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ENVIRONMENTAL ASSESSMENT OF WASTE FEEDSTOCK MONO-DIMENTIONAL AND BIO-REFINERY SYSTEMS: COMBINING MANURE CO-DIGESTION AND MUNICIPAL WASTE ANAEROBIC DIGESTION

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ABSTRACT:

Organic municipal solid waste (OMSW) as a feedstock for energy recovery and material recycling offers the potential to reduce environmental impacts from energy production while displacing emission-intensive waste management strategies such as landfills. This paper quantifies the environmental impact of anaerobic digestion of local, residual biomass. A life-cycle assessment was jointly performed for two scenarios for the biological treatment of local organic municipal solid waste and pig manure in the Netherlands. Scenario 1 was a separate treatment using anaerobic digestion, and Scenario 2 was a bio-refinery system that integrates anaerobic digestion of organic, municipal solid waste, and co-digestion of pig manure and other organic co-substrates\. For both scenarios, electricity and heat are generated using a combined heat and power engine. The bio-refinery system (Scenario 2) contribution to climate change resulted in 0.16 Mt CO₂ eq./yr, which is lower than the 0.17 Mt CO₂ eq./yr of Scenario 1. Both scenarios are found to be beneficial with regard to resource depletion and human toxicity. The integration of organic waste and manure anaerobic digestion has no effect on acidification and terrestrial eutrophication impact categories, resulting in 43.59 AE eq. and 86.33 AE eq. for Scenario 1 and 43.58 AE eq. and 86.30 AE eq. for Scenario 2. Moreover, Scenario 2 yields 18% lower emissions than those from natural gas derived electricity in the Netherlands. The biorefinery system represents an opportunity to improve organic waste-management strategies, at the same time as reducing the environmental impact from energy production and the costs for surplus manure disposal by producing highquality commodities that can be traded on the market.

KEYWORDS:

Biomass; Life-cycle assessment; Anaerobic digestion; Bioenergy; CHP.

HIGHLIGHTS:

- A life-cycle assessment of organic feedstock anaerobic digestion was performed.
- A bio-refinery was compared to a mono-dimensional technology set
- The bio-refinery performed better for climate change and human toxicity.
- Environmental benefits with regard to resource depletion were achieved in both scenarios.

1. Introduction

The European 20-20-20 strategy aims to achieve a 20 % cut in GHG emissions from 1990 levels by, among other things, increasing energy consumption from renewable sources by 2020. The increased use of residual biomass is one of the potential means of achieving this target (SWD 259, 2014). Combined economic and environmental benefits can be created by using residual biomass (Maes et al., 2015), and competition with food and fiber production can be avoided (Rentizelas et al., 2009). Organic municipal solid waste (OMSW) as a feedstock for energy recovery offers the potential to reduce environmental impacts from energy production while displacing emissionintensive waste management strategies such as landfills. Waste material recycling and energy recovery have been recognized as effective strategies for sustainable waste management (Soltani et al., 2016). Similarly, circular economy (CE) can be considered to be an appropriate approach to waste management (Ghisellini et al., 2014). Despite many similarities, CE prioritizes the economic system with primary benefits for the environment, while the concept of sustainability embeds the equal treatment of economic, social and environmental dimensions (Geissdoerfer et al., 2017). However, circular systems may bring potential environmental costs. The energy required and the environmental impacts generated for recovering energy and materials from waste may generate more burdens than using conventional sources (Allwood, 2014).

Landfilling, incineration, composting and anaerobic digestion (AD) are some of the technologies available to obtain energy from organic wastes (Fodor and Klemeš, 2012). Landfilling is a simple and low-cost technology, which is associated with water pollution, air pollution and land use (Sawatdeenarunat et al., 2016). Emission of pollutants and energy depletion can be reduced by waste incineration thanks to energy recovery (Belboom et al., 2013), but it requires high capital, operational, and maintenance costs (Fodor and Klemeš, 2012). Anaerobic digestion is preferable to landfilling in terms of energy use and emissions of GHG, while composting could be an interesting opportunity if transport distances are kept low (Finnveden et al., 2005). Furthermore, for manure and OMSW, AD provides evidence of better environmental performance than landfilling and composting (Laurent et al., 2014). This has been confirmed by several studies applying life-cycle assessment (LCA) to quantify the environmental benefits and drawbacks of bio-waste treatment. The AD of organic biomass is the best organic waste management option because it makes it possible to recover energy (Belboom et al., 2013). Morris et al. (2013) evaluated 82 peer-reviewed studies, using mostly LCA, quantifying the management options for organic waste. The authors concluded that anaerobic digestion and composting are preferable management strategies for the organic waste compared to incineration and landfill with energy recovery. Boldrin et al. (2011) developed an LCA-based model (EASEWASTE) for evaluating potential environmental effects of different organic waste biological treatments. The EASEWASTE model is based on previous waste-LCA studies and includes downstream and upstream processes in modeling organic waste-management systems (Boldrin et al., 2009). Using existing treatment facilities, the authors found AD to be more beneficial than composting in terms of global warming and acidification. Evangelisti et al. (2014) found that AD is the best treatment option for CO₂ and SO₂ emissions, when heat and energy from bio-gas were substituted for fossil fuel-derived energy (electricity and heat) and digestate for chemical fertilizers. Mezzullo et al. (2013) found that AD was beneficial in terms of GHG emissions, and fossil fuel use compared to conventional energy production pathways, but only if all processes were properly managed for reducing methane emissions. Battini et al. (2014) combined on-farm manure AD with energy production as an effective strategy for reducing the environmental impacts of dairy farming. Despite the issues related to competing land use, nutrient overprovisioning (De Vries et al., 2012), and profitability (Van Dael et al., 2013b), bioenergy technologies are considered a more reliable way to help reduce the impacts of the energy sector than generating fossil energy (Hijazi et al., 2016). The present study adds to this literature by analyzing the environmental impacts of treating local residual biomass (OMSW and pig manure) for energy and materials recovering using anaerobic digestion. The research concentrates on the Netherlands, where the National Waste Management plan 2009 - 2021 (VROM, 2010) focuses, among other technologies, on waste-toenergy anaerobic digestion to achieve the material recovery and GHG reduction targets set out in the national policy (Corsten et al., 2013). In a previous paper, Van Dael et al. (2013b) performed a techno-economic assessment to compare the profitability of a combined AD system (AD of OMSW and co-digestion of manure) and the two mono-dimensional processes (Van Dael et al., 2013b). It was concluded that profitability could be increased through integrating technologies in the biorefinery. The existing study has been complemented by comparing the environmental performances of the mono-dimensional and integrated processes with regard to global warming, acidification, eutrophication, resource depletion, and human toxicity.

