Life Cycle Assessment (LCA) of End-of-Life Dairy Products' (EoL-DPs) management in Cyprus, via their energetic valorizationthrough anaerobic co-digestion with agro-industrial wastes

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ABSTRACT

Purpose: The aim of this study was to generate information on the environmental performance of End-of-Life Dairy Products' (EoL-DPs) management in Cyprus through their co-treatment in a centralized biogas facility with other agro-industrial wastes (AgW), such as cow and pig manure, cheese whey etc., by using the existing approaches of Gate-to-Gate LCA methodology.

Methods: Twodifferent treatment scenarios were assessed, both in lab- and pilot-scale, under the framework of the LIFE+ DAIRIUS project (http://www.dairiusproject.com/). In the first scenario, co-treatment of EoL-DPs with various AgWwas evaluated in a one-stage anaerobic digestion (AD) process,i.e. their mixture was fed directly in a CSTR(Continuous Stirred Tank Reactor) digester. In the second scenario, in view of boosting the biogas production yield, the EoL-DPs were acidified in a CSTR acidogenic reactor prior to their entrance in the methanogenic digester with the mixture of raw AgW. SimaPro 8.0.2 software was used to quantify the environmental impacts associated with the reported materials' use and emissions.

Results: The study revealed that when both anaerobic systems are operating under the same Organic Loading Rate (OLR) conditions the acidification of the EoL-DPs could increase the environmental performance of the overall AD system.

Conclusion: The mixing devices in a biogas plant were identified as the equipment parts having the highest impact among the main equipment of the plant, as a result of their high energetic consumption. However, further analysis is needed on the environmental performance of the developed process by extending the systems boundaries towards a Cradle- to-Grave approach.

Keywords: End-of-Life Dairy Products, Agro-industrial wastes, Anaerobic Digestion, Two-stage system, LCA, LCI.

INTRODUCTION

Nowadays, general scientific consensus believes that global warming is caused by the emission of anthropogenic greenhouse gases (GHG), mainly derived from fossil fuel combustion [1]. As a result, the demand for renewable energy is rising because of increasing social awareness of consequences related to non-renewable energy use, e.g. fossil fuel depletion, energy security, and climate change (CC). Renewable energy production in the European Union, for example, is targeted to reach 20% of total energy production by 2020 [2]. This transition requires insight into environmental consequences of producing renewable energy, including CC, fossil fuel depletion, and land use changes.Bioenergy is a renewable energy produced from biomass, including energy crops, wood, microbial biomass as well as wastes from household, agricultural, cattle, forestry and industrial activities [3]. Currently, there is a growing interest on the use of biomass for energy purposes in order to satisfy energy requirements all over Europe

[4], which would imply lower dependency on imports of fossil fuels for many European Union countries where biomass is a local resource [5].

Biomass can be converted by anaerobic digestion (AD) into biogas, composed of methane (CH_4), carbon dioxide (CO_2) and some trace gases (e.g., hydrogen gas), which can then be used to produce bio-energy in the form of electricity and heat. The remaining product after AD, i.e. the digestate, can be recycled as organic fertilizer for crop cultivation to substitute mineral fertilizers[6]. Main substrates for AD include agricultural biomass in the form of animal manures and energy crops (e.g. maize), organic residues from the processing industry (e.g. glycerin, food waste, beet tails, slaughterhouse wastes etc.), and other residues such as, roadside grass or forest residues [7]. According to Holm-Nielsen et al. [8], biogas as potential renewable energy source could represent 25% of all the bioenergy in Europe in the near future.

Under the framework of LIFE+ DAIRIUS project a methodology has been developed in lab and pilot (demonstration) scale, for the integrated management of EoL-DPs in Cyprus. The methodology included the collection and transportation of EoL-DPs in a centralized biogas plant to be co-treated withagroindustrial wastes(AgW). The scenarios tested under the aforementioned operating conditions werethe anaerobic co-digestion of the EoL-DPs with AgW in a single-stage Continuous Stirred Tank Reactor (CSTR) and the anaerobic co-digestion of the EoL-DPs with AgW in a two-stage CSTRs system, where the the EoL-DPs are acidified in a CSTR prior to their mixing with AgW and entrance in the methanogenic CSTR. The systems were tested for about 9 months under pilot-scale conditions and, in this study, their environmental performance usinga gate-to-gate LCA model was assessed.

METHODOLOGY

Life cycle assessment (LCA) is an internationally accepted methodology to gain insight into the environmental consequences of a product or system [9].Its aim is to evaluate holistically the environmental consequences of a product system or activity, by quantifying the energy and materials used, the wastes released to the environment, and assessing the environmental impacts of those in terms of energy, materials and wastes. The environmental analysis developed in this work was carried out according to ISO 14040 guidelines and recommendations [10].

This LCA studywas focused onthe evaluation of the two AD processes tested in the LIFE+ DAIRIUS projectfor the optimum valorization of EoL-DPs.In particular, the partial LCA (from gate to gate) that was conducted aimed at determining appropriate and practical for evaluating possible environmental impacts. In such a gate-to-gate LCA, the upstream and downstream processeswere not considered,whereasthe treatment phase was the fundamental part in the assessment boundaries.

Goal and scope

The *goal* of this assessment was to examine and identify the life cycle environmental impacts from a full-scale anaerobic co-digestion plant (AD) fed with AgW and EoL-DPs either in a single- or two-stage process with the acidification of the EoL-DPs taking place in an acidogenic reactor prior to their mixing with AgW and entrance in the methanogenic reactor. The objective was to identify the most important factors that affect the environmental load of a biogas generation plant. From these factors, the damages caused by the process were analyzed, including the damages avoided from the displacement of fossil fuels and the comparison of the two processes based on their environmental performance. By determining the environmental load of biogas production from AD, is possible to identify whether the processes havebeneficial or detrimental effects on the environment. The two scenarios of AgW – EoL-DPs processing, considered in this study,are shown in **Table 1**.

