous operation. *Appl. Energy* **2014**, *128*, 307–314. [CrossRef]
11. Carlini, M.; Castellucci, S.; Mennuni, A.; Ferrelli, S.; Felicioni, M.A. Application of a circular & green economy model to a ceramic industrial district: An Italian case study. *AIP Conf. Proc.* **2019**, *2123*, 020087. [CrossRef]
12. Carlini, M.; Castellucci, S.; Moneti, M. Anaerobic co-digestion of olive-mill solid waste with cattle manure and cattle slurry: Analysis of bio-methane potential. *Energy Procedia* **2015**, *81*, 354–367. [CrossRef]
13. Carlini, M.; Castellucci, S.; Moneti, M. Biogas production from poultry manure and cheese whey wastewater under mesophilic conditions in batch reactor. *Energy Procedia* **2015**, *82*, 811–818. [CrossRef]
14. Carlini, M.; Mosconi, E.M.; Castellucci, S.; Villarini, M.; Colantoni, A. An Economical Evaluation of Anaerobic Digestion Plants Fed with Organic Agro-Industrial Waste. *Energies* **2017**, *10*, 1165. [CrossRef]
15. Santoro, F.; Anifantis, A.S.; Ruggiero, G.; Zavadskiy, V.; Pascuzzi, S. Lightning protection systems suitable for stables: A case study. *Agriculture* **2019**, *9*, 72. [CrossRef]
16. Scarlat, N.; Dallemand, J.F.; Fahl, F. Biogas: Developments and perspectives in Europe. *Renew Energy* **2018**, *129*, 457–472. [CrossRef]
17. Fagerström, A.; Al Seadi, T.; Rasi, S.; Briseid, T. *The Role of Anaerobic Digestion and Biogas in the Circular Economy*; Murphy, J.D., Ed.; Cork, IE, IEA Bioenergy Task 37: Paris, France, 2018.
18. GSE. Quarta Relazione Dell'Italia in Merito Ai Progressi Ai Sensi Della Direttiva 2009/28/CE. 2017. Available online: https://www.gse.it/documenti_site/Documenti%20GSE/Studi%20e%20scenari/Progress%20Report%20Rinnovabili%20Italia%202017.pdf (accessed on 9 April 2020).
19. Italian Decree Dlgs 2 March 2018, n.d. Available online: https://www.gse.it/documenti_site/DocumentiGSE/Serviziperte/BIOMETANO/NORMATIVA/D.M.MiSE2marzo2018.pdf (accessed on 9 April 2020).
20. Decreto Legislativo 16 Marzo 1999 n. 79. Available online: https://www.gazzettaufficiale.it/eli/id/1999/03/31/099G0136/sg (accessed on 9 April 2020).
21. Blanchet, C.A.C.; Pantaleo, A.M.; van Dam, K.H. A process systems engineering approach to designing a solar/biomass hybrid energy system for dairy farms in Argentina. Comput. *Aided Chem. Eng.* **2019**, *46*, 1609–1614. [CrossRef]
22. Liu, M.; van Dam, K.H.; Pantaleo, A.M.; Guo, M. Optimisation of Integrated Bioenergy and Concentrated Solar Power Supply Chains in South Africa. *Comput. Aided Chem. Eng.* **2018**, *43*, 1463–1468. [CrossRef]
23. Pantaleo, A.M.; Camporeale, S.; Shah, N. Natural gas-biomass dual fuelled microturbines: Comparison of operating strategies in the Italian residential sector. *Appl. Therm. Eng.* **2014**, *71*, 686–696. [CrossRef]
24. Pantaleo, A.M.; Camporeale, S.M.; Shah, N. Thermo-economic assessment of externally fired micro-gas turbine fired by natural gas and biomass: Applications in Italy. *Energy Convers. Manag.* **2013**, *75*, 202–213. [CrossRef]
25. Pantaleo, A.M.; Camporeale, S.M.; Sorrentino, A.; Miliozzi, A.; Shah, N.; Markides, C.N. Hybrid solar-biomass combined Brayton/organic Rankine-cycle plants integrated with thermal storage: Techno-economic feasibility in selected Mediterranean areas. *Renew Energy* **2020**, *147*, 2913–2931. [CrossRef]
26. Pantaleo, A.M.; Camporeale, S.M.; Miliozzi, A.; Russo, V.; Shah, N.; Markides, C.N. Novel hybrid CSP-biomass CHP for flexible generation: Thermo-economic analysis and profitability assessment. *Appl. Energy* **2017**, *204*, 994–1006. [CrossRef]
