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Embodied Exergy-based analysis of a Municipal Solid Waste treatment system with uncertainty inclusion

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Abstract: The development of an Integrated Solid Waste Management (ISWM) system is still a matter of interest in many countries. One of the main challenges is to efficiently allocate the material streams in order to save energy and recover materials. The aim of this paper is to use the Embodied Exergy criteria to evaluate the distribution of the material streams into a Solid Waste (SW) treatment system composed by: a Mechanical Biological Treatment (MBT) plant for Refuse Derived Fuel (RDF) production and a paper recycling plant for cardboard production. Two scenarios are compared, based on the inlet mass flow to the MBT plant and the cardboard production. Stochastic tools based on Monte Carlo simulation are adopted for generating simulation scenarios, in order to account for the uncertainty that occurs in external (e.g. waste composition) and internal (e.g. equipment energy consumption) parameters.

Keywords: Municipal Solid Waste, Mechanical Biological Treatment, Paper recycling, Uncertainty analysis, Embodied Exergy, Exergy analysis

Biographical notes

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1. Introduction

The development of an effective Integrated Solid Waste Management (ISWM) system is still a crucial challenge for many countries, even in Europe. According to the definition of (IECT, 2016), the ISWM refers to the strategic approach to sustainable management of Solid Waste (SW), from their generation, segregation, sorting and transport to the treatment, recovery and disposal, with the aim of maximizing the efficiency of resource utilization. One of the main issues is an efficient repartition of the material streams within the system, minimizing the cost and the environmental impact and optimizing the energy and/or material recovery. Various examples are present in literature of ISWM analysis. An environmental assessment of waste management scenarios including energy recovery using Life Cycle Assessment (LCA) and multi-criteria analysis is performed in (Milutinović *et al.*, 2017), while the environmental performance of household waste management in 7 European countries is reported in (Bassi, Christensen and Damgaard, 2017). The major source of wastes is represented by Municipal Solid Waste (MSW). If a Selective Collection (*SC*) system is present, the quantity of Total Unsorted Wastes (TUW) is the sum of the collected streams of different materials m_i and the Residual Unsorted Waste (RUW). The global Selective Collection SC_{gl} value is defined as the weight percentage of MSW that is separated and collected (*Rapporto Rifiuti ISPRA*, 2018). SC_{gl} can be calculated as the weighted average of m_i (where *i* can refer to paper, plastic, organic matter, wood, metal, glass and textile), where the weight is the degree of selective collection of the single stream SC_i (expressed in %). The separated materials are directed to specific recycling plants for production of new manufactured products. The rejected material from recycling processes together with the RUW have to be treated before final disposition (e.g. landfill or incinerator), according to the Italian law LD 211/2015 art. 48. The Mechanical Biological Treatment (MBT) plant appears to be a valid alternative for waste treatment and stabilization (Fei *et al.*, 2018; Stegmann, 2018). The main aim of the MBT plants is to separate the light and dry fraction of the RUW from the wet one, in order to increase the calorific value of the outlet stream, which is called Refused Derived Fuel (RDF) (Montejo *et al.*, 2013; Trulli *et al.*, 2018). In addition, the organic part is stabilized before the final disposal and the ferrous and non-ferrous metals are recovered, decreasing the volume of wastes to be disposed in landfill (Juniper, 2005). RDF can only be used in incinerators, cement factories or thermal power plants of more than 50 MW, otherwise it is disposed in landfill (Di Lonardo *et al.*, 2015; Paolo and Paola, 2015). Besides, the MBT works as a buffer for the variation of the selective collection. Among the recycling chains, paper recycle is one of the most well established with the highest index of recyclability (up to 80%) (Comieco, 2018). Besides recycled paper substitutes a material which production cost from raw material is about 50% higher in terms of energy consumption. In this work, only cardboard production is considered, since it represents the first paper product from recycled pulp of the total European production (Suhr *et al.*, 2015). Examples of modelling and analysis of MBT and paper recycle separately are present in literature, mainly based on material and energy balance. The influence of the input waste to MBT plant and processing technologies on RDF characteristics are studied in (Edo-Alcón, Gallardo and Colomer-Mendoza, 2016). Experimental analyses are conducted with the aim to show the environmental advantage of inserting a MBT plant before landfill (Trulli *et al.*, 2018). In Grosso *et al.*(2016), the LCA approach is used for evaluating the energetic and environmental performance of a MBT plant producing RDF for cement kiln co-combustion; an LCA methodology is also implemented in Montejo *et al.* (2013) for comparing eight European MBT plants. A comparison between virgin paper production and recycled paper using recycling metrics indicators is conducted in Ewijk, Stegemann and Ekins (2017). An assessment of pulp and paper mill through energy and exergy analysis is performed in Utlu and Kincay (2013). A broader vision is adopted in Dewulf and Van Langenhove (2002), where different waste treatment options are analysed for various material streams using exergy criteria. The application of Exergoeconomics concepts and instruments appears promising in the analysis of SW systems, since exergy can be used as a rational basis for comparing flows of different nature (material and non-material). Among the others, the concept of Embodied Exergy (EE) is an effective way to account the exergy invested in the entire production chain, from the extraction, processing and transport of raw materials to the process itself (Liao *et al.*, 2013). EE concept has been used for the assessment of the energy and resource consumption in the building sector (Meng *et al.*, 2014) or in the evaluation of manufactured products lifecycle (Liao *et al.*, 2013). However, no examples of EE-based analysis applied to ISWM system are present in the literature.

Many factors (e.g. social, political, geographical, technological and economical) can affect the functioning of an ISWM system (Edjabou *et al.*, 2015). In order to test the sensibility of the system to the randomness that derives from multiple scenarios, an uncertainty analysis is performed. The uncertain variables can be divided into the ones external to the treatment plant (e.g. the degree of selective collection of materials or the structure of the collection) and the internal ones (e.g. change in equipment energy consumption due to failures or different inlet material characteristics). The instruments of the uncertainty analysis consist in generating random scenarios using stochastic tools, usually based on Monte Carlo simulation (Clavreul *et al.*, 2012). Very few examples of inclusion of uncertainty in the analysis of ISWM systems are present (Maqsood and Huang, 2003).

In summary, the aim of this paper is to use the Embodied Exergy criteria to evaluate the allocation of the material streams into the MSW treatment system and to test its sensibility to uncertain working conditions.