If not all of the Life Cycle Assessment (LCA) can be carried out on the full life cycle (from cradle-to-grave), special attention should be given in the analysis of the intermediate stages of a product's life (from cradle-to-gate or from gate-to-gate) [11]. For this LCA study, the complete life cycle inventory of industrial scale biogas production with EoL-DPs is unavailable at the early design stage, which makes the partial LCA (from gate-to-gate and nearly gate-to-grave) appropriate and practical for evaluating possible environmental impacts. In the *gate-to-gate LCA*, the upstream (i.e. the stages of production, collection and transportation of AgW and EoL-DPs to the AD plant) and downstream stages (final use of generated products) of the process developed will not be considered unless otherwise mentioned, or werepartially considered. The biomass processing and energy production was the fundamental part in the considered assessment boundaries.

Table 1: Scenariosinvestigated in the present LCA analysis of EoL-DPs energetic valorization via AD

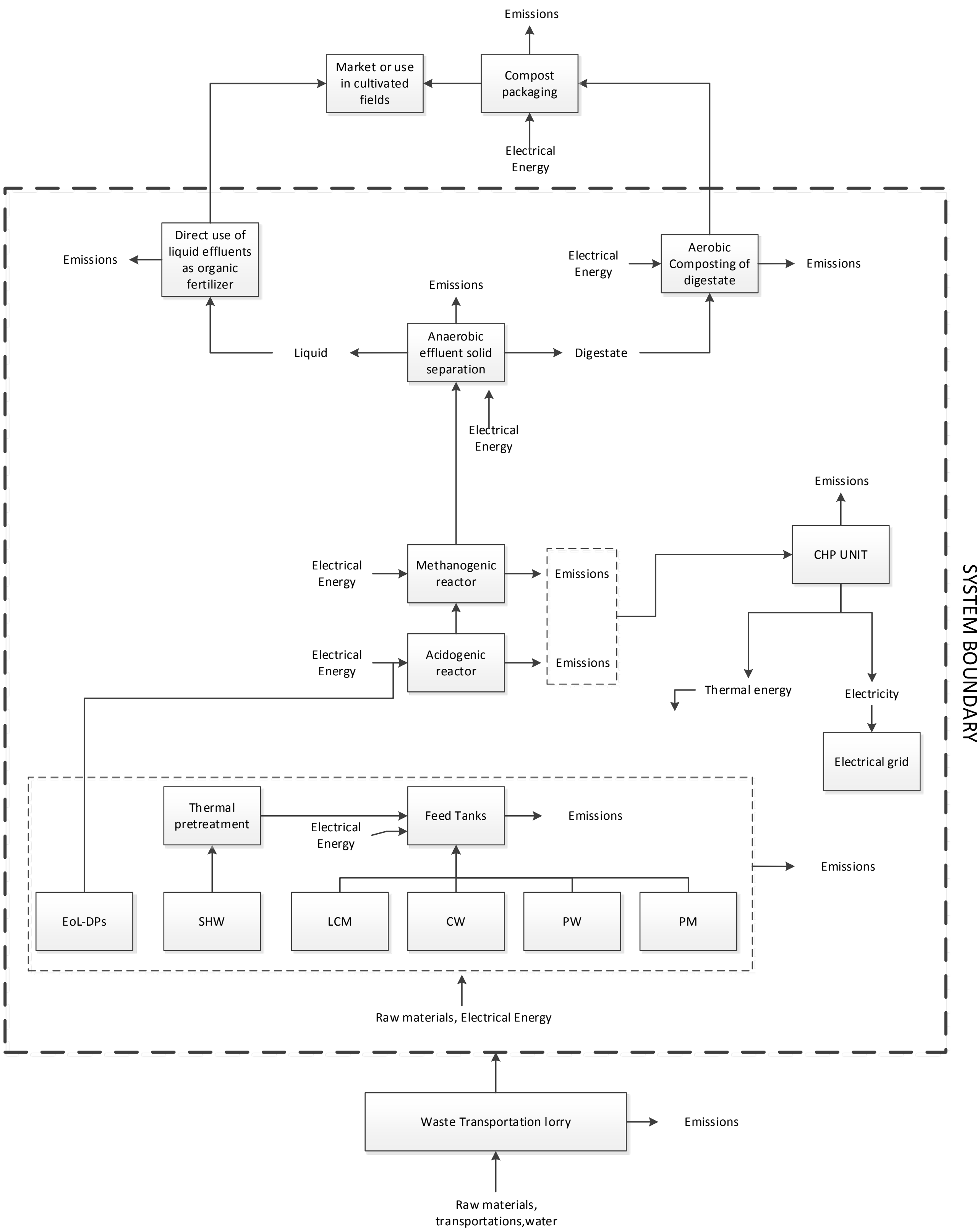
Scenario No.	Acidification	Methanization
1.	20% EoL-DPs	80% AgW
2.	-	80% AgW + 20% EoL-DPs

Key assumptions

The *functional unit* must represent the function of the options compared [12].For all processes and treatment scenarios assessed, 1 tn of raw biomass was decided to be used as the functional unit. In all scenarios studied in this LCA analysis, the system boundaries were drawnwithin the biogas plant limits once raw AgW materials and EoL-DPs were delivered to the plant. The present assessment examined the use of producedbiogas for electricity and thermal energy production, from which electricity is directed to the grid and consumed at the vicinity of the plant (gate-to-grave approach) ignoring thus any electricity loses in the grid due to distribution, whereas thermal energy wasonly used to cover the plant's own needs. However, AgW production and transportation tothe plant, supply of the feedstock to the plant, transportation of the EoL-DPs to the plant, de-packaging and packages recycling, transportation and distribution of the digestate were not included in this LCA, since the main target of this work was to compare the two developed treatment scenarios which are not affected by the upstream and downstream processes. Possible methane emissions from manure and digestate storage on the total global warming potential (GWP) of the biogas system were not taken into account due to the fact that feedstockwasused immediately for feeding the system. It was also considered that the time needed for the various AgW to be treated via anaerobic digestion is negligible compared to the time-scale of environmental impacts. The processing of produced digestate (centrifugation and solid by-product treatment via aerobic composting with mechanical agitation, packing of the material and distribution to the market or direct spreading as a fertilizer) was also kept out of the systems boundary (gate-to-gate approach). However it is assumed that the liquid by-products of the AD process (anaerobic effluents), are used in the surrounding area of the facility for cultivation purposes, avoiding thus any transportation stage (gate-to-grave approach). Alternative processing of the liquid anaerobic effluent, such as aerobic or membrane treatment was not considered due to the complexity that would have been added to the scenarios compared in this study, potentially producing misleading results. The comparison of such alternative practices could be the goal of another LCA and thus is considered to exceed the scope of the present studywhich mainly deals with the environmental assessment of the LIFE+ DAIRIUS technology for the exploitation of the EoL-DPs.

