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LCA OF WASTE MANAGEMENT SYSTEMS

Comparing technologies for municipal solid waste management using life cycle assessment methodology: a Belgian case study

Sandra Belboom · Jean-Marc Digneffe · Robert Renzoni · Albert Germain · Angélique Léonard

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Abstract
Purpose The present study aims at identifying the best practice in residual municipal solid waste management using specific data from Liège, a highly industrialized and densely populated region of Belgium. We also illustrate the importance of assumptions relative to energy through sensitivity analyses and checking uncertainties regarding the results using a Monte Carlo analysis.
Methods We consider four distinct household waste management scenarios. A life cycle assessment is made for each of them using the ReCiPe method. The first scenario is sanitary landfill, which is considered as the base case. In the second scenario, the refuse-derived fuel fraction is incinerated and a sanitary landfill is used for the remaining shredded organic and inert waste only. The third scenario consists in incinerating the whole fraction of municipal solid waste. In the fourth scenario, the biodegradable fraction is collected and the remaining waste is incinerated. The extracted biodegradable fraction is then treated in an anaerobic digestion plant.
Results and discussion The present study shows that various scenarios have significantly different environmental impact. Compared to sanitary landfill, scenario 4 has a highly reduced environmental impact in terms of climate change and particulate matter formation. An environmental gain, equal to 10, 37, or 1.3 times the impact of scenario 1 is obtained for, respectively, human toxicity, mineral depletion, and fossil fuel depletion categories. These environmental gains are due to energetic valorization via the incineration and anaerobic digestion. Considering specific categories, greenhouse gas emissions are reduced by 17 % in scenario 2 and by 46 % in scenarios 3 and 4. For the particulate matter formation category, a 71 % reduction is achieved by scenario 3. The figures are slightly modified by the Monte Carlo analysis but the ranking of the scenarios is left unchanged.
Conclusions The present study shows that replacing a sanitary landfill by efficient incineration significantly reduces both emissions of pollutants and energy depletion, thanks to electricity recovery.

Keywords Incineration · Life cycle assessment · Monte Carlo Analysis · ReCiPe · Waste management

1 Introduction

All human activities generate waste. This issue has become an important problem over the years with urbanization and the growth of population (Giusti 2009). Sustainable development encompasses several actions as the reduction of polluting emissions and the establishment of sustainable waste management practices (Cherubini et al. 2009). Concerns regarding this issue have increased considerably over the years with the adoption and application of the waste hierarchy as the "rule of thumb" proposed by the European Union (2006). This approach primarily promotes prevention, aiming to reduce the production of waste in the first place, and advocating reuse,

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S. Belboom (✉) · R. Renzoni · A. Germain · A. Léonard
Department of Chemical Engineering, Processes and Sustainable Development, University of Liège, 3 Allée de la Chimie, 4000, Liège, Belgium
e-mail: sbelboom@ulg.ac.be

J.-M. Digneffe
Intradel, Port de Herstal–Pré Wigi, 4040, Herstal, Belgium

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recycling, and energy recovery before resorting to the final option of landfilling (Finnveden et al. 2005).

Life cycle assessment is a methodology often used to compare several waste treatment technologies or to make an environmental evaluation of approaches to waste management. The validity of the waste management hierarchy, as defined by the European Union, is generally well supported through the results of life cycle assessment studies but the order can change depending on energetic assumptions and system boundaries (Moberg et al. 2005; Finnveden et al. 2005). Many papers have been published in the last 10 years relating to different locations in Europe with, for example, studies being conducted in Spain (Bovea et al. 2010; Bovea and Powell 2006; Rodriguez-Iglesias et al. 2003), Italy (Morselli et al. 2008; Buttol et al. 2007; Tarantini et al. 2009; Arena et al. 2003), Germany (Winkler and Bilitewski 2007), and Sweden (Bernstad and la Cour Jansen 2011).

The present paper evaluates a case study for Belgium. It uses, as far as possible, the recommendations and level of transparency required by the International Expert Group on Life Cycle Assessment for Integrated Waste Management (Coleman et al. 2003) as mentioned in the publication dealing with limitations of life cycle assessment methodology in the waste management field (Ekvall et al. 2007).

2 Methodology

2.1 Goal definition

The goal of the present study is to identify the best practice in the field of municipal solid waste (MSW) management. We focus on the case of Liège, a highly industrialized and densely populated region of Belgium. High-quality data coming from a specific industrial plant is used.

The studied fraction includes municipal solid waste after collection of recyclable components such as cardboard, glass, plastics, and metals. Four waste management technologies are modeled in four scenarios. These scenarios are (1) landfilling in a sanitary site, (2) incineration coupled with landfilling in a sanitary site, (3) incineration of the whole MSW fraction, and (4) anaerobic digestion of the biodegradable fraction extracted from the MSW coupled with incineration of the remaining waste. Scenario 2 is representative of the past situation for waste management in Liège from 1993 until 2008. Scenario 3 is relative to the current one and scenario 4 is considered as a prospective management solution for the future.