2. Methodology and assumptions

The MSW treatment system composed by a MBT plant and a paper recycling plant (Figure 1) was modelled and simulated according to the steps reported below. The validation was performed with data declared by real MBT plants and literature data on paper recycling based on BAT (Suhr *et al.*, 2015), by comparing the values of yield, Lower Heating Value (LHV) and moisture content of products and Global Energy Consumption (GEC). MATLAB software was used to create and simulate the system model. The structure of the MBT chain was chosen according to real plant layouts and literature review based on (Stegmann, 2018). The treatment phases for RUW were considered, in succession: first shredding, pre-screening, magnetic separation, eddy current separation, storage, second shredding, fine screening, Near-Infrared Removal (NIR), third shredding. The paper recycling plant was modelled considering only two macro parts: the stock preparation, which includes screening, shredding and pulping of the inlet paper material; the cardboard making process, composed by the pulp magnetic separation and the screening, spraying, drying and pressing. The characteristics of each equipment are summarized in Table 1.

2.1. Material flows

The linearity of the relations between the system components (no chemical or nuclear reactions occur) allows the utilization of transfer matrices for mass balance calculation. The Recovery Factor Transfer Function (RFTF) matrix (see Appendix A) introduced by Diaz, Savage and Golueke (1982) is used for modelling and calculating the material flows in the MBT plant. The elements of the RFTF matrix are the transfer factors of the wet and dry part of each i-th material stream associated to the j-th equipment. The relation between the input and output flow is expressed by Equation 1. The wet and dry part and ultimate analysis of each material stream composing the *RUW* are calculated according to the values found in literature (Liley *et al.*, 1942). For evaluating the material recovery, the Yield of RDF is calculated as the ratio between the outlet RDF and the inlet RUW flow (Equation 2).

$$m_{i_{out}} = m_{i_{in}} \cdot RFTF(j) \quad (1)$$

$$Yield_{RDF}(\%) = \frac{\dot{m}_{RDF}}{\dot{m}_{RUW}} \quad (2)$$

In the paper recycling model, paper recovery factor and water consumption are given on inlet paper basis. The water consumption for pulping formation varies from 1.5 to 35 m^3/ton of paper, while waste water and waste fibres are 5.4% and 1.62% respectively of the inlet paper flow (Liley *et al.*, 1942; Laurijssen, 2013).

2.2. Energy flows

The MBT plant get electricity directly from the grid for moving the equipment. According to literature review, a range of energy consumption (kWh/Mg of inlet RUW) is indicated for each equipment, as resumed in Table 1. The LHV of the inlet RUW and of the outlet RDF were calculated using the Mendeleev Equation (3), where the coefficients of Carbon, Hydrogen, Oxygen, Sulphur (C, H, O, S) and the Moisture Content (MC) are given on wet basis (Magrinho and Semiao, 2008).

$$LHV\left[\frac{kJ}{kg}\right] = 4.187 \cdot [81C + 300H - 26(O - S) - 6(9H + MC)) \quad (3)$$

In case of paper recycling, electricity is needed for the movement of the material and the pulping formation, depending on the type and quality of paper grade (Laurijssen, 2013). In this work, the deinking and dispersion phases are not considered, since cardboard is produced; this assumption reduces considerably the GEC of the recycling, which is defined as the direct sum of the consumption of every equipment and the one of auxiliaries. Thermal needs for drying purposes are usually covered by superheated steam at 428 K and 1 bar (Utlu and Kincay, 2013); in this case the steam consumption is 5.54 kg of steam/kg of paper.

2.3. Exergy flows

Since the inlet RUW is composed by organic, inorganic and wet part, the inlet exergy flow $\dot{B}_{RUW_{in}}$ (kW) was calculated accounting for each contribution. The chemical exergy content b_{ch_i} (kJ/kg) of organic materials (i.e. paper, organic matter, wood, leather, plastics and textiles) was calculated using Equation 4 (Kotas, 1985), where φ is the Szargut coefficient of correction of LHV (Szargut J, David RM, 1988), which depends on the O/C ratio, while W ad S are the water and sulphur content (%).

$$b_{ch_i} = \varphi \cdot (LHV_i + 2442W) + b_{ch_{wat}} \cdot W + 9683 \cdot S \quad (4)$$

The inorganic part is composed by the metals and the glass, (since the exergy of the inert material can be disregarded). The exergy of pure iron and aluminium was assumed for ferrous and non-ferrous metal respectively; the exergy of glass was calculated considering the solid mixing of the glass components (1.5% Al_2O_3, 10.8% CaO, 13.2% Na_2O, 73.3% SiO_2) (Ayres and Ayres, 1998). For the water W, only the chemical exergy was considered ($b_{ch_{wat}}$= 50 kJ/kg), since reference temperature (T_0) and pressure (p_0) were assumed. The exergy of the steam was calculated considering the contribution of physical ($b_{ph} = (h - h_0) - T_0(s - s_0)$) and chemical exergy. Exergy Efficiencies ($\eta_{ex} = \dot{B}_{pr}/\dot{B}_{input}$) were calculated for the two plants, expressing the ratio between the exergy flow of the products and the total input exergy flow.

2.4.The Embodied Exergy concept

Using the definition of Ulgiati (2000), the Embodied Exergy (EE) is defined as the sum of the actual exergy of the system or product plus the exergy previously used to produce and provide the resources for creating it. As stated in (Liao *et al.*, 2013), the EE balance is a product-specific methodology to account the consumption mode of energy embodied in the product lifecycle. Therefore, the enlargement of the system boundaries lead to a more accurate evaluation of all the contributions to the EE of the products, which in this case are RDF fuel and cardboard; besides, it is useful in order to account for the avoided exergy and material consumption of the alternative scenarios. For this reason, the exergy cost of extraction (or collection, in case of MSW), process and transport of raw materials are included in the global balance, in addition to the contribution of the single treatment process. Assuming that the RDF is used in a cement kiln, the substitute fuel can be the pulverized coal (Asthana and Pati, 2006), while the alternative process to paper recycling for cardboard production is mechanical pulping with wood as raw material. The exergy used to extract and process the coal is accounted for using the Thermo-Ecological Cost (TEC) indicator (Stanek, 2017), in the hypothesis of barge transport. The exergy cost for processing wood $Ex_{wood_{pr}}$ includes the harvesting and transportation in a radius of 80 km (Furtula *et al.*, 2017) . The contribution of the input waste collection and transport ($Ex_{UW_{tr}}$ and $Ex_{paper_{tr}}$) were calculated considering an average distance of 30 km between the generation point and the treatment plant (Larsen *et al.*, 2009). All these factors were evaluated in terms of diesel consumption ($Ex_{diesel} = 45.6\ MJ/kg$). Table 2 resumes all the terms, internal and external to the process, used for calculating the EE balances expressed by Equations 5-8, for RDF, cardboard from recycling, cardboard from wood and coal, respectively. The balances are expressed in kW, being $\dot{B}$ the product between the specific exergy and the mass flow. The difference in global EE balance (Eq. 9) is expressed by the algebraic sum of the difference of all the terms respect to the base case scenario (ΔEE_i); for example, an increase in SC_{paper} will lead to an increase in $EE_{card_{rec}}$ and EE_{coal} ($\Delta EE > 0$) and a decrease in EE_{RDF} and virgin paper $EE_{card_{wood}}$ ($\Delta EE < 0$).