System description

Once agroindustrial wastes (i.e.pig manure (PM), liquid cow manure (LCM), cheese whey (CW), poultry wastes (PW) andslaughterhouse wastes (SHW)) and EoL-DPs are collected,they are transportedto the main plant. In the first scenario which is proposed in the LIFE+ DAIRIUS project, the EoL-DPs are acidified, with simultaneous biohydrogen production, in an acidogenic CSTR reactor under mesophilic conditions and then are fed, after mixing with the AgW, into the methanogenic mesophilic digester. On the other hand, in the second scenario,the EoL-DPs are mixed with the AgW and are fed directly into the main mesophilic digester.The recovered biogas from both reactors, containing carbon dioxide and either methane (methanogenic reactor) or hydrogen (acidogenic reactor), is burnt in a Combined Heat and Power (CHP) unit for the production of electrical and thermal energy. The operating hydraulic retention time (HRT) in both methanogenic reactors was considered to be the same (37 days). The system boundaries of the two process scenarios are illustrated in **Fig. 1**and**Fig. 2**respectively.



Emissions
Market or use in cultivated fields
Compost packaging
Electrical Energy
Emissions
Direct use of liquid effluents as organic fertilizer
Electrical Energy
Aerobic Composting of digestate
Emissions
Emissions
Anaerobic effluent solid separation
Liquid
Digestate
Electrical Energy
Emissions
Electrical Energy
Methanogenic reactor
Emissions
CHP UNIT
Electrical Energy
Acidogenic reactor
Emissions
Thermal energy
Electricity
Electrical grid
SYSTEM BOUNDARY
Thermal pretreatment
Feed Tanks
Emissions
Electrical Energy
Emissions
EoL-DPs
SHW
LCM
CW
PW
PM
Raw materials, Electrical Energy
Waste Transportation lorry
Emissions
Raw materials, transportations,water

Fig. 1: System boundaries for an anaerobic co-digestion plant utilizing AgW and acidified EoL-DPs as feedstocks for biogas production in a two-stage process

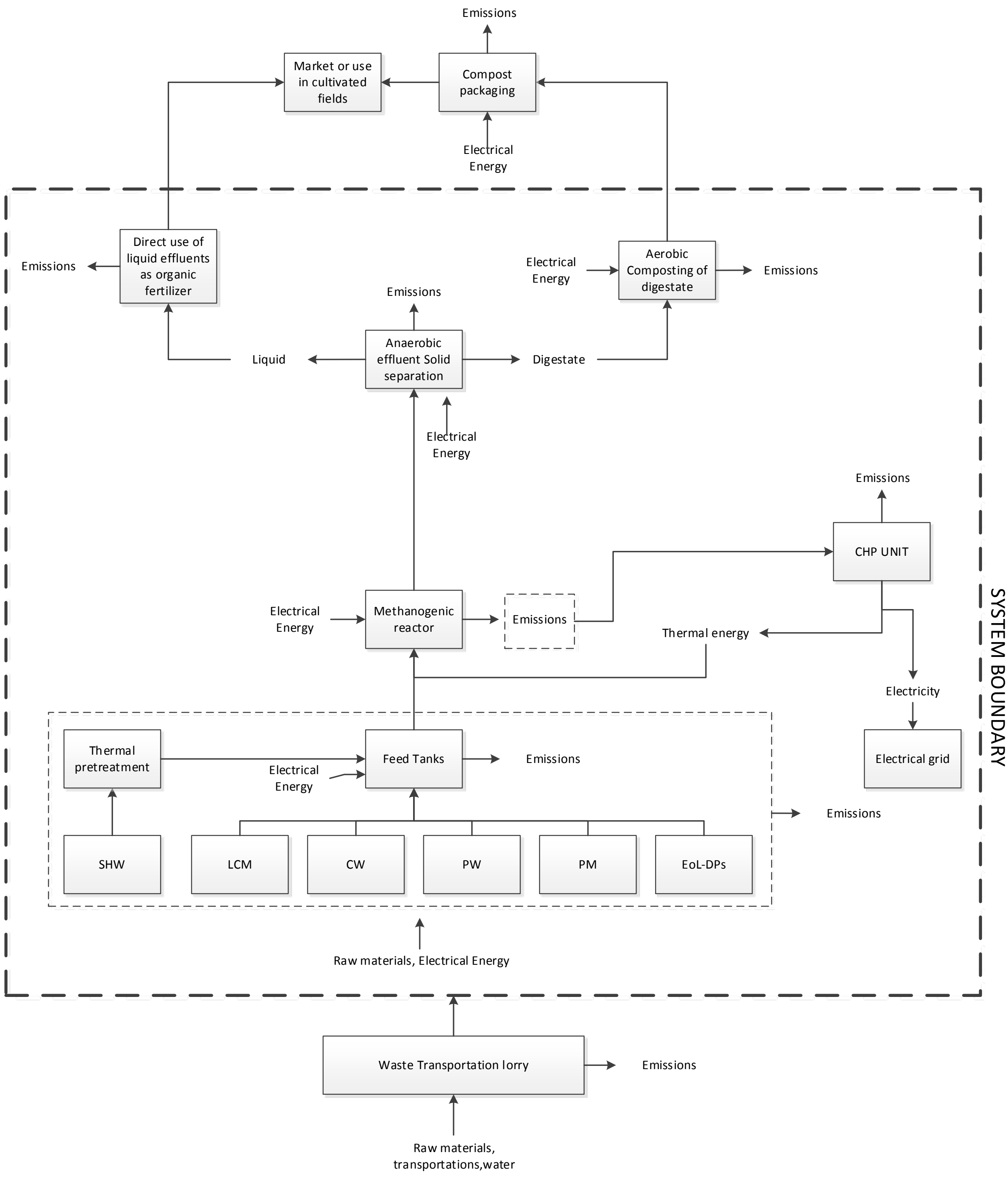


Fig.2: System boundaries for an anaerobic co-digestion plant utilizing AgW and EoL-DPs as feedstocks for biogas production in a single-stage process