This study is performed in accordance with the four steps specified by the International Standardization Organization (ISO) standards (International Standardization Organization 2006a, b). The environmental impacts of scenarios investigated are evaluated using the ReCiPe method (Goedkoop et al. 2009) with a midpoint hierarchist perspective. This level of investigation provides results for each impact category expressed in terms of a physical unit, e.g., in kg_{eq} CO_2 for climate change. The ReCiPe method, the most recent life cycle impact assessment method, is chosen for use in the present study because it can be said to represent the culmination and improvement of the two most used European methods, namely Eco-Indicator 99 and CML 2001. Characterization factors of this method are updated, uncertainties and weaknesses reduced and the choice of both a midpoint or endpoint approach is available in a single method (Goedkoop et al. 2009).

This study also highlights the importance of energetic assumptions using both attributional and consequential approaches. Sensitivity studies are performed as well as a Monte Carlo analysis on data uncertainties. This is not yet common practice but is known to improve the credibility of results (Sonnemann et al. 2003; Huijbregts 1998a, b).

2.2 Scope definition

The functional unit of our model represents 1 t of average residual municipal solid waste. The function is the treatment of this amount of waste, using different technologies and valorizing its energetic or matter content.

The boundaries of the systems incorporate waste treatment until the point of final disposal including the production of electricity or heat. The collection step and associated transport, which are assumed to be the same for all scenarios, are also considered. Emissions and inputs relative to the operation of the plant are included but not the construction, implementation, maintenance, or demolition of the plant. These steps are not taken into account due to a lack of data and they have been described as negligible in several papers (Gentil et al. 2010; Finnveden et al. 2005). The management, treatment, and valorization of slag and ash waste are also part of our systems.

2.3 Life cycle inventory analysis

To increase the credibility and the specificity of our results, measured data are used for scenario 2 (sanitary landfill and the incineration of the refuse-derived fuel (RDF) fraction) and scenario 3 (incineration of the whole fraction of MSW). They are provided in environmental and technical reports published by the waste treatment plant operator (INTRADEL and IBH 2005, 2009, 2010). Other data are obtained using scientific literature and ecoinvent database v2.2 (Swiss Centre for Life Cycle Inventories 2010). Energy and material flows taken into account for each technology are described below. Figures 1, 2, 3, and 4 present the general scheme for each scenario.

Characteristics and composition of the functional unit, based on technical reports (INTRADEL and IBH 2005, 2009, 2010), are presented in the Electronic supplementary material (ESM). The carbon content is related to experimental

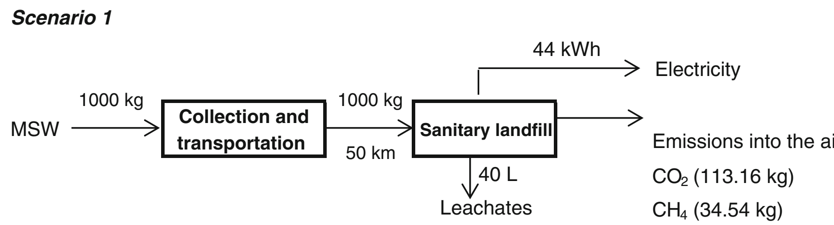

Fig. 1 Scenario 1—Landfilling–sanitary site

results corrected to capture the correct lower heating value. As the part of biogenic carbon is unknown, the entire carbon content is considered as from fossil origin.

This waste composition is used to calculate the energy content of each waste fraction using the Dulong formula and the greenhouse gas (GHG) emissions depending on the used technology. Even though the composition of waste is the same for all the technologies in our model, treatment and valorization differ and some adjustments need to be performed on a case by case basis.

The collection step is considered for all scenarios with 50 km as an average distance between houses and the treatment plant (incinerator and sanitary landfill) performed with a garbage truck. The distance traveled by lorry between the anaerobic digestion plant and composting sites is about 20 km.

2.3.1 Scenario 1—Landfilling–sanitary site

The landfilling of MSW is no longer recommended by the European Union (2008) but it serves here as a base case reference to which all other scenarios are compared. The released biogas is recovered and valorized by electricity generation. Leachates are emitted into groundwater which is subsequently treated. Because no site-specific data is available, scientific literature is used for leachate and gas emissions as presented in the ESM (Manfredi and Christensen 2009; Obersteiner et al. 2007). No energy consumption is taken into account in this case; it is assumed that no engine or machine is used to manage the landfills.

Electricity as a co-product of waste treatment is included within the system boundaries of our model. This advantage is taken into account, using the system expansion approach. We consider that the produced electricity replaces the one made by the typical energetic mix, which is country specific. The type of electricity is assumed to correspond to the Belgian energetic mix mentioned by the International Energy Agency (IEA) for 2009 (International Energy Agency 2009b) and presented in the ESM.

Although this type of product allocation is not unanimously accepted (Heijungs and Guinée 2007), it is the approach usually employed (Winkler and Bilitewski 2007) and complies with the ISO standard (International Standardization Organization 2006b).

In the sanitary landfill, the combustion of biogas generates 44 kWh of electricity per ton of residual MSW. The same quantity produced from the Belgian mix of fuels is assumed to be avoided, leading to an environmental gain. Two sensitivity analyses—the first using the attributional approach with various energetic mixes and the second using the consequential approach—are carried out to analyze electricity recovery from waste management. Details of these analyses appear in Section 3.3.1 below.

