Analysis of the environmental performance of life-cycle building waste management strategies in tertiary buildings

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ABSTRACT

At urban level, the generation Municipal Solid Waste and Construction and Demolition Waste is mostly related to the life-cycle of buildings. An evaluation method based on Life Cycle Assessment methodology is presented in this paper to make an analysis of the environmental performance of different life-cycle building waste management strategies in tertiary buildings. As a case study, several waste management strategies considering a tertiary building located in the city of Zaragoza in Spain, are studied. The aim of the case study is to compare the environmental impacts, in terms of Global Warming Potential, of the scenarios proposed focusing on the waste minimisation and avoidance of landfilling of at least 10% for the Municipal Solid Waste generation during a building´s use stage, and Construction and Demolition Waste generated during its construction and end-of-life. In case of Municipal Solid Waste, the results show that when a recovery scenario includes energy recovery from the residual fraction of the mechanical-biological treatment plant in the form of Refuse Derived Fuel, greater benefits in terms of the Global Warming Potential are obtained than with current scenarios of landfill deposition of the residual fraction. On the other hand, in case of Construction and Demolition Waste, a similar situation can be observed in case of an increase of the recovery rates of metals.

KEYWORDS

Municipal solid waste, construction and demolition waste, life cycle assessment, eco-efficiency, industrial ecology

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NOMENCLATURE

i. Variables

Ea – CO_2-eq emissions avoided, [t]

Eg – CO_2-eq emissions generated, [t]

ii. Greek Symbols

β – difference between generated and avoided CO_2-eq emissions, [t]

iii. Subscripts and Superscripts

Subscripts

i – MSW and CDW management system

j – scenario for MSW and CDW treatment and recovery methods

x – subsystem or activity within the MSW management system i

y – MSW treatment and recovery method considered in scenario j

iv. Acronyms

CDW – Construction and Demolition Waste

EPD – Environmental Product Declaration

LCA – Life Cycle Assessment

GHG – Greenhouse Gas

GWP – Global Warming Potential

LCI – Life Cycle Inventory

MBT – Mechanical-biological treatment

MSW – Municipal Solid Waste

RDF – Refuse Derived Fuel

SRF – Solid Recovered Fuel

tCO_2-eq – tonnes of CO_2 equivalent

HHV – Higher Heating Value

LHV – Lower Heating Value

tkm – tonnes perkilometre

1. INTRODUCTION

Over the last years, in Europe, waste management is becoming increasingly complex due the growing generation of different waste streams that need tailored management systems, e.g., Municipal Solid Waste (MSW) and Construction and Demolition Waste (CDW). On the one hand, MSW consists of all waste generated in urban and municipal environments (Kreith, 1994). In 2010, more than 250 million tonnes of MSW were generated in the EU-27 countries (Eurostat Data Centre on Waste, 2012). On the other hand, CDW arises from the construction and total of partial demolition of buildings and civil infrastructure. Currently, CDW accounts for approximately 25% - 30% of all waste generated in the EU (European Commission, 2014).

At urban level, the generation MSW and CDW is mostly related to the life-cycle of buildings. In these sense, several waste management strategies have been developed in order to an efficient use of the resources following the European legislation, mainly the Waste Framework Directive 2008/98/EC (European Parliament, 2008). Regarding MSW, from the point of view of the waste management hierarchy included in this Directive and when facing scarce alternatives for reuse, recycling and material supplies; energy recovery from the residual fraction of MSW after mechanical-biological treatment (MBT) plants becomes an option to be considered in lieu a landfill (Zambrana Vasquez et al., 2012). During the last decade, MBT plants in European countries have been the subject of active research because they represent important technological alternatives in MSW management. This active research was focused mainly on (i) the literature review of models and tools in waste management practices at EU level, considering different systems engineering models to solid waste management system analysis (Pires et al., 2011); (ii) mass balance research, e.g a mass balance divided in three steps (mechanical operations, biological operations and whole process) (De Araújo Morais et al., 2008) and waste fractions characterization, mass and biogas emissions reduction and biostability of the organic fraction from the mechanical–biological treatment plant in Mende, France (Bayard et al., 2010); (iii) different analysis of the organic fraction and its implications in the management efficiency, e.g., the assessment of the potential end uses and sustainable markets for organic residue from MBT (Farrell and Jones, 2009), the analysis of the improper materials in the composting process in 10 different MBT plants in Castilla y León, Spain (Montejo et al., 2010), several alternatives for organic waste management in Umbria region in Italy (Buratti et al., 2015) and the assessment of biological processes and sample analysis in different Austrian MBT plants (Tintner et al., 2010); (iv) the assessment of the implementation of new technologies, e.g., the experiment of low-cost MBT without material splitting for size reduced MSW as possible and suitable scenario in France (Lornage et al., 2007); (v) the energy recovery and production of alternative fuels, e.g., the determination of the main energy properties of MSW and Refuse Derived Fuel (RDF) for energy recovery (Montejo et al., 2011) and the assessment of biodrying technology as variation of aerobic decomposition for the production a high quality solid recovered fuel (SRF) in MBT plants (Velis et al., 2009); and (vi) the environmental assessment through the application of Life Cycle Assessment (LCA) methodology to the operation of the MBT plant of Ano Liossia in Attica, Greece (Abeliotis et al., 2012) and Zaragoza´s MBT plant (Zambrana Vasquez et al., 2012), as cases studies.

