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Material flow analysis applied to a waste treatment plant in Lombardy (Italy)

DUARTE CASTRO F.[1,*], FABBRI M.[1], VACCARI M.[1] and CUTAIA L.[2]

[1] University of Brescia, Via Branze, 43 – 25123, Brescia, Italy

[2] Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Via Anguillarese, 301, Santa Maria di Galeria, Rome, Italy

*corresponding author:
e-mail: f.castro@unibs.it

Abstract Material flow analysis (MFA) allows to quantify inputs, outputs and stocks of a system and to communicate results visually. It can be used for calculating process effectiveness, losses and for identifying critical points within a system, being useful for strategically intervening in a corporative environment. When linked with environmental indicators, actions to promote sustainable development and circular economy can be defined. In this study, a waste treatment plant located in Lombardy (Italy) was selected for a case study. An inventory analysis for three consecutive years was conducted and the MFA of the whole plant was developed. In addition, 11 environmental indicators were calculated. During the period in study, the company processed $720x10^3 \pm 4x10^3$ t of materials, including metals, inorganic materials and others (e.g., plastic, cardboard, glass). The highest recovery rates were achieved for metals (98.40 ± 6.26%). The overall percentage of materials recovered in the plant equals 78.50 ± 1.81 %. The company showed high eco-efficiency (0.78 ± 0.01), low energy intensity (0.20 ± 0.01 GJ/t/y) and relatively low water input ($4.65x10^4 \pm 8.14x10^3$ t/y). Indirect emissions due to energy consumption accounted for $5.79x10^3 \pm 2.35x10^2$ t-CO_{2eq}, which can be reduced by adopting cleaner transportation services.

Keywords: Circular economy, Eco-efficiency, Solid waste management, Recycling, Environmental indicators

1. Introduction

Since 2015, the European Union officially adopts circular economy (CE) policies on its legislative framework. The CE concept is based upon the principle of waste minimization. It is aimed at prolonging the value of materials for as long as possible, by the adoption of strategies such as the reduction of resources consumption, reuse of products, and recycling of materials (European Commission, 2018).

Indeed, recycling activities are essential to reduce waste disposal and to guarantee the reinsertion of raw materials into the economy, contributing to a reduced rate of primary resources extraction, and consequently avoiding material scarcity (EASAC, 2015). The production of secondary raw materials (SRM) through recycling also requires lower energy and water consumption, in comparison to primary raw materials extraction (EASAC, 2016a). Therefore, evaluating and improving the performance of recycling processes is fundamental to guarantee a high circularity of materials.

Within the CE framework, material flow analysis (MFA) is an important tool for the quantification of material flows from, to, and within a system, enabling the identification of losses, process efficiency, waste generation, recycling rates, and circularity of materials (EASAC, 2016b). The MFA methodology can be applied at municipal (Turner et al., 2016), regional (De Meester et al., 2019), or national (Wang et al., 2016) levels, and also for companies (Vaccari et al., 2020) and industrial areas (Sendra et al., 2007). When allied to appropriate indicators, a complete overview of the system in study is obtained, which allows to identify its strengths and weaknesses, based on reference values. Moreover, the adoption of indicators facilitates the communication of results, comparisons between systems, definition of targets to be achieved, and performance monitoring (Tanzer and Rechberger, 2019). Therefore, they are widely used in the legislative framework. For instance, the European Union (EU) relies on several indicators to track the performance of Member States, such as: waste generation, recycling rates, self-sufficiency for raw materials, among others (Moraga et al., 2019). They are a managerial and policy-making tool useful to support decision-making.

In this context, this study aimed at evaluating the performance of a waste treatment plant located in the North of Italy. A MFA of the whole plant was conducted and 11 environmental indicators were calculated, analyzed and compared to results found in the literature.

2. Plant description

The case study plant is a multi-functional platform located in Lombardy, Northern Italy. The company carries out activities of recovery, disposal and/or treatment of hazardous and non-hazardous waste, and marketing of raw materials. The company is authorized to conduct recovery (R1, R3, R4, R5, R12 R13) and disposal operations (D8, D9, D13, D14, D15), according to the European Directive 2008/98/EC on waste. Such operations include: energy recovery; recycling/reclamation of organic substances, metals and metal compounds, other inorganic materials (inert fractions, glass, etc.); mixing/grouping/exchanging waste for submission to recovery and disposal operations; storage of waste pending any of the recovery and disposal operations; bioremediation; physical-chemical treatment; repackaging prior to disposal operations. Material recycling/reclamation is performed by means of physical (e.g., comminution, sorting, electromagnetic selection, palletization, drying), physicochemical (e.g., flotation, washing, carbonation) and biological processes (e.g., biopile). In case of non-practicability or inconvenience of the planned process at the platform, final disposal or recovery is carried out at authorized third-party plants.