The system boundaries for both processes in this gate-to-gate analysis were defined from the physical limits of a typical centralized biogas plant, starting from the raw materials processing inside the biogas plant limits and including the energy production,the aerobic composting of produced digestate as well as the direct spreading and use of liquid anaerobic effluents to adjacent arable land as water for irrigation. Only the inputs (e.g. raw materials, energy) and outputs (e.g. emissions) associated with the processes within the boundary limits were included. The inputs used for the LCI database werethe raw material and energy needs,whereasoutputs were the emissions resulting from the processes. Upstream activities (e.g. animal breeding in cow farms, milk processing, cheese making, etc), transport and downstream activities (e.g. distribution of the electrical energy to the grid, compost packaging and usage) were not included in the boundaries of this study.

Inventory data sources

Inventory analysis aims to quantify the inputs and outputs in the system boundary. The result of an inventory is a long list of material and energy requirements, products and co-products as well as waste and releases into air, soil and water. This list is referred to as the mass and energy balance or the inventory table. To establish a life cycle inventory, the first phase is to survey and collect the life cycle data related to the product system, from inputs to outputs. Life-cycle data concerning gaseous emissions from biogas burning were obtained from a library of SimaPro 8.0.2 referring to a 100kW_{el} (kilowatt electrical power) CHP engine having an electrical efficiency of 38% and a thermal efficiency of 46%.

Table 2summarizes the data from the LCI,calculated on the basis of the functional unit of 1 tn of raw material entering the plant, and the energetic needs for its treatment. For all processes, the calculation of the energetic needs and electricity production was carried out with the hypothesis that all processes are carried out in Cyprus.

Cyprus does notcurrently have any primary energy sources and thus generation of electricity by the Electricity Authority of Cyprus (EAC) is based exclusively on imported fuels, mainly crude oil. Electricity production takes place in three power stations with a total installed capacity of 1478 MW, as presented in **Table 3**.

Table 2: Energetic needs of the main equipment used for the treatment of 1 tn of raw material in a full-scale anaerobic digestion plant

Type of equipment	*Installed Power (Kw)*	**100% AgW**	**80% AgW+ 20% EoL-DPs**	**Treatment phase**
		OPERATION TIME (h/d)		
Storage Mixer 1	11	12	12	***FEEDSTOCK STORAGE***
Storage Mixer 2	11	12	12	
Storage Mixer 3	11	12	12	
Storage Mixer 4	11	12	12	
Storage Mixer 5	11	12	12	
Influent Pump	7.5	3	3	
Feed Pump 1	17	3	3	
Vacum pump 1	0.25	24	24	
Vacum pump 2	0.25	24	24	
Vacum pump 3	0.25	24	24	
Vacum pump 4	0.25	24	24	
Pasteurization	10	2	5	***PRETREATMENT***
Screw Pump 1	8	2	1	

Table 2: Energetic needs of the main equipment used for the treatment of 1 tn of raw material in a full-scale anaerobic digestion plant (cont'd)

Mixer 1	11	0	12	*ACIDOGENIC REACTOR*
Mixer 2	11	0	12	
Paddle mixer 1	10	0	12	
Feed Pump	7.5	0	3	
Mixer 1	11	12	12	*METHANOGENIC REACTOR*
Mixer 2	11	12	12	
Mixer 3	11	12	12	
Paddle mixer 1	10	12	12	
Mixer	6	12	12	*EQUALIZATION TANK*
Effluent Pump	7	2	2	
Separator	7.5	3	3	*SBR*
feed pump	7.5	2	2	
mixer 1	11	8	8	
mixer 2	11	8	8	
jet pump 1	11	12	12	
jet pump 2	13.5	12	12	
Flocculation Tank ($3\ m^3$) Mixer	6	4	4	*SOLID SEPARATION*
Influent Pump	5	4	4	
Effluent Pump	5	4	4	
Decanter	14	8	8	

The inputs into the AD process were the electricity use for transferring wastes between tanks within the limits of the biogas plant and stirring of different tanks (i.e. mixing tank, acidogenesis and methanogenesis reactors, buffering and storage tank). The thermal energy required for heating the anaerobic digester(s) at mesophilic conditions (i.e. 37 ^{o}C) and also for the pretreatment of SWH (80^{o}C for 2 hours) was a fraction from the thermal energy recovered by the CHP unit after the combustion of the biogas. Thus external use of heat energy was not considered in the LCA, since it was produced and consumed within the boundaries of the system.

The energy yields of the scenariosinvestigated in this study and depicted in **Table 4,** were based on calculations made from the results of the demonstration pilot plant which was operated in the framework of LIFE+ DAIRIUS project in Cyprus during the period from May 2014 – March 2015.

Table 3: Analysis of electricity production in Cyprus (ref. to year 2014)

Vasilikos PowerStation	
3 x 130 MW Steam Units	390 MW
1 x 38 MW Gas Turbine	38 MW
2 x 220 MW Combined Cycle Units	440 MW
Dhekelia PowerStation	
6 x 60 MW Steam Units	360 MW
2 x 50 MW Internal Combustion Engines	100 MW
Moni PowerStation	
4 x 37,5 MW Gas Turbines	150 MW
Total Installed Capacity	**1478 MW**

Table 4: Energetic yields of the two scenarios considered in the present study based on DAIRIUS pilot-plant operation

Scenario No.	$m^3\ CH_4/m^3_{feed}$	***Energy Yields***
1. Two-stage system	22.883	**229.25 kWh/m^3 of feed**
2. Single-stage system	17.452	**174.85 kWh/m^3 of feed**

The energy equivalents used for the determination of the energetic yields of the systems after combustion in a typical CHP generator are presented in **Table 5**.