2. Material and Methods

2.1. The case study

The case study is performed in the region of Moerdjjk (51° 39′ NB, 4° 32′ OL), situated in the south-west of the Netherlands. The case studies are located in the Netherlands, where there is significant public concern regarding the environmental burden of animal-manure and organic waste management. Large amounts of OMSW and pig manure are available in the Region (Van Dael et al., 2013a). However, pig manure cannot be used on the land because of the European Nitrate directive and must therefore be transported abroad. In this context, two technology scenarios for the biological treatment of local OMSW and pig manure were studied: the separate treatment of local OMSW and pig manure (Scenario 1); and a multi-dimensional system combining AD of OMSW and co-digestion of pig manure (Scenario 2). Based on the inventory, both scenarios are modeled with a focus on energy efficiency. The anaerobic digestion process in both systems is based on thermophilic Dranco® technology (Organic Waste System, Belgium). Overall, the two scenarios had combined electricity demand of 16,579 MWh per year and a heat demand of 10,856 MWh per year. In Scenario 2 (Figure 2), the electricity and heat demand was fully met by the biogas combustion, while in Scenario 1 (Figure 1) external heating is needed for the co-digestion of pig manure.

electrical grid and the avoided emissions from the displacement were credited to both scenarios. Moreover, the surplus heat was assumed to be transferred to consumers over a few kilometers, but only during autumn and winter (six months per year).

The foreground system consists of the dry AD process excluding the OMSW pre-treatment, the composting of the digestate and pig manure (mixed with co-substrates), CHP production, and the treatment of the digestate to produce substitutes of fertilizers. The background system includes the displaced production of electricity, heat and fertilizers.

2.2. Scenario 1: The Mono-dimensional system

The separate scenario consists of the two separate biomass treatment processes: the AD of OMSW (OMSW digestion); and the AD of pig manure and co-substrates (co-digestion). In the OMSW digestion, the feedstock was 100 percent OMSW, while the co-digestion was a mixed feedstock with 66 percent manure and 33 percent co-substrates to feed the anaerobic digester. All bio-gas produced by both AD installations were converted into electricity and heat, using a combined heat and power engine (CHP). The CHP was assumed to be installed at the plants sites. The effluent form OMSW digestion were further composted in aerated in-vessel tunnels. The outflows from the co-digestion was further treated by separation, drying, ultrafiltration, and reverse osmosis to produce compost and macronutrients. The main characteristics of the feedstock biomass are reported in Table 1.

2.3. Scenario 2: The bio-refinery system

In Scenario 2, the same biomass feedstock is processed using the same technologies (Table 1), but the bio-gas produced is processed in the same CHP installation. To be consistent, all the bio-gas produced by both OMSW AD and co-digestion are converted into electricity and heat using the same CHP engine as Scenario 1. All materials and energy flows were considered the same as in the separate scenario.

Table	1:	Main	charac	teristics	of	the	input	biomass.
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Inputs	Unit	Value	Source
Organic Municipal Solid Waste			
Fresh matter input	ton/year	64,000	
Water content of fresh matter	%	63%	Personal communication company 2012; (Faaij et al., 1997) Personal communication company
Biogas production (dry digester)	Nm³/ton	100	2012
Methane yield OMSW bio-gas	%	55%	Personal communication company 2012
Co-substrates (green waste)			
Fresh matter input	ton/year	31,150	
Water content of fresh matter	%	40%	(Faaij et al., 1997)
Wood fraction in green waste	%	11%	Personal communication composting company, 2012
Pig manure			
Fresh matter input	ton/year	16,000	
Water content of fresh matter	%	94%	(Gebrezgabher et al., 2010)
Density of manure	kg/m³	1,000	(Mosquera et al., 2010)
Phosphorus	g/kg raw manure	0.99	(Prapaspongsa et al., 2010)
Nitrogen	g/kg raw manure	3.67	(Prapaspongsa et al., 2010)

2.4. The Life-Cycle Impact Assessment

Figure 1 and 2 show a schematic representation of the modeled scenarios; the AD and codigestion processes, its mass and energy balances; and the system boundaries. The life-cycle inventory was built using primary data (Table 2). The emissions factors for the different processes were adapted from peer-reviewed literature (Table 3).





Figure 1: System boundaries and material flows diagram for the mono-dimensional system (Scenario 1) (adapted from Van Dael et al. (2013)

The system perspective approach suggested by Eriksson et al. (2005) was used to describe the scenarios. As suggested by Cherubini et al. (2009b), and similar to Turner et al. (2016), the functional unit (FU) of the environmental assessment was defined as the total weight of the yearly processed OMSW, , manure, and co-substrates in the local area.

The final products – electricity, heat, compost, and nutrients – were included using the substitution approach. Considering the critical importance of the type of energy substituted (Bernstad Saraiva Schott et al., 2016), the production of electricity and heat from bio-gas combustion was included as a substitute for conventional heat and electricity production, according to the Dutch country energy mix.