27. Rajabi Hamedani, S.; Del Zotto, L.; Bocci, E.; Colantoni, A.; Villarini, M. Eco-efficiency assessment of bioelectricity production from Iranian vineyard biomass gasification. *Biomass Bioenergy* **2019**, *127*, 105271. [CrossRef]
28. Rajabi Hamedani, S.; Colantoni, A.; Gallucci, F.; Salerno, M.; Silvestri, C.; Villarini, M. Comparative energy and environmental analysis of agro-pellet production from orchard woody biomass. *Biomass Bioenergy* **2019**, *129*, 105334. [CrossRef]
29. Shen, Y.; Linville, J.L.; Urgun-Demirtas, M.; Mintz, M.M.; Snyder, S.W. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: Challenges and opportunities towards energy-neutral WWTPs. *Renew Sustain. Energy Rev.* **2015**, *50*, 346–362. [CrossRef]

30. Jürgensen, L.; Ehimen, E.A.; Born, J.; Holm-Nielsen, J.B. A combination anaerobic digestion scheme for biogas production from dairy effluent—CSTR and ABR, and biogas upgrading. *Biomass Bioenergy* **2018**, *111*, 241–247. [CrossRef]
31. Al-Addous, M.; Saidan, M.N.; Bdour, M.; Alnaief, M. Evaluation of biogas production from the co-digestion of municipal food waste and wastewater sludge at refugee camps using an automated methane potential test system. *Energies* **2019**, *12*, 32. [CrossRef]
32. Yong, Z.; Dong, Y.; Zhang, X.; Tan, T. Anaerobic co-digestion of food waste and straw for biogas production. *Renew Energy* **2015**, *78*, 527–530. [CrossRef]
33. De Menna, F.; Malagnino, R.A.; Vittuari, M.; Molari, G.; Seddaiu, G.; Deligios, P.A.; Solinas, S.; Ledda, L. Potential biogas production from artichoke byproducts in Sardinia, Italy. *Energies* **2016**, *9*, 92. [CrossRef]
34. Hassaan, M.A.; Pantaleo, A.; Tedone, L.; Elkatory, M.R.; Ali, R.M.; Nemr, A.E.; Mastro, D.G. Enhancement of biogas production via green ZnO nanoparticles: Experimental results of selected herbaceous crops. *Chem. Eng. Commun.* **2019**. [CrossRef]
35. Amirante, R.; Demastro, G.; Distaso, E.; Hassaan, M.A.; Mormando, A.; Pantaleo, A.M.; Tamburrano, P.; Tedone, L.; Clodoveo, M.L. Effects of Ultrasound and Green Synthesis ZnO Nanoparticles on Biogas Production from Olive Pomace. *Energy Procedia* **2018**, *148*, 940–947. [CrossRef]
36. Pantaleo, A.D.E.; Gennaro, B.; Shah, N. Assessment of optimal size of anaerobic co-digestion plants: An application to cattle farms in the province of Bari (Italy). *Renew Sustain. Energy Rev.* **2013**, *20*, 57–70. [CrossRef]
37. Bulgakov, V.; Pascuzzi, S.; Santoro, F.; Anifantis, A.S. Mathematical model of the plane-parallel movement of the self-propelled root-harvesting machine. *Sustainability* **2018**, *10*, 3614. [CrossRef]
38. Bulgakov, V.; Pascuzzi, S.; Anifantis, A.S.; Santoro, F. Oscillations analysis of front-mounted beet topper machine for biomass harvesting. *Energies* **2019**, *12*, 2774. [CrossRef]
39. Guerrieri, A.S.; Anifantis, A.S.; Santoro, F.; Pascuzzi, S. Study of a large square baler with innovative technological systems that optimize the baling effectiveness. *Agric* **2019**, *9*, 86. [CrossRef]
40. Carlini, M.; Castellucci, S.; Mennuni, A.; Selli, S. Poultry Manure Biomass: Energetic Characterization and ADM1-based Simulation. *J. Phys. Conf. Ser.* **2019**, *1172*, 012063. [CrossRef]
41. De Vries, J.W.; Vinken, T.M.W.J.; Hamelin, L.; De Boer, I.J.M. Comparing environmental consequences of anaerobic mono-and co-digestion of pig manure to produce bioenergy – a life cycle perspective. *Bioresour. Technol.* **2012**, *125*, 239–248. [CrossRef] [PubMed]
42. Comparetti, A.; Greco, C.; Navickas, K.; Venslauskas, K. Evaluation of potential biogas production in sicily. *Eng. Rural. Dev.* **2012**, *24*, 555–559.