On the other hand, CDW has been identified over last years as a priority waste stream by the European Union due its high potential for recycling and reuse. According to the report "Management of CDW in the EU - requirements resulting from the Waste Framework Directive and assessment of the situation in the medium term" conducted on behalf of the European Commission (European Commission (DG ENV), 2011), the level of recycling and re-use of CDW varies from less than 10% and over 90%. Additionally, from the Waste

Framework Directive 2008/98/EC, the art. 11.2 stipulates that the Member States shall take the necessary measures designed to achieve that by 2020 a minimum of 70% (by weight) of non-hazardous CDW shall be prepared for re-use, recycled or other material recovery (including backfilling operations using waste to substitute other materials) (European Parliament, 2008). In this sense, several strategies have been developed around the European countries following this target objective supported by different waste management systems and technologies for separation and recovery of CDW (European Commission (DG ENV), 2011). These strategies are also studied by (Pacheco-Torgal, 2013) which introduces an overview of the recycling of CDW, under the aforementioned recycling target for 2020, and (Hiete, 2013) which makes an analysis of the technologies in waste management plants for CDW fractions, changes in CDW supply in terms of quality and quantity and the demand of recycled aggregate materials. Also, against the CDW recycling target for 2020, (Dahlbo et al., 2015) have focused their research on the combination of material flow analysis (MFA), LCA and environmental life cycle costing (ELCC) for the assessment of the performance CDW management system in Finland.

In this context, accurate assessment of the environmental implications of material and energy recovery from the residual fraction refused by MBT plants and from the CDW, which is landfilled, is essential in planning and promoting waste management methods at urban level. Such assessment would help to reduce the environmental impacts of waste management strategies, lower the consumption of energy resources, ensure safe and environmentally sound waste disposal, and reduce associated economic costs.

According the roadmap to a Resource Efficient Europe[1], there is a challenge to improve the environmental performance of the current waste management strategies from a Life Cycle Thinking approach, and considering the recent published Life cycle indicators by the Joint Research Centre (JRC) (Manfredi and Goralczyk, 2013). Thus, the life cycle thinking can aid decision-making in the selection of the best available technologies to minimise the environmental impact of building waste management strategies through their entire life cycle. Appropriate design and construction can reduce the environmental impact of buildings over their entire life cycle (Polster et al., 1996). Also, decisions during these stages are connected with the generation of MSW and CDW, including their management. Ekanayake, L.L. and G. Ofori (2004) (Ekanayake and Ofori, 2004) have demonstrated that the design phase of a building has a major influence on waste generation.

Several studies in the literature have focused on different aspects of the environmental impact generated at different stages of MSW management. From these studies, several discuss the application of LCA to the assessment of different waste management models considering all stages from an integrated waste management system (collection, transport, handling, treatment, material/energy recovery and disposal), e.g., Gentil et al. (2010) have reviewed eight waste LCA models in order to analyse their technical assumptions and methodologies (Gentil et al., 2010); Bovea et al. (2010) analyse 24 scenarios of the of the waste management life cycle, including the pre-collection, pre-treatment, treatment and disposal in a landfill with/without energy recovery from an environmental point of view (Bovea et al., 2010); also,

[1] EC – European Commission, Roadmap to a resource efficient Europe. COM, vol. 571 Final (2011) Available online at http://ec.europa.eu/environment/resource_efficiency/pdf/com2011_571.pdf

Zhao et al. (2009) have focused on the application of LCA to the analysis of alternative scenarios of MSW management in Tianjin, China, with regard to GHG emissions considering the whole management system (Zhao et al., 2009). Other studies discuss the analysis of specific stages, e.g., Eisted et al. (2009) have studied the energy consumption and greenhouse gas (GHG) emissions of six examples of management systems considering only the collection, transfer and transport of waste (Eisted et al., 2009); also, Teerioja et al. (2012) have focused on the analysis of collection and transport stages by the analysis of an hypothetical stationary pneumatic waste collection system vs. a vehicle-operated door to door collection system in an existing urban area (Teerioja et al., 2012). Additionally, some studies have focused on MSW treatment facilities, e.g., Abeliotis et al. (2012) have studied the environmental assessment of the operation of an MBT plant in Ano Liossia, Greece, as preferred stage in lieu to landfilling (Abeliotis et al., 2012); Erses Yay (2015) analyses the MSW management system with the integration of a Material Recovery Facility (MRF) plus composting, incineration and landfilling in Sakarya, Turkey (Erses Yay, 2015); and Papageorgiou et al. (2009) have focused on the environmental analysis of three technologies for energy recovery (mass burn incineration, MBT via bio-drying and mechanical heat treatment plants) from MSW in England (Papageorgiou et al., 2009).

On the other hand, regarding CDW, some papers have focused their research on the analysis of the environmental impacts related to material recovery from CDW from a LCA approach in a residential building (Blengini, 2009); the recycling of CDW as masonry waste, considering the feasibility of replacement of natural sand by the recycled sand from masonry waste in the production of mortar (Ledesma et al., 2015); and material recovery and final disposal of CDW with the identification of transport, sorting and disposal as main contributors to the overall environmental impacts in the CDW management systems (Mercante et al., 2012). Additionally, (Russell-Smith and Lepech, 2015) combines LCA and target value design through sustainable target value methodology to produce more sustainable buildings.

