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Exergy Profit Evaluation of Municipal Solid Waste Processing

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This article evaluates the processing of Municipal Solid Waste (MSW) and its contribution to sustainability from the viewpoint of its net exergy balance. The evaluation follows the recent framework for estimation of Exergy Footprint and Exergy Profit for a given Process System. The method evaluates the Exergy Assets and Liabilities, estimating the Exergy Profit as the balance of these two. The concept of avoided exergy by substituting the useful chemical to its primary production, similar to the concept of avoided emission is also proposed in this work. The obtained estimate is the specific contribution of the considered MSW processing system. For estimating the overall impacts, the obtained Exergy Profit has to be added to the contributions of the potential upstream and downstream processes. The results show the potential value that can be obtained and sustainability contribution to be achieved by the extraction of useful chemicals from waste and waste-to-energy conversion. The chemical extraction option shows a marginally higher Exergy Profit compared with the typical MSW incineration practice, indicating that, as long as there is a sufficient market demand for the chemical products, this route can be more beneficial. An important outcome is that the product substitution can lead to three-fold increase in the Exergy Profit and the related emission savings.

1. Introduction

The strive for developing more sustainable industrial processes has led to the formulation and application of the concepts of Circular Economy (Korhonen et al., 2018) and Industrial Ecology (Bailey et al., 2008), which were recently analysed from the viewpoint of Exergy Profit (Varbanov et al., 2020). Considering these works, reveals that there are two main perspectives of evaluating a Process System: (a) mass flows and cycles; (b) energy flows. This defines the need to account for both dimensions of the problem in a seamless way.

A typical composite indicator of sustainability contribution of a Process System is the Environmental Performance Strategy Map (De Benedetto and Klemeš, 2009) – a normalised multi-dimensional criterion combining a number of footprints and the system cost. From the viewpoint of basic understanding and formulating mathematical optimisation problems, this is sufficient. However, to gather a thorough understanding of the trade-offs and possible implications for both mass and energy flows, an additional criterion is needed.

A Process System can have various input and output streams of a different nature. They exert environmental impacts and can have different economic significance. All output streams cannot be simply deposited to the surroundings. They have to be brought to a certain desired state at the point of environmental release or shipment as a product. That state is characterised by composition, temperature and pressure. The state for waste streams is usually defined by environmental regulations. For instance, the European Union regulations require that discharged wastewater contains a maximum of 25 mg/L BOD5 at 20 °C (EC, 1991). Similarly, regulatory limits on effluent discharge temperature have been instituted – an example is the set of rules by King County - Seattle, US (King County, 2019). They allow a maximum of 40 °C at the entry of wastewater treatment plants. Another example is the Taiwan Environmental Protection Agency (Turner, 2019), which limits the discharge temperature to sea between 35 to 42 °C, with the added a constraint not to deviate from the surrounding surface water by more than 4 °C.

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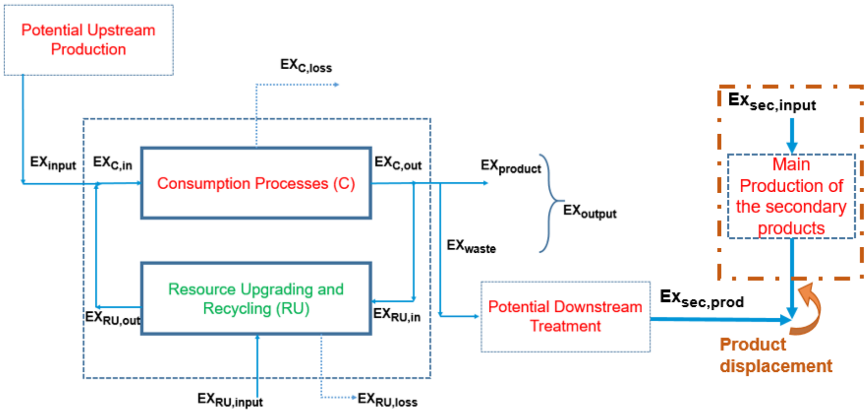
It becomes clear that the environmental impacts of energy and material flows, entering and leaving a process system, are tightly related to the conditions of the surrounding environment. This brings up the exergy (Dincer and Rosen, 2013) supplied to or extracted from a Process System as the indicator to compare the possible alternatives of implementing it. The reference conditions meant are not necessarily the currently existing ambient conditions. The effluent discharge state specifications also provide a suitable reference point for minimising the potential environmental impacts. The COVID-19 pandemics made those issues even more crucial (Klemeš et al., 2020). That approach has been applied to an industrial case study, evaluating implications from the potential increased circularity (EUROSTAT, 2018) of MSW processing. The base incineration route is compared with a potential alternative for recovery of materials and chemical components before using the remaining waste for energy valorisation. The highlight of this study is to showcase the systematic exergy accounting on the example of an MSW treatment system, including the potential avoided exergy by displacing the primary with a secondary product.