43. Risberg, K.; Cederlund, H.; Pell, M.; Arthurson, V.; Schnürer, A. Comparative characterization of digestate versus pig slurry and cow manure—Chemical composition and effects on soil microbial activity. *Waste Manag.* **2017**, *61*, 529–538. [CrossRef]
44. Al saedi, T.; Drosg, B.; Fuchs, W.; Rutz, D.; Janssen, R. Biogas digestate quality and utilization. In *The Biogas Handbook*; Woodhead Publishing: Cambridge, UK, 2013; pp. 267–301.
45. Longhurst, P.J.; Tompkins, D.; Pollard, S.J.T.; Hough, R.L.; Chambers, B.; Gale, P.; Tyrrel, S.; Villa, R.; Taylor, M.; Wu, S.; et al. Risk assessments for quality-assured, source-segregated composts and anaerobic digestates for a circular bioeconomy in the UK. *Environ. Int.* **2019**, *127*, 253–266. [CrossRef]
46. Pivato, A.; Vanin, S.; Raga, R.; Lavagnolo, M.C.; Barausse, A.; Rieple, A.; Laurent, A.; Cossu, R. Use of digestate from a decentralized on-farm biogas plant as fertilizer in soils: An ecotoxicological study for future indicators in risk and life cycle assessment. *Waste Manag.* **2016**, *49*, 378–389. [CrossRef]
47. Al Seadi, T.; Lukehurst, C. Quality management of digestate from biogas plants used as fertiliser. *IEA Bioenergy Task* **2012**, *40*.
48. Bustamante, M.A.; Alburquerque, J.A.; Restrepo, A.P.; De Fuente, C.; Paredes, C.; Moral, R.; Bernal, M.P. Co-composting of the solid fraction of anaerobic digestates, to obtain added-value materials for use in agriculture. *Biomass Bioenergy* **2012**, *43*, 26–35. [CrossRef]
49. Martínez-ruano, J.A.; Restrepo-serna, D.L.; Carmona-garcia, E.; Alejandro, J.; Giraldo, P.; Aroca, G.; Cardona, C.A. Effect of co-digestion of milk-whey and potato stem on heat and power generation using biogas as an energy vector: Techno-economic assessment. *Appl. Energy* **2019**, *241*, 504–518. [CrossRef]

50. Martínez-ruano, J.A.; Caballero-galván, A.S.; Restrepo-serna, D.L.; Cardona, C.A. Techno-economic and environmental assessment of biogas production from banana peel (Musa paradisiaca) in a biorefinery concept. *Environ. Sci. Pollut. Res.* **2018**, *25*, 35971–35980. [CrossRef] [PubMed]
51. Hamzehkolaei, F.T.; Amjady, N. A techno-economic assessment for replacement of conventional fossil fuel based technologies in animal farms with biogas fueled CHP units. *Renew Energy* **2018**, *118*, 602–614. [CrossRef]
52. Hijazi, O.; Munro, S.; Zerhusen, B.; Effenberger, M. Review of life cycle assessment for biogas production in Europe. *Renew Sustain. Energy Rev.* **2016**, *54*, 1291–1300. [CrossRef]
53. Vochozka, M.; Marous, A. Obsolete Laws: Economic and Moral Aspects, Case Study—Composting Standards. *Sci. Eng. Ethics* **2016**, 1–6. [CrossRef]
54. Bickel, P.; Friedrich, R.; Droste-Franke, B.; Bachmann, T.; Greßmann, A.; Rabl, A.; Hunt, A.; Markandya, A.; Tol, R.; Hurley, F.; et al. *ExternE—Externalities of Energy, Methodology 2005 Update*; Bickel, P., Friedrich, R., Eds.; Office for Official Publications of the European Communities: Luxembourg, 2005; Volume EUR, ISBN 92-79-00423-9.
55. Bielecki, A.; Ernst, S.; Skrodzka, W.; Wojnicki, I. The externalities of energy production in the context of development of clean energy generation. *Environ. Sci. Pollut. Res.* **2020**, *27*, 11506–11530. [CrossRef]
56. Patrizio, P.; Leduc, S.; Chinese, D.; Kraxner, F. Internalizing the external costs of biogas supply chains in the Italian energy sector. *Energy* **2017**, *125*, 85–96. [CrossRef]
57. *ISO 14040:2016 Environmental Management—Life Cycle Assessment—Principles and Framework*; ISO: Geneva, Switzerland, 2016.