Table 5: Lower heating values of the gaseous biofuels produced in the biogas plant

	Hydrogen	**Methane**
Energy density (MJ/m^3)	10.783	36.1
Energy density (kWh/m^3)	2.79	10.02

Impact assessment

Life cycle impact assessment is the phase where the results of the inventory analysis are interpreted in terms of the impacts they have on the environment. The impact assessment of the LIFE+ DAIRIUS processes was based on the internationally accepted ReCipe v.1.03 which has certain advantages comparing to other approaches, such as the Eco-Indicator 99. The primary advantage is that ReCiPe comprises a broadest set of midpoint impact categories, including several environmental issues, to assess sustainability. Moreover, the results were simulated using the three different perspectives, namely individualist (I), hierarchist (H) and egalitarian (E). The latter was finally chosen to evaluate the results, since it takes into account the long term, precautionary environmental impacts, which better correspond to the scope of this study and thus the following impact categories were identified:Climate change, Human health, Ozone depletion, Human toxicity, Photochemical oxidant formation, Particulate matter formation, Ionising radiation, Climate change Ecosystems, Terrestrial acidification, Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine ecotoxicity, Agricultural land occupation, Urban land occupation, Natural land transformation, Metal depletion, Fossil depletion.

RESULTS AND DISCUSSION

Based on the goals of this study, the most pollutant stages during processing of EoL-DPs and AgW via the proposed treatment scenarios were identified. Moreover, the overall environmental performance of each treatment scenario per tn of raw organic mixture entering the system, was quantified per impact category andispresented.

Overview of the results for Scenario 1 (two-stage system)

The operating scenario of the two-stage process included the acidification of the EoL-DPs in a mesophilic CSTR and their co-digestion with the AgW mixture. Under the frame of this operating strategy an overall increase in the energetic yield of the systemwas evident. The main difference in the two operating scenarios, as regards their operating conditions, was the addition of an acidification step on the system and thus the supplementation of the LCI with the relative energetic inputs and outputs as a result of the hydrogen production by the process. Moreover,a new calculation on the energetic yield of the methanogenic reactor was made as a result of the increase of the overall process performance and the increase in the energy efficiency of the system.

The LCIA results of the process for the co-treatment of EoL-DPs with the aforementioned agroindustrial waste mixture, expressed per tn of raw biomass entering the plant, are presented in **Fig. 3**and **Table 6**. As can be seen, the environmental performance of this scenario is generally affected by the composting process, the application of the liquid digested matter to the land as fertilizer and the biogas production stage, as a result of the atmospheric emissions generated after the combustion of the biogas in the CHP engine. The pretreatment stage has negligible effect on the environmental performance of the system. The main inputs of the LCIA werethe electricity consumptions of the equipment,whilethe main outputs were the biogenic emissions (CO_2) generated by the CHP engine during the combustion of the biogas and the metabolic activity the microorganisms during composting. The use of digested liquid (anaerobic effluent) as fertilizer in agricultural soil in the surrounding area of the biogas unit (without taking into account the transportation of thisliquid fertilizer) is also part of this inventory.

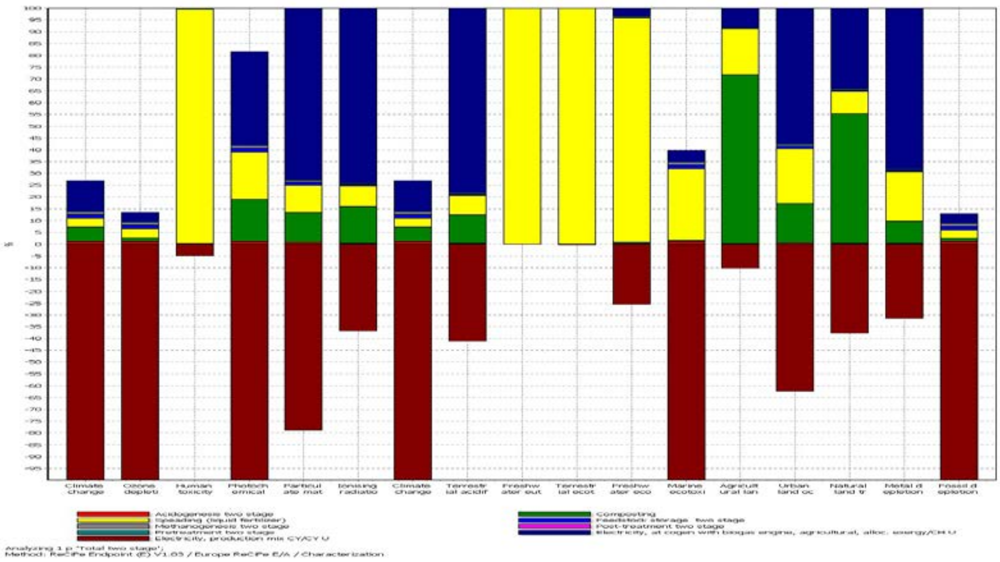


Fig.3: Characterizationdata for Scenario 1 (two-stage system operation)

Table 6: Characterization data for Scenario 1 (two-stage system operation)