2. Summary of the Exergy Profit calculation procedure

The exergy accounting framework starts by identifying the exergy assets and exergy liabilities. The term exergy asset defines the useful exergy that could be recovered from a stream in the form of heat, power, pressure or chemical exergy. Definition of the exergy components are defined in (Dincer and Rosen, 2013). Exergy liability defines that the exergy input required for an output (waste) stream to be brought to the conditions required by environmental regulations. Some of the waste can be sent to the downstream process to produce secondary products, which can be an added value to the exergy asset. This is because producing secondary products can replace the production of identical primary products that require inputs of exergies (energy and virgin raw materials) – see Figure 1. The overall exergy footprint could be reduced, which is in-line with the concept of recycling waste materials could potentially yield net GHG emissions saving (Björklund and Finnveden, 2005).



$$EX = \begin{cases} Asset, & if\ EX \geq 0 \\ Liability, & if\ EX < 0 \end{cases}$$

Figure 1: Generic process description with the exergy accounting framework

Figure 1 shows a generic process description with exergy accounting. Exergy assets are assigned to a product stream only if it is intended as exergy supply for driving activities – such as chemical processes or transport operations. The upstream environmental impacts should be included to enable accounting over complete supply chains and overall LCA (Klemeš, 2015), which leads to the need to account for the exergy embodied into the input streams (Colombo et al., 2015). Adding exergy to the current process is assigned as a liability. The estimation of exergy assets and liabilities of a waste stream follows a notional workflow, involving attempted operations for exergy recovery first, followed by the end of pipe treatment and discharge of the residual stream. If the residual stream can be used as a product to displace some of the demand by the original production, the avoided exergy footprint by the original production can be reduced. The secondary products produced from waste materials is assumed to replace themselves from the primary production (i.e., products produced from virgin resources) (Turner et al., 2015). The substituted amount is then calculated as the amount produced based on the assumed basis of the input material to the consumption process (see Figure 1). The market for the primary production of the waste treatment by-products is assumed to have high flexibility and elasticity for the replacement by the secondary products.

After the exergy assets and liabilities for input and output streams of the system are estimated, they can be added and produce the Total Exergy Assets – Eq(1) and Eq(2) denotes the Total Exergy Liabilities Eq(3) is the avoided exergy by displacing the secondary product into its primary production from virgin resources.

$$EX_{asset} = \sum_{input,i} EX_{asset,i} + \sum_{output,j} EX_{asset,j} \tag{1}$$

$$EX_{liability} = \sum_{input,i} EX_{liability,i} + \sum_{output,j} EX_{liability,j} \tag{2}$$

$$EX_{avoided} = \left(EX_{liability} - EX_{asset}\right)_{displacement\ of\ secondary\ products} \tag{3}$$

3. Case study

The summarised exergy accounting concepts have been applied to an MSW processing system. A reference point is needed to be specified for exergy evaluation. In this study, it is set at 25 °C and 1 atm.