58. *ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines*; ISO: Geneva, Switzerland, 2006.
59. Del, A.; Di, F. DCO 2/08 2008. Available online: https://www.arera.it/it/docs/dc/08/080220_2.htm (accessed on 10 April 2020).
60. Poeschl, M.; Ward, S.; Owende, P. Environmental impacts of biogas deployment—Part I: Life cycle inventory for evaluation of production process emissions to air. *J. Clean. Prod.* **2012**, *24*, 168–183. [CrossRef]
61. Lijó, L.; González-garcía, S.; Bacenetti, J.; Fiala, M.; Feijoo, G.; Lema, J.M.; Moreira, M.T. Life Cycle Assessment of electricity production in Italy from anaerobic co-digestion of pig slurry and energy crops. *Renew Energy* **2014**, *68*, 625–635. [CrossRef]
62. Rajabi Hamedani, S.; Kuppens, T.; Malina, R.; Bocci, E.; Colantoni, A.; Villarini, M. Life cycle assessment and environmental valuation of biochar production: Two case studies in Belgium. *Energies* **2019**, *12*, 2166. [CrossRef]
63. Villarini, M.; Rajabi Hamedani, S.; Marcantonio, V.; Colantoni, A.; Cecchini, M.; Monarca, D. Comparison of Environmental Impact of Two Different Bioelectricity Conversion Technologies by Means of LCA. *Innov. Biosyst. Eng. Sustain. Agric. For. Food Prod.* **2020**. [CrossRef]
64. Rajabi Hamedani, S.; Villarini, M.; Colantoni, A.; Moretti, M.; Bocci, E. Life Cycle Performance of Hydrogen Production via Agro-Industrial Residue Gasification—A Small Scale Power Plant Study. *Energies* **2018**, *11*, 675. [CrossRef]
65. Lim, S.R.; Kim, Y.R.; Woo, S.H.; Park, D.; Park, J.M. System optimization for eco-design by using monetization of environmental impacts: A strategy to convert bi-objective to single-objective problems. *J. Clean. Prod.* **2013**, *39*, 303–311. [CrossRef]
66. Weidema, B.P.; Brandão, M.; Pizzol, M. The use of monetary valuation of environmental impacts in life cycle assessment: State of the art, strengths and weaknesses. *SCORE-LCA Rep. Nb 2012-03. Aalborg University.* **2013**.
67. Pizzol, M.; Weidema, B.; Brandão, M.; Osset, P. Monetary valuation in Life Cycle Assessment: A review. *J. Clean. Prod.* **2015**, *86*, 170–179. [CrossRef]
68. Weidema, B. Using the budget constraint to monetise impact assessment results. *Ecol. Econ.* **2009**, *68*, 1591–1598. [CrossRef]
69. Grebe EU Project, n.d. Available online: http://grebeproject.eu/ (accessed on 9 April 2020).
70. Salerno, M.; Gallucci, F.; Pari, L.; Zambon, I.; Sarri, D.; Colantoni, A. Costs-benefits analysis of a small-scale biogas plant and electric energy production. *Bulg. J. Agric. Sci.* **2017**, *23*, 357–362.
71. Lovarelli, D.; Falcone, G.; Orsi, L.; Bacenetti, J. Agricultural small anaerobic digestion plants: Combining economic and environmental assessment. *Biomass Bioenergy* **2019**, *128*, 105302. [CrossRef]

72. Wang, Y.; Zhang, J.; Li, Y.; Jia, S.; Song, Y.; Sun, Y.; Zheng, Z.; Yu, J.; Cui, Z.; Han, Y.; et al. Methane production from the co-digestion of pig manure and corn stover with the addition of cucumber residue: Role of the total solids content and feedstock-to-inoculum ratio. *Bioresour. Technol.* **2020**, *306*, 123172. [CrossRef] [PubMed]
73. Monarca, D.; Cecchini, M.; Guerrieri, M.; Colantoni, A. Conventional and alternative use of biomasses derived by hazelnut cultivation and processing. *Acta Hortic.* **2009**, *845*, 627–634. [CrossRef]
74. Zambon, I.; Colantoni, A.; Carlucci, M.; Morrow, N.; Sateriano, A.; Salvati, L. Land quality, sustainable development and environmental degradation in agricultural districts: A computational approach based on entropy indexes. *Environ. Impact Assess. Rev.* **2017**, *64*, 37–46. [CrossRef]

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