2.3.2 Scenario 2—Incineration coupled with sanitary landfill

This scenario, representative of the situation in Liège between 1993 and 2008, considers the incineration of the RDF fraction and the sanitary landfill of the remaining fraction. These two fractions are separated following two steps.

Firstly, shredding and sorting of waste is performed to obtain the RDF fraction, with a lower heating value (LHV)

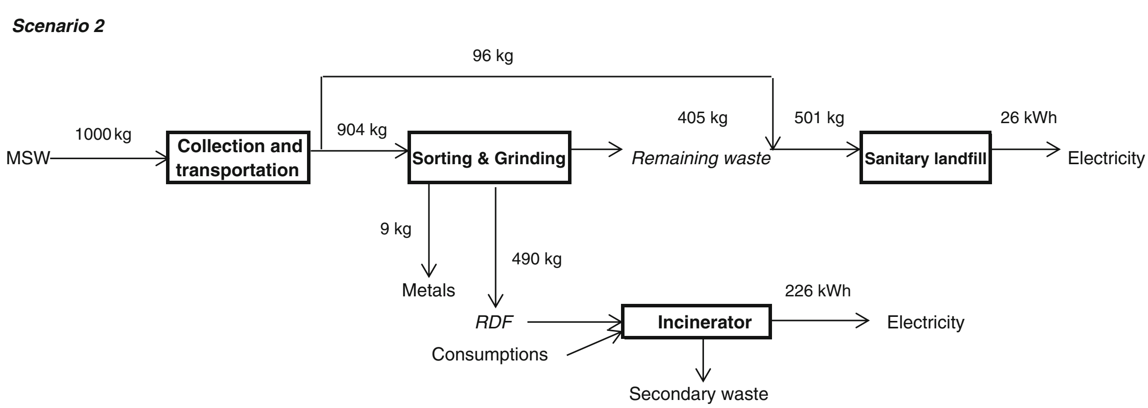

Fig. 2 Scenario 2—RDF incineration and sanitary landfill

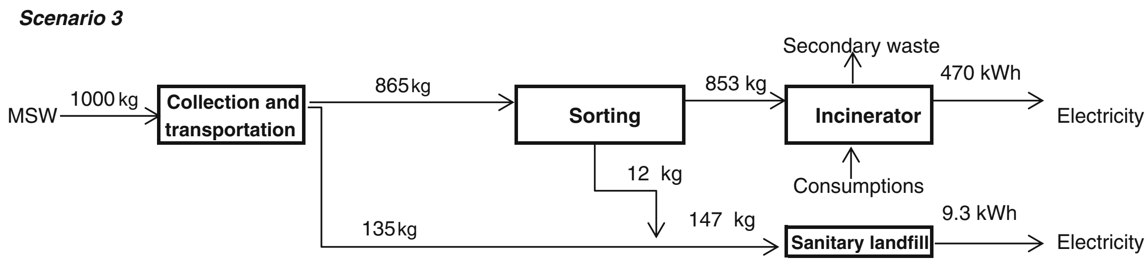

Fig. 3 Scenario 3—Incineration of the whole municipal solid waste fraction

of 11.63 MJ/kg. This fraction is incinerated on site in a plant with a capacity of approximately 170,000 t of waste per year, producing 226 kWh of electricity per functional unit which is valorized in the grid.

This leaves the second fraction—a mix of shredded waste (biodegradable and inert)—which is dumped into a sanitary landfill (cf. scenario 1) with ground protection and gas recovery for electricity generation. The quantity of biodegradable waste to sanitary landfill is about 140,000 t per year with a lower heating value of 6.89 MJ/kg.

Incineration of waste requires chemical inputs for flue gas treatment, such as hydrochloric acid, lime, and ammonia but also the use of diesel and electricity to power the incinerator. Ecoinvent database (Swiss Center for Life Cycle Inventories 2010) is used to obtain the environmental inventory for these consumptions.

The amount of pollutants emitted into the air due to the incineration is based on the composition of incinerated waste and on environmental reports. The combustion process is assumed to be complete and the entire carbon content of the incinerated waste is then emitted as CO_2.

After incineration and the cleaning of flue gas, slag and fly ash, called secondary waste, are recovered and must be treated. As no specific values are available from the plant for this step, the scientific literature is used to obtain the required features of this stage. Quantities of recovered metals, used instead of virgin metals, depend on the content of the incinerated waste but the used values are in accordance with the range presented in several papers (Grosso et al. 2011; Sabbas et al. 2003; Shen and Forssberg 2003). Metals recovered after sorting and before incineration are almost completely composed of iron which can be valorized in replacement of virgin iron. After separation, treatment, and stabilization, bottom ash can replace an equivalent mass of sand or of gravel for roads as well as a proportion of fly ash (approximately 25 %), and the remaining fraction is landfilled (Born 1994; Rem et al. 2004). The ecoinvent database is used to obtain the inventory of these secondary waste components.

Further details about energy and chemical inputs, flue gas emissions, and secondary waste are provided in the ESM.

2.3.3 Scenario 3—Incineration of the whole fraction of waste

In scenario 3, modeling the current situation in Liège, the whole fraction of municipal solid waste is burned in an incinerator with a nominal capacity of 320,000 t per year. A fraction of approximately 13.5 % of the functional unit is landfilled in a sanitary site, representing the excess of the incinerator capacity.