Figure 2: System boundaries and material flows diagram for the biorefinery system (Scenario 2) (adapted from Van Dael et al. (2013)

Moreover, it was assumed that all outputs from composting and physical treatments of the digestate were suitable for agricultural use for both the OMSW digestion and co-digestion. Therefore, utilization of the digestate fractions as soil fertilizers were included as substitutes of the production of fertilizers. For the macro-nutrient composition of the different digestate fractions, data from Gebrezgabher et al. (2010) were taken into account. According to Møller et al. (2009), no nutrients were lost during AD. Therefore, the nutrient content of the digestate from OMSW digestion was assumed to be the same as in the waste. The specific waste composition was not available for the case study, so the average nutrient content in the organic fraction of municipal solid waste from Evangelisti et al. (2014) was used. The life-cycle inventory data for the substituted products was taken from the ecoinvent v2.2 database (Weidema et al., 2009; Weidema and Hischier, 2010). The infrastructure (AD plant, CHP generation unit) was included in the environmental impact assessment to guarantee the complementarity between the economic (Van Dael et al., 2013b) and environmental assessment. Emissions related to infrastructure were also modeled using the ecoinvent v2.2 database. However, the stabilization of organic material implied the emissions of four main substances: Carbon dioxide (CO₂), methane (CH₄), volatile organic compounds (VOC), and nitrous oxides (NO₂) (Saer et al., 2013). Colón et al. (2012)

simultaneously measured gaseous emission on the surface of the emissions from different MSW treatment including anaerobic digestion, followed by composting of the digestate using the same technologies as specified in this case study. Emissions from manure and digestate storage in the co-digestion may change, according to several parameters related to the manure type and storage technologies (Battini et al., 2014). In this study, NO₃, N₂ and NH₃ losses were estimated according to Prapaspongsa et al. (2010), which characterized the emissions form the treatment and storage of pig manure based on European practices. The emissions from the CHP engine were adapted from Agostini et al. (2015). The authors reported methane slip and accidental emissions for a gas-fired CHP unit with power less than 25 MW. Table 3 provides an overview of the emission factors for the different processes included in the LCA model.

Several studies (Bare, 2010) pointed out the lack of standardization in different impact categories in the LCA literature. To undertake this limitation, the International Reference Life-Cycle Data System (ILCD) recommendations (European Commission - Joint Research Center, 2011) were used in this study to define the best-suited methods for characterizing the impact categories at the midpoint level. The following five impact categories were investigated: Climate change (CC); Human toxicity (HT); Acidification (AC); Terrestrial eutrophication (TE); and Resource depletion (RD). Data in these categories was gathered using the IPCC 2007 global warming potential (GWP) at 100 years, USEtox, CML 2001, and Accumulated Exceedance methodologies, respectively.

All model-input parameters were deterministically defined. This meant that the initial parameter uncertainty was unknown. Therefore, only local sensitivity analysis could be implemented (Groen et al., 2014) to capture the influence of the model configuration on the outcomes. Perturbation analysis was carried out using the one-at-a-time (OAT) approach. The sensitivity ratio (SR) for each parameter and impact category was also estimated using the approach developed by Bisinella et al.(2016). The goal of this quick scan was to identify the parameters that had the greatest impact on the variance of the environmental impact for each impact category.

			Value	Unit			Value	Unit			Value	Unit			Value	Unit
		OMSW	64,000	ton		Digestate	56,223	ton		Pig manure	16,000	ton		Biogas dry digester	6,188,483	m³/yr
			9	ton/h		Dry Matter	20,802	ton		Co- substrates	8,000	ton		Biogas co- digester	1,243,885	m³/yr
		Total input dry digester	64,000	ton		Water	63	%		Total input	24,000	ton		Total bio-gas	7,432,368	m³/yr
	t	Water content	40,320	ton		Green waste	31,150	ton		Heat	720	MWh /yr		Hethane	4,112,866	m³/yr
robic digestion	Inpu		63	%		Drv Matter	18,305 ton 41 % in 11,985 ton 11,985 ton	Electricity	2,161	MWh /yr		II				
		Volume needed dry digester	5,389	m ³		The Water		Biogas pig manure	326,400	m ³	ne)	Power engine	8.08	MW		
		Number of digesters	2.00	#	Composting	Recirculation part		Biogas co- substrates	960,000	m ³	s engiı	Electric efficiency	42	%		
		Size dry digester	2,695	m³		Dry Matter	7,790	7,790 ton 35 %	Total bio- gas	1,286,400	m³	IP (ga	Electric power	3.36	MWe	
Ana		Heat	3,457	MWh /yr		Water	35		Fraction bio-gas CHP	100	%	CE	Thermal efficiency	43	%	
		Electricity	10,371	MWh /yr		Total input	99,358	ton	ton	Methane 펄 yield	57	%		Heat	17,558	MWh/yr
		Biogas OMSW	6,400,000	m ³		Total DM input	46,898	ton		Digestate	22,437	ton		Total heat use efficiency	35	%
		Methane yield	55	%		Total water input	53	%						Electricity	16,775	MWh/yr
	ıtput	Digestate	56,223	56,223 ton		Electricity	3,880	MWh								
	10 0	Fraction bio-gas CHP	100	%		tin Compost O	23,183	ton								

Table 2: Main inputs and outputs for the processes. Own elaboration based on Van Dael et al. (2013b)

Process	Value	Unit	Source
Anaerobic digestion OMSW +			
Composting			
CH_4	2.39	kg/ton	
N_2O	0.04	kg/ton	(C_{0}) at (C_{0})
VOC	0.86	kg/ton	$(Colon et al., 2012)^{2}$
NH ₃	2.00	kg/ton	
CO_2	All biogenic		
Co-digestion			
CH ₄	1.00	% of the total	(Agostini et al., 2015)
NH ₃	20.00	kg/ton of manure	
N_2O	5.00	kg/ton of manure	(Prapaspongsa et al.,
N_2	15.00	kg/ton of manure	2010)*
Energy production from bio-			
gas			
N_2O_X	145.80	g/MWh	
CH_4	87.21	g/MWh	
NMVOC	3.78	g/MWh	$(\Lambda \text{ as stining to all } 2015)$
CO	73.71	g/MWh	(Agostini et al., 2015) ²
N ₂ O	0.14	g/MWh	
SO ₂	5.13	g/MWh	

Table 3: Emission factors for the different processes included in the scenarios.

^a EFs calculate for the combination of anaerobic digestion and digestate composting.

^b EFs attributed to anaerobic digestion combined with storage tank.

^c EFs assigned to a CHP engine with power lower than 25 MW.