3.1 MSW processing – Exergy Profit evaluation

A case study compiled using information from Sadhukhan et al. (2016) is used to investigate the exergy performance of the integrated Mechanical Biological Chemical Treatment (MBCT) of MSW. The input-output balance is presented in Figure 2. The potential production of Levulinic Acid (LA) through the chemical conversion of MSW can be used to displace the original production of LA using sugarcane bagasse. Table 1 shows the elemental components of MSW in this study. Table 2 shows the mass balances data for the LA primary production process.

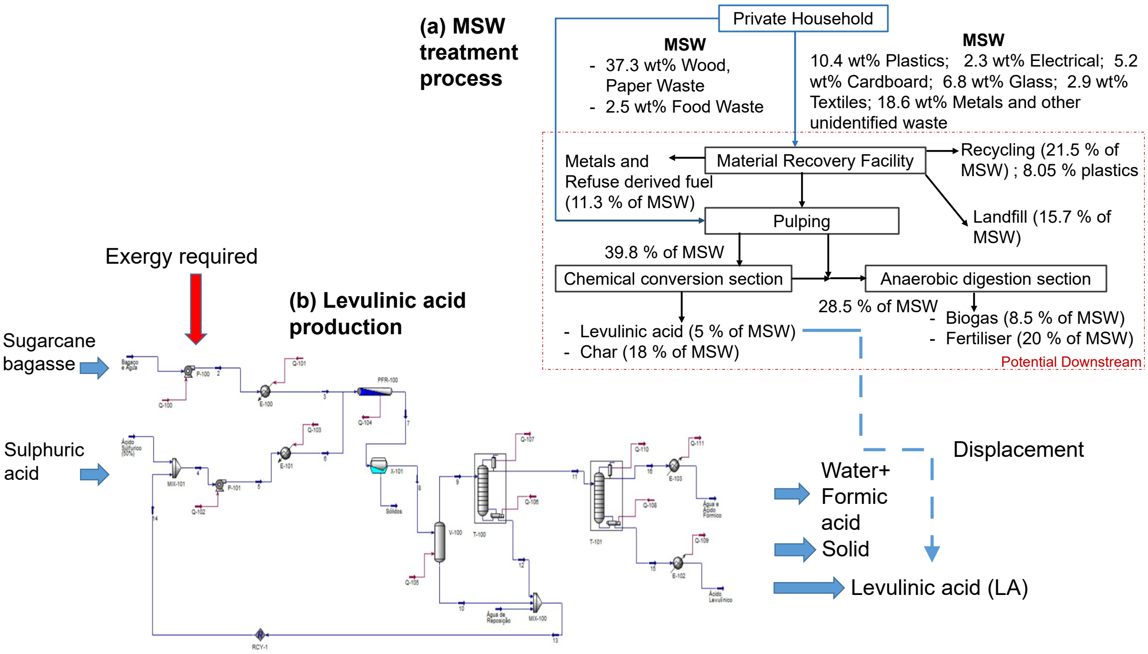


Figure 2: Input-output mass balances for MBCT of MSW, adapted from (Sadhukhan et al., 2016). LA production process is adapted from (Gaudereto et al., 2017)

Table 1: Data of Municipal Waste from Sadhukhan et al. (2016)

Composition of the fuels	Amount (wt % wet basis)	Amount (wt % dry ash-free basis)
Carbon	26.7	57
Hydrogen	3.37	7.19
Oxygen	16.14	34.46
Nitrogen	0.52	1.11
Sulphur	0.11	0.235
Ashes	11.87	-
Water	41.3	-

The exergy of MSW, EX_{MSW} (kJ/kg) is a function of the elemental composition (Eboh et al., 2016), assumed to start the processing at ambient temperature. In Eq(4), C is the carbon content in %, H is the hydrogen content in %, O is the oxygen contents in %, N is the nitrogen content in %, S is the sulphur content in %, Cl is the chlorine contents in %. All percentages are on a dry, ash-free basis.