In scenario 3, the steps and assumptions are similar to those of scenario 2. The difference is that, in this scenario, the whole fraction of the MSW with a LHV of 8.85 MJ/kg,

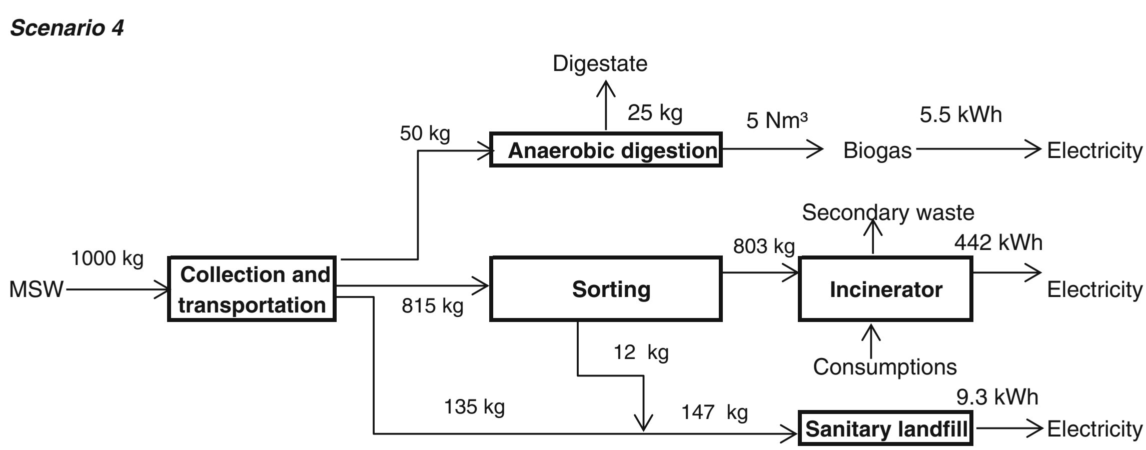

Fig. 4 Scenario 4—Implementation of an anaerobic digestion plant

goes for incineration. The more efficient flue gas treatment implemented in the new plant allows the reduction of air emissions. Electricity recovery increases to 470 kWh per ton of residual MSW (in comparison with 226 kWh for scenario 2).

2.3.4 Scenario 4—Anaerobic digestion

The biodegradable fraction of the MSW can be collected as a recoverable portion and treated by anaerobic digestion. One further step is then added to those described in scenario 3, i.e., the collection of the biogas produced and the maturation of the anaerobic digestate. This digestate can be used in place of chemical fertilizers on agricultural fields. Biogas is used for electricity production due to its available direct use in the grid. The valorization of biogas as heat with district heating or as biofuel is not taken into account because the infrastructure is not yet available in the current context. Further studies would need to be performed in order to highlight the best use of the biogas in our regional context.

The organic waste deposit is estimated by some prospective studies (INTRADEL 2010) to be 14,000 t per year in Liège, equivalent to approximately 50 kg of our functional unit. This deposit is selectively collected from waste that has previously been incinerated. Limited participation of citizens in recycling their household waste means that a higher level of organic deposit is currently not available. This feature is specific to the region of Liège and its high population.

Anaerobic digestion is modeled with a production of 100 Nm^3 of biogas per ton of biodegradable waste with a gas composition of 55 % CH_4, 44.5 % CO_2, and 0.5 % H_2S. These quantities are in accordance with previous studies (Møller et al. 2009; Tambone et al. 2010; Khalid et al. 2011). The produced gas, entirely collected, is sent to power the engine for 95 % as against 5 %, which goes to flare. After the deduction of energy needed for the operation of the anaerobic digestion plant, a recovery of 5.5 kWh of electricity is obtained from the 50 kg of biodegradable waste. The heat produced is used on site to dry the digestate before transportation. No environmental gain is considered to be obtained from this heat production. Biogas combustion emits mainly CO_2 and water, and also some CH_4 due to losses reaching 1.5 % of the produced amount (Møller et al. 2009).

An amount of approximately 500 kg of digestate per ton of treated biodegradable waste is produced (Møller et al. 2009). The maturation of the digestate leads to emissions of CO_2, CH_4, and dinitrogen oxide (N_2O) due to an emission factor of 89 and 2 %, respectively, for carbon (Bruun et al. 2006) and 1.25 % for nitrogen (Hansen et al. 2006). After maturation, the digestate is used on fields. A proportion of the carbon is assumed to be stocked in the soil for more than 100 years. The nitrogen content allows the avoidance of the use of nitrogen inorganic fertilizer by a factor of 50 % (Hansen et al. 2006). The potassium and phosphorus content of the digestate can also be used as chemical fertilizer with a replacement factor of 100 % (Boldrin et al. 2009; Møller et al. 2009). Further details about anaerobic digestion are provided in the ESM.

3 Results and discussion

3.1 Results

Figure 5 presents a breakdown of the results for all the relevant environmental impact categories of our study. Categories relating to occupation of soil are not taken into account due to their low impact at the normalization step.