Although these publications represent specific case studies that address the methods and stages of MSW and CDW management, the estimates reported vary considerably, indicating the need for further research. Additionally, no relevant studies in the literature were found that focused specifically on the application of an evaluation method, which uses LCA methodology, to determine the environmental implications of different life-cycle building waste management strategies. Thus, a methodology for evaluation, based on LCA, is presented in this paper in order to make a compressive comparison analysis of the environmental performance of different life-cycle building waste management strategies, considering the MSW generation during a building´s use stage, and CDW generated during its construction and end-of-life.

As a case study, this paper analyse different waste management scenarios for a tertiary building located in the city of Zaragoza in Spain. Several variables are considered, such as the amount and type of waste generated, the degree of source separation, the collection system used and the possible material/energy recovery treatments within an integrated waste management system. Finally, a proper discussion of the results and potentials to reduce the environmental impacts of the selected waste management systems with the better environmental performance is included.

2. METHODS

The evaluation method proposed is based on the method described by Aranda Uson et al. (2012). This methodology has been also adapted for the environmental-benefit analysis of two urban waste collection systems of MSW (a system based on traditional truck transportation and manual collection, and a stationary vacuum waste collection system) (Aranda Usón et al., 2013), and the study of the environmental implications of the valorisations of the residual fraction refused by MBT plants for MSW (Zambrana Vasquez et al., 2012).

Equations 1-3 and Table 1 summarise the methodology used in this paper in terms of CO_2 eq emissions, which corresponds to the impact category of global warming potential (GWP). This methodology can be replicated also in terms of other impact categories such as acidification (SO_2 eq) or eutrophication (PO_4 eq), among others. Table 1 presents a matrix for general analysis.

The matrix of Table 1 represents the relationship of MSW and CDW management systems and recovery scenarios. This relationship can be expressed in terms of the difference between the amount of CO_2-eq emissions generated by an MSW/CDW management system *i* and the amount of CO_2-eq emissions avoided in a recovery scenario *j*. The elements of the matrix that are presented in Table 1, β_{ij} are calculated following Equations 1-3:

$$\beta_{ij} = E_{g_i} - E_{a_j} \qquad (1)$$

$$E_{g_i} = \sum_{x=1}^{x=n} E_{g_x} \qquad (2)$$

$$E_{a_j} = \sum_{y=1}^{y=m} E_{a_y} \qquad (3)$$

where E_{gx} represents the CO_2-eq emissions generated by *n* subsystems of the *i-th* MSW/CDW management system and E_{ay} represents the CO_2-eq emissions avoided by *m* valorisation methods considered by the recovery stage *j*. The matrix elements β_{ij} may have positive or negative values. If the values are positive, the emissions generated are greater than the emissions avoided in each particular scenario. If the values of the matrix elements are negative or zero, the emissions avoided are greater than or equal to the emissions generated.

Note that a lower negative value in the matrix indicates a higher net profit in terms of CO_2-eq emissions.

The amount of CO_2-eq emissions generated (E_{gi}) includes CO_2-eq emissions caused by the collection system, the transportation of the residual waste from MSW and CDW from collection points to the central collection station and from there to the corresponding treatment plants. It considers also the CO_2-eq emissions due to the operation of these last and the CO_2-eq emissions associated with the processing operations in the material and energy recovery plants and the final disposal methods.

To estimate the CO_2-eq emissions avoided for a variety of recovery methods considered (E_{aj}), it is necessary to quantify the amount of each fraction recovered in the treatment plant with respect to material and energy recovery. In case of the MBT plant for MSW management, the residual fraction comprises the various rejected fractions from the mechanical processes. A similar case occurs in case of a mechanical treatment facility for CDW management. One way of characterising this fraction and evaluating the performance of the plant is by mass balance analysis. The methodology used in this paper to conduct mass balance analysis properly is described in the study of Aranda Usón, A. et al. (2012) (Aranda Usón et al., 2012).

2.1. LCA

The LCA methodology has been used to evaluate the environmental impacts of each of the stages under consideration. This provides a structured analysis of inputs and outputs at each stage of the life cycle of products and services (Tukker, 2000). ISO 14040:2006 (International Organisation for Standardisation, 2006) prescribes the clear definition of the goal and scope of all LCA studies including the system boundary, the functional unit and the inventory analysis within the system boundary. Additionally, it considers the life cycle inventory analysis and impact assessment followed by the interpretation of the results.

2.1.1. Functional unit

In this case, the functional unit is 1 tonne of waste, MSW and CDW, generated, collected and treated during the building construction, use stage and end-of-life.

2.1.2. Target building and quality data

A tertiary building called "CIRCE II" (useful surface of 2365,63 m^2), located in the city of Zaragoza in Spain, is considered as a case study. The type of use of the building corresponds to an office/tertiary/research centre building. The number of inhabitants was estimated as 155 people, with an occupancy rate of 100% during the period from September to June, and during the summer season: 70% and 40%, corresponding to July and August, respectively. The construction of this building is developed on the framework of the NEED4B project "New Energy Efficient Demonstration for Buildings" financed by the European Union through the Seventh Framework Programme (FP7/2007-2013). The design and construction of CIRCE II is on developing following different innovative methodologies, including the LCA methodology based on the CEN/TC 350 standard, EN 15643-2 (AENOR, 2011). Table 2 presents the life cycle stages of the building based on the CEN/TC 350 standard, EN 15643-2.