$$EX_{MSW} = 376.461 \times C + 791.018 \times H - 57.819 \times O + 45.473 \times N - 1536.24 \times S + 100.981 \times Cl \quad (4)$$

Table 2: Stream data for the LA primary production process (Gaudereto et al., 2017)

	Input		Output		
Exergy to be added* (MJ/kg of LA)	168				
	Sugarcane bagasse	Sulphuric acid	Levulinic Acid (LA)	Water	Solid
Flow (kg/h)	8,990.01	33	189.39	8,334.6	999.13
Flow/LA (kg/kg)	47.468	0.174	1	44.01	5.276
T (°C)	25	25	25	25	150
P (kPa)	101	101	101.32	101.32	810.8
Total exergy: Chemical + Physical (kJ/kg)	2.229	0.7333	-156.4	-1.921	9.118
Composition					
Lignin**	0.025	0	0	0	0.227
Cellulose**	0.054	0	0	0	0.0001
Water	0.89	0.5	0	0.9912	0.2692
Sulphuric acid	0	0.5	0.0039	0	0.0158
Hemicellulose**	0.0322	0	0	0	0.2896
Glucose**	0	0	0	0	0.0001
Humines	0	0	0	0	0.1893
Formic acid	0	0	0.0055	0.0088	0.0024
LA	0	0	0.99	0	0.0064

*The heat energy is assumed to be supplied by 300 °C steam and the cold energy is supplied by 20 °C water.
**The exergy values are retrieved from (Liu et al., 2017)

The exergy asset of MSW represents the exergy contents of the output products from different processes - Eq(5). including landfill, recycling, anaerobic digestion, anaerobic digestion and chemical conversion. The exergy required for all the processes is the exergy liability of MSW - Eq(6). Eq(7) denotes the avoided exergy calculation for LA. The difference between asset and liability, plus the avoided exergy represents the exergy profit of the MSW- Eq(8). These concepts are discussed in detail in (Varbanov et al., 2020).

$$EX_{liability,MSW} = \sum_i EX_{added\ to\ process\ "i"} \quad (5)$$

$$EX_{asset,MSW} = \sum_{(i,j)} EX_{output\ "j"\ from\ process\ "i"} \quad (6)$$

$$EX_{avoided,LA} = EX_{added\ to\ LA\ production} + \sum_i EX_{input\ "i"\ to\ LA\ production} - \sum_j EX_{output\ "j"\ from\ LA\ production} \quad (7)$$

$$EX_{profit,MSW} = EX_{asset,MSW} - EX_{liability,MSW} + EX_{avoided,LA} \quad (8)$$

The necessary exergy data for the treatment processes are shown in Table 3.
The following defines the meaning of the superscripts from the Table:

(a) The mean exergy values for plastic wastes are obtained from (Dewulf and Langenhove, 2004).
(b) The output products of AD (Fan et al., 2019) include Biogas = 150 m^3/t waste. Using the biogas 1.81 kWh/m^3 power and 2.27 kWh/m^3 heat at 55 °C are generated. The assumed biogas density is 1.15 kg/m^3. No exergy can be retrieved from the fertilisers, as they are intended for returning to the environment (Wu et al., 2014).
(c) The heat and power generated and used are used to evaluate the cumulative exergy added. The secondary products containing extractable exergy are biogas, char andLA for chemical conversion process (Sadhukhan et al., 2016). The exergy values of biogas and char can be calculated as proportional to their lower heating value, assuming that they will be used as fuels (Dincer and Rosen, 2013).
(d) Data on heat and power required are retrieved from (Sadhukhan et al., 2016).

(e) The exergy of recycling plastics is considered only. The recycling process includes separating the plastic as a primary product, and the remaining is sent to incineration to produce heat and power, see (Dewulf and Langenhove, 2004). The presented exergy values have accounted for the mentioned processes.