$$\Delta EE_{gl} = \Delta EE_{RDF} + \Delta EE_{card_{rec}} + \Delta EE_{card_{wood}} + \Delta EE_{coal} \quad (9)$$

The presented global embodied exergy balance can be considered as an opportunity cost, since it is an indicator of the savings or additional consumption encountered when a certain scenario is chosen respect to the base case (characterized by a certain value of SC_{paper}). Since the EE is considered as the exergy cost B_i^* of products, a unit exergy cost of the material stream c_i^* can be defined by dividing B_i^* by the corresponding exergy (Eq.10).

$$c_i^* = B_i^*/B_i \tag{10}$$

As stated in Asthana and Pati (2006), the exergy cost is an emergent property, so it acquires value only for comparing the cost of different flows in a given structure. In this case, the unit exergy based costs of RDF and cardboard are calculated.

2.5. Sensitivity analysis

First, a sensitivity analysis is performed by varying the SC_{paper} in a range between -30/+30% respect to the base case, which characteristics are summarized in Table 3. The effect of the linear variation is investigated for two simulation scenarios: (A) fixed cardboard production $\dot{m}_{card}$; (B) fixed MBT input mass flow $\dot{m}_{RUW}$ and fixed $\dot{m}_{card}$. The second case is the more realistic, since the plants are always designed for working at a Nominal Capacity (NC) or in order to reach a certain production. In order to perform the simulation, the cardboard production $\dot{m}_{card}$ was fixed to 2200 kg/h, while the input MBT flow to 5000 kg/h; these values are chosen according to the material flows of the base case scenario. The idea is to account the sensitivity of the system to the variation of the input conditions, evaluating the effects on the global exergy costs. In fact, if the generation of RUW is different from the NC of the MBT plant, an additional cost of transport has to be accounting for importing ($\dot{m}_{RUW}$ lower than NC) or exporting ($\dot{m}_{RUW}$ higher than NC) the remaining RUW from or to another waste transfer station (which is supposed to be in an area of 50 km). On the other side, a virgin paper production plant covers the fluctuations in cardboard production, due to variations in paper input to recycling plant.

2.6. Uncertainty analysis

- External variables

The inclusion of uncertainties in waste composition is performed trough a random sampling on uniform distributions of SC_i values using a Monte Carlo simulation, which is based on the random generation of a high number of values. SC_i are varied in extent ranges (approximately ±50%) in order to represent multiple recycling situations. For each random-generated scenario, RUW percentage composition and SC internal repartition were calculated. The percentage composition of the UW before the collection is assumed as constant. The mean values μ and the Relative Standard Deviation (%RStD) of the output parameters were compared in order to evaluate the sensibility of the system.

- Internal variables

The equipment energy consumption is considered as the internal uncertain variable, since variation in inlet material characteristics (e.g. density, size, moisture content) or random failures can influence its value. Differently from the case of external uncertainties, a normal probability distribution is associated to the energy consumption of each equipment, being the mean value calculated according to the ranges reported in Table 1. The procedure for sampling from the normal distribution consists of two steps. First, following the percentage repartition of the standard curve, a normal-like discrete probability distribution is created and the respective μ value and RStD are calculated. These values are used for creating the Cumulative Distribution Function (CDF) of a continuous normal distribution, which is then sampled using the Inversion method (Equations 11-12) (Larson and Odoni, 1981) within a Monte Carlo simulation (i.e. a high number of values U between 0 and 1 are generated and the correspondent value X on the CFD curve is found).

$$F(X) = P\{X < x\}, \quad \textit{CFD of x distribution values} \tag{11}$$

$$U \in \{0,1\}, \;\; X = F^{-1}(U) \tag{12}$$

3. Results

3.1. The paper exergy path

The allocation of the paper stream into a specific treatment path entails a different destiny for its internal exergy. The distribution of exergy losses is displayed in the Grassmann diagrams (Figure 2), visualizing the contribution of material losses for the MBT plant (a) and the paper recycling chain (b). The major losses of internal (chemical) exergy of paper are associated with the equipment with the higher degrees of material losses, namely the primary and secondary screening phase, followed by the eddy current and magnetic separators. The others components' contribution is not significant. The portion of recovered internal exergy of paper is major in case of paper recycling (82% versus 73.2%), due to the small amount of rejected fibres.

3.2. Global Embodied Exergy Balance

The results of the linear variation of SC_{paper} are reported in Table 4 for the two simulation scenarios; the behaviour of each ΔEE_i in the reported ranges is linear. Global EE values for the base case of the two scenarios are 28,354 kW and 27,974 kW respectively. The $\Delta EE_{UW_{tr}}$ associated to RUW transport is accounted separately.