From the four stages proposed by the CEN/TC 350 standard, EN 15643-2 (product, construction process, use, and end-of-life stage), the studied waste management systems in this paper considers the MSW generated during the use stage of the building and the CDW generated at its construction and deconstruction-demolition stages. Note that for the study of the MSW and CDW generation, the production stage of the building is also considered. In order to characterise the different fractions of the CDW generated, a proper inventory analysis of the different materials for the product stage was made. In this sense, for its corresponding modules (raw materials supply, transport and manufacturing), the final project building data, related to the amount of materials required for the construction of the building, was considered. Also, the Ecoinvent v2.0 database and the available environmental product declarations (EPD), were used for the elaboration of the product stage inventory. Thus, for a proper analysis of the MSW and CDW generation of the CIRCE II building, the fourth stages of its LCA were studied.

Following the aforementioned stages, Table 3 presents the amount of construction (demolished and wreckage) and packaging waste (e.g. wood, plastics and paper/cardboard), composed mainly by concrete (67%), light clay brick (11%), sand and gravel (9%), steel, (5%), wood (4%), and mixed construction waste (4%); generated during the construction process stage. A total constructed surface area of 2711,8 m^2 has been considered. An estimated average values of 120 kg/m^2 and 3,6 kg/m^2 for construction and packaging waste, respectively, is assumed. Also, it has been taken into account the generation ratios of construction site waste presented by Zabalza et al. (2013).

On the other hand, Table 4 presents an estimation of the MSW generated per day of general fractions: paper/cardboard, plastic (including plastic packaging), organic waste, glass (mainly bottles), CD/DVD, batteries (Hazardous Waste), printer/toner cartridges, metals (including aluminium and ferrous packaging), wood, textile and others. The reference for the estimation of MSW generation was the CIRCE I building, which is a similar type of building of CIRCE II building, with an actual occupation of 93 inhabitants. The characterisation of each fraction was developed based on the methodology presented by Aranda Usón et al. (2012), for the characterization of MSW. Following this methodology several samples were manually segregated on-site into different physical components. The most representative, in terms of weight, was paper/cardboard, plastic (including plastic packaging), organic waste and glass, among the other fractions presented in Table 4. Each of these materials was weighed to determine its fraction and daily generation rate in the total solid waste sample collected. The remaining material, called “others”, was a uniform mixture of, e.g., organic material, light packaging (including tetrabrick) and mixed waste.

Finally, within the end-of-life stage of the building, the processes of deconstruction of all materials and the energy equipment used throughout the building´s service life were considered. Table 5 presents an estimation of the total waste generated grouped in general fractions. The amount of the demolition waste was estimated considering the inventory data of the building in the construction stage (construction-installation on-site processes) and the use stage (replacement and refurbishment).

2.1.3. System Description

Three main stages of the waste management systems studied are considered: (i) management of the upstream waste flows of the treatment plants by means of a collection and transportation system for the residual household waste of MSW and CDW; (ii) the treatment plants itself, e.g., MBT plant for MSW and mechanical treatment plant for CDW; and (iii) alternatives for material and energy recovery from the residual fractions from these plants.

Regarding the MSW and CDW management system, the local government follows a mandatory waste recycling program, called Integrated Waste Management Plan of Aragón

(G.I.R.A.) for 2009-2015(Gobierno de Aragón, 2009), that establishes, in case of MSW, a selective collection of residual household waste (mixed waste including organic waste), cardboard/paper, light packaging (e.g. plastic, tetra brick, ferrous and non-ferrous) and glass; using additional complementary systems such as door-to-door collection for large waste production centres and clean points. In case of the CIRCE II building location, an additional selective collection system for batteries and printer/toner cartridges is used. The MSW management system has been described by Aranda Usón et al. (2013) and (Zambrana-Vasquez et al., 2013) in the comparison analysis of two different collection and transport systems for residual household waste in the Ecocity Valdespartera which is located within the study area of the CIRCE II building.

MSW collection and transport system uses surface containers made of high-density materials and located in public places for the residual household waste of MSW (including organic waste), glass, light packaging, and paper/cardboard. A side-loading collection truck collects the fractions from surface following a weekly schedule and considering the daily generation of MSW. The diesel consumption associated with collection depends primarily on the amount and volume of waste transported the storage capacity of the containers, the route and frequency of collection, and the energy required for compaction of waste in the vehicle. Also, a MBT plant for MSW is considered in the system. This plant has been described and studied by Aranda Usón, A. et al. (2012) (Aranda Usón et al., 2012) and Zambrana Vasquez, D. et al. (2012) (Zambrana Vasquez et al., 2012). The Zaragoza´s MBT receives the MSW from the selective collection of 62 municipalities spread across four regions of the region of Aragon in Spain. The target building is located within the study area described in the city of Zaragoza.

For the CDW, the conceptual model of the management system is presented by Solís-Guzmán, J. et al. (2009) at Spanish level (Solís-Guzmán et al., 2009). Based in this model, the corresponding CDW for the target building includes a mechanical treatment plant for mixed inert non-hazardous waste, e.g., concrete, ceramic materials, earth and stones and mixed construction waste, were all material is crushed and recovered in different granular sizes. Currently, the main uses of the fractions obtained are rural tracks, quarry restoration and land refills. These plants are located near non-operational quarries with the aim to use the residual materials to restore the plant site. Figure 1 presents the stages involved in the CDW management system studied. This system is based on the National Decree 105/2008, which regulates the production and management of CDW (Spanish Government – Ministry of the Presidency, 2008).