The company is authorized to treat 620,000 t/y of waste through the operations R3, R4, R5, R12, D8, D9, D13, and D14. It can receive 720,000 t/y of incoming waste and deposit 32,000 m^3 of waste (operations R13 and D15). Currently, the main types of processed materials are: ferrous and non-ferrous metallic materials from mechanical selection and sorting, or other metal-containing materials; inert material from recovery operations carried out on land and rocks from excavation, materials from contaminated land reclamation or waste-containing fractions; bottom ash from waste-to-energy plants; metal-containing materials from municipal waste enrichment operations, sifting, and sorting.

The aims of the treatment processes are to obtain: Secondary Raw Materials (SRM), products, and/or "end of waste" (EoW) to be commercialized; or waste, which is qualitatively more easily recoverable and/or disposed of by third parties with specific processing technologies.

3. Methods

3.1. *Data collection and material flow analysis*

The collection of information on the case study plant took place via on-site visits, direct meetings with the company staff, and analysis of official company documents. Data were collected for three consecutive years (2018, 2019, and 2020), and summarized. The following information were obtained: consumption of water, energy and chemicals; energy source; input of waste for treatment; waste destination inside the plant; output destination after treatment; distribution of input and output materials by macro categories (metals, minerals/inert materials and other); emissions. Masses of waste, products, byproducts, water, wastewater, and gaseous emissions were processed on Excel and inputted to the software Stan 2.5 (Technische Universität Wien).

The input of chemicals was available only for one year and was considered constant in the triennium. The estimated volume of collected rainwater was calculated using data from ARPA Lombardia and the draining surface area of the plant. Only the amount of precipitation exceeding 5 mm was considered in the calculation (second water). Since there are no data about rainwater consumption, a minimum and a maximum value for the total water input were considered, taking into account only the municipal water and taking into account both the municipal water and all the second water collected. Due to lack of data regarding CO_2 absorption during ashes carbonation, water evaporation and discharge of rainwater, a generic flow identified as “other” was created to represent the weight variations due to such inputs and outputs. This difference was calculated by the software by mass balance.

The indirect emissions due to energy consumption were estimated in $CO_{2\text{-eq}}$, by using the Italian energy mix (IEA, 2020), and emission factors (UN, 2021) (Eq. 1 and 2).

$$CO_{2-eq} = QxEF \qquad \text{(Eq. 1)}$$
$$EF = ECxGWP \qquad \text{(Eq. 2)}$$

Where: Q (in kilograms or liters) is the amount of fuel/gas, EC (J/kg) represents its energy content, and GWP (kg $CO_{2\text{-eq}}$/J) accounts for its global warming potential.

3.2. *Environmental indicators*

The following environmental indicators were calculated, based on Sendra et al. (2007): direct material input (DMI), total production (P), worker productivity (WP), eco-efficiency (EE), eco-inefficiency (EI), total wastes generation (TWG), material inefficiency (M-Inef), total water input (TWI), total wastewater generation (TWWG), total energy input (TEI), and eco-intensity (EI). In Table 1, each indicator is briefly described. All indicators were calculated on a yearly basis.

4. Results

The MFA for the case study plant is displayed in Figure 1. The average waste input over the three years in study was equal to $720x10^3 \pm 4x10^3$ t. It can be observed that this value is lower than the average waste/ product output ($730x10^3 \pm 21x10^3$ t), due to differences in stock from one year to the other and mass variations during waste treatment (e.g., water absorption and evaporation, CO_2 absorption, etc.). All direct emissions to air were within the limits defined by the Italian legislation.

Table 2 displays the results obtained for various environmental indicators. The DMI calculated for the plant was high, $7.28x10^5 \pm 4.02x10^3$ t, among which 99% represented the waste input and the remaining 1% were the chemicals used for waste and wastewater processing. The eco-efficiency indicator can be considered high (0.78 ± 0.01) and the material inefficiency low (0.22 ± 0.01). Most non-recovered materials consist of plastic, glass, cardboard, wood, and textiles (recovery: 21.7 ± 1.29% including energy recovery), followed by inert materials (recovery: 72.40 ± 1.10%). Metals were fully recovered (98.4 ± 6.26%). The overall percentage of materials recovered (including recycling, backfilling and energy recovery) equals 78.5 ± 1.81 %.

