Closing the Loop: a Sustainable Strategy for MSW Management with Zero Residues and Energy Production

Original
Closing the Loop: a Sustainable Strategy for MSW Management with Zero Residues and Energy Production / GOMEZ CAMACHO, CARLOS ENRIQUE; Giansante, Loris; Ruggeri, Bernardo. - In: CHEMICAL ENGINEERING TRANSACTIONS. - ISSN 2283-9216. - 86:(2021), pp. 1351-1356. [https://doi.org/10.3303/CET2186226]

Publisher:
AIDIC

Published
DOI:https://doi.org/10.3303/CET2186226

CHEMICAL ENGINEERING TRANSACTIONS
VOL. 86, 2021
A publication of AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš

ISBN 978-88-95608-84-6; **ISSN** 2283-9216
DOI: 10.3303/CET2186226

Closing the Loop: a Sustainable Strategy for MSW Management with Zero Residues and Energy Production

Carlos E. Gómez-Camacho*, Loris Giansante, Bernardo Ruggeri*

Politecnico di Torino, Dep. of Applied Science and Technology (DISAT), C/so Duca degli Abruzzi 24, 10129 Torino.
carlos.gomezcamacho@polito.it and bernardo.ruggeri@polito.it

The management of Municipal Solid Waste (MSW) has always represented an important challenge of our society, and it is a constantly evolving issue characterized by variable temporal and spatial specificities. Despite recent technological developments, Waste-to-Energy (WtE) approaches considering environmental and energy sustainability factors and their implementation in real contexts are rather scarce. Unsorted MSW (the residue aside from the differentiate collection of recyclables) can be divided into key fractions for WtE applications, such as the gasification of the Refuse Derived Fuel (RDF) cut or the anaerobic digestion (AD) of the Organic Fraction of Municipal Solid Waste (OFMSW); however, there are certain residues of these processes as well as other fractions of MSW which typically end up in landfills. The present *ex-ante* study evaluates the convenience of introducing a Plasma Torch (PT) in the management strategy for unsorted MSW replacing the landfill option. The research is based on the modeling of the PT, considering the possible feed streams to this unit. In addition, sensitivity studies are carried to shed light on suitable operating conditions (temperature, equivalence ratio, gasifying agent) and the convenience of the process is assessed from an environmental and energy point of view, by comparing the PT scenario with the baseline case of landfilling. The Life Cycle Assessment (LCA) suggests that the environmental loads can be significantly reduced (>80%) by introducing the PT unit, while the system shows an increase of more than 50 % in the Energy Sustainability Index (ESI).

1. Introduction

MSW generation in the European Union has shown a modest reduction during the last few years; estimates suggest that per capita yearly MSW generation shifted from 513 kg/(y·inhab) in 2000 to 492 in 2018 (i.e., roughly a 4 % reduction). In the latter year, according to Eurostat, the treatment of MSW involved landfill for 23.78 % of the generated waste, while incineration accounted for 26.6 %, recycling amounted to 30.5 % and composting to 16.9 %, while other treatments represented a small proportion (<2.5 %). The distribution of these treatment scenarios for MSW at European level has been dynamically reshaped during recent decades, with a decrease in landfill and an increase in incineration, material recycling, and composting (Eurostat, 2020). Although the prevention and the minimization of MSW generation lie at the highest hierarchical level, other policies such as the separate collection and dedicated sorting and processing strategies for unsorted MSW are key factors of an efficient and holistic waste management approach.

There is an urgent need to further decrease the amount of MSW which ends up in landfills due to: *i)* the problems related to a wide range of toxins (e.g., As, Cr, Cd, Hg, Ni, Pb, Zn, organic halogens, heavy organic compounds, cyclic aromatic hydrocarbons), *ii)* the leachate streams that might disperse these toxins into the environment and *iii)* the greenhouse gas emissions issued for several decades. As a matter of fact, the European Union has revisited the Landfill Directive and has set an ambitious goal that encourages member states to reach a target of 10 % landfill or less of the total amount of municipal waste generated (*w/w*) by 2035 (EU, 2018). Depending on the local waste management strategy, MSW tends to be collected as sorted fractions (which can undergo specific treatments in well-structured waste management systems) or as unsorted MSW. Typically, the unsorted MSW contains a small fraction of metals, an important organic and inorganic part, as well as mixed scrap materials (see Figure 1). Based on key properties such as the water content, the C:N ratio, the volatile matter and ash content, unsorted MSW can be split into two major fractions:

Paper Received: 4 November 2020; Revised: 17 February 2021; Accepted: 7 May 2021
Please cite this article as: Gomez Camacho C.E., Giansante L., Ruggeri B., 2021, Closing the Loop: a Sustainable Strategy for Msw Management with Zero Residues and Energy Production, Chemical Engineering Transactions, 86, 1351-1356 DOI:10.3303/CET2186226

the RDF and the OFMSW. The RDF fraction contains low moisture levels (<25 % *w/w* FM) and it is constituted by mixed plastics, papers, textiles and other refuse, while the OFMSW presents a higher moisture content (>40% *w/w* FM) and an elevated organic matter content (>60 % *w/w* TS). Both RDF and OFMSW are suitable feedstocks for WtE applications, where energy is typically recovered in the form of energy carriers, such as syngas and biogas, which can be fed to Combined Heat and Power (CHP) units for the production of electricity and/or heat. WtE technologies can be grouped into two major categories: thermo-chemical processes (combustion, pyrolysis and gasification) and biological processes (mechanical biological treatment, AD and other fermentations). The RDF cut is suitable for the Traditional Gasification (TG) process. This process is known for its flexibility, allowing it to operate in a wide range of temperatures, using different gasifying agents and equivalence ratios (i.e., supplied oxidant flow/stoichiometrically required flow) and produces a syngas (mainly CO, H_2, CO_2, CH_4) and a solid residue (char) that could end up in landfills. However, most TG applications require a flue gas cleaning system, which implies greater utilization of materials and chemicals, as well as a dedicated treatment option for effluent management. Conversely, the OFMSW is a suitable feedstock for AD, which produces biogas (CH_4 and CO_2) and a digestate that is successively dewatered. The solid fraction of the digestate must undergo an aerobic treatment and a maturation phase for the production of the compost, while the liquid part is recycled to obtain an adequate degree of humidity of the OFMSW to feed the AD process, and any surplus must be treated before it is discharged. Frequently, biogas is directly fed to CHP units (since trace contaminants such as H_2S, NH_3, BTEX and siloxanes are found in a lower proportion than in syngas), while some plants have flue upgrade systems to produce biomethane, which then can be injected into methane distribution networks. Through the post-digestion processing of the digestate, an important fraction of OFMSW (>75%) is recycled on land, while the remaining portion is landfilled (Iacovidou et al., 2013). Other important technology that belongs to the thermo-chemical axis of WtE applications is plasma gasification, which can be conducted using plasma torches (PT). Similar to TG, this process takes place at sub-stoichiometric levels of oxygen, but the temperature conditions provided by the plasma generator (plasma arc and electrodes) are higher. PT also produce a syngas, which can be sent to CHP units, and a solid vitrified residue with variable characteristics depending on the waste input. Hence, in PT processes, the volumes of the flue gases and the cleaning section tend to decrease and certain pollutant emissions (NO_x, SO_x, H_2S, NH_3, dioxins, furans) are avoided or annihilated due to the high temperatures and the chemistry involved. The solid residue can be used as construction material or as feedstock for various industries (ceramic).

This study expands a previous work on WtE applications, targeting the reduction of landfilling. Here, a comprehensive valorization strategy for unsorted MSW is presented, comprising the splitting into key fractions (RDF and OFMSW) and the utilization of traditional WtE technologies (TG and AD) as in (Lombardelli et al., 2017). However, the main focus is the integration of a PT to treat certain residues of these processes (that would otherwise end up in landfills) and rationalizing the overall suitability. The *ex-ante* analysis is supported by a Life Cycle Assessment (LCA), to compare the environmental impact with the landfill scenario, and the calculation of the Energy Sustainability Index (ESI), to evaluate the energy convenience of the whole system.