In both cases the exergy efficiency of the MBT plant diminishes by about 13%, as a consequence of the less amount of paper in the final RDF; in fact, the Yield decrease (-28.8%) is not compensated by an equal increment in RDF specific exergy content (+13.5%). The exergy efficiency of the paper recycling plant is not influenced by the inlet composition, since the cardboard yield is fixed. Scenario A presents a quite symmetric distribution of values of ΔEE_i apart from ΔEE_{coal}, since it depends on the yield of RDF. This is the same cause of the asymmetry in ΔEE_{RDF} of scenario B; besides in this case ΔEE_{tr} is always positive, since it includes the transport cost for covering the capacity of the MBT plant. The trend of the resultant ΔEE_{gl} is shown in Figure 3. The greatest increments are associated to low degrees (-30%) of SC_{paper} for both scenarios (+1.73% for case A and +1.6% for case B); the major positive costs are associated to the production of cardboard from raw material, followed by the RDF production. The trend is generally decreasing, presenting a minimum of -0.53% for SC_{paper} = +20% (A) and of -0.13% for SC_{paper} = +10% (B). A new growth occurs for high percentage of SC_{paper}; this effect is more marked in scenario B, due to the higher additional costs of transport of the alternative fuel.

3.3. The effect of the uncertainty

Table 5 reports the μ values and RStD of the main output parameters resulted by the Monte Carlo sampling on external and internal uncertain variables. The μ value of SC_{gl} represents the most probable value obtained by a random variation of the independent random variables SC_i and its resulting probability distribution is normal-like. Considering the external uncertainties, the RStD values demonstrate that in a MBT plant the dispersion of values around μ diminishes for the output parameters (Yield, LHV of RDF and exergy efficiency). In fact, the sequential treatment phases of the process have the effect to uniform the inlet material characteristics, absorbing the fluctuations of its composition.

The trend of the evaluation parameters is graphically shown in Figure 4a. The Yield presents a behaviour similar to the normal one, while the unit exergy cost and exergy efficiency are markedly not centred, following approximately an inverse Weibull distribution more than a normal one. The behaviour of the EE of RDF follows the normal one, since it is influenced by the random variation of the different material streams; however, there is no direct correlation with one single parameter (SC_{gl}, SC_{paper}), but rather with a combination of SC_{paper} , SC_{plastic} and $SC_{\text{organic.}}$. Differently, the EE of cardboard present a more uniform distribution since only the paper random variation affects its behaviour; in fact, the value of the RStD is about 2.2 times higher than in the case of the EE of RDF. The global EE balance,ΔEE_{gl}, is strongly influenced by the behaviour of the EE of RDF, even if the resulting distribution is not normal centred. Results show that the random variation of waste composition has a moderate effect on the global balance of EE; the major differences respect to the base case are in the range of values between -500 and +750 kW (about +/-2% of the total), which means that the various exergy costs of the system quite compensate each other.

With regard to the internal uncertainties, the evaluation parameters affected by the random variation of energy consumption are the exergy efficiency, the unit exergy costs of products, the global energy consumption and, as a consequence, the embodied exergy. As it can be seen in Table 5, the RStD of the product costs and the efficiency is about two orders of magnitude lower than the one of the GEC. This result is a direct consequence of the less impact of energy consumption on system efficiency; besides, as in the case of external uncertainties, it shows that the effect of variation of energy consumption is reduced within the system. As expected, the discrete distribution of the values follows the behaviour of the normal distribution, as can be seen in Figure 4b.

4. Conclusion and discussion

A Municipal Solid Waste treatment system composed by a MBT and a paper recycling plant was modelled and mass, energy and exergy balances were calculated in order to follow the path of the inlet paper material stream. In general, a paper recycling plant requires, as expected, major energy consumption with respect to a MBT plant; however, it is not only a better alternative for recovering the waste paper internal exergy, but it is also cost-effective compared with cardboard production from raw material (wood). The aim of the work was to use the Embodied Exergy (EE) concept to evaluate the allocation of the paper material stream into the MSW treatment system, according to the variety of operating conditions that can be faced in real working conditions. The use of exergy balance in this context appeared to be particularly useful since material and non-material streams are involved. At the same time, the enlargement of the boundaries of the system lead to a more accurate evaluation of all the contributions to the EE of the products, namely the RDF fuel and the cardboard. This idea combined with sensitivity analysis allowed the calculation of the avoided or additional exergy and material consumption of the alternative scenarios (i.e. coal instead of RDF for cement kilns and wood-based cardboard production). The degree of Selective Collection of paper (SC_{paper}) was varied linearly in a range between +/-30% respect to the base case. The variation of the paper input has a moderate effect on the exergy efficiency of MBT plant, due to the combined effect on yield and LHV of RDF. It is interesting to notice the effect of the global EE variation on the entire system. In fact, a decrease in SC_{paper} leads to greater values of ΔEE_{gl}, but savings on EE diminish for high collection of paper, because of the influence of MSW transport and coal cost. Anyway, the variations are very moderate, in the order of +/- 2%. This led to the conclusion that even if the SWM system has a good degree of self-regulation, high share of selective collection can still be hindered by economic burdens, most of them linked to transport issues. An optimized location of recycling plants will reduce the global exergy cost. At the same time, RDF utilization for energy production purpose should be limited to flexible systems, better if coupled with non-fossil fuels. A sensitivity analysis to external (waste composition) and internal (electric energy consumption of the equipment) uncertain variables was conducted in order to give indications for realistic working scenarios. The resulted mean values and RStD of efficiencies, costs and energy consumption can be useful at the time of designing a new plant. The analysis of the uncertainties reveals that the influence of external variations is higher than the internal ones. In any case, the structure of the system (for both the MBT and the paper recycling plant) tends to absorb and uniform the input fluctuations, even if this effect is more evident in the MBT plant. This is consistent with the fact that these plants are aimed at manufacturing products with the standard characteristics required by the final users.

Andreasi Bassi, S., Christensen, T. H. and Damgaard, A. (2017) ‘Environmental performance of household waste management in Europe - An example of 7 countries’, *Waste Management*. Elsevier Ltd, 69, pp. 545–557. doi: 10.1016/j.wasman.2017.07.042.

Asthana, S. R. and Pati, R. K. (2006) ‘Use of Alternative Fuels in Indian Cement Industry’, *Advances in Energy Research*, (July), pp. 347–349. doi: 10.1016/j.jbusvent.2005.09.004.

ATO RIFIUTI (2015) 'Solid Waste: Production and Selective Collection' (*In Italian*) pp. 17–64.

Ayres, R. U. and Ayres, L. W. (1998) *Accounting for resources*. p. 264, Edward Elgar Publishing Ltd.