Impact category	Unit	Total	Feedstock storage	Pre-treatment	Acidogenesis	Methanogenesis	Post-treatment	Composting	Speading of liquid anaerobic effluent to land	Electricity, with biogas engine	Electricity, production mix CY/CY U
Climate change Human Health	DALY	-0.00047	5.67E-06	4.09E-05	2.3E-05	1.05E-05	7.2E-06	0	1.12E-07	8.5E-05	-0.00064
Ozone depletion	DALY	-5.6E-08	5.72E-10	1.12E-09	2.46E-09	1.06E-09	7.27E-10	0	1.13E-11	2.79E-09	-6.5E-08
Human toxicity	DALY	0.00488	2.23E-06	4.31E-06	0.005103	4.13E-06	2.83E-06	0	4.38E-08	1.45E-05	-0.00025
Photochemical oxidant formation	DALY	-2.8E-09	1.34E-10	2.73E-09	3.04E-09	2.49E-10	1.7E-10	0	2.64E-12	6.04E-09	-1.5E-08
Particulate matter formation	DALY	1.94E-05	6.49E-07	1.18E-05	1.06E-05	1.21E-06	8.25E-07	0	1.28E-08	6.77E-05	-7.3E-05
Ionising radiation	DALY	7.56E-08	3.92E-10	1.86E-08	1.06E-08	7.29E-10	4.99E-10	0	7.73E-12	8.9E-08	-4.4E-08
Climate change Ecosystems	species.yr	-2.5E-06	3.02E-08	2.18E-07	1.22E-07	5.61E-08	3.84E-08	0	5.95E-10	4.53E-07	-3.4E-06
Terrestrial acidification	species.yr	2.25E-08	1.4E-10	4.61E-09	3.13E-09	2.59E-10	1.78E-10	0	2.75E-12	3E-08	-1.6E-08
Freshwater eutrophication	species.yr	3.17E-08	1.1E-13	4.31E-12	3.17E-08	2.05E-13	1.4E-13	0	2.17E-15	6.44E-12	-1.2E-11
Terrestrial ecotoxicity	species.yr	1.22E-05	4.42E-10	3.18E-10	1.22E-05	8.21E-10	5.62E-10	0	8.71E-12	1.9E-09	-5E-08
Freshwater ecotoxicity	species.yr	1.83E-10	5.62E-13	1.36E-12	2.34E-10	1.04E-12	7.14E-13	0	1.11E-14	8.65E-12	-6.3E-11
Marine ecotoxicity	species.yr	-3.7E-10	5.45E-12	4.54E-12	1.86E-10	1.01E-11	6.93E-12	0	1.07E-13	3.16E-11	-6.2E-10
Agricultural land occupation	species.yr	9.38E-09	9.55E-12	7.49E-09	2.06E-09	1.77E-11	1.21E-11	0	1.88E-13	8.74E-10	-1.1E-09
Urban land occupation	species.yr	2.72E-09	4.01E-11	1.21E-09	1.69E-09	7.45E-11	5.1E-11	0	7.91E-13	4.19E-09	-4.5E-09
Natural land transformation	species.yr	5.98E-07	3.22E-09	5.29E-07	8.97E-08	5.99E-09	4.1E-09	0	6.35E-11	3.3E-07	-3.6E-07
Metal depletion	$	0.158453	0.000647	0.021705	0.048725	0.001201	0.000822	0	1.27E-05	0.158365	-0.07302
Fossil depletion	$	-933.729	9.508376	15.69195	38.41856	17.65841	12.08454	0	0.187357	46.51229	-1073.79

The *normalization*stepresults areshown in **Fig.4**. The most significant impacting categories are shown to be the *Human toxicity* and the *Terrestrial ecotoxicology* of the liquid digested streamafter its application as organic fertilizer. The rest of the parametershadnegligible effect on the environmental parameters assessed.

Based on the pilot plant results, the effect of the acidification stage on the energetic consumptions of a unit is negligible. So the environmental performance of such a plant isnot affected as regard the energetic consumptions of the equipment used by the acidification stage.

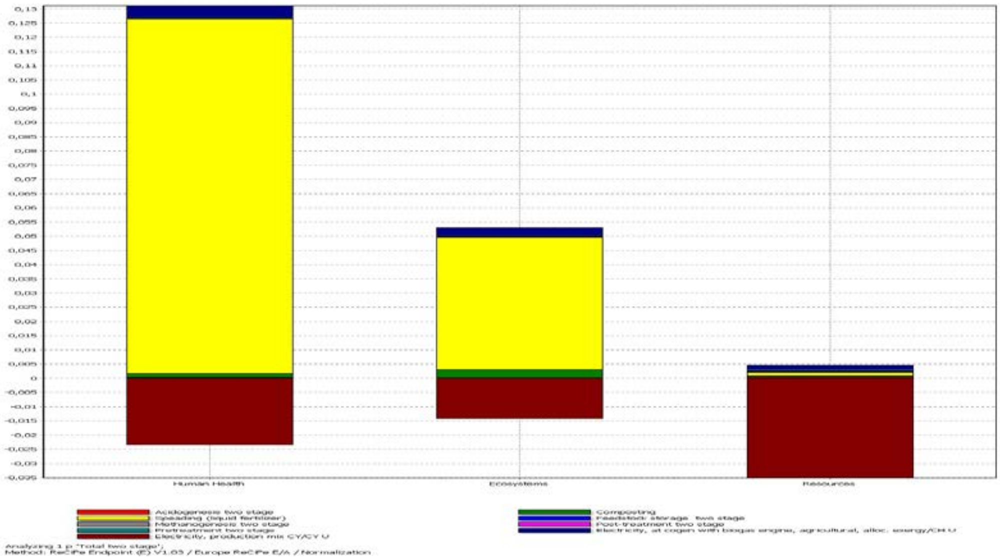


Fig. 4: Normalization results for Scenario 1 (two-stage system operation)

In the weighting **Table 7**,wherea total impact of 52.44 Pt is presented, the disposal of the liquid digested streamis responsible for 68.82Pt. Moreover, the merits on the environment from the renewable energy produced and the positive effect on fossil depletion are also presented.

