Optimisation of material waste fluxes of a Portuguese city from a Life-Cycle Costing perspective.

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Abstract

A Life Cycle Assessment (LCA) followed by Life Cycle Costing (LCC) of municipal waste (MW) management in a residential area of the Portuguese city of Aveiro were conducted. The results showed a poor environmental performance in terms of greenhouse effect gases (GHG) emissions and lack of economic sustainability, due to the high amounts of waste landfilled, the low extent of separate collection, low performance of mechanical-biological treatment as well as absence of production of refuse-derived fuel (RDF). An alternative improved scenario was defined, where separate collection was enhanced, biogas production was increased and RDF production was introduced, in order to improve the environmental balance of GHG emissions until reaching a balanced situation between positive and negative effects, as well as improving the economic balance of the system. The proposed changes were sufficient to achieve environmental sustainability, but not for achieving economic sustainability due to the great influence of collection costs, especially for separate collection. Nevertheless, it was found that it is possible to turn MW into a more sustainable activity using an adequate combination of several treatment options and increasing the separate collection of recyclable materials.

1. Introduction

The separate collection of recyclable materials in the Portuguese city of Aveiro has not been able to grow accordingly to the targets set by legislation: only 6% of the total municipal waste (MW) generated are separately collected, and the trend in last years corresponds to a slight decrease [1], a situation analogous to the rest of Portugal [2]. A relevant consequence of this low extent of source-separation is the excessive presence of heterogeneous materials within residual MW which are difficult to separate. thus resulting in most part of them being finally landfilled.

The Life Cycle Assessment (LCA) methodology, followed by an economic assessment based on Life Cycle Costing (LCC) technique, were applied in this present work to analyse MW management in a particular residential neighbourhood in the city of Aveiro. LCA has been useful to demonstrate that increasing recovery of waste materials brings decisive environmental benefits, if compared to other treatment options [3–5]. Several authors tested the performance of given MSW management systems comparing scenarios which assumed different levels of source separation, including separate collection of biowaste [6, 7]. The results showed that an increased recovery of recyclable materials brings environmental benefits as a consequence. However, as pointed by Rigamonti et al. [8], a limitation would be the likely loss of quality in recyclable materials due to higher contamination: in their study, this effect would render separate collection ineffective beyond a 50% level. Moreover, the economic and social implications of the distribution of waste in its different fluxes have not been yet widely studied [9]. While Tulokhonova and Ulanova [10] concluded in their study that landfilling was the MW treatment option with lower costs, Tan et al. [11] concluded that valorisation processes of MW can be economically profitable, contrary to landfilling. Similarly, Mirdar Harijani et al. [12] associated the economic sustainability with the environmental one. Fernández González et al. [13] pointed to energy recovery from residual MW as an economically attractive option, a result coincident with Massaruto et al. [14]; however, this study differs in methodology, since the authors also considered assigning monetary values to reflect the adverse health consequences of air pollution and disamenities, overlapping environmental and economic assessments.

The current trend in Portugal, encouraged by environmental authorities, is to impose financial balance of MW management adapting MW fees to cover all expenses not being already recovered. However, this approach alone does not take into account the efficiency of MW management, resulting in citizens financing inefficient management systems: i.e., those which do not recover valuable resources from waste. It is expected that this work will contribute to illustrate the concept of true economic sustainability and the feasibility for the current MW management systems to achieve it.

2. Methodology

2.1. Goal and scope

The goal of the study is to assess the environmental and economic balance of MW management in the designated area, considering both mixed MW and separately collected MW streams. The functional unit selected for the assessment corresponds to the annual MW amount generated within the area: 449 t of mixed MW, 28 t of paper and cardboard, 20 t of plastic and metal packaging and 6 t of glass. The year 2017 was established as temporal reference for all data.

2.2. Life Cycle Inventory

The system encompassing all the analysed activities (unit processes) is shown in Figure 1, in form of a flow diagram where solid arrows represent waste fluxes, dashed arrows represent primary resources replaced by resources recovered from waste and a dotted arrow represents waste outputs in form of gaseous emissions: mainly carbon dioxide, methane and water resulting from biologic degradation.