Julie Clavreul, Dominique Guyonnet, Thomas H. Christensen. Quantifying uncertainty in LCA- modelling of waste management systems. Waste Management, Elsevier, 2012, 32, pp.2482-2495. <10.1016/j.wasman.2012.07.008>. <hal-00763701>

Comieco (2018) *Report Collection , Recycling , and Recovery of paper and board in 2017*. (In Italian)

Dewulf, J. P. and Van Langenhove, H. R. (2002) ‘Quantitative Assessment of Solid Waste Treatment Systems in the Industrial Ecology Perspective by Exergy Analysis’, *Environmental Science & Technology*. American

Chemical Society, 36(5), pp. 1130–1135. doi: 10.1021/es010140o.

Diaz, L. F., Savage, G. M. and Golueke, C. G. (1982) *Resource Recovery from Municipal Solid Wastes: Primary processing*. CRC Press (Resource Recovery from Municipal Solid Wastes). Available at: https://books.google.es/books?id=9WVCAQAAIAAJ.

Edjabou, M. E. *et al.* (2015) 'Municipal solid waste composition: Sampling methodology, statistical analyses, and case study evaluation', *Waste Management*. Elsevier Ltd, 36, pp. 12–23. doi: 10.1016/j.wasman.2014.11.009.

Edo-Alcón, N., Gallardo, A. and Colomer-Mendoza, F. J. (2016) 'Characterization of SRF from MBT plants: Influence of the input waste and of the processing technologies', *Fuel Processing Technology*. Elsevier B.V., 153, pp. 19–27. doi: 10.1016/j.fuproc.2016.07.028.

Ewijk, S. Van, Stegemann, J. A. and Ekins, P. (2017) 'Global Life Cycle Paper Flows , Recycling Metrics , and Material Efficiency', 22(4). doi: 10.1111/jiec.12613.

Fei, F. *et al.* (2018) 'Mechanical biological treatment of municipal solid waste: Energy efficiency, environmental impact and economic feasibility analysis', *Journal of Cleaner Production*. Elsevier Ltd, 178, pp. 731–739. doi: 10.1016/j.jclepro.2018.01.060.

Furtula, M. A. *et al.* (2017) 'Energy consumption and equivalent emission of Co2tpellet at wood pellets production in Serbia', *Thermal Science*, 21(5), pp. 1905–1915. doi: 10.2298/TSCI170220099F.

Grosso, M. *et al.* (2016) 'Case study of an MBT plant producing SRF for cement kiln co-combustion, coupled with a bioreactor landfill for process residues', *Waste Management*. Elsevier Ltd, 47, pp. 267–275. doi: 10.1016/j.wasman.2015.10.017.

Hryb, W. (2015) 'Sorting Tests of Unsorted Municipal Solid Waste from Germany for a Selected Opto-Pneumatic Sorting Machine', 24(1), pp. 99–105. doi: 10.15244/pjoes/26387.

IECT International Environmental Technology Centre (2016) *Integrated Solid Waste Management*.

Juniper (2005) *Mechanical-Biological-Treatment : A Guide for Decision Makers Processes, Policies and Market*.

Kotas, T. J. (1985) 'The Exergy Method of Thermal Plant Analysis', in Kotas, T. J. B. T.-T. E. M. of T. P. A. (ed.). Butterworth-Heinemann, pp. 162–196. doi: https://doi.org/10.1016/B978-0-408-01350-5.50012-X.

Larsen, A. W. *et al.* (2009) 'Diesel consumption in waste collection and transport and its environmental significance', *Waste Management and Research*, 27(7), pp. 652–659. doi: 10.1177/0734242X08097636.

Larson, R. C. and Odoni, A. R. (1981) 'Urban Operation Research', in. Prentice-Hall, p. 530.

Laurijssen, J. (2013) *Energy use in the paper industry-An assessment of improvement potentials at different levels*.

Liao, M. *et al.* (2013) 'Decomposition of embodied exergy flows in manufactured products and implications for carbon tariff policies', *Asia Europe Journal*, 11(3), pp. 265–283. doi: 10.1007/s10308-013-0357-3.

Liley, P. E. *et al.* (1942) *Chemical Engineers' Handbook. Second edition (Perry, John H., ed.)*, *Journal of Chemical Education*. doi: 10.1021/ed019p449.2.

Di Lonardo, M. C. *et al.* (2015) 'The application of SRF vs . RDF classification and specifications to the material flows of two mechanical-biological treatment plants of Rome : Comparison and implications', *WASTE MANAGEMENT*. Elsevier Ltd, 47B, pp. 195–205. doi: 10.1016/j.wasman.2015.07.018.

Magrinho, A. and Semiao, V. (2008) 'Estimation of residual MSW heating value as a function of waste component recycling', *Waste Management*. Elsevier Ltd, 28(12), pp. 2675–2683. doi: 10.1016/j.wasman.2007.12.011.

Maqsood, I. and Huang, G. H. (2003) 'A two-stage interval-stochastic programming model for waste management under uncertainty', *Journal of the Air and Waste Management Association*, 53(5), pp. 540–552. doi: 10.1080/10473289.2003.10466195.

Meng, J. *et al.* (2014) 'Embodied exergy-based assessment of energy and resource consumption of buildings', 8(1), pp. 150–151. doi: 10.1007/s11707-013-0397-4.

Milutinović, B. *et al.* (2017) 'Environmental assessment of waste management scenarios with energy recovery using life cycle assessment and multi-criteria analysis', *Energy*, 137, pp. 917–926. doi: 10.1016/j.energy.2017.02.167.

Montejo, C. *et al.* (2013) 'Mechanical-biological treatment: Performance and potentials. An LCA of 8 MBT plants including waste characterization', *Journal of En vironmental Management*. Elsevier Ltd, 128, pp. 661–673. doi: 10.1016/j.jenvman.2013.05.063.

Paolo, M. and Paola, M. (2015) 'RDF: From waste to resource - The Italian case', *Energy Procedia*, pp. 569–584. doi: 10.1016/j.egypro.2015.12.136.

Rapporto Rifiuti ISPRA (2017).(In Italian)

Sirini, P., Tchobanoglous, G. and Noto La Diega, R. C. (2010) *Ingegneria dei rifiuti solidi*. Milano: McGraw-Hill.

Stanek, W. (ed.) (2017) *Thermodynamics for sustainable management of natural resources*. Springer.

Stegmann, R. (2018) 'Mechanical biological pretreatment', in *Solid Waste Landfilling*, pp. 141–155. doi: 10.1016/B978-0-12-407721-8.00008-5.