3. Results

The mono-dimensional system (Scenario 1) shows a higher impact on CC (0.17 Mt CO₂ eq.) than the bio-refinery system (0.16 Mt CO₂ eq.). Both scenarios show the same impacts for AC and TE (43.5 AE eq. and 86.3 AE eq., respectively), and register equal environmental benefits in terms of RD (16.4 kg Sb eq.). In terms of HT, the impact is positive for both scenarios, but higher for Scenario 2 (Table 4).

The anaerobic digestion and the conversion of bio-gas in heat and electricity are the main contributors to the CC impact, accounting for almost the entire negative environmental impact (Table 4). This outcome is mainly caused by the co-generation of heat and electricity, which contributes greatly to global warming. The AD and co-digestion processes have a meaningful contribution to the impact on CC (approximately 40 percent of the overall kg CO₂ eq.) due to occasional methane leaks during bio-gas production and manure stabilization. The composting of pig manure and co-substrates produce all the environmental impacts for AC and TE impact categories in Scenarios 1 and 2. Although higher positive impacts were estimated for the monodimensional system, the avoided production of electricity was the main determinant of the outcomes by both scenarios in terms of HT (approximately 60 percent). The displacement of fertilizers and electricity contribute to the environmental benefit for the RD impact category. Separate scenarios were developed, accounting for an increase/decrease of the initial values for treated biomass, the CHP conversion efficiency and the productivity of bio-gas and methane (Table 5). In Scenario_{*FEED*}, a 10 % increase of all feedstock (OMSW, pig manure, and co-substrates) was considered, whereas for Scenario_{*CHP*}, the given conversion efficiencies (electricity and heat) were decreased by 5 percent. Bio-gas and methane productivity, as well as nutrient content of the compost produced from OMSW AD, were related to the chemical characteristics of feedstock materials (Gebrezgabher et al., 2010). Therefore, these parameters were included in the sensitivity analysis. Both methane yield (Scenario_{*MET*}) and nutrient concentrations (Scenario_{*NUT*}) were increased by 10 % for both feedstock.

Table 4: Yearly characterization impacts for the modeled scenarios and processes. Bolded more relevant contributing process for each impact category.

 Percentages represent the absolute contribution of each process to the total impact.

	Products	Climate change (t CO ₂ eq.)	%	Human toxicity (CTU _h ^a)	%	Acidification (AE ^b eq.)	%	Terrestrial Eutrophication (AE ^b eq.)	%	Resource depletion (kg Sb eq.)	%
	Digestate refinement	2.54E+03	1.48	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
	Digestate	6.41E+04	37.32	7.63E-05	-0.01	8.63E-08	0.00	1.70E-07	0.00	5.04E-06	0.00
	N fertiliser	-5.87E+03	-3.41	-6.80E-02	11.31	-2.12E-02	-0.05	-4.11E-02	-0.05	-2.68E-01	1.63
	K ₂ O fertilizer	-2.78E+02	-0.16	-5.57E-02	9.26	-1.57E-02	-0.04	-3.07E-02	-0.04	-8.55E+00	52.09
	P_2O_5 fertiliser	-2.03E+02	-0.12	-7.37E-02	12.25	-1.92E-02	-0.03	-2.69E-02	-0.03	-7.22E+00	43.99
Scenario 1	Compost production	7.86E+03	4.57	3.71E-05	-0.01	4.37E+01	100.28	8.65E+01	100.28	5.89E-06	0.00
	Heat	-2.64E+03	-1.54	-3.64E-02	6.06	-4.47E-02	-0.01	-8.83E-02	-0.01	-6.93E-03	0.04
	Electricity	-8.81E+03	-5.13	-3.68E-01	61.15	-9.38E-03	-0.15	-1.86E-02	-0.15	-3.68E-01	2.24
	Electricity co-gen	5.56E+04	32.34	4.31E-05	-0.01	4.55E-06	0.00	8.81E-06	0.00	2.90E-05	0.00
	Heat co-gen	5.95E+04	34.65	4.62E-05	-0.01	4.60E-06	0.00	8.91E-06	0.00	3.10E-05	0.00
	Total	1.72E+05		-0.60		43.59		86.33		-16.42	
	Digestate refinement	2.60E+03	1.55	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00	0.00E+00	0.00
	Digestate	6.41E+04	38.21	7.63E-05	-0.01	8.63E-08	0.00	1.70E-07	0.00	5.04E-06	0.00
	N fertiliser	-5.99E+03	-3.57	-6.94E-02	9.64	-2.14E-02	-0.05	-4.15E-02	-0.05	-2.73E-01	1.66
	K ₂ O fertilizer	-2.86E+02	-0.17	-5.59E-02	7.77	-1.57E-02	-0.04	-3.07E-02	-0.04	-8.56E+00	52.02
G • •	P ₂ O ₅ fertiliser	-2.05E+02	-0.12	-7.44E-02	10.33	-1.38E-02	-0.04	-2.71E-02	-0.03	-7.30E+00	44.36
Scenario 2	Compost production	7.86E+03	4.68	3.71E-05	-0.01	4.37E+01	100.25	8.65E+01	100.24	5.89E-06	0.00
	Heat	-4.36E+03	-2.60	-6.01E-02	8.34	-3.30E-03	-0.10	-6.54E-03	-0.10	-1.14E-02	0.07
	Electricity	-1.10E+04	-6.57	-4.61E-01	63.94	-6.73E-02	-0.02	-1.33E-01	-0.02	-3.09E-01	1.88
	Electricity co-gen	5.93E+04	35.35	4.60E-05	-0.01	4.59E-06	0.00	9.30E-06	0.00	3.09E-05	0.00
	Heat co-gen	5.58E+04	33.24	4.33E-05	-0.01	4.31E-06	0.00	8.75E-06	0.00	2.91E-05	0.00
	Total	1.68E+05		-0.72		43.58		86.30		-16.45	

^a Comparative Toxic Unit for humans (CTUh) as defined by Rosenbaum et al. (2008)

^b Accumulated Exceedance (AE) as defined by Seppälä et al. (2006)

Parameter	Unit	Baseline	Feedstock	CHP unit efficiency	Methane efficiency	Nutrient efficiency
			Scenario _{FEED}	Scenario _{CHP}	Scenario _{MET}	Scenario _{NUT}
Amount of processed feedstock	ton/year	88,000	96,800	-	-	-
Methane yield	% of total bio-gas produced	55%	-		65%-	-
Nutrient content						
N	g/kg _{TS}	31.30	-	-		28.17
Р		4.87	-	-		4.383
Κ		12.90	-	-		11.61
CHP unit efficiency						
Electricity efficiency	% of converted	42%	-	37%	-	
Thermal efficiency	energy	43%	-	38%	-	

Table 5: Parameters considered in the baseline scenario and in the alternative scenarios in the sensitivity analysis.