Results are expressed as a percentage due to different category units. Scenario 1 with sanitary landfill obtains the highest score for each impact category except for terrestrial acidification, photochemical oxidant formation, particulate matter formation, and water depletion. The environmental impact decreases when replacing sanitary landfill by incineration as shown in Morselli et al. (2008).

The particulate matter formation and acidification categories regroup pollutants such as ammonia (NH_3), nitrogen oxide (NO_X), and sulfur oxide (SO_2). They are produced during the waste incineration step involved in scenarios 2–4 where the level of these pollutants is higher than in the scenario 1 where only biogas combustion appears. The same explanation can be used for the photochemical oxidant formation category. Data for the water depletion category come from commercial databases used to model the different steps of scenarios.

As stated above, the environmental impact category of occupation of soil is not taken into account in the present study. Nevertheless, incineration requires less land than landfilling. In Belgium, because of the scarcity of available land, consideration of occupation of soil is then a further strengthening of the case for incineration over landfill.

Table 1 focuses on the five environmental impact categories representing the most significant issues for waste treatment and management: climate change, human toxicity, particulate matter formation, mineral depletion, and fossil fuel depletion.

As shown in Table 1, the change from sanitary landfill to controlled treatments diminishes the quantity of emitted pollutants and consumed resources. The increase of electricity production from scenarios 1 to 2 allows a decrease in the climate change score in accordance with the results of previous studies (Bovea and Powell 2006; Bovea et al. 2010; Hong et al. 2010).

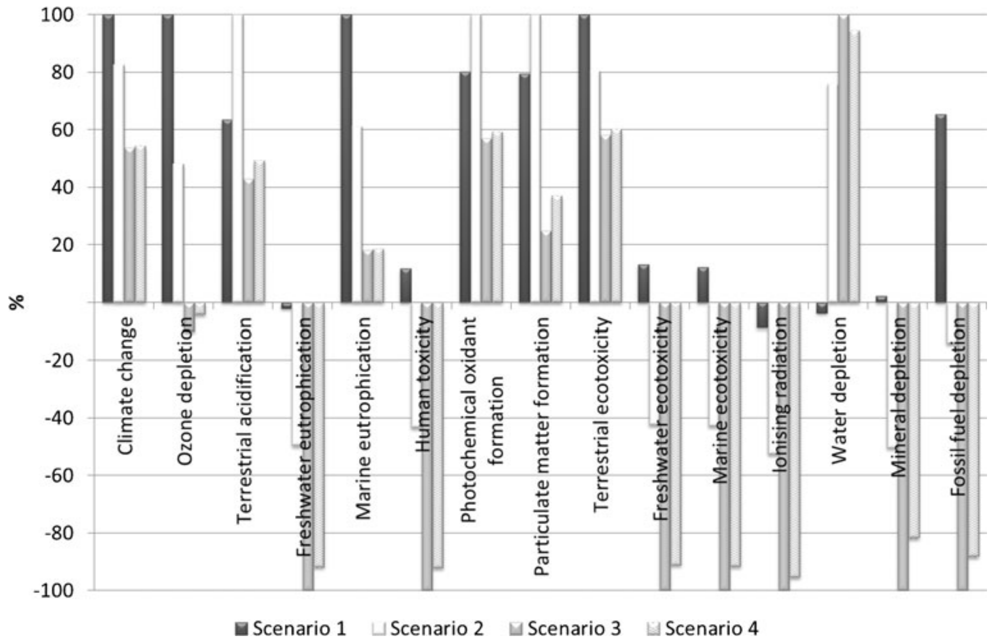

Fig. 5 Comparison of the environmental impacts of the four waste management scenarios using relevant midpoint indicators of ReCiPe

3.2 Waste management phases

In order to identify the most damaging waste management steps and to illustrate possible improvements that may be made, Table 2 shows the impact of each step in relation to climate change, particulate matter formation and fossil fuel depletion categories.

Table 2 highlights the impact of the landfill step on the climate change category with a high level of GHG emissions. These emissions can be reduced by replacing the landfill step with incineration as shown in scenarios 2–4. Production of electricity avoids the same amount of GHG and oxide emissions produced by fossil fuels and leads to a decrease in these emissions and in fossil fuel depletion.

The incineration and the collection steps are both most important stages in scenarios 2–4, especially for the particulate matter formation and the fossil fuel depletion categories. The incineration step can be separated into three stages: firstly, secondary waste requiring final disposal; secondly, emissions due to combustion; and thirdly, chemical inputs for flue gas treatment and energy for powering the incinerator.

As shown in Fig. 6, CO_2 emissions caused by the combustion of waste lead to the greatest environmental impact in the climate change category. For the particulate matter formation category, emissions of NO_X and NH_3 represent a high level of impact but these are compensated by the valorization of secondary waste and the replacement of virgin metals with recovered metals. Metals recovery leads to an environmental gain in the fossil fuel depletion category, but this is reduced by the resources needed in terms of the chemicals and energetic inputs of the incinerator.

In scenario 4, scores for the climate change and particulate matter formation categories are slightly higher, in comparison with scenario 3, due to emissions of N_2O and CH_4 during maturation of the digestate. The use of biogas in the form of electricity allows a slight reduction in fossil fuel depletion category.