2. Methodology

The proposed strategy is evaluated using: *i)* a Life Cycle Assessment (LCA) and the Energy sustainability index (ESI). The former quantifies the impacts at the biophysical level and it is conducted according to the ISO standards 14040–44; the LCA is performed using the *SimaPro v.7.2* and the *Ecoinvent v.2.2* database, while impact category indicators belong to the CML2001, NL 1997. On the other hand, the ESI seeks to evaluate the convenience from the anthropogenic perspective of energy utilization (Gómez-Camacho and Ruggeri, 2019) (Gómez-Camacho et al., 2021). The ESI is a short-term indicator, and it is the first step towards the quantification of the full energy sustainability of the technological chain. The ESI serves to determine whether the produced energy is able to cover the direct energy expenses needed to run the technology. The scope of the analysis is to compare through the LCA different impact categories between two options for the hard-to-process fractions in a comprehensive strategy for unsorted MSW. The two options are the landfill scenario and the utilization of a PT unit. The case study considers a progressive substitution of landfilling for the PT, highlighting the targeted scenario in the EU context. The LCA analysis is conducted following a cradle-to-grave approach by first constructing an Analogical Model of the process, then estimating the required chemicals and materials in the inventory phase. The chosen functional unit is using 1 ton of MSW given as input to the comprehensive plant under analysis. The ESI indicator is calculated following Eq. 1:

$$ESI = \frac{\sum_{i=1}^{n} Eproduced_i + \sum_{i=1}^{n} Eavoided_i - \sum_{i=1}^{n} Ealready\ spent_i}{\sum_{i=1}^{n} Edirect_i} \quad (1)$$

The aggregated produced energy ($\Sigma E_{produced,i}$, in MJ/ton MSW) corresponds to the sum of the calorific power of the produced energy carriers (i.e., biogas, syngas from the TG, syngas from the PT). The already spent energy corresponds to the upstream processing stages (i.e., the energy collection cost of MSW, estimated around 1.5 MJ/ton MSW/km) while the avoided energy comprehends the alternative end-of-life scenario for MSW (incineration, c. 1470 MJ/ton MSW). The reduction in energy terms of the flue cleaning step for TG syngas due to the use of the PT unit is reflected as diminished direct energy to be given to the process, while the energy cost of landfilling MSW is assumed to be c. 0.42 MJ/kg.

3. Case study

The case study considers a comprehensive strategy for the management of MSW in an urban center of one million inhabitants in a combined plant. The local MSW generation is assumed to be 488.0 kg/(y·inhab), while the percentage of the sorted collection is set at 42.5 %. First of all, the unsorted MSW first undergo a splitting step for the removal of plastic bags and to obtain key process streams such as: ferrous and metal particles, mixed scrap materials, and the RDF and OFMSW cuts. The RDF stream is sent to the TG (i.e., a fluidized bed gasifier), while the OFMSW is valorized through the AD process (i.e., a mesophilic CSTR digester). These basic settings (TG for RDF and AD for the OFMSW) are similar to the well-described case-study presented in (Lombardelli et al., 2017), however, the present evaluation pertains the inclusion of a final step (Plasma Torch) in the WtE valorization strategy, avoiding the landfilling of certain waste streams and seeking to reduce the energy-intensive process of syngas treatment after the TG process. The virtual plant under analysis is considered to work 320 days per year, 24 h a day, hence the total unsorted MSW feed to the plant is approximately 35 ton/h (see Figure 1) .