Suhr, M. *et al.* (2015) *Best Available Techniques (BAT) - Reference Document on Best Available Techniques in the Pulp and Paper Industry*, *JRC Science and Policy Reports*. doi: 10.2791/370629.

Szargut J, David RM, S. F. (1988) *Exergy analysis of thermal, chemical, and metallurgical processes. Hemisphere Publishing, New York*. New York: Hemisphere Publishing.

Trulli, E. *et al.* (2018) 'Sustainable mechanical biological treatment of solid waste in urbanized areas with low recycling rates', *Waste Management*. Elsevier Ltd, 71, pp. 556–564. doi: 10.1016/j.wasman.2017.10.018.

Ulgiati, S. (2000) 'Energy, Emergy and Embodied Exergy:

deverging or converging approaches?', *First Biennial Emergy Analysis Research Conference*, pp. 15–31.

Utlu, Z. and Kincay, O. (2013) 'An assessment of a pulp and paper mill through energy and exergy analyses', *Energy*. Elsevier Ltd, 57, pp. 565–573. doi: 10.1016/j.energy.2013.05.054.

Westenbroek, A. (2011) 'Maximum value from paper for recycling Towards a multi-product paper mill', 2011. *Confederation of European Paper Industries*

Tables

Table 1. *Equipment description and energy consumption, elaborated by the author based on* (Liley *et al.*, 1942; Sirini, Tchobanoglous and Noto La Diega, 2010; Westenbroek, 2011; Montejo *et al.*, 2013; Suhr *et al.*, 2015)

MBT plant		
Equipment	Description	Range of Energy consumption (kWh/Mg)
Primary shredding	First shredding after the delivery of the material. The energy consumption depends from the dimensional reduction following the Kick's Law $E = C \cdot \ln\left(\frac{F_0}{X_0}\right)$ with F_0=170mm and X_0=80mm and C=8.22÷16.44	6.2 ÷ 12.4
Secondary shredding	The air-classified light fraction requires more energy for shredding than the mixed waste	15 ÷ 25
Magnetic separator	Removal of ferrous metal. The energy consumption is due to the movement system of the conveyor belt.	0.2 ÷ 2.4
Eddy current separator	Removal of non-ferrous metal.	0.7 ÷ 1.2
Pre-trommel	First screening for the primary separation of the organic wet fraction from the light one; the size of the screening is generally 80 mm. Energy consumption is due to the movement of the grid.	0.7 ÷ 1.5
Fine screening	Secondary screening from removal of fines and residual organic part after the shredding. The size of the screening can be 50 mm or less.	0.7 ÷ 1
NIR (Near Infrared Removal)	Removal of hard plastic (PVC) trough optical separation with an infrared generator.	3.3 ÷ 6.1
Third 'Rocket' shredding	Hard shredding with hammer mill. High-energy consumption and maintenance but good quality of RDF.	33.6 ÷ 62.4
Auxiliary		
Conveyor/Raising	Empirical relation for a belt length L=20m and a raising height H=2m.	6.722e-03/ 5.46e-03
Fan	It is associated to storage and air classifier.	3.8
Press	It can be included at the end of the chain or between the first and second treatment section.	1.5
Paper recycle		
Stock preparation	Screening and cutting of inlet paper	150-250
Paper making	Conveyor for magnetic separation, vibrant screening, spraying and pressing	150-300

Table 2. Balance of embodied exergy for each stream; reported values are calculated by the author basing on (Asthana and Pati, 2006; Laurijssen, 2013; Furtula *et al.*, 2017; Stanek, 2017)

Waste	$Ex_{UW_{tr}}$	0.289	MJ_{ex}/kg	$EE_{RDF} = \dot{B}_{el\_MBT} + \dot{B}_{UW} - \dot{B}_{rej} + \dot{B}_{tr_{UW}}$	(5)
Paper	$Ex_{pap_{mix}}$ Ex_{fib} $Ex_{paper_{tr}}$	19.093 18.624 0.235	MJ_{ex}/kg MJ_{ex}/kg MJ_{ex}/kg	$EE_{card_{rec}} = \dot{B}_{el_{rec}} + \dot{B}_{paper_{mix}} + \dot{B}_{steam} + \dot{B}_{water} - \dot{B}_{fib} + \dot{B}_{tr_{pap}}$	(6)
Wood	$Ex_{wood_{ch}}$ $Ex_{wood_{pr}}$	19.223 0.51	MJ_{ex}/kg MJ_{ex}/kg	$EE_{card_{wood}} = \dot{B}_{el} + \dot{B}_{wood_{pr}} + \dot{B}_{wood_{ch}} + \dot{B}_{water} - \dot{B}_{fib}$	(7)
Coal	TEC_{coal} $Ex_{coal_{tr}}$	1.12 3.1	MJ_{ex}/MJ MJ_{ex}/kg	$EE_{coal} = \Delta En_{RDF} \cdot TEC_{coal} + \dot{B}_{tr_{coal}}$	(8)

Table 3. Base case characteristics of waste composition (data declared for the metropolitan city of Torino, Italy (ATO RIFIUTI, 2015)

Material Stream	**Gravimetric composition of TUW**	**% SC_i**	**Internal repartition of SC (%)**
	%wg (w.b)	w.b.	w.b.
Paper	26.97	52.6	27.45
Plastics	17.16	50.27	16.7
OP	0.94	0	0
OM	33.8	58.4	38.2
Wood	6.13	73.46	8.7
Leather	0.26	0	0
NF Metal	1.08	27.84	0.585
Ferrous metal	1.49	20.19	0.585
Glass	6.29	56.29	6.85
Textile	3.05	15.97	0.94
OI	2.8	0	0
		% SC_{gl} 51.7	

Notes: %wg: weight percentage; w.b.: wet basis

Table 4. Ranges of evaluation parameters and ΔEE_i resulting by a linear variation of SC_{paper}

	Scenario A	**Scenario B**
	Range (min/max value)	
Exergy efficiency MBT (%)	58.3/50.9	57.8/50.9
Yield RDF (%)	40.9/29.1	40.9/29.1
Exergy RDF (kJ/kg)	19214/21817	19214/21817
ΔEE_{RDF} (kW)	+2842.8/-2843.4	+875.2/-1213.3
$\Delta EE_{card_{rec}}$ (kW)	-5668/+5669	-5668/+5669
$\Delta EE_{card_{wood}}$ (kW)	+6385/-6387	+6385/-6387
ΔEE_{coal} (kW)	-3080/+3450	+1270/-1972
$\Delta EE_{UW_{tr}}$ (kW)	+12.5/-12.5	+126.61/+61.63