This anaerobic digestion step can be divided into two stages: firstly, emissions due to maturation of the digestate and the combustion of biogas and secondly, valorization of the digestate in the form of fertilizers and the environmental gain associated with this. Avoiding fertilizers allows a reduction in the impact of the fossil fuel depletion category as presented in Fig. 7. Emissions of digestate and biogas are not compensated by this gain in the two other categories—climate change and particulate matter formation—where the impact has a positive value.

Table 1 Impact results at the characterization step for five midpoint categories

Impact category	Unit	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Climate change	kg CO_2 eq	1,030.23	851.54	554.65	560.30
Human toxicity	kg 1–4 dB eq	3.88	−14.23	−32.82	−30.23
Particulate matter formation	kg PM_{10}eq	0.14	0.17	0.04	0.06
Mineral depletion	kg Fe eq	0.40	−9.15	−18.15	−14.84
Fossil fuel depletion	kg oil eq	17.14	−3.72	−26.26	−23.18

Table 2 Impact of waste management phases in relation to three environmental impact categories: climate change, particulate matter formation, and fossil fuel depletion

	Climate change (kg_{eq} CO_2)				Particulate matter formation (kg_{eq} PM_{10})				Fossil fuel depletion (kg_{eq} oil)			
	Sc 1	Sc 2	Sc 3	Sc 4	Sc 1	Sc 2	Sc 3	Sc 4	Sc1	Sc 2	Sc 3	Sc 4
Collection and transportation	65.3	65.3	65.3	65.3	1.47E-01	1.47E-01	1.47E-01	1.47E-01	21.21	21.21	21.21	21.21
Landfill	976.7	489.9	143.2	143.2								
Electricity—landfill	−11.8	−7.0	−2.5	−2.5	−9.50E-03	−5.64E-03	−1.99E-03	−1.99E-03	−4.07	−2.41	−0.85	−0.85
Incineration		363.2	473.1	439.7		7.99E-02	−1.40E-03	1.06E-02		−1.82	−3.64	−2.28
Electricity—incineration		−59.9	−124.5	−117.1		−4.84E-02	−1.00E-01	−9.45E-02		−20.7	−43	−40.5
Anaerobic digestion		0.0	0.0	33.0				4.21E-03				−0.35
Electricity—anaerobic digestion		0.0	0.0	−1.4				−1.16E-03				−0.49
Digestate transportation				0.1				1.12E-04				0.03

3.3 Sensitivity analyses

This section describes the sensitivity analyses performed in order to check the validity of the life cycle assessment undertaken and its associated results, as recommended in Cleary (2009).

3.3.1 Electricity

Table 2 above shows that electricity recovery plays an important role in the environmental impact of our scenarios. Due to the context of our study, the Belgian mix of resources for electricity is used in assessing both energetic depletion and environmental gains. In the following section, we consider the different origins of electricity in order to highlight the importance of the regional context, using an attributional approach. The consequential approach is also used taking into account the marginal effect of waste management on the Belgian mix of resources for electricity production. Both possibilities are examined in the following paragraphs.

The attributional approach—Electricity produced from various energetic mixes Electricity recovery from waste avoids some fossil fuel depletion based on assumptions regarding the origin of the mix. Results described in the previous paragraphs are relative to the Belgian energetic mix, with the majority of electricity being produced within nuclear or gas power plants. In order to identify the importance of the energetic context, three other mixes are considered: the Swiss mix characterized by a high use of renewable resources, the German mix using a majority of coal, and a regional mix representing the European average. The compositions of these energetic mixes come from the IEA statistics (International Energy Agency 2009a) and are presented in the ESM.

Results from applying the different energetic mixes for electricity production to our model show non-negligible variations for climate change, particulate matter formation, and fossil fuel depletion categories. Replacing Belgian electricity with Swiss electricity avoids the environmental gain for fossil fuel depletion category. The main inputs in the Swiss case are of renewable and nuclear fuels; hence, there is a low level of fossil fuels avoided for electricity production. In the two other impact categories, Swiss electricity creates an average increase in impact of 21 % for climate change and of 115 % for particulate matter formation. Regarding replacement with European or German electricity, this leads to higher environmental gains due to coal forming the largest constituent of the energetic mix.

This analysis shows the high importance of assumptions concerning energy recovery; results can be modified in a significant way by changing the energetic context.

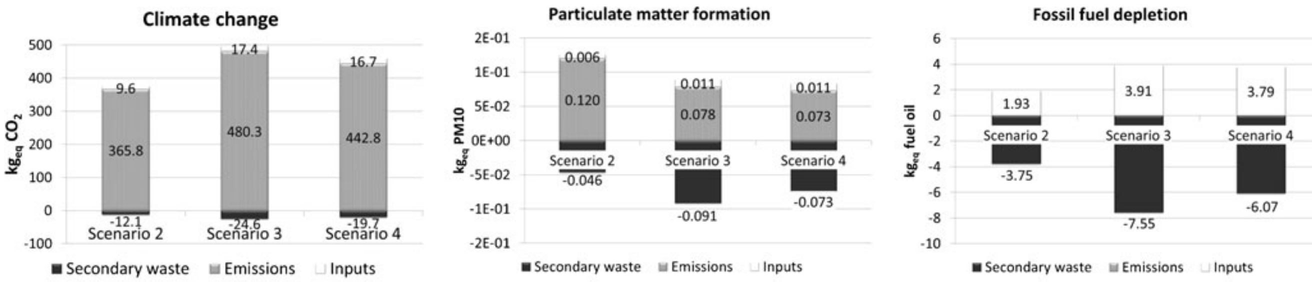

Fig. 6 Impact of the three stages of the incineration step for three environmental impact categories