Table 1. Environmental indicators and calculation

Indicator
DMI: input of material to be used and/or processed (excluding water input)
P: material output, excluding waste destined for landfills or inertisation
WP: P divided by the number of workers
EE: percentage of DMI converted into product (EE = P / TMR, $0 \leq EE \leq 1$)
EI: weight of material input required to produce 1 t of product (EI = TMR / P)
TWG: total amount of wastes produced (materials which are not intended for recovery or energy production)
M-Inef: represents the fraction of unused input material, which becomes emission (M-Inef = Outputs to nature / DMI)
TWI: amount of water consumed (both from own sources and imported)
TWWG: amount of wastewater produced during waste processing
TEI: amount of energy consumed by the system
E-In: ratio between the total energy input and the total production

Table 2. Average values for the environmental indicators in study

Indicators	Average ± std deviation
DMI (t)	$7.28 \times 10^5 \pm 4.02 \times 10^3$
P (t)	$5.71 \times 10^5 \pm 7.75 \times 10^3$
WP (t/worker)	$1.85 \times 10^3 \pm 1.92 \times 10^2$
EE	0.78 ± 0.01
EI	1.27 ± 0.02
TWG (t)	$1.57 \times 10^5 \pm 9.67 \times 10^3$
TWGw (t/worker)	$5.08 \times 10^2 \pm 5.66 \times 10^1$
M-Inef	0.22 ± 0.01
TWI (m^3/y)	$4.65 \times 10^4 \pm 8.14 \times 10^3 \leq TWI \leq 8.28 \times 10^4 \pm 7.68 \times 10^3$
TWWG (m^3/y)	$3.39 \times 10^4 \pm 6.56 \times 10^2$
TEI (GJ)	$1.14 \times 10^5 \pm 5.19 \times 10^3$
TEIw (GJ/worker)	$3.70 \times 10^2 \pm 2.56 \times 10^1$
E-in (GJ/t)	0.20 ± 0.01

21.5% of the material output was sent to final disposal (e.g., incineration, landfill), against the European average of 45.4% (Eurostat, 2018). However, this value is still higher than the Italian average of 15%, which may be related to the types of waste considered in the calculation at national level (all waste) and the ones treated by the plant (mainly fractions containing metals and inert materials). The percentage of material output used as fuel or other means of energy generation was equal to 1.3%, against the Italian average of 5.7%. Meanwhile, 41.2% were sold as secondary raw materials and 36.1% were sent to reuse/recovery. The high share of recovered materials contribute to the improvement of trades in SRM, share of SRM in the demand for raw materials and may potentially help achieving the self-sufficiency in raw materials within the EU, as proposed by the European Commission in the CE action plan (CEAP). The company contributed to around 1.14% of Italian trades in SRM (or end-of-waste – EoW) within the period in study (Eurostat, 2021).

The treatment process required an annual input of $4.65 \times 10^4 \pm 8.14 \times 10^3$ t of water, 6.6×10^3 t of chemicals, and $1.14 \times 10^5 \pm 5.19 \times 10^3$ GJ of energy. Most energy consumed by the plant activities within the period in study were due to electric energy consumption (68%) for maintaining the plant activities and gas oil (31%) for waste transportation (Figure 2A). Considering the average Italian energy mix presented in Figure 2B, an annual average of indirect emissions due to energy consumption equal to $5.79 \times 10^3 \pm 2.35 \times 10^2$ t-CO_{2eq} was obtained. These emissions are partly counterbalanced by the CO_2 consumption during the carbonation process.