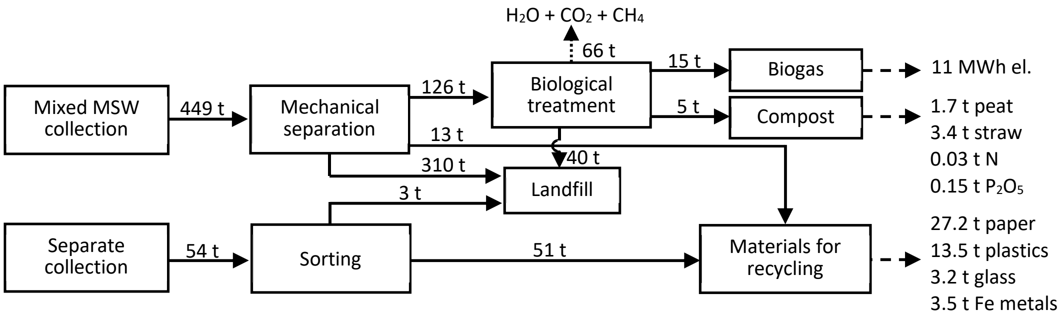

Figure 1. Representation of the analysed system

As seen in Figure 1, several products are obtained as outcomes from the system. Accordingly, the system expansion procedure commonly used in LCA to assess multifunctional systems was applied to include the environmental benefits derived from the substitution of primary resources by the secondary products obtained. For the actual performing of the system expansion procedure, it was decided to follow the approach suggested by Bala Gala et al. [15]. For the credits derived from biogas utilisation in electric generators, a 1:1 substitution for an equivalent Portuguese electricity average production was applied.

Information required for the modelling of the unit processes featured in Figure 1 was gathered firstly from directly involved sources: Aveiro municipality provided data for mixed MW collection – including fuel consumption and details on street containers and collection vehicles (Fernández-Braña et al., in prep.). The responsible MW management company for the treatment processes). For fuel consumption of separate collection, the approach proposed by Moreira Monteiro [16], based on a specific study for the city of Aveiro, was deemed as a reasonable estimation.

The Mechanical Biological Treatment (MBT) facility where MW from Aveiro city are treated was modelled combining the waste composition previously obtained with the mass balances annually declared by the managing company [1]. Composition of biogas was calculated following the same approach as in ecoinvent 3.3® database for the case of biogas obtained from biowaste, but complemented with own composition measurements of the digested matter. Methane emissions were considered as for the worst cases in Dinkel et al. [17] and emissions from combusted biogas were adapted from Nielsen et al. [18]. The electric generation efficiency was set at 40%. For compost use on land, it was chosen to follow the approach of Hermann et al. [19]. Substitution capacity regarding fertiliser potential was set as in Boldrin et al. [20]. Other data concerning utilities, consumable goods and buildings was obtained through personal communication or adapted from other facilities.

2.3. Costs and revenues inventory

In parallel to the development of the life-cycle inventory, the costs and revenues related to the main activities comprised by MW management were extrapolated to the scale of the analysed neighbourhood and grouped together in an analogous inventory, shown in Table 1:

Table 1. Costs and revenues inventory

Costs			**Revenues**		
Expenses	Unitary cost	Total	Incomes (sales)	Unitary price	Total
Municipal administrative staff	3 €/t	1300€	Beverage cardboard	564 €/t	1289€
Mixed MW collection	46 €/t	20862€	Glass	36 €/t	207€
Gate fee for mixed MW	27 €/t	12256€	Paper/cardboard	173 €/t	4890€
Separate MW collection & sorting	225 €/t	12192€	Fe metals (from mixed MW)	131 €/t	564€
Landfill tax	5 €/t	2421€	Fe metals (from separate MW)	649 €/t	1752€
			Non-Fe metals (from mixed MW)	180 €/t	59€
			Non-Fe metals (from separate MW)	761 €/t	184€
			Plastics (from mixed MW)	136 €/t	1080€
			Plastics (from separate MW)	545 €/t	6377€
			Compost	10 €/t	51€
			Electricity production	115 €/MWh	1292€
TOTAL COSTS		**49031€**	**TOTAL REVENUES**		**17744€**