Table 3: Additional data for the case study

Process	Overall exergy required (MJ/kg of waste feed)	Overall useful exergy of the secondary product (MJ/kg of waste feed)
Incineration[a]	1.2	16.586
Landfill[a]	0.336	0.242
Recycling[a]	10.442[e]	33.086[e]
Anaerobic digestion (AD)[b,c]	1.09	1.41
Chemical conversion[c,d]	3.01	9.83

Table 4 shows the exergy results of the MBCT system. The net exergy profit, with and without considering the avoided exergy, are shown. Detailed calculation is shown in Varbanov et al. (2020). Assume the demand for LA is 189.39 kg/h, the potential displacement of the LA by MSW is about 50 kg/h (5 % x 1,000 kg/h). The avoided exergy by displacing the LA product can be calculated using Eq(7) and data in Table 2.

Table 4: Exergy assets, liabilities and profit on the basis of 1 t/h of MSW

Exergy of MSW stream (MW)	6.9
Exergy Liability (MW)	0.484
Exergy Asset (MW)	1.39
Exergy Profit, without avoided exergy (MW)	0.906
Exergy Profit, with avoided exergy (MW)	3.24

The default exergy flow of the MSW stream is about 6.9 MW which shows it has a high potential of fuel. If the avoided exergy is excluded, the exergy profit for the MSW stream is 0.906 MW. The profit is positive due to the significant useful exergy from the secondary products. The chemical conversion to secondary products results in high exergy assets. As for the recycling process, although it requires a high input of exergy, the presented data only applied to plastic which is a relatively small amount (8.05 % of 21.5 % of MSW). The useful exergy and its exergy liability have a minor contribution to the profit. If avoided exergy by displacing the primary production of LA is considered, a significant amount of exergy can be avoided (3.24 – 0.906 = 2.34 MW). This is due to the high exergy required for the LA production process. If all the LA from the MSW can be used to substitute to the primary process, a significant amount of exergy (heat and power) can be saved. The negative exergy values of the output products, especially water stream, also contribute to the high exergy can be avoided. Negative exergy of the output stream means the additional exergy required to transform the stream to the reference condition (environment condition in this case). The presence of formic acid in the water stream, even in small amount constitutes to the negative exergy because it has high negative specific chemical exergy (-223 MJ/kg at 25 °C and 1 atm). Displacing the primary LA production helps to reduce the production of negative exergy output water stream, but not too much compared to the energy streams.

4. Conclusions

This article presents an application of the Exergy Profit concept, as an extension of the framework developed previously. The calculated values for Exergy Assets, Exergy Liabilities, and Exergy Profit are used for comparative sustainability assessment of process alternatives. The case study clearly shows the advantage, in terms of sustainability, of the MBCT option for MSW treatment. This is rooted in the combined valorisation path, simultaneously obtaining useful energy directly and extracting useful chemicals. The avoided exergy intake from conventional production of the useful chemicals being substituted is also considered. The results show that, if there is sufficient market demand for these chemicals, the MBCT route can be considered as a viable alternative to the traditional incineration practice.

The proposed concept can be further developed in several ways. The framework has to be complemented with a procedure for estimating the origin of the supplied exergy – taking into account the potential use of fossil fuels for harvesting and supply of renewables, further estimating the fraction of the renewable flow from the overall supply. That can be used directly as a sustainability metric, based on the understanding that any non-renewable supply causes simultaneous depletion of terrestrial reserves and environmental pollution. Another important element to add is a procedure for selecting the system boundary and implementation of the defined criteria within the Life Cycle Analysis meta-framework. The future work should enrich the evaluation with economic metrics. This will provide a complete toolset accounting for both the technical and economic performance of the process systems. Full Life Cycle Assessment requires collecting a large amount of information. Some of that information is not available merely because it is not collected and recorded. Some Life Cycle stages bear much more significant environmental and exergy impacts than the other. This requires the development of a significance evaluation procedure based on quantitative estimates.

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