Table 7: Weighting of the impacts for Scenario 1 (two-stage system operation)

Impact category	Unit	Total	Feedstock storage	Pre-treatment	Acidogenesis	Methanogenesis	Post-treatment	Composting	Speading of liquid anaerobic effluent to land	Electricity, with biogas engine	Electricity, production mix CY/CY U
Human Health	Pt	43.07651	0.154213	0.007363	0.083038	0.105535	0.154213	0.554054	49.92952	1.626042	-9.37752
Ecosystems	Pt	15.47014	0.094357	0.004505	0.050808	0.064573	0.094357	1.134744	18.63849	1.22394	-5.73777
Resources	Pt	-6.10555	0.115494	0.005514	0.062189	0.079038	0.115494	0.102767	0.251576	0.305226	-7.02307
Total	**Pt**	**52.4411**	**0.364064**	**0.017382**	**0.196034**	**0.249147**	**0.364064**	**1.791565**	**68.81958**	**3.155208**	**-22.1384**

Overview of the results for Scenario 2 (one-stage system)

The LCIA results of the process for the co-treatment of EoL-DPs with the aforementioned agroindustrial waste mixture, expressed per tn of raw biomass treated in the plant, are presented in **Fig.5** and **Table 8**. The environmental performance of this scenario is generally affected by the composting process (as was Scenario 1), the application of the liquid digested matter to the land as fertilizer and the biogas production stage as a result of the atmospheric emissions generated after the combustion of the biogas in the CHP engine. The pretreatment stage has negligible effect on the environmental performance of the system. A positive effect is shown because of the energy recovery, either as electricity to the grid or as thermal energy for the supplement of the needs of the plant. The main inputs of the LCIA were the electricity consumptions of the pilot plant equipment and the main outputs the biogenic emissions (CO_2) generated by the CHP engine during the combustion of the biogas and the metabolic activity the microorganisms during composting. The use of digested liquid as fertilizer in agricultural soil and specifically in the surrounding area of the biogas plant (without taking into account the transportation of the liquid fertilizer to the agricultural soil) is also part of this inventory.

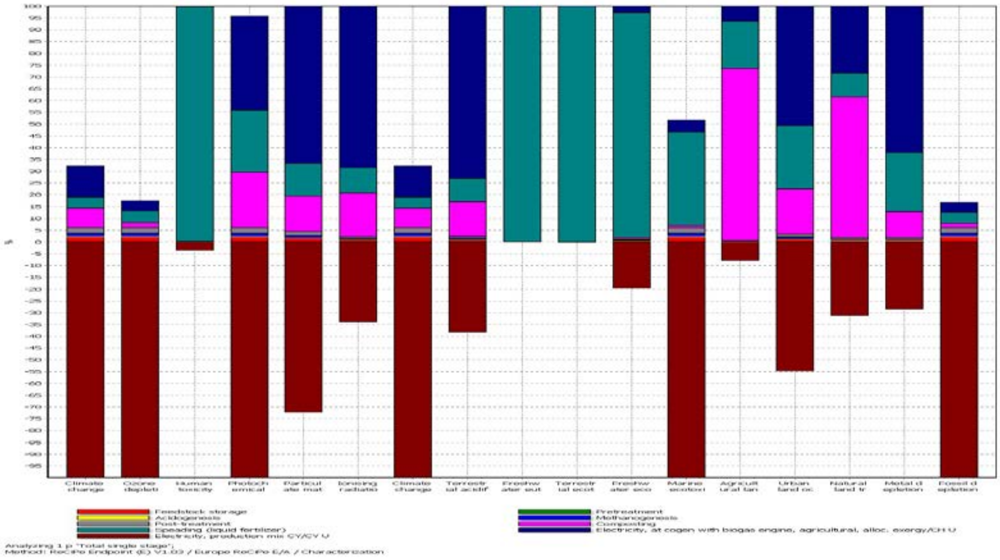


Fig.5: Characterization data forScenario 2 (one-stage system operation)

Table 8: Characterizationdata for Scenario 2 (one-stage system operation)

Impact category	**Unit**	**Total**	**Feedstock storage**	**Pre-treatment**	**Methanogenesis**	**Post-treatment**	**Composting**	**Speading of liquid anaerobic effluent to land**	**Electricity, with biogas engine**	**Electricity, production mix CY/CY U**
Climate change Human Health	DALY	-0.00033	1.05E-05	5.03E-07	7.2E-06	1.05E-05	4.09E-05	2.3E-05	6.48E-05	-0.00049
Ozone depletion	DALY	-4.1E-08	1.06E-09	5.07E-11	7.27E-10	1.06E-09	1.12E-09	2.46E-09	2.13E-09	-4.9E-08
Human toxicity	DALY	0.004938	4.13E-06	1.97E-07	2.83E-06	4.13E-06	4.31E-06	0.005103	1.11E-05	-0.00019
Photochemical oxidant formation	DALY	-4.8E-10	2.49E-10	1.19E-11	1.7E-10	2.49E-10	2.73E-09	3.04E-09	4.61E-09	-1.2E-08
Particulate matter formation	DALY	2.14E-05	1.21E-06	5.76E-08	8.25E-07	1.21E-06	1.18E-05	1.06E-05	5.16E-05	-5.6E-05
Ionising radiation	DALY	6.53E-08	7.29E-10	3.48E-11	4.99E-10	7.29E-10	1.86E-08	1.06E-08	6.79E-08	-3.4E-08
Climate change Ecosystems	species.yr	-1.8E-06	5.61E-08	2.68E-09	3.84E-08	5.61E-08	2.18E-07	1.22E-07	3.45E-07	-2.6E-06
Terrestrial acidification	species.yr	1.93E-08	2.59E-10	1.24E-11	1.78E-10	2.59E-10	4.61E-09	3.13E-09	2.29E-08	-1.2E-08
Freshwater eutrophication	species.yr	3.17E-08	2.05E-13	9.77E-15	1.4E-13	2.05E-13	4.31E-12	3.17E-08	4.91E-12	-9.5E-12
Terrestrial ecotoxicity	species.yr	1.22E-05	8.21E-10	3.92E-11	5.62E-10	8.21E-10	3.18E-10	1.22E-05	1.45E-09	-3.8E-08
Freshwater ecotoxicity	species.yr	1.97E-10	1.04E-12	4.98E-14	7.14E-13	1.04E-12	1.36E-12	2.34E-10	6.6E-12	-4.8E-11
Marine ecotoxicity	species.yr	-2.3E-10	1.01E-11	4.83E-13	6.93E-12	1.01E-11	4.54E-12	1.86E-10	2.41E-11	-4.7E-10