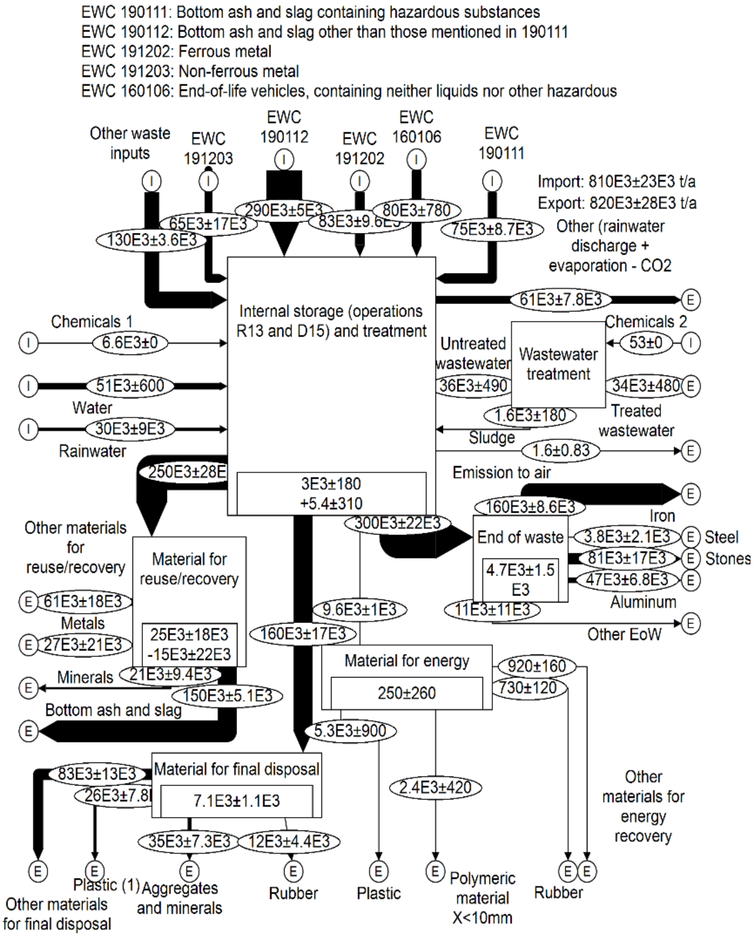

Figure 1. Material Flow Analysis of the plant: average mass values for the years of 2018, 2019 and 2020 (t/y)

The energy intensity of the plant is low, in comparison to metal extraction from ores and scrap. The extraction of Fe, Al and Cu from ores, require 20-100 GJ/t, 238-925 GJ/t and 31-2,040 GJ/t, respectively, while their extraction for scrap require 6 GJ/t, 10 GJ/t, and 14 GJ/t (EASAC, 2016a). The TEI for the case study plant represented 0.25% of the total energy consumption of the Italian province where it is located, and 0.39% of the provincial energy consumption in the industrial sector (ASR Lombardia, 2018). The maximum TWI displayed in Table 2 (equivalent to 0.08±0.01 m^3/t of product) was also low in comparison to water use for metal extraction from ores and scrap: 50-600 m^3/t Fe, 11-320 m^3/t Al, 40-200 m^3/t Cu (ores), and 12-16 m^3/t Fe, 2 m^3/t Al, 15 m^3/t Cu (scrap) (EASAC, 2016a). The usage of municipal water by the plant represents 0.028% of the total volume of water used in industry in Lombardy in 2018 (ISTAT, 2020; The European House Ambrosetti, 2018). The good performance of the company in comparison to others in terms of water consumption is related to the collection and use of rainwater and due to a water recirculation system implemented inside the plant, which allows to reduce the water input.

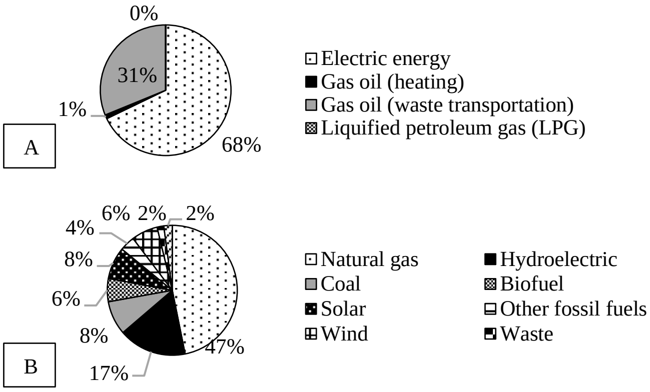

Figure 2. (A) Average energy consumption by source and (B) average Italian energy mix for the period in study (Source: IEA, 2020)

5. Conclusions

Business-oriented MFA and environmental indicators are useful for process understanding, monitoring, and comparison. They allow identifying strengths and weaknesses within the companies' activities, which can be later translated into improvement. They are also part of the EU Eco-Management and Audit Scheme (EMAS), which has been recognized in the CEAP as an important tool for improving resource efficiency and achieving CE.

The case study plant showed a satisfactory environmental performance, especially for water and energy consumption, and metal recovery. The company's activities contribute to the CE, being therefore in line with the new CEAP and the EU Green Deal, as it helps increasing the end of life recycling input rates, circular material use rate, EU self-sufficiency for raw materials, recycling rates, trades in recyclable raw materials, and resource-efficiency. A significant fuel consumption during waste transportation was identified, increasing indirect GHG emissions related to the company's activities. Thus, the adoption of cleaner transportation services could improve environmental performance. Moreover, sustainable options to improve the circularity in the lifecycle of plastic, glass, cardboard, wood, and textiles are needed.

The results found in this study can be used for process comparison with other businesses performing similar activities and adhering EMAS. This investigation will be extended in the future, in order to create a lifecycle assessment (LCA) of the plant, providing the whole picture of its current environmental performance, and allowing the plant managers to push further towards the CE goals.

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