3. Results

3.1. Environmental assessment

The environmental variable chosen to present the environmental impact assessment of the studied system was the contribution to climate change through GHG emissions (CO_2 eq.). The impact assessment method for evaluating this category was the 2013 IPCC characterisation methodology for a 100-year period (version 1.02). The environmental impact assessment was performed using the commercial software SimaPro (version 8.2.0.). The corresponding results are shown in Figure 2:

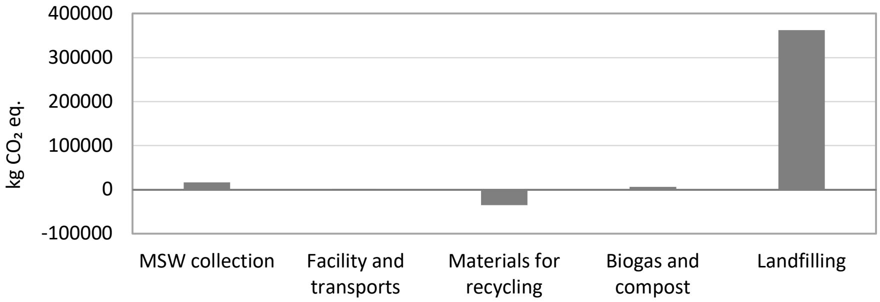

Figure 2. Contribution of current MW management to climate change (emissions of CO_2 eq.)

The global GHG emissions amounted to 351,936 kg CO_2 eq., assigned to the functional unit. This result confirms the low environmental performance of current MW management within the selected Aveiro neighbourhood, due to the considerable amount of landfilled waste resulting in a high environmental impact.

In view of this situation, taking the scenario of Figure 2 as a baseline, without modifying the actual treatment options, it was decided to test to which extent would be required to improve the performance of the system – in terms of separately collected materials for recycling and energy recovery trough production of biogas and refuse-derived fuel (RDF) –, in order to turn the initial environmental prejudice caused by MW management activities into a positive outcome. In the resulting alternative scenario generated (Figure 3), this condition was attained when all materials suitable for recycling were sent to the respective separate collection schemes, along with proper valorisation of the refuse in form of refuse-derived fuel (RDF). Firstly, it was considered that the separate collection of MSW on the studied area increased from the previous 12% until 33%. If the waste composition initially considered is not altered, this would be the highest possible separation level without introducing a separate collection of biowaste, and is typical in cases of successful application of incentives for source separation. Consequently, as an undesired side effect, contamination of separate collection fluxes was increased until 30% for plastic and metal packaging, 10% for paper and cardboard and 5% for glass, typical reported values in Portugal. Nonetheless, the recovery of non-recyclable materials as RDF was introduced as a secondary valorisation option – although not currently usual in Portugal due to low price RDF concurrence from foreign countries, namely UK. The calorific power of RDF was set at 12 MJ/kg, and natural gas was chosen as replaced fuel. Finally, production of biogas and application of compost were maximised – corresponding to a higher quality of the substrate waste used: 242 t of biowaste were assigned to biologic treatment (instead of 126 t in Figure 1), producing 30 t of biogas with a typical 65% of CH_4 in volume and 115 t of compost, of which 73 t are used on agricultural application and the rest is used in the sanitary landfill. However, great uncertainty exists on quantification of fugitive methane emissions during composting, which, depending on their extent, might partially mitigate the positive effect of substituting fossil fuels for energy production.

