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WASTE-TO-ENERGY OPTIONS WITHIN A CIRCULAR ECONOMY STRATEGY IN A DEVELOPING COUNTRY: THE CASE OF THE BIO BIO REGION IN CHILE

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ABSTRACT

In Chile, during the last 40 years the municipal solid waste (MSW) generation rate has shown a 4-fold increase due to population growth, fast urbanization and improved material standards. As in most developing countries, this trend is expected to continue as economic policies foster greater industrial investment and increases in domestic consumption.

Currently, MSW are landfilled near ever expanding urban areas, leading to growing public concerns, and prompting new control legislation. Up-to-date MSW management practises are being promoted in order to maximise waste valorisation, including recycling, and waste-to-energy, within a circular economy strategy. However, new resource consumption, waste streams, air emissions and effluents may arise when changing from a linear to a circular economy model. Therefore, environmental performance of alternative scenarios must take into consideration the complete life cycle to avoid problem shifting. Within this context, this paper presents a case study of three alternative waste-to energy scenarios, as part of a circular economy strategy, involving combustion, gasification, and landfill biogas, at the Bio Bio Region in Southern Chile. This is an industrial region housing over 2 million inhabitants and generating more than one million tonnes of MSW per year. The study assesses waste-to energy alternatives considering an integrated waste management life cycle approach. Boundaries include waste collection, transport, pre-treatment processes, by-products generation, and heat/power production. MSW transport, recycling rates, chemical compositions, and calorific values, were obtained from primary sources, whereas energy conversion efficiencies and other data gaps were estimated from the Ecoinvent database. Results provide a complete view of the environmental performance of each alternative scenario, including potential climate change effects and other environmental impacts, and also the positive contributions of material and energy recovery. This work illustrates the value of life cycle assessment in the context of decision making concerning circular economy scenarios.

Keywords: biogas, electricity generation, gasification, Incineration, life cycle assessment, Municipal solid waste, waste-to-energy.

1 INTRODUCTION

The disposal of municipal solid waste (MSW) in landfills has been identified as the source of various negative environmental impacts, such as air and water pollution due to gas emissions and leachate, respectively, among others [1], [2]. In Chile, during the last 40 years, the MSW generation rate has shown a 4-fold increase due to population growth, fast urbanization and improved material standards. As in most developing countries, this trend is expected to continue as economic policies foster greater industrial investment and increases in domestic consumption.

Currently, MSW are landfilled near ever expanding urban areas, leading to growing public concerns, and prompting new control legislation. Modern MSW management and treatment strategies aim at minimizing the amount of landfilled waste as well as maximising material and energy recovery [3]. Up-to-date MSW management practises are being promoted in order to maximise waste valorisation, including recycling, and waste-to-energy (WTE), within a circular economy strategy. Due to its significant energy potential and high organic content, MSW has attracted increasing interest as a feedstock for fuel and energy production leading

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to various WTE options. In this respect, a primary alternative is to directly incinerate organic waste in order to produce steam and/or electricity and is by far the most widely applied WTE route [4], [5]. Indeed, more than 1400 incineration plants are reported in operation worldwide, mostly based on fixed bed furnaces featuring low electricity efficiency [5], [6].

In recent times, more advanced thermochemical processes, such as pyrolysis and gasification, have been implemented in order to firstly convert MSW into secondary energy carriers, and then burn these fuels to produce heat and/or electricity [4]. Pyrolysis generates combustible fluids and char, whereas gasification produces gaseous products, that could be burned in appropriate combustion/electricity generation systems such as steam turbines, gas turbines or gas engines [7]–[9].

In addition to those thermochemical processes, biological degradation of residual biomass represents a valuable source of energy. Indeed, methane emissions from anaerobic bacterial activity in landfills significantly contribute to global warming, representing around 30% of worldwide methane emissions [10]. Moreover, recovery and use of such biogas for heat/electricity production is a well established practise in various countries offering interesting economic advantages [11]–[13].

Economic, technical, and environmental considerations ought to be taken into account when designing WTE strategies. Besides, new resource consumption, waste streams, air emissions and effluents may arise when changing from a linear to a circular economy model. Therefore, environmental performance of alternative scenarios must take into consideration the complete life cycle to avoid problem shifting. In recent years, life cycle assessment (LCA) has been widely used to identify and evaluate potential environmental benefits and drawbacks of WTE options [2], [3], [14–17].