2.1.4. Boundaries of the system

Within the boundaries of the MSW and CDW management systems under study, attention was paid to the activities of the collection and transportation system for the residual household waste of MSW and CDW, to the operation of the MBT plant and the mechanical treatment plant for CDW, and to different scenarios of material/energy recovery of the outflows. Specifically, the following system boundaries were selected:

- Components weighing more than 1% of the final weight of the product are considered.
- Components representing less than 1% of the total economic value of the product are not considered.
- The sum of the excluded flows that enter or leave each of the modules of the life cycle not exceed 5% of the total materials used in the Life Cycle Inventory (LCI).
- No stages that contribute less than 1% of the inventory analysis or less than 1% of the total environmental impact are considered.

The boundaries of the analysed systems (processes, manufacturing, waste transportation and processing, and the inputs and outputs considered) are as follows:

- Second-order boundaries are defined considering the stages of production and the production of energy and raw materials for each component.
- Third-order boundaries are defined considering the infrastructure and the production of the materials required for their implementation. Stages defined beyond these limits include the manufacture of the machinery for construction and installations purposes, and its corresponding transport. Also, this study did not take into account personnel.

2.1.5. LCI

The LCI of the construction process stage includes the electricity and fuel consumption due machinery use for the construction processes and transport of the construction and packaging waste generated. Based on data from the European project CICLOPE[2], the electricity and diesel consumption of 24,23 MJ/m^2 and 23,40 MJ/m^2 are considered. Additionally, a transportation distance of 22,4 km between CIRCE II building and classification plant for the construction and packaging waste is considered. Similar to demolition waste management, a collection truck lorry of 20 - 28t, as described in the Ecoinvent 2.2 database is assumed. Finally a construction period of 1,5 years was considered.

On the other hand, the LCI of the MSW management system has been presented in the studies from Aranda Usón, A. et al. (2013) (Aranda Usón et al., 2013) and Zambrana Vasquez, D. et al. (2012) (Zambrana Vasquez et al., 2012). From these studies, 9,2 $kgCO_2$ eq/t and 3,1 $kgCO_2$ eq/t are considered for the collection and its infrastructure, respectively. A transportation distance of 22,4 km between CIRCE II building and Zaragoza's MBT plant is considered for residual household waste, light packaging, CD/DVD, batteries and printer/toner cartridges. In the case of glass a transportation distance of 25,1 km between

[2] http://circe.cps.unizar.es/ciclope/texto/inicio.html

CIRCE II building and the treatment plant is considered. Finally, in the case of paper/cardboard a transportation distance of 4,2 km between CIRCE II building and the treatment plant is considered. In case of residual household waste from MSW, a collection truck of 21 tonnes, as described in the Ecoinvent 2.2 database, with diesel consumption of 0,336 kg per tkm is assumed. Also, a washing vehicle for monthly cleaning of containers (3 containers can be estimated: mixed waste (green), light packaging (yellow), paper/cardboard (blue)) which corresponds to a 28t lorry (fleet average), as described in the Ecoinvent 2.2 database, is used. For this last, a diesel consumption of 0,28 kg per tkm is assumed.

Regarding the operation of the Zaragoza´s MBT plant, the life cycle inventory per tonne of MSW treated is presented by Zambrana Vasquez et al. (2012). The composition of the residual fraction deposited in the MBT plant landfill in Zaragoza, as well as the material fractions and by-products obtained by mechanical and biological treatment operations, were estimated using the methodology proposed by Aranda Usón et al. (2012), considering the composition of the residual household waste of MSW that enters the plant and the fractions presented in Table 4. Note that for the estimation of the total amount of MSW generated a life span of the building of 50 years was assumed.

Recycling materials decreases emissions by reducing the use of raw materials in the manufacture of new products (Papageorgiou et al., 2009). Indeed, producing paper and cardboard from recycled materials requires less energy than does manufacturing the same products from raw materials (Feo and Malvano, 2009). The amounts of material and energy recovered in the fractions were estimated taking into account the different outflows for 1 tonne of residual household waste of MSW processed at the MBT plant and its corresponding recovery rate. In the case of the MBT plant in Zaragoza, these recovery rates correspond to 74,45%, 35,10%, 8,93%, and 78,70% for organic material, paper/cardboard, plastics, and metals, respectively (Aranda Usón et al., 2012).

For the end-of-life stage of the building, the processes of deconstruction, transport and final disposal of all construction materials and the energy equipment used throughout the service life of the building were considered. The European averages datasets of the Ecoinvent v2.0 were selected for all analysed stages considered in Figure 1 and based on the fractions of CDW at the end-of-life of the building from Table 5. Since this is an average data, its applicability to each European country depends on the level to which its specific characteristics (e.g. energy mix (the electrical energy inputs were estimated considering the electricity generation mix by fuels in Spain), manufacture technology, origin of the starting materials, etc.) are adapted to these averages. In this paper, the use of the Ecoinvent v2.0 database was carried out according to a static focus, so the life cycle inventories include intermediate values of the current processes within the system analysed, without analysing their variation over time. Additionally, the input data for demolition operations has been considered from the data presented in the study of Blengini, G. A. (2009) (Blengini, 2009). Finally, a transportation distance of 22,4 km between CIRCE II building and classification plant is considered. The classification and mechanical treatment plant are located in the same area. A collection truck lorry of 20 - 28t, as described in the Ecoinvent 2.2 database is assumed.