Table 5. Mean values and standard deviations of evaluation parameters resulting by uncertainty analysis

	External uncertainties		**Internal uncertainties**	
	μ	*RStD (%)*	*μ*	*RStD (%)*
SC_{gl} (%)	49.5	16.3	-	-
Yield RDF (%)	39.05	13.2	-	-
RDF LHV (kJ/kg)	15415	6.14	-	-
Exergy efficiency MBT (%)	55.9	3.9	55.2	0.14
Exergy efficiency Paper recycle (%)	-	-	79.1	0.4
Embodied exergy RDF (kW)	11296	15.5	11017	0.24
Embodied exergy Cardboard (kW)	9430.5	34.5	9940.2	0.42
Unit exergy cost RDF (kW/kW)	1.062	1	1.032	0.12
Unit exergy cost Cardboard (kW/kW)	-	-	1.249	0.42
Global energy consumption MBT (kWh/Mg)	-	-	124.15	4.2
Global energy consumption Paper recycle (kWh/Mg)	-	-	424.6	7.2

Figures

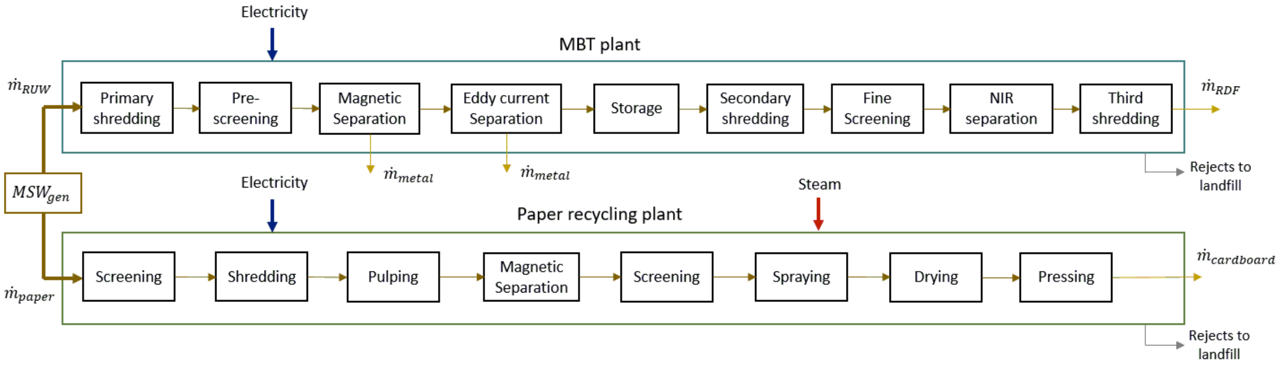

Figure 1. MSW treatment system under analysis

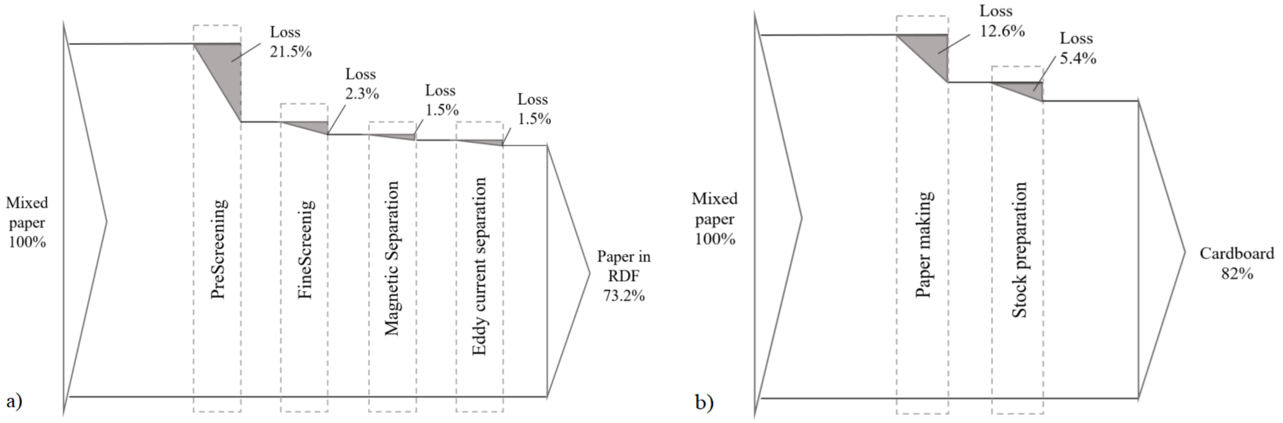

Figure 2. Grassmann diagram representing the exergy destruction due to material losses for MBT plant (a) and paper recycle (b)

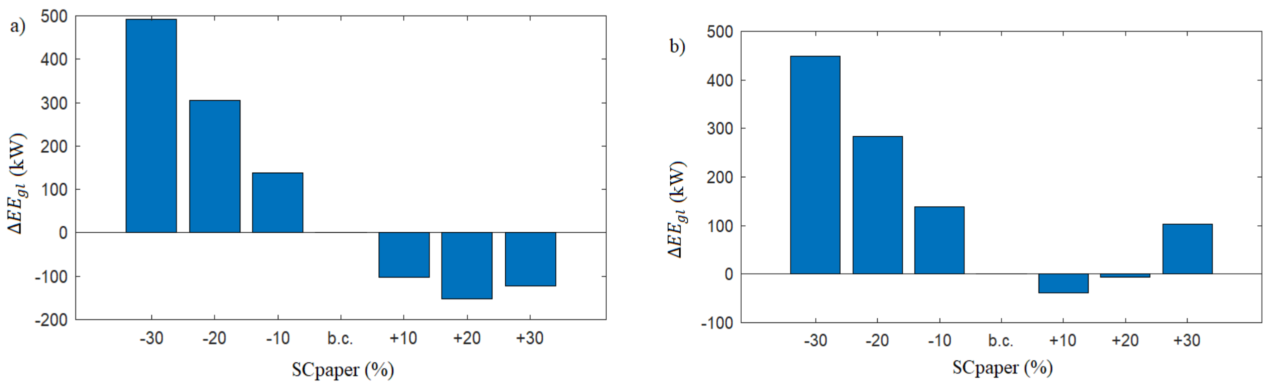

Figure 3. Difference in Global Embodied Exergy respect to the base case for the two scenarios: A) fixed $\dot{m}_{card}$; (B) fixed $\dot{m}_{RUW}$ and $\dot{m}_{card}$