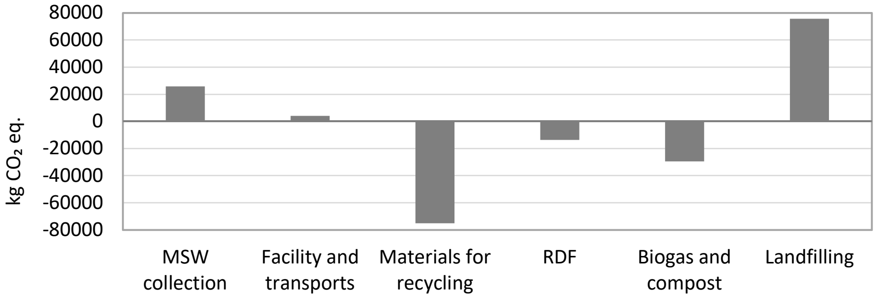

Figure 3. Climate change contribution of improved MW management scenario

In this alternative scenario GHG emissions showed a negative value: -12642 kg CO_2 eq., meaning a positive environmental outcome, since GHG emissions are avoided. All major sources of impact in Figure 3 progressed in a more environmentally beneficial direction: less landfilling, more recycling and other valorisation. The exception are the emissions of collection, now higher due to the increased separate collection effort.

3.2. Economic assessment

The aggregation of the monetary inputs and outputs listed in Table 1 results in a negative economic balance: -31287 €, for the functional unit considered. That means: revenues derived from MW in form of recovered resources are not enough to compensate the necessary expenses for MW management activities, thus resulting in a net cost. This gap in the recovery of expenses is actually borne by the citizens, through the MW management fee. In analogous manner to the environmental analysis made in the previous section, an equivalent question arose concerning the feasibility for MW management in the studied area to become economically sustainable. The alternative improved scenario defined in Section 3.1 was transformed into monetary equivalence, using the same unitary values previously applied in Section 2.3 for the baseline scenario. The price for RDF, introduced as a new valorisation option, was set as 10 €/tonne as typical price – although this is highly dependent on the calorific power and the market fluctuations. The resulting balance equals -17659 €. The value is again negative, although the gap between expenses and revenues has been reduced in more than 40%.

4. Discussion and Conclusions

The result allows understanding the different influence of the system elements, depending on the analysed perspective: the driving factors in environmental performance are different from those governing the economic outcome. For instance: collection of mixed and separated MW accounts for more than half of the total costs, with labour costs being the largest expense – as shown by Sousa et al. [21]. On the contrary, collection has only a slight influence on GHG emissions, contributing to less than 5% of total. On the other hand, the recovery of recyclable materials is the main source of income, as well as the most positive process regarding GHG emissions outcome. But this recovery alone is not enough to overcome the negative gap. Other valorisation activities, such as the electricity generation derived from biogas, compost and RDF production, also contribute to avoid landfilling of MW and reduce the consumption of primary materials. Even if these secondary processes – except electricity generation – are not so profitable in economic terms, they are necessary in order to close life-cycle loops of products in the best available way – e.g. biowaste – or, at least, mitigate its effects – the case of RDF.

Moreover, it has to be noticed that collection costs were kept constant when calculating the economic assessment of the alternative scenario. This assumption would be strictly valid only if the collection scheme was already working in a fully optimised manner, therefore making scale economy not applicable to the case. While this assumption may hold for the mixed MW collection, it is less probable for separate collection, as shown by the much higher costs presented in Table 1. It is to some extent reasonable to expect that costs associated to separate collection and sorting of recyclable materials might be lower if source separation is increased, thus improving the economic performance of the system, and even reaching complete economic sustainability. In terms of life-cycle assessment, this would require a further analysis performed from a consequential perspective, suitable for a future study. The same consideration would be expected for the performance of the MBT facility: less presence of materials other than biowaste would contribute to a better separation of the biowaste and hence, the biogas production yield may be increased.

It can be concluded that it is technically viable to achieve sustainability of MW management even in complex situations like the one analysed in this work. Notwithstanding, an optimal result would be only obtained through a careful combination of all the available options to reach this goal.

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