2.2. Impact assessment

The impact category of GWP was selected in this paper considering the present energy and environmental problem at European level, and focus on the need to reach the 20-20-20 targets. This impact category is determined from a midpoint-level approach [26]. Considering the stages of impact assessment (classification, characterisation, normalisation, and weighting) at the midpoint-level, the characterisation factors used to quantify the potential environmental impact of the LCI are those presented in the IPCC 2007 GWP 100a V1.02 impact assessment method (Intergovernmental, 2007), by using the Software SimaPro v.7.3.2

(Rebitzer et al., 2004), which summarises the GHG emissions in terms of CO_2 equivalent emissions. GWP impact category is among the most-used categories in the studies reviewed by Cleary (2009); it is used to quantify the environmental impact at different stages of a MSW and CDW (Blengini, 2009) management systems. In this sense, the results obtained in this paper are compared with those reported by other authors.

3. RESULTS AND DISCUSSION

3.1. Baseline scenarios

Table 6 and Figure 2 present the results of the impact assessment considering the baseline scenarios for (i) the construction and packaging waste management at building construction stage, (ii) the MSW management at building use stage, and (iii) the demolition waste management at building end-of-life stage; in terms of kg CO_2 eq per tonne of construction and packaging waste, MSW and demolition waste treated, respectively. Proper descriptions of these baseline scenarios are presented in subsections 3.1.1, 3.1.2 and 3.1.3.

3.1.1. Construction and packaging waste management at building construction stage

Based on the amount and characterization of construction and packaging waste generated at the building construction stage (Table 3), the baseline scenario considers a recovery of the 10% of the construction waste and 0% of the packaging waste. Landfilling of the rest of materials is assumed. The entire construction and packaging waste fractions was assumed to send to the treatment plant (distance of 22,4 km and truck lorry of 20 - 28t, as described in the Ecoinvent 2.2 was asumed). The production of recycled aggregates was considered as an avoided impact equal to the environmental impacts related with the displaced natural aggregates. Additionally, considering that 5% of the construction waste is steel, emissions avoided by the use of ferrous waste and by reducing the need for production of new steel (e.g., 1 tonne of steel requires 1.19 tonnes of scrap) is assumed.

3.1.2. MSW management at building use stage

Based on the general inventory shown in the LCI section and considering the mass balance on a wet basis of the MBT plant in Zaragoza shown by Aranda Usón et al. (2012), the baseline scenario assumes the use of 40% of the produced compost for fertilising soil. Given the composition of the waste generated in the CIRCE II, about 10% of the mixed waste corresponds to organic fraction. This means 32,96 kg/month of organic fraction that can be recovered for material and energy recovery (compost or biogas production). Taking into account the biological treatment rate at Zaragoza's MBT plant 74,45 % of the organic matter is separated for biological treatment. The use of 100% of ferrous metals, the use of biogas generated by anaerobic digestion for self-consumption of electricity and heat from a cogeneration system, use of 100% of compost and use of 85% of the aluminium recovered. In this baseline case, the deposit of the residual fraction and the remaining fractions in a landfill is considered. The density of the material deposited in landfill can be estimated as 1.4 tonne/m^3 (Abeliotis et al., 2012).

In the above analysis, avoidance of the following emissions has been considered: (i) emissions avoided due to the use of compost to replace the use of chemical fertilisers containing nitrogen and phosphorus; (ii) emissions avoided by the use of ferrous waste and by reducing the need for production of new steel (e.g., 1 tonne of steel requires 1.19 tonnes of scrap); and (iii) emissions avoided by the recovery of aluminium. The overall emissions avoided by recycling materials (e.g., ferrous and non-ferrous metals, paper/cardboard, and plastics), compost, and biogas for 1 tonne of material recovered from the MBT plant, as well as plant operation for the recovery of different materials, have been reported in several studies (Environmental Protection Agency, 2006). For example, (Abeliotis et al., 2012) considers steel, aluminium, Fertilizer-N, Fertilizer-P and coal as avoided products; (Bovea et al., 2010) considers virgin materials (e.g. fertilizer in case of compost) avoided for each of the recycled fractions; (Feo and Malvano, 2009) considers avoiding impacts related to transport, virgin materials and energy use in the 12 management scenarios with 16 management phases studied; finally, (Papageorgiou et al., 2009) considers GHG emission savings and avoidance derived from energy recovery from waste and recycling of materials.

The energy, electricity, and diesel consumption required to obtain compost and the emissions per tonne of waste from the composting process were obtained from the study of (Banar et al., 2009), while the energy consumption of the recovery plants for the recyclable fractions expressed per tonne of recycled material was obtained from the inventories submitted by (Feo and Malvano, 2009) and (Rigamonti et al., 2009).

The results demonstrate no negative values in the impact category under study; this means that, in this scenario, there are no environmental benefits associated with the recovery of steel, aluminium, biogas, or compost at the percentages under study. While the recovery of steel has the highest factor for emissions avoided per tonne of waste, most of the recovery of steel occurs in the selective collection of fractions. In other studies, scenarios in which the residual fraction represents approximately 50% of the input waste stream give rise to CO_2-eq emissions values ranging from 291 to 1510 kg CO_2-eq/t according the scenario considered. In case of the study of (Banar et al., 2009) according the scenario considered a range of 1360 to 1510 kg CO_2-eq/t waste managed is estimated. In case of (Mohareb et al., 2011) is estimated a net emissions of 291 to 396, 6 kg CO_2-eq/t considering landfill and including composting and transportation, respectively. Finally, (Abeliotis et al., 2012) in the baseline scenario MBT plant operation under their study have estimated 1030 kg CO_2-eq/t.