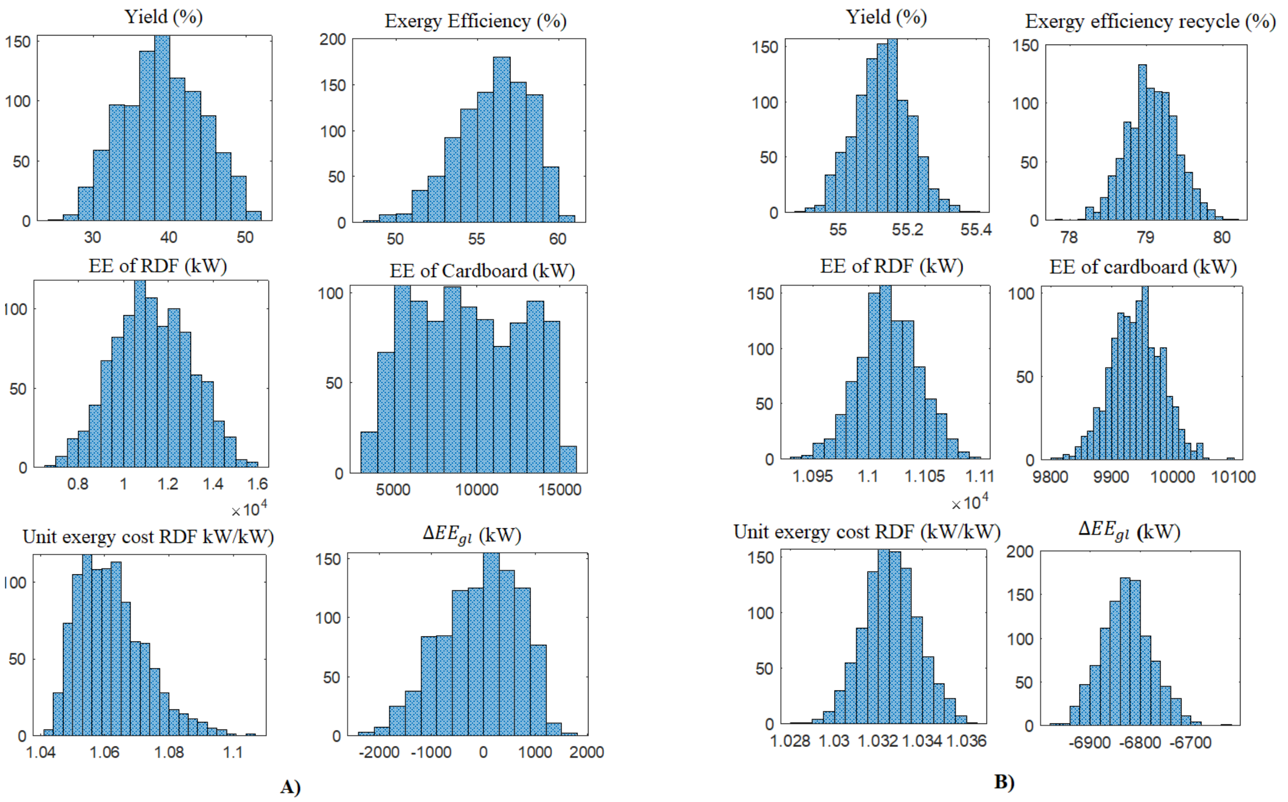

Figure 4. Distribution of values due to external (A) and internal (B) uncertainties

Appendix A

j-th component		*i-th material stream*										
		Paper	Plastic	OP	OM	Wood	Leather	NF metal	Ferrous metal	Glass	Textile	OI
Storage	Dry	1	1	1	1	1	1	1	1	1	1	1
	Moisture	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Shredder	Dry	1	1	1	1	1	1	1	1	1	1	1
	Moisture	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
Magnetic separator	Dry	0.98	0.98	0.98	0.95	0.98	0.98	1	0.2	1	0.98	0.95
	Moisture	0.98	0.98	0.98	0.95	0.98	0.98	1	0.2	1	0.98	0.95
Eddy current separator	Dry	0.98	0.98	0.98	0.98	0.98	0.98	0.1	1	1	0.98	0.98
	Moisture	0.98	0.98	0.98	0.98	0.98	0.98	0.1	1	1	0.98	0.98
Preliminary screening	Dry	0.785	0.69	0.69	0.166	0.73	0.73	0.52	0.52	0.198	0.73	0.468
	Moisture	0.785	0.69	0.69	0.166	0.73	0.73	0.52	0.52	0.198	0.73	0.468
Fine screening	Dry	0.97	0.96	0.96	0.46	0.96	0.96	0.91	0.91	0.08	0.96	0.7
	Moisture	0.97	0.96	0.96	0.46	0.96	0.96	0.91	0.91	0.08	0.96	0.7
Air classifier -shredded refuse	Dry	0.98	0.98	0.98	0.7	0.98	0.98	0.5	0.1	0.7	0.98	0.2
	Moisture	0.882	0.882	0.882	0.63	0.882	0.882	0.45	0.09	0.43	0.882	0.18
Air classifier -un-shredded refuse	Dry	0.98	0.98	0.98	0.4	0.98	0.98	0.5	0.1	0.02	0.98	0.15
	Moisture	0.882	0.882	0.882	0.36	0.882	0.882	0.45	0.09	0.018	0.882	0.135
Optical NIR	Dry	1	0.94	0.01	1	1	1	1	1	1	1	0.7
	Moisture	1	0.94	0.01	1	1	1	1	1	1	1	0.7
Pelletizer	Dry	1	1	1	1	1	1	1	1	1	1	1
	Moisture	1	1	1	1	1	1	1	1	1	1	1

RFTF table, elaborated by the author based on (Diaz, Savage and Golueke, 1982; Hryb, 2015; Grosso *et al.*, 2016)