Table 6 provides the results of the perturbation analysis as a sensitivity ratio (SR) for the selected parameters and impact categories. The SRs can be positive or negative, depending on the sign of the impact assessment score. The most relevant parameter can only be identified within the same impact category (Bisinella et al., 2016). For AC and TE, Scenarios_{CHP} presents high SR scores. In Scenario 2, however, Scenario_{CHP} was more sensitive to parameters perturbation than Scenario 1. The amount of methane produced (Scenario_{MET}) and fertilizers displaced (Scenario_{NUT}) are the most sensitive parameters for all the other impact categories for both Scenarios 1 and 2.

		CC	Rank	HT	Rank	AC	Rank	TE	Rank	RD	Rank
Scenario 1	Scenario _{FEED}	0.82	4	0.52	3	1.04	2	1.04	2	0.99	4
	Scenario _{CHP}	0.60	3	0.67	4	-439.33	1	-440.68	1	0.02	2
	Scenario _{MET}	-5.01	2	-2.14	2	394.26	3	394.66	3	-0.06	1
	Scenario _{NUT}	-8.93	1	-4.7	1	595.41	4	596.03	4	0.86	3
Scenario 2	Scenario _{FEED}	0.84	4	-0.12	1	1.04	2	1.04	2	0.97	3
	Scenario _{CHP}	0.59	2	0.72	4	-444.43	1	-444.81	1	0.02	2
	Scenario _{MET}	0.63	3	0.63	3	394.47	3	394.79	3	0.02	1
	Scenario _{NUT}	-0.04	1	0.28	2	591.94	4	592.55	4	0.98	4

Table 6: Sensitivity ratios for the selected alternative scenarios for Scenarios 1 and 2.

CC = climate change, HT = Human toxicity, AC = Acidification, TE = Terrestrial euthrophication, RD = Resource depletion

4. Discussion

The modeled bio-refinery system (Scenario 2) processes biomass streams in a more environmentally efficient way than the mono-dimensional system (Scenario 1). The differences between the two scenarios only apply to CC and HT, while both scenarios result in almost the same outcomes for AC, TE and RD. One of the main drivers of using biomass-derived energy is their potential contribution to mitigating global climate change (Staples et al., 2017); therefore, the impacts of the two systems with regard to climate change have been compared relative to producing electricity from natural gas in the Netherlands. In order to do so, a decision needs to be made with regard to the allocation of emissions among the different products produced within each of the two scenarios assessed (electricity, heat, fertilizer). In this paper, emissions are allocated according to their relative market prices. In market based allocation emissions are normalized amongst co-products according to their economic value, measured through market prices (Wang et al., 2011). This is especially important if co-products have different uses (Seber et al., 2014), as in the case of electricity, heat and fertilizer. Relative market prices of the different co-products are taken from van Dael et al. (2013). The resulting allocation factors are listed in the supplementary material (Table S2). Lifecycle emissions of electricity produced in the Netherlands using

natural gas as a feedstock are taken directly from the ecoinvent database v2.2¹. Using this approach, Scenario 1 yields lifecycle emissions of 2.6 kg CO₂ eq./kwh, which is 13% higher than lifecycle GHG emissions of electricity generated from natural gas in the Netherlands (2.3 kg CO₂ eq./kwh). Scenario 2 yields lifecycle emissions of 1.9 kg CO₂ eq./kwh, 18% lower than the natural gas-derived counterpart in the Netherlands.

Moreover, our study corroborates the outcomes of Lopez-Ridaura et al. (2009) and Styles et al. (2016) by establishing that the environmental profile of AD of OMSW and livestock manure is negatively affected by the acidification and eutrophication impact categories. Agostini et al. (2015) attained similar conclusions from analyzing the environmental profile for co-digestion of cattle manure and energy crops. These results give an overview of the contribution of Scenarios 1 and 2 toward the five impact categories. However, unlike global impact (such as global warming), acidification and eutrophication impact categories require a finer connection between source and type of emission, and receiving environment (Reap et al., 2008). Huijbreghts and Seppälä (2000), revealed that regional environmental sensitivities control, by three orders of magnitude, the variability in acidification and eutrophication impacts between European regions. In Europe, N and P excreted by animals are only partially recycled as organic fertilizers in agricultural land (Oenema et al., 2007). The EU Nitrates Directive limits the amount of manure that can be applied to agricultural land (170 kg/ha). Therefore, all EU member states enforced programs to cut nitrate losses to the environment (European Commission, 2010). Moreover, the amount of phosphate, which can be spread on arable land in the Netherlands, is limited to 60 kg/ha. Therefore, almost 20 percent of pig manure is processed and exported from the Netherlands to neighboring countries in 2012 (Willems et al., 2016). Further processing and disposal of livestock manure is an unavoidable, costly operation that increases the need for more economically and environmentally efficient management strategies. On average, the disposal of pig manure accounted for 5 percent of farm's production cost in the Netherlands (Willems and Van Grinsven, 2013).

¹ The "Natural gas, burned in power plant/NL U" has been used from the ecoinvent v2.2 database.

From the environmental perspective, De Vries et al. (2015) estimated the impacts of different manuremanagement strategies in livestock and crop production using an impact-assessment method distinct from the one used in our study. In order to compare the results of the two studies, the outcomes of this study have been re-calculated using the same approach. Results are presented in the supplementary material. Overall, the combined treatments of OMSW and pig manure, with the mono-dimensional or integrated system reduces the acidification and terrestrial eutrophication impacts of manure management (Table S1).