3.1.3. Demolition waste management at building end-of-life stage

Based on the amount and characterization of demolition waste generated at the building end-of-life (Table 5), the baseline scenario considers a recovery of the 30% of the rubble and 50% of the steel. The rest of materials will be landfilled after the life span of the building. It is important to note that currently in Spain more than 80% of the CDW is disposed of in dumps, so direct or partial recycling is clearly a minority. A distance of 22,4 km and truck lorry of 20 - 28t, as described in the Ecoinvent 2.2, was assumed for all waste fractions. The production of recycled aggregates was considered as an avoided impact equal to the environmental impacts related with the displaced natural aggregates. Additionally, emissions avoided by the use of ferrous waste and by reducing the need for production of new steel (e.g., 1 tonne of steel requires 1.19 tonnes of scrap) is assumed.

Finally, Table 7 presents the comparison of the results of the waste management systems for the baseline scenarios.

3.2. Scenario analysis

Table 6 and Figure 3 present the results of the impact assessment considering (i) a recovery scenario for the construction and packaging waste generated at building construction stage, (ii) a waste minimization scenario for the MSW generated at building use stage, and (iii) a recovery scenario for the demolition waste generated at building end-of-life stage; in terms of kg CO_2 eq per tonne of construction and packaging waste, MSW and demolition waste treated, respectively. Proper descriptions of the scenarios considered are presented in subsections 3.2.1, 3.2.2 and 3.2.3.

3.2.1. Construction and packaging waste generated at building construction stage.

Based on the baseline scenario of the construction and packaging waste generated, a recovery scenario of 100% of the rubble and steel from the construction waste and 0% of the packaging waste is assumed. Landfilling of the rest of materials is assumed. From the results obtained, a net benefit in terms of GWP can be obtained due the total recovery of rubble and steel. Note that, in comparison with the baseline scenario, an increment of the amount of the material recovery leads to an increase of the emissions generated due mainly to the mechanical treatment operations required for a greater amount of waste.

Additionally, an alternative on the waste minimization of construction waste can be focussed on the use of the “clean” construction waste (mainly the broken concrete without protruding metal bars) for erosion control and reusing the rubble in the construction site. In this case, considering the above scenario of recovery, a reduction on the construction waste generation assuming a ratio of construction waste generated per square meter of 107,27 kg/m^2 presented by Blengini (2009), leads to total net (generated-avoided) GWP of -16,20 kg CO_2 eq /t. Note that the emissions avoided per tonne of construction waste are the same, but a waste minimization strategy leads to a reduction of the emissions associated to transport and mechanical treatments (including landfilling)

3.2.2. MSW generated at building use stage

Based on the baseline scenario of the MSW generated at building use stage, a MSW minimization scenario considering a reduction of 30% and 20% of paper and plastic waste generation, respectively, is assumed. An effective waste management system, focused on the main type of waste generated (paper), includes the following waste minimization measures:

- Archiving most the information in digital form (hard disks, CD or DVD) doing the minimum of paper copies.
- The draft version of documents can be corrected on the screen and / or saved as drafts on PC and thus save ink and paper.
- Make two-sided copies and if possible make reductions to the original documents to reduce paper usage.
- Install a water source in the office avoiding drinking bottled water (plastic packaging minimization)

Additionally, a recovery scenario that includes the use of Refuse Derived Fuel (RDF) from the residual fraction of the MBT plant in Zaragoza was evaluated from the baseline scenario. The G.I.R.A. 2009-2015 does not consider energy recovery by incineration as a final treatment option for the outflows of MBT plants, specifically, of the residual fraction.

However, several studies have demonstrated the environmental benefits of energy recovery from the residual fraction as an alternative to the use of landfill, both through incineration with energy recovery (Montejo et al., 2011) and through use of the recovered material as fuel for co-firing in a cement plant (Abeliotis et al., 2012). For the case study of this paper, the impact of the use of 100% of the residual fraction in a cement plant in the town of Morata de Jalón, near the city of Zaragoza, will be analysed. The composition of the residual fraction, considering the composition of the MSW from Table 4, was estimated as 3,06 %, 64,25 %, 30,95 %, 0,07 %, 0,34 %, 0,21 % and 1,12 %, for organic material, Paper/cardboard, Plastic, Glass, Metal, Textile and Others. The higher calorific value of this residual fraction was determined to be 26449,23 kJ/kg using the methodology described by Aranda Usón et al. (2012). Considering the Ecoinvent 2.2 database and a HCV of 34000 kJ/kg for the pet coke used in the cement plant, the emissions avoided per tonne of waste treated at the MBT plant were estimated. Treatment and transportation to the cement plant, which is 76 km from the MBT plant, were also considered; however, quantification of the emissions from the incineration of RDF in the cement plant was not performed due to the difficulty of quantifying a ratio of contribution for CO_2 emissions from the production of clinker (Genon and Brizio, 2008).

From the results obtained, it can be observed that the emissions avoided are greater than those generated when energy recovery in a cement plant for the residual fraction of the MBT plant is used as a final disposal alternative for the residual fraction.