The consequential approach In the consequential approach, the marginal effect of the valorization gained from the treatment of one supplementary ton of municipal solid waste is taken into account. The amount of additional electricity produced by the treatment of waste can lead to the closure of an oil or coal power plant due to their small proportion in the Belgian energetic mix. For coal, this change leads to a doubling of the environmental gain for the fossil fuel depletion category and to a reduction by maximum 80 % of GHG emissions. Oil leads to the same results for the fossil fuel depletion category but the decrease of the impact on climate change reaches a maximum of 57 % of the base results. If the production of electricity from waste is to lead to the closure of a coal power plant, the environmental gain is twofold compared to the base results of this study.

3.3.2 No valorization of digestate

The anaerobic digestion plant envisaged in scenario 4 is assumed to produce both electricity and a digestate, which could be used as fertilizer on agricultural fields, depending on specific regulations. The worst case for the digestate is chosen to be no possibility of valorization and for it to be consigned to landfill. Results show, in comparison with scenario 4, an increase of 14.7 kg_{eq} CO_2 for the climate change category, and a decrease of 0.3 kg_{eq} oil for the environmental gain relative to the fossil fuel depletion category. However, neither of these changes is significant compared to the environmental impacts presented in Table 1. Therefore, we can conclude that the use of digestate is not the main environmental gain of scenario 4.

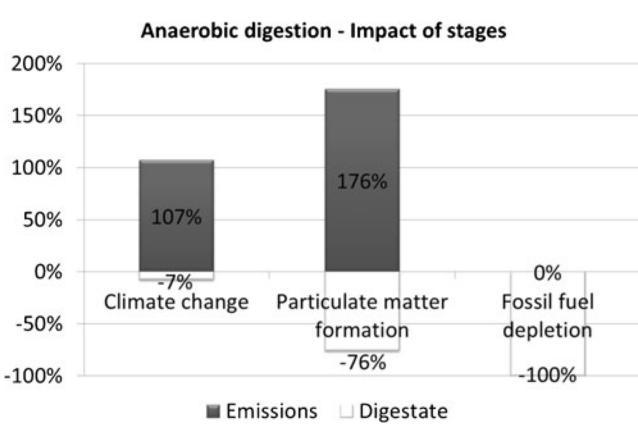

Fig. 7 Impact of the two anaerobic digestion stages on three environmental impact categories

3.3.3 Method

Results of this study are expressed in terms of physical units for each impact category using the ReCiPe 2008 method with the midpoint level. Another way to present results is to measure the environmental damage caused by waste management technologies using the endpoint level. The environmental impact categories are grouped into three main categories: human health, ecosystems, and resources. The same study is performed with this endpoint approach in order to highlight any differences and to evaluate the strength of the results previously obtained using the midpoint level.

For the characterization step, the same trends are observable for the both the endpoint and the midpoint approach: the highest score was obtained by scenario 1 in all the environmental impact categories except for photochemical oxidant formation, particulate matter formation, and terrestrial acidification. Using an endpoint or a midpoint perspective leads to the same trends, but the meaning of the results is not the same due to the different level of implication.

3.4 Uncertainties analysis

The uncertainties of our results are assessed using the Monte Carlo method (PRé Consultants 2010) with a log normal law and uncertainties linked to the data. These uncertainties are based on the Ecoinvent database with a mentioned standard deviation. When emissions from industry are used, the standard deviation is calculated using the Simapro tool with criteria as accuracy, reliability, and time and technology reproducibility. Figure 8 illustrates the uncertainty in the waste life cycle inventory for each scenario for climate change, particulate matter formation, and fossil fuel depletion categories.

Figure 8 shows uncertainties for each of the three categories, but this does not allow us to draw conclusions

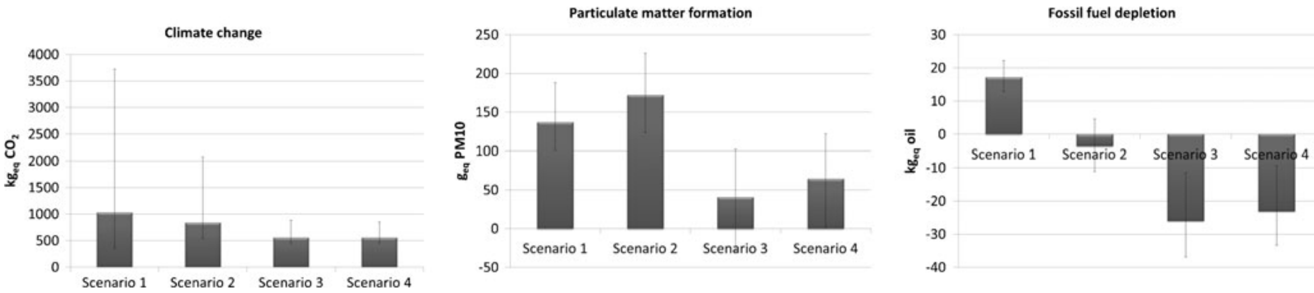

Fig. 8 Uncertainties analysis at the midpoint stage for each scenario

regarding the uncertainty of the characterization scores. Another way to present these Monte Carlo results is required to compare systems. Figure 9 presents the results of the percentage at which scenario A attains a higher impact than scenario B. For example, in the comparison between scenarios 1 and 2, the environmental impact in the fossil fuel depletion category is higher for each experimental run for scenario 1. The difference between both scenarios is assumed to be significant for a result of at least 90–95 %.