5. Conclusion

In Europe, energy recovery from organic waste is a highly supported alternative to landfill and incineration (Whiting and Azapagic, 2014). Several technologies (such as AD, composting, and pyrolysis) are currently used to produce bio-gas, biofuel, biochar, and other bio-products to substitute for other fossil-fuel products.

In this study, two AD scenarios were investigated: a mono-dimensional system including the separate AD of manure and OMSW (Scenario 1); and a bio-refinery system (Scenario 2) that is a facility integrating different biomass-conversion processes to produce energy, heat, and value-added chemicals. The analysis complements a previous techno-economic assessment by studying the environmental impact of AD of OMSW and livestock manure. Van Dael et al. (2013) concluded that Scenario 2 was more economically viable than Scenario 1, but only if manure processing was obligatory. However, it is more viable to only process OMSW from an investor's perspective. Therefore, the relevance of the different impact categories should be considered carefully, especially when the analysis aims to support decision-making processes. The biorefinery scenario yields 18% lower emissions than those from natural gas derived electricity in the Netherlands. The analyzed waste-to-energy systems represent an opportunity to improve organic wastemanagement strategies, while displacing the emissions from energy production and reducing the costs for surplus manure disposal. When the two systems are taken together, it is found that the bio-refinery model shows higher benefits than the separate AD of OMSW and pig manure from an environmental perspective.

This paper only accounts for the treatment of OMSW and livestock manure, whereas additional analysis could include feedstock logistics, such as collection, storage, and transportation. The costs and environmental impacts of logistics can be intensive up to the point of offsetting (or even outweighing) the benefits emerging from biomass energy recovery (Brambilla Pisoni et al., 2009). Moreover, investment in biomass-to-energy facilities will only occur if feedstock supply can be secured and the environmental risks can be minimized. Therefore, the economic and environmental optimization of OMSW and manure logistics should be taken into account for decision-making and technology selection.

REFERENCES

- Agostini, A., Battini, F., Giuntoli, J., Tabaglio, V., 2015. Environmentally Sustainable Biogas? The Key Role of Manure Co-Digestion with Energy Crops. Energies 5234–5265. doi:10.3390/en8065234
- Allwood, J.M., 2014. Squaring the Circular Economy: The Role of Recycling within a Hierarchy of Material Management Strategies, in: Handbook of Recycling: State-of-the-Art for Practitioners, Analysts, and Scientists. pp. 445–477. doi:10.1016/B978-0-12-396459-5.00030-1
- Amon, T., Amon, B., Kryvoruchko, V., Machmüller, A., Hopfner-Sixt, K., Bodiroza, V., Hrbek, R., Friedel, J., Pötsch, E., Wagentristl, H., Schreiner, M., Zollitsch, W., 2007. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. Bioresour. Technol. 98, 3204–3212. doi:10.1016/j.biortech.2006.07.007
- Bare, J.C., 2010. Life cycle impact assessment research developments and needs. Clean Technol. Environ. Policiy 341–351. doi:10.1007/s10098-009-0265-9
- Battini, F., Agostini, A., Boulamanti, A.K., Giuntoli, J., Amaducci, S., 2014. Mitigating the environmental impacts of milk production via anaerobic digestion of manure : Case study of a dairy farm in the Po Valley. Sci. Total Environ. 481, 196–208. doi:10.1016/j.scitotenv.2014.02.038
- Belboom, S., Digneffe, J.-M., Renzoni, R., Germain, A., Léonard, A., 2013. Comparing technologies for municipal solid waste management using life cycle assessment methodology: a Belgian case study. Int. J. Life Cycle Assess. 18, 1513–1523. doi:10.1007/s11367-013-0603-3
- Bernstad Saraiva Schott, A., Wenzel, H., La Cour Jansen, J., 2016. Identification of decisive factors for greenhouse gas emissions in comparative life cycle assessments of food waste management - An analytical review. J. Clean. Prod. 119, 13–24. doi:10.1016/j.jclepro.2016.01.079
- Bisinella, V., Conradsen, K., Christensen, T.H., Astrup, T.F., 2016. A global approach for sparse representation of uncertainty in Life Cycle Assessments of waste management systems. Int. J. Life Cycle Assess. 21, 378–394. doi:10.1007/s11367-015-1014-4
- Boldrin, A., Andersen, J.K., Møller, J., Christensen, T.H., Favoino, E., 2009. Composting and compost utilization: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 789–799. doi:10.1177/0734242x09348529
- Boldrin, A., Neidel, T.L., Damgaard, A., Bhander, G.S., Møller, J., Christensen, T.H., 2011. Modelling of environmental impacts from biological treatment of organic municipal waste in EASEWASTE. Waste Manag. 31, 619–630. doi:10.1016/j.wasman.2010.10.025
- Bouwman, A.F., Beusen, A.H.W., Billen, G., 2009. Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. Global Biogeochem. Cycles 23. doi:10.1029/2009GB003576
- Brambilla Pisoni, E., Raccanelli, R., Dotelli, G., Botta, D., Melià, P., 2009. Accounting for transportation impacts in the environmental assessment of waste management plans. Int. J. Life Cycle Assess. 14, 248–256. doi:10.1007/s11367-009-0061-0
- Cherubini, F., Bargigli, S., Ulgiati, S., 2009a. Life cycle assessment (LCA) of waste management strategies : Landfilling, sorting plant and incineration. Energy 34, 2116–2123. doi:10.1016/j.energy.2008.08.023
- Cherubini, F., Bird, N.D., Cowie, A., Jungmeier, G., Schlamadinger, B., Woess-gallasch, S., 2009b. Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems : Key issues , ranges and recommendations. Resour. Conserv. Recycl. 53, 434–447. doi:10.1016/j.resconrec.2009.03.013