3.2.3. Demolition waste generated at building end-of-life

Based on the baseline scenario of the demolition waste generated, a scenario of a recovery of 100% of the rubble and steel from the demolition waste is considered. Landfilling of the rest of materials is assumed. From the results obtained, a net benefit in terms of GWP can be obtained due the total recovery of rubble and steel. Note that, in comparison with the baseline scenario, an increment of the amount of the material recovery leads to an increase of the emissions generated due mainly to the mechanical treatment operations required for a greater amount of waste.

Finally, Table 8 presents the results of the three scenarios studied for the construction waste (baseline, recovery of 100% of the rubble and steel from the construction waste, and waste minimization of approximately 11%). Table 9 presents the results of the comparison of the baseline scenario, the MSW minimisation scenario and the MSW energy recovery scenario. It should be noted that Table 8 and Table 9 are presented in terms of the matrix presented in Table 1.

4. CONCLUSIONS

The results presented in this study show that when a recovery scenario includes energy recovery from the residual fraction of the MBT (in case of MSW) in the form of RDF, greater benefits in terms of the GWP are obtained than with current scenarios of landfill deposition of the residual fraction. A similar situation can be observed in case of an increase of the recovery rates of metals in case of CDW. Also, the recovery of demolition materials, in replacement of virgin building materials, saves capacity of waste dumps.

Regarding recovery scenarios of downstream waste flows in the MBT plant, energy recovery is a sustainable way of using the energy resources contained in waste, which might otherwise be wasted when deposited in landfill. Such recovery helps reducing long-term pollution and decreases the continued use of fossil fuels for energy production. This type of recovery scenario is part of the focus of Industrial Ecology in order to add value, reduce costs and reduce environmental impact by taking advantage of sub-products (Korhonen, 2004).

Sustainable development, which renders unnecessary the use of landfill disposal methods, requires a high degree of utilisation of by-products in an MBT plant. For this reason, such methods as energy recovery are continually evolving. The concluding remarks of the studies reviewed for the project on MSW management indicate that if the material recovery sector is not strongly developed, new strategies will be required for energy recovery to increase the utilisation of waste. These studies indicate that thermal treatment of waste streams is an integral part of the MSW management system. For this reason, alternatives that give preference to landfill deposition according to the Waste Management Hierarchy and are aimed at meeting the targets set forth in Directive 1999/31/EC of April 26, 1999 on landfill waste should be promoted (European Parliament, 1999). In this sense, and based on the results obtained in this study, energy recovery is shown to be a viable alternative from the point of view of the energy content of waste and in terms of the environmental implications of energy recovery from the residual fraction.

The amount of CDW is directly linked to the design phase of the building (Ekanayake and Ofori, 2004), in this sense, following the methodology presented in this paper it is possible to predict the waste generation (MSW and CDW) and their environmental implications for management purposes. The results help us recognise the most efficient and sustainable waste management system to be implemented in the location, establishing additional scientific criteria for the design and planning of waste management strategies and, in general, the evaluation method proposed can be applied at urban level considering also the infrastructures related to the main alternatives for water and waste water treatment, electricity and fuel supply, public lighting, the citizens' mobility, the architectural design and equipment of buildings (heating, ventilation and air conditioning, hot water and lighting systems) and green areas. Finally, as mentioned in the methodology, a line of research to be developed as future work from this study will focus on the application of the evaluation method proposed, both at building and urban level, with the analysis of other impact categories at midpoint-level as acidification (kg SO2 eq), eutrophication (kg PO4 eq), photochemical oxidation (kg C2H4 eq), abiotic depletion (kg Sb eq) and ozone layer depletion (CFC-11 eq kg.), among others.

Finally, considering the building life cycle stages described in CEN/TC 350 standard, EN 15643-2, an appropriate waste management strategy can helps to the reduction of the associated environmental impacts and moving toward zero emissions buildings in waste management of the MSW generated by its inhabitants and those CDW generated at its construction and end-of- life stages.

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TABLE CAPTATION

Table 1. Relationship matrix of MSW and CDW management systems and recovery scenarios

Table 2. Life cycle stages of a building based on the CEN/TC 350 standard, EN 15643-2

Table 3. Construction and packaging waste generated during the construction process stage (considering a construction period of 1,5 years)

Table 4. MSW generated per day estimated for the use stage of the building

Table 5. Estimation of the demolition waste at the end-of-life stage of the building

Table 6. Environmental implications of the baseline and minimization/recovery scenarios for (i) the construction and packaging waste management at building construction stage, (ii) the MSW management at building use stage, and (iii) the demolition waste management at building end-of-life stage (kg CO_2 eq /t)

Table 7. Comparison of waste management systems for the baseline scenario for treatment and recovery

Table 8. Net CO_2-eq emissions – Relationship matrix of construction waste management systems and recovery scenarios

Table 9. Comparison of waste management systems for the baseline scenario for treatment and recovery

FIGURE CAPTATION

Figure 1. CDW management system for the target building

Figure 2. Emissions generated (G) and emissions avoided (A) of the baseline scenarios for (i) the construction and packaging waste management at building construction stage, (ii) the

MSW management at building use stage, and (iii) the demolition waste management at building end-of-life stage

Figure 3. Emissions generated (G) and emissions avoided (A) of the minimization/recovery scenarios for (i) the construction and packaging waste management at building construction stage, (ii) the MSW management at building use stage, and (iii) the demolition waste management at building end-of-life stage