For the climate change category, scenarios 1 and 2 cannot be discriminated but both these scenarios obtain in all cases a higher environmental impact than both scenarios 3 and 4. For fossil fuel depletion category, the impact of scenario 1 is the worst followed by scenario 2, for which the lowest score is still higher than the highest ones for scenarios 3 or 4. For particulate matter formation category, scenario 2 leads to a higher environmental impact than scenario 1. Scenario 3 reaches the lowest score.

This analysis confirms the credibility of our results for these three environmental impact categories. For scenarios 3 and 4, it is not possible to differentiate the scenarios from an environmental point of view for the climate change category. For the fossil fuel depletion and particulate matter formation categories, scenario 3 shows the best environmental score on each experimental run.

4 Conclusions and recommendations

The life cycle assessment methodology, in accordance with the ISO standards, was applied to four scenarios of waste management illustrating improvements taking place through technologies in this field. The ReCiPe 2008 method was used with the most relevant environmental impact categories and several sensitivity and uncertainties analyses were made changing energetic hypotheses or the employed method.

4.1 Conclusions

The present study shows that replacing landfill in a sanitary site by efficient incineration significantly reduces both emissions of pollutants and energy depletion thanks to electricity recovery. The situation in Liège has improved over the years from scenarios 2 to 3. The amount of landfill waste has decreased and performances of the incinerator have been enhanced through a greater energy and flue gas treatment efficiency. Scenario 4, considered as a prospective solution for the waste management, shows similar results to the current scenario.

A sensitivity analysis regarding the origin of electricity shows the importance of the energy context. Results change depending on the fossil fuels consumed and then avoided by the recovery of electricity. Two other sensitivity analyses—regarding the digestate and the methodology—lead to the same conclusions as made in the base case. An uncertainties analysis shows the strength of the results for the first three scenarios. It also confirms that both scenarios 1–2 and 3–4 cannot be discriminated from an environmental point of view for the climate change category.

The main conclusion of this research is to show the environmental significance of landfill replacement by more controlled processes, for the region of Liège with its specific

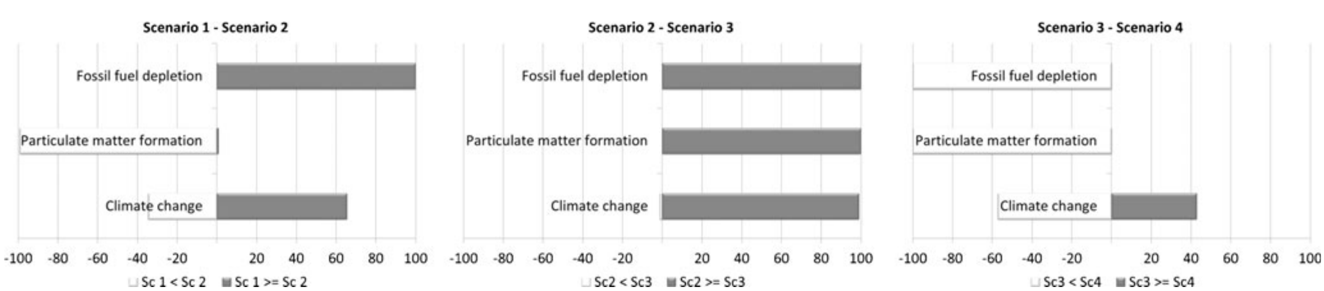

Fig. 9 Uncertainties comparisons for each waste management scenario for three environmental impact categories

features such as a high population density, a specific relationship between the agricultural and industrial sectors, a significant level of energy consumption, and a typical type of waste.

4.2 Recommendations

Despite the fact that efforts to improve waste management technologies have already been made with some success, further improvement can still take place with, for example, the achievement of an optimum balance between pollutant emissions in flue gas and chemical inputs. Another possibility is to recover a greater proportion of energy from the incinerator by extracting steam from the turbine for applications such as district heating or industrial activities. In scenarios 3 and 4, a proportion of waste still goes to sanitary landfill because the capacity of the incinerator is exceeded. The replacement of sanitary landfill by incineration or other higher performing technologies would allow a more significant environmental gain for these scenarios.

The results of the present study, based solely on environmental considerations, show that the more waste is energetically valorized in conjunction with careful management of pollutant emissions, the smaller the environmental footprint is. In order to examine waste management technologies as a part of a sustainable development approach, an economic study using the concepts of life cycle cost will be conducted in the near future and will allow the discrimination of sustainable scenarios for waste management.

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