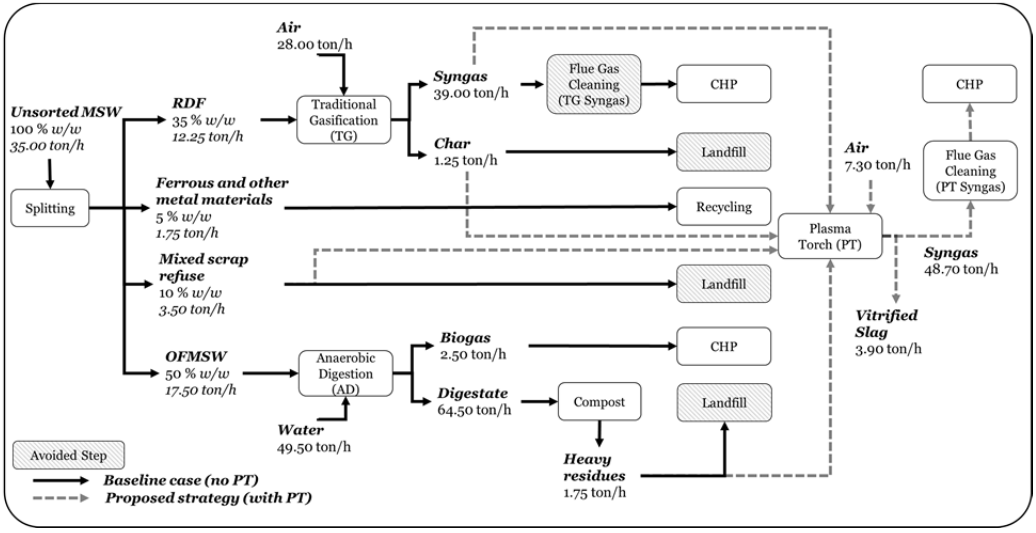

Figure 1. The comprehensive Waste-to-Energy (WtE) proposed strategy for unsorted MSW management.

The technical calculations and simulations regarding the proposed PT system are performed using the software AspenPlus® *v8.8*; a more thorough description of the model can be found in (Giansante, 2020). In brief, the PT is modeled as a two reactions zone process, by solely considering the organic fraction in the feed to the PT (the inorganic fraction undergoes a vitrification process which is not simulated on Aspen). The modeled PT process is composed by the High Temperature Reactor (HRT) and the Low Temperature Reactor (LTR), both simulated as *RGIBBS* blocks in Aspen. The chosen thermodynamic property method is the Peng-Robinson-Boston-Mathias (PR-BM) based on the working conditions and initial simulation tests. However, due to the complex nature of certain streams, their simulation is performed using *RYIELD* blocks and considering the decomposition into the constituent elements as non-conventional compounds by means of the HCOALGEN and DCOALIGT models (based on their proximate and ultimate analyses, see Table 1). The feed to the PT unit is composed by: *i)* the mixed scrap materials obtained from the upstream splitting of the unsorted MSW, *ii)* the heavy residues of the composting step of the digestate (resulting from the AD of the OFMSW), *iii)* the RDF traditional gasification products (the raw syngas containing volatile organic carbon compounds and TAR and the solid CHAR residue), and *iv)* the ferrous and metals residues originally present in the unsorted MSW. In order to set nominal working conditions for the PT process, which are necessary to carry out the LCA and to calculate the ESI, sensitivity analyses are conducted to test the effect of the flow and type of gasifying agent, and the working temperature.

Table 1. Proximate and Ultimate composition of the RDF and OFMSW and gas composition of the main energy carriers present in the strategy

Proximate composition						*Ultimate composition*					
	MC	VM	FC	Ash	LHV	C	H	N	Cl	S	O
	w/w FM				MJ/kg FM	*w/w* DM					
RDF	23.30	59.80	6.90	10.00	14.00	52.10	7.40	0.90	0.09	0.50	39.01
OFMSW	45.80	27.90	3.40	22.90	9.70	58.50	5.80	2.40	0.20	0.30	32.80

Composition of key energy carriers involved in the process (% v/v)

	N_2	H_2	CO	H_2O	CO_2	HCl	H_2S	CH_4	NH_3	LHV (MJ/Nm^3)
Biogas	-	<1	-	-	45	-	<1	55	<2	19.7
Syngas - TG	55.39	1.67	20.22	8.33	14.11	0.19	0.08	$<10^{-3}$	$<10^{-3}$	2.75
Syngas - PT	49.42	11.98	12.07	16.09	10.20	0.15	0.06	$<10^{-3}$	$<10^{-3}$	2.83

FM: Fresh Matter, MC: Moisture Content, VM : Volatile Matter, FC: Fixed Carbon, LHV: Low Heating Value

4. Results and Discussion

The block diagram of the baseline strategy (Lombardelli et al., 2017) is presented in Figure 1, also including the current proposed integration of the Plasma Torch. The reference mass balances are also depicted in Figure 1 considering the current average efficiencies of full-scale plants. For the baseline case, a total flow of 6.5 ton/h is hypothesized to be treated in landfills, which represents a share of approximately 18.5 % (*w/w*) of the total input. The evaluation of the proposed strategy is performed by progressively increasing the fraction which can be treated by the PT, hence reducing the amount which is sent to landfills. In particular, the PT is evaluated for scenarios that consider reductions of 25, 50, 75 and 100 % of the baseline flow which is treated in landfills.