- Colón, J., Cadena, E., Pognani, M., Barrena, R., Sánchez, A., Font, X., Artola, A., 2012. Determination of the energy and environmental burdens associated with the biological treatment of source-separated municipal solid wastes. Energy Environ. Sci. 5, 5731. doi:10.1039/c2ee01085b
- Corsten, M., Worrell, E., Rouw, M., Van Duin, A., 2013. The potential contribution of sustainable waste management to energy use and greenhouse gas emission reduction in the Netherlands. Resour. Conserv. Recycl. 77, 13–21. doi:10.1016/j.resconrec.2013.04.002
- De Vries, J.W., Groenestein, C.M., Schröder, J.J., Hoogmoed, W.B., Sukkel, W., Groot Koerkamp, P.W.G., De Boer, I.J.M., 2015. Integrated manure management to reduce environmental impact: II. Environmental impact assessment of strategies. Agric. Syst. 138, 88–99. doi:10.1016/j.agsy.2015.05.006
- De Vries, J.W., Vinken, T.M.W.J., Hamelin, L., De Boer, I.J.M., 2012. Bioresource Technology Comparing environmental consequences of anaerobic mono- and co-digestion of pig manure to produce bio-energy – A life cycle perspective. Bioresour. Technol. 125, 239–248. doi:10.1016/j.biortech.2012.08.124
- Eriksson, O., Reich, M.C., Frostell, B., Björklund, A., Assefa, G., Sundqvist, J.O., Granath, J., Baky, A., Thyselius, L., 2005. Municipal solid waste management from a systems perspective. J. Clean. Prod. 13, 241–252. doi:10.1016/j.jclepro.2004.02.018
- European Commission, 2010. The EU Nitrates Directive, The EU Nitrates Directive.
- European Commission Joint Research Center, 2011. International Reference Life Cycle Data System (ILCD) Handbook Reccomandation for Life Cycle Impact Assessemnt in the European context, First edit. ed. Luxemburg. doi:10.278/33030
- Evangelisti, S., Lettieri, P., Borello, D., Clift, R., 2014. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. Waste Manag. 34, 226–237. doi:10.1016/j.wasman.2013.09.013
- Faaij, A., Van Ree, R., Waldheim, L., Olsson, E., Oudhuis, A., Van Wijk, A., Daey-Ouwens, C., Turkenburg, W., 1997. Gasification of biomass wastes and residues for electricity production. Biomass and Bioenergy 12, 387–407. doi:10.1016/S0961-9534(97)00010-X
- Finnveden, G., Johansson, J., Lind, P., 2005. Life cycle assessment of energy from solid waste--part 1: general methodology and results. J. Clean. 13, 213–229. doi:10.1016/j.jclepro.2004.02.023
- Fodor, Z., Klemeš, J.J., 2012. Waste as alternative fuel Minimising emissions and effluents by advanced design. Process Saf. Environ. Prot. 90, 263–284. doi:10.1016/j.psep.2011.09.004
- Gebrezgabher, S.A., Meuwissen, M.P.M., Prins, B.A.M., Lansink, A.G.J.M.O., 2010. Economic analysis of anaerobic digestion-A case of Green power biogas plant in the Netherlands. NJAS Wageningen J. Life Sci. 57, 109–115. doi:10.1016/j.njas.2009.07.006
- Geissdoerfer, M., Savaget, P., Bocken, N.M.P., Hultink, E.J., 2017. The Circular Economy A new sustainability paradigm? J. Clean. Prod. 143, 757–768. doi:10.1016/j.jclepro.2016.12.048
- Ghisellini, P., Cialani, C., Ulgiati, S., 2014. A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. doi:10.1016/j.jclepro.2015.09.007
- Groen, E.A., Heijungs, R., Bokkers, E.A.M., de Boer, I.J.M., 2014. Methods for uncertainty propagation in life cycle assessment. Environ. Model. Softw. 62, 316–325. doi:10.1016/j.envsoft.2014.10.006
- Groen, E.A., Heijungs, R., Bokkers, E. a M., Boer, I.J.M. De, 2014. Sensitivity analysis in life cycle

assessment. Proc. 9th Int. Conf. LCA Food San Fr. USA 8-10 Oct. 2014 482-488.

- Hijazi, O., Munro, S., Zerhusen, B., Effenberger, M., 2016. Review of life cycle assessment for biogas production in Europe. Renew. Sustain. Energy Rev. 54, 1291–1300. doi:10.1016/j.rser.2015.10.013
- Huijbreghts, M.A.J., Seppälä, J., 2000. Towards Region-Specific, European Fate Factors for Airborne Nitrogen Compounds Causing Aquatic Eutrophication. Int. J. Life Cycle Assessment 5, 65–67.
- Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H., 2014. Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. Waste Manag. 34, 573–588. doi:10.1016/j.wasman.2013.10.045
- Lopez-Ridaura, S., Werf, H. Van Der, Marie, J., Le, B., 2009. Environmental evaluation of transfer and treatment of excess pig slurry by life cycle assessment. J. Environ. Manage. 90, 1296–1304. doi:10.1016/j.jenvman.2008.07.008
- Maes, D., Van Dael, M., Vanheusden, B., Goovaerts, L., Reumerman, P., M??rquez Luzardo, N., Van Passel, S., 2015. Assessment of the sustainability guidelines of EU Renewable Energy Directive: The case of biorefineries. J. Clean. Prod. 88, 61–70. doi:10.1016/j.jclepro.2014.04.051
- Mezzullo, W.G., McManus, M.C., Hammond, G.P., 2013. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. Appl. Energy 102, 657–664. doi:10.1016/j.apenergy.2012.08.008
- Møller, J., Boldrin, A., Christensen, T.H., 2009. Anaerobic digestion and digestate use: accounting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 813–824. doi:10.1177/0734242X09344876
- Morris, J., Scott Matthews, H., Morawski, C., 2013. Review and meta-analysis of 82 studies on end-oflife management methods for source separated organics. Waste Manag. 33, 545–551. doi:10.1016/j.wasman.2012.08.004
- Mosquera, J., Schils, R., Groenestein, K., Hoeksma, P., Velthof, G., Hummelink, E., 2010. Emissies van lachgas, methaan en ammoniak uit mest na scheiding. Wageningen.
- Oenema, O., Oudendag, D., Velthof, G.L., 2007. Nutrient losses from manure management in the European Union. Livest. Sci. 112, 261–272. doi:10.1016/j.livsci.2007.09.007
- Potting, J., Schopp, W., Hauschild, M., 1998. Site-Dependent Life-Cycle Impact Assessment of Acidification. J. Ind. Ecol. 2.
- Prapaspongsa, T., Christensen, P., Schmidt, J.H., Thrane, M., 2010. LCA of comprehensive pig manure management incorporating integrated technology systems. J. Clean. Prod. 18, 1413–1422. doi:10.1016/j.jclepro.2010.05.015
- Reap, J., Roman, F., Duncan, S., Bras, B., 2008. A survey of unresolved problems in life cycle assessment. Part 2: Impact assessment and interpretation. Int. J. Life Cycle Assess. 13, 374–388. doi:10.1007/s11367-008-0009-9
- Rehl, T., Müller, J., 2011. Life cycle assessment of biogas digestate processing technologies. Resour. Conserv. Recycl. 56, 92–104. doi:10.1016/j.resconrec.2011.08.007
- Rentizelas, A., Karellas, S., Kakaras, E., Tatsiopoulos, I., 2009. Comparative techno-economic analysis of ORC and gasification for bioenergy applications. Energy Convers. Manag. 50, 674–681. doi:10.1016/j.enconman.2008.10.008
- Rosenbaum, R.K., Bachmann, T.M., Jolliet, O., Juraske, R., Koehler, A., Hauschild, M.Z., 2008. USEtox — the UNEP-SETAC toxicity model : recommended characterisation factors for human toxicity and