Nevertheless, the environmental performance of WTE options is highly dependent on energy conversion efficiencies, waste composition, waste pre-treatment, emission controls, seasonal and climatic features, geographical location, lifestyle and living standards, among others. Despite the wide coverage of WTE in the academic literature, there are contradicting views about the environmental attributes of alternative courses of action, and there is still the need for further site-specific data from primary sources, with view to supporting decision making involving WTE within the framework of a circular economy model in developing countries.

Recently, a techno-economic assessment on the potential energy that could be derived from MSW in Chile was reported, concluding that electricity generation potentials from landfill biogas and direct MSW incineration could be around 125 MW_e and 250 MW_e, respectively, with interesting economic revenues [18]. However, there is no information on the environmental implications of such WTE options under Chilean conditions.

In this context, this paper presents a case study of three alternative WTE scenarios, as part of a circular economy strategy, involving electricity and heat generation from MSW combustion, gasification, and landfill biogas, at the Bio Bio Region in Southern Chile.

2 METHODOLOGY

The ISO 14040:2006 and 14.044:2006 standards were used as the methodological framework to conduct this comparative LCA study [19], [20].

The study was based on primary MSW data, complemented with technical information provided by suppliers of combustion and gasification commercial technologies, environmental reports, questionnaires, interviews, and other primary sources. Additionally, data gaps were bridged using literature information and publicly available LCA databases.

2.1 MSW characterisation

MSW was obtained from the Borough of Concepcion landfill (36°45’51”S, 72°57’48”W). This landfill site receives around 240 ton MSW /day all year round, mainly from households and commerce. Every day, 40 trucks collect garbage from routes serving different kinds of neighbourhoods covering a total population of nearly 250.000 inhabitants, featuring an average MSW generation rate around 0.96 kg/person/day.

Collection and classification procedures were carried out according to standard procedures [21], [22]. Samples were obtained from municipal refuse trucks at the landfill entrance yard twice a month. A total of twenty-four non-stratified random samples were collected during 2016, to cover seasonal variations. Vehicles for sampling were selected at random every time; each sorting sample weighed 90–110 kg as received, and was properly mixed, coned and quartered from each discharged MSW vehicle load, using a front-end loader. After sampling, hand sorting was applied for the classification of MSW into three main categories of fuel-grade municipal solid wastes, namely, paper-cardboard, plastic and organic MSW. Samples were stored in water-proof sealed bags and transported to the Environmental Engineering Laboratory at the University of Concepcion within a 4 h timespan after sampling, for storage and further characterization.

Physical–chemical characterization of MSW samples was carried out using standard procedures. Proximate analysis was carried out following standard procedures, as follows, moisture content [23], ash [24], and volatile matter [25]. Calorific values were determined in a PARR-6400 automated calorimeter [26], whereas elemental analysis was performed in a LECO True Spec Analyzer, according to established standards [27].

Landfill methane, carbon dioxide and other gaseous emissions generated from biological degradation of MSW were estimated on the basis of the US-EPA LandGEM model version 3.02 [28], which uses a first-order decomposition rate equation. Site-specific parameters related to landfill design and operational features were kindly provided by the landfill operators.

2.2 Definition of goals and scope

The goal of this LCA is to compare the environmental attributes of different WTE alternatives considering an integrated waste management life cycle approach. The study focusses on municipal solid waste generated at the Borough of Concepcion, Bio Bio Region in Southern Chile, representing a typical medium size urban settlement in developing countries, featuring housing as well as commercial, public services and light manufacturing activities. Currently, the 200,000 m^2 municipal landfill features leachate treatment and water recycling; however, it operates without any material or energy recovery system. Alternatives for WTE include biogas capture for electricity generation, biomass incineration and/or gasification. Studies have already shown the technical and economic feasibility of such options [4], [13], [18]; therefore, the present work is expected to provide further information on the corresponding environmental attributes based on site-specific conditions.

The functional unit, which enables the system inputs/outputs to be quantified and normalised, is 1000 kg of MSW as received at the municipal landfill serving the Borough of Concepcion.

The boundaries for the environmental life cycle assessment include waste collection, transport to the waste treatment plant, pre-treatment processes, material recovery for recycling, and heat/power production. Distribution of steam and electricity is not included here. Main material and energy supplies are also included, as well as management and disposal of final solid residues from transformation processes.

2.3 Data