4.1 Operative conditions for the plasma torch (PT)

The first investigated factor is the effect of the gasifying agent on the PT product distribution. Particular attention is given to the fraction of H_2 and CO, since these compounds have an enthalpic component that can be valorized (i.e., their LHV) in the produced syngas. As shown in Figure 2a, when the gasifying agent is air, then higher fractions of H_2 and CO are obtained (Case A); while the use of oxygen-enriched air (Case B) tends to decrease the yield in these products. Finally, Case C shows that by simultaneously increasing the flow of the gasifying agent and its composition in oxygen, the yield in the desired gases of energetic interest is further decreased. This last fact is probably due to the tendency of the gasification process to shift towards complete oxidation reactions (instead of the reforming and cracking reactions) in the presence of higher gasifying agent flows and higher oxygen concentrations (which mainly generate CO_2).

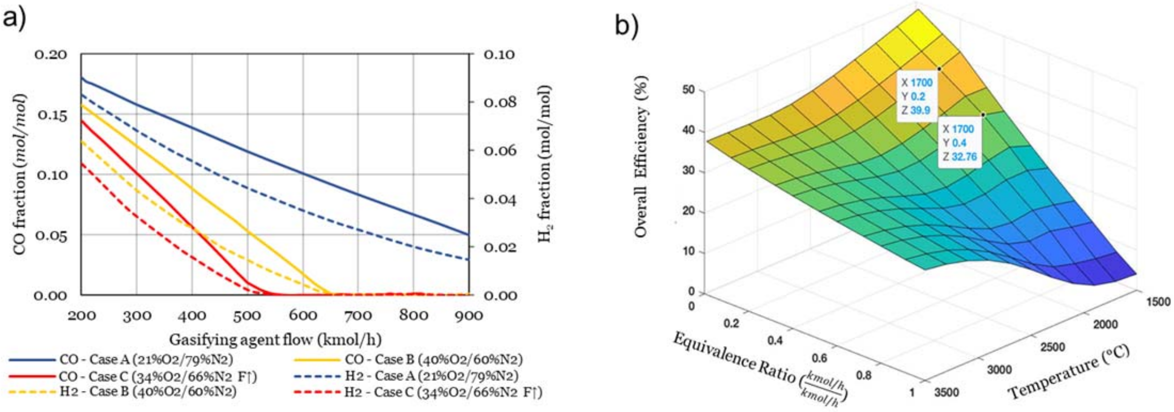

Figure 2. Sensitivity Analyses for the operating conditions of the Plasma Gasification (PT) process

The second sensitivity analysis regards the optimal operating temperature and equivalence ratio (ER). Although a specific H_2/CO ratio could be interest for chemicals synthesis, in the present case the PT is evaluated by means of the global efficiency (η) (see Figure 2b). The η value is calculated considering the weighted sum of the calorific power of the components of the syngas, divided by the energy input which must be given to the process (Giansante, 2020). Moderate temperatures are required for the PT due to the specific conditions of the process, which receives a complex feed containing in gas phase high amounts of volatile organic and condensable (TAR) carbon compounds, as well as solid heavy and fixed carbon residues and ashes. The best performing resulting conditions from the simulations step are the ER in the 0.2-0.4 range, and temperature in the 1500-1900 °C. It should be noted that the present exploratory simulations are based on the chemical equilibrium modeled in the *Rgibbs* reactor in Aspen, however, experimental studies have suggested that plasma-generated reactive species might enhance the conversion of organic residues into syngas in the plasma torch. Hence, further research is still required in the field of complex feedstocks and WtE processes to study the role of plasma chemistry in the conversion of TAR and char in the plasma torch, as well as to differentiate among thermal activation effects and radiation contributions (Lee et al., 2013).