Agricultural land occupation	species.yr	9.44E-09	1.77E-11	8.46E-13	1.21E-11	1.77E-11	7.49E-09	2.06E-09	6.67E-10	-8.2E-10
Urban land occupation	species.yr	2.84E-09	7.45E-11	3.56E-12	5.1E-11	7.45E-11	1.21E-09	1.69E-09	3.19E-09	-3.5E-09
Natural land transformation	species.yr	6.09E-07	5.99E-09	2.86E-10	4.1E-09	5.99E-09	5.29E-07	8.97E-08	2.52E-07	-2.8E-07
Metal depletion	$	0.1388	0.001201	5.73E-05	0.000822	0.001201	0.021705	0.048725	0.120786	-0.0557
Fossil depletion	$	-681.155	17.65841	0.843107	12.08454	17.65841	15.69195	38.41856	35.47513	-818.985

Whilst the characterized data show the relative contribution of the stages of the LCA to it, the characterization step does not show the relative significance of the impacts. Thus, a normalization step was undertaken, the results of which are shown in **Fig. 6.** The most significant impacting categories are shown to be the *Human toxicity* and the *Terrestrial ecotoxicology* of the liquid digested matter after its application as organic fertilizer. The rest parameters have negligible effect on the environmental parameters assessed.

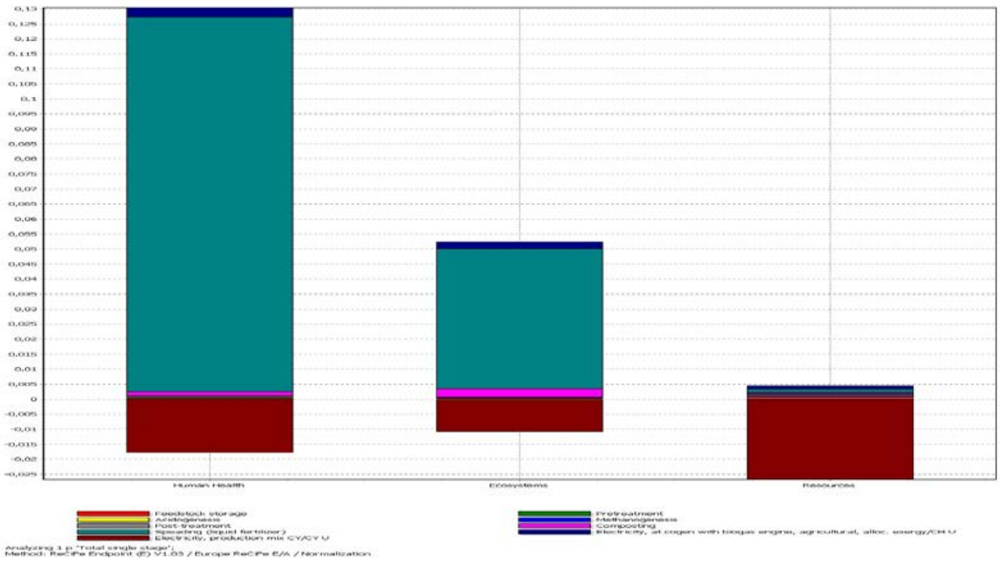


Fig.6: Normalized data for Scenario 2 (one-stage system operation)

In the weighting **Table 9** a total impact of 57.13 Pt is illustrated. The disposal of the liquid digested matter is responsible for the 68.82 Pt. Moreover, the merits on the environment from the renewable energy produced and the positive effect on fossil depletion are also presented.

CONCLUSIONS

In the present study an analysis was conducted to determine the environmental performance of two integrated waste management processes for the energetic valorization of EoL-DPs, developed under the framework of LIFE+ DAIRIUS project. The main objective was the identification of the key environmental hotspots of the two operating scenarios of EoL-DPs treatment, in order to provide feedback to support the sustainable development of these processes or future similar ones, in full-scale. The proposed plant, was examined as a gate-to-gate case. The recognized negative impacts on the environment are mainly due to the combustion process of the biogas in the CHP generator, which produces gaseous emissions, and the electrical energy demands for its operation. Therefore, air emissions and energy and thermal inputs during processing are the key contributors to the environmental impacts in this LCIA. The use of the liquid effluent (digestate)for cultivation purposes also contributes to the negative impacts of the plant operation. Usually, the anaerobically digested liquid effluent still contains increased amounts of organic compounds (mostly recalcitrant ones) and nutrients which are essential for cultivation purposes and can therefore replace chemical fertilizers.

Table 9: Weighting of the impacts for Scenario 2 (one-stage system operation)

Impact category	Unit	Total	Feedstock storage	Pre-treatment	Methanogenesis	Post-treatment	Composting	Speading of liquid anaerobic effluent to land	Electricity, with biogas engine	Electricity, production mix CY/CYU
Human Health	Pt	44.99281	0.154213	0.007363	0.105535	0.154213	0.554054	49.92952	1.240189	-7.15228
Ecosystems	Pt	16.58831	0.094357	0.004505	0.064573	0.094357	1.134744	18.63849	0.933504	-4.37622
Resources	Pt	-4.45385	0.115494	0.005514	0.079038	0.115494	0.102767	0.251576	0.232797	-5.35653
Total	**Pt**	**57.12727**	**0.364064**	**0.017382**	**0.249147**	**0.364064**	**1.791565**	**68.81958**	**2.406491**	**-16.885**

However, in this study, the positive effects due to replacement of chemical fertilizers have not been considered because of the type of analysis carried out (Gate-to-Gate).Nevertheless, positive impacts were diagnosed because of the replacement of electrical energy in the grid and thermal requirements with electricity and thermal energy produced *in situ* in the plant. Based on the DAIRIUS pilot plant results, the effect of the acidification stage on the energetic consumptions of such a plantin this Gate-to-Gate system is negligible. However, the overall energetic efficiency and as a result the environmental performance of the system is increased due to the increase of the biogas yield in the two-stage scenario. The current LCA analysis was based on the existing DAIRIUSpilot plant data. Therefore, further verification of resultsis needed on the environmental performance of such a system usinginputs from a full-scale two-stage plant.The environmental assessment of such a system should be extended to a Cradle-to-Grave analysis, as part of future work.

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