freshwater ecotoxicity in life cycle impact assessment. Int. J. Life Cycle Assessment 532–546. doi:10.1007/s11367-008-0038-4

- Saer, A., Lansing, S., Davitt, N.H., Graves, R.E., 2013. Life cycle assessment of a food waste composting system : environmental impact hotspots. J. Clean. Prod. 52, 234–244. doi:10.1016/j.jclepro.2013.03.022
- Sawatdeenarunat, C., Nguyen, D., Surendra, K.C., Shrestha, S., Rajendran, K., Oechsner, H., Xie, L., Khanal, S.K., 2016. Anaerobic biorefinery: Current status, challenges, and opportunities. Bioresour. Technol. doi:10.1016/j.biortech.2016.03.074
- Seber, G., Malina, R., Pearlson, M.N., Olcay, H., Hileman, J.I., Barrett, S.R.H., 2014. Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. Biomass and Bioenergy 67, 108–118. doi:10.1016/j.biombioe.2014.04.024
- Seppälä, J., Posch, M., Johansson, M., Hettelingh, J., 2006. LCA Methodology Country-Dependent Characterisation Factors for Acidification and Terrestrial Eutrophication Based on Accumulated Exceedance as an Impact Category Indicator. Int. J. Life Cycle Assessment 11, 403–416.
- Soltani, A., Sadiq, R., Hewage, K., 2016. Selecting sustainable waste-to-energy technologies for municipal solid waste treatment: A game theory approach for group decision-making. J. Clean. Prod. 113, 388–399. doi:10.1016/j.jclepro.2015.12.041
- Staples, M.D., Malina, R., Barrett, S.R.H., 2017. The limits of bioenergy for mitigating global life-cycle greenhouse gas emissions from fossil fuels. Nat. Energy 2, 16202. doi:10.1038/nenergy.2016.202
- Styles, D., Dominguez, E.M., Chadwick, D., 2016. Science of the Total Environment Environmental balance of the UK biogas sector : An evaluation by consequential life cycle assessment. Sci. Total Environ. 560–561, 241–253. doi:10.1016/j.scitotenv.2016.03.236
- SWD 259, 2014. State of play on the sustainability of solid and gaseous biomass used for electricity, heating and cooling in the EU. Brussels.
- Turner, D.A., Williams, I.D., Kemp, S., 2016. Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. J. Clean. Prod. 129, 234–248. doi:10.1016/j.jclepro.2016.04.077
- Van Dael, M., Marquez, N., Reumermann, P., Pelkmans, L., Kuppens, T., Van Passel, S., 2013a. On the Map Development and techno-economic evaluation of a biorefi nery based on biomass (waste) streams – case study in the Netherlands. Biofuels, Bioprod. Biorefining 5, 635–644. doi:10.1002/bbb
- Van Dael, M., Van Passel, S., Pelkmans, L., Guisson, R., Reumermann, P., Luzardo, N.M., Witters, N., Broeze, J., 2013b. A techno-economic evaluation of a biomass energy conversion park. Appl. Energy 104, 611–622. doi:10.1016/j.apenergy.2012.11.071
- VROM, 2010. Landelijk afvalbeheerplan 2009-2021 Naar een materiaalketenbeleid [National waste managment plan 2009-2021 towards a material life cycle policy]. The Netheralands.
- Wang, M., Huo, H., Arora, S., 2011. Methods of dealing with co-products of biofuels in life-cycle analysis and consequent results within the U.S. context. Energy Policy 39, 5726–5736. doi:10.1016/j.enpol.2010.03.052
- Weidema, B., Hischier, R., 2010. ecoinvent data v2.2. the 2010 version of the most comprehensive and most popular public LCI database 3.
- Weidema, B., Hischier, R., Althaus, H., Bauer, C., 2009. Code of Practice. ecoinvent report No. 2. Swiss Cent. Life Cycle Invent. 1, 32. doi:10.1108/eb003163

- Whiting, A., Azapagic, A., 2014. Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. Energy 70, 181–193. doi:10.1016/j.energy.2014.03.103
- Willems, J., Van Grinsven, H.J.M., Jacobsen, B.H., Jensen, T., Dalgaard, T., Westhoek, H., Kristensen, I.S., 2016. Why Danish pig farms have far more land and pigs than Dutch farms? Implications for feed supply, manure recycling and production costs. Agric. Syst. 144, 122–132. doi:10.1016/j.agsy.2016.02.002
- Willems, W.J., Van Grinsven, H.J.M., 2013. Ex Ante Evaluatie Mestbeleid 2013, Gevolgen van de invoering van verplichte mestverwerking en het afschaffen van productierechten in de veehouderij. Planbureau voor de Leefomgeving, Wageningen UR, Den Haag.