4.2 Environmental sustainability of the process

The results of the LCA are presented in Figure 3. The progressive introduction of the PT in MSW management systems is analyzed as described above, by considering increasing fractions to be disposed in this unit. The main selected indicators for the comparison among scenarios are: acidification (AC), eutrophication (E), global warming potential 20a (GWP), human toxicity 20a (HT), and photochemical oxidation (PO). The inventory for the PT considers the main materials required for the unit, which are high grade steel, the refractory material for the internal structure (alumina bricks) and the graphite electrodes (with periodic substitution, considering the literature mean lifetime of these components).

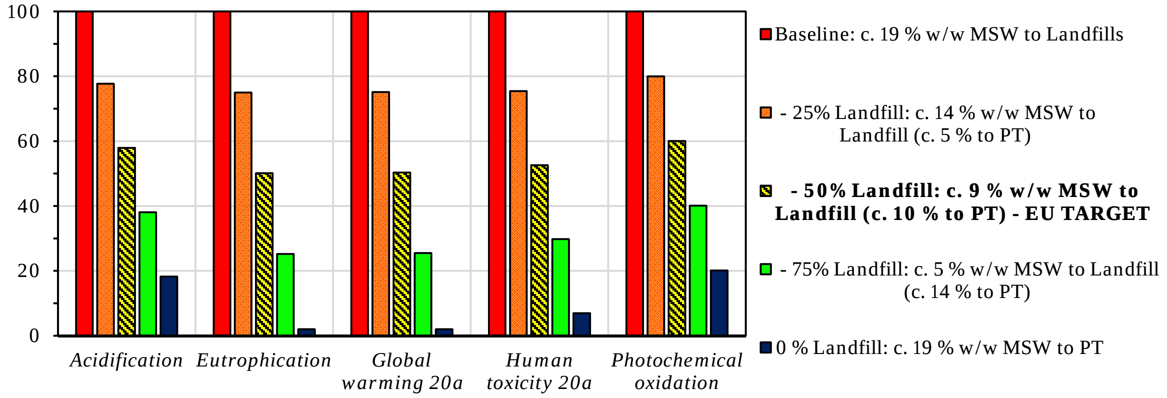

Figure 3. LCA impact assessment (CML2001 method) regarding the progressive introduction of the Plasma Torch in MSW management strategies as alternative to landfill.

The results are normalized taking as reference for the 100% the effects of the scenario that considers the original flow sent to landfills as well as the strong gas flue cleaning treatment for the raw syngas obtained in the TG process. On the other hand, the 0 % Landfill scenario presents the maximum theoretical attainable environmental burden reduction due to the utilization of the PT and the reduced treatment of the produced syngas. The EU target scenario for 2035 is highlighted also in Figure 3. As shown in this figure, the progressive substitution of landfilling for the PT can theoretically improve the environmental performance of MSW management by decreasing the burden in all the selected categories. In particular, the integrated system could achieve (for the 0% Landfill & 100 % PT scenario) a reduction of 82 % in the AC category, c. 80 % in the PO category and more than 93 % reduction in the GWP, E, and HT. The rest of the categories (data not shown) of the CML2001 method present similar reduction values (> 80 %). In fact, similar outcomes are presented in (Evangelisti et al., 2015); their results suggest that reductions of 60 % in the PO category, a 76 % reduction in the GWP and more than 80 % in the E category due to the use of PT to treat raw syngas from traditional gasification and for the inertization of heavy solid residues of MSW that otherwise would end up in landfills.

4.3 Energy sustainability of the process

For the energy assessment, the ESI index is calculated (as reported in Section 2). Although this indicator is generally associated with short-time perspectives, it also provides key information on the process, which is essential to determine whether an energy technology chain could achieve energy sustainability. The evaluated energy flows in each stage of the global strategy are reported in Table 2, as well as the theoretical achievable flows with the PT (and the hypothesized direct energy consumption). For the baseline case, the ESI results in 3.64, which means that during operation for every 3.64 units of produced energy, the system requires a direct energy supply of 1 unit. On the other hand, the introduction of PT leads to a higher generation of syngas (with small changes in the calorific value of this syngas) but with lesser amounts of pollutants (which reduces the energy cost of their treatment). Then, the ESI of the system with PT results in 5.61, which represents an increase of more than 54%. This outcome is of extreme importance since the inclusion of PT seems to moderately increase the short-term energy sustainability of the process. Generally, technologies with ESI> 1 can then be subjected to long-term level of study, where not only the direct energy of the process is considered, but also the indirect share for a full quantification (Gómez-Camacho and Ruggeri, 2019)

Table 2. Energy flows for the calculation of the Energy Sustainability Index (ESI) and the results for the analyzed scenarios.

	Flow	LHV	Energy Carrier	Flow	LHV	Produced energy	Direct Energy	Already Spent Energy	Avoided Energy
	(ton/h)	(MJ/kg FM)		(Nm^3/ton MSW)	(MJ/Nm^3)	(MJ/ton MSW)			
MSW	35.00	9.85	-	-	-			787.50	1470.00
OFMSW	17.50	9.70	Biogas	60.04	19.69	1182.26	153.50	-	-
RDF	12.25	14.00	TG Syngas	924.36	2.75	2540.41	638.06	-	-
Others	5.25	0.65	PT Syngas	1343.68	2.83	1257.82	211.02	-	-
								ESI (-)	
Baseline: Landfill scenario (18 % *w/w* MSW to Landfill)								3.64	
Case study: 18 % *w/w* MSW to PT (0 % MSW to Landfill)								5.61	

Conclusion

The analysis of the proposed strategy seems to indicate that significant improvements could be achieved by integrating the Plasma Torch into a comprehensive strategy for processing unsorted MSW. The equilibrium simulation model suggests that the treatment of the traditional gasification raw syngas could slightly improve the calorific value of the gas due to cracking reactions of unreacted complex organics, while inorganics and ash particle undergo a vitrification process at high temperatures that require further attention. The *ex-ante* LCA study indicates that environmental burdens can be progressively reduced by integrating the PT unit for the cleaning of gasification raw gas and to decrease the amount of waste which is sent to landfills; the limit case shows a theoretical reduction of these burdens of more than 80 % for the AC and PO categories, and more than 90 % reduction for the GWP, E and HT categories. Finally, the ESI shows an increase of more than 54% with the use of the PT unit, which indicates that the present strategy can be candidate for a more comprehensive energy analysis (and consider the long-term level of energy sustainability analysis).

References

Eurostat, 2020, Municipal waste treatments EU-27 1995-2018 - Statistics Explained<ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Municipal_waste_landfilled,_incinerated,_recycled_and_composted,_EU-27,_1995-2018.png>accessed 01.12.2020.

Evangelisti, S. et al., 2015, Life cycle assessment of conventional and two-stage advanced energy- from-waste technologies for municipal solid waste treatment, Elsevier Journal of Cleaner Production, 100, 212–223.

Giansante, L., 2020, Utilizzo della torcia al plasma per la valorizzazione energetica di RSU nel sistema integrato di smaltimento. MSc. Thesis, Politecnico di Torino, Turin, IT.

Gómez-Camacho, C. E. and Ruggeri, B., 2019, Energy Sustainability Analysis (ESA) of Energy-Producing Processes: A Case Study on Distributed H_2 Production, MDPI Sustainability, 11(18), 4911.

Gómez-Camacho, et al., 2021, Is the Anaerobic Digestion (AD) sustainable from the energy point of view? Elsevier Energy Conversion and Management, 231, 113857.

Iacovidou, E. et al., 2013, Anaerobic digestion in municipal solid waste management : Part of an integrated, holistic and sustainable solution, Elsevier Waste Management, 33(5), 1035–1036.

Lee, D. H. et al., 2013, Mapping Plasma Chemistry in Hydrocarbon Fuel Processing Processes, Springer Plasma Chemistry and Plasma Processing, 33, 249–269.

Lombardelli, G., et al., 2017, LCA Analysis of different MSW treatment approaches in the light of energy and sustainability perspectives, Chemical Engineering Transactions, 57, 469–474.

EU, 2018, The European Parliament and Council Directive (EU) 2018/850 - amending Directive 1999/31/EC on the landfill of waste <eur-lex.europa.eu/eli/dir/2018/850/oj>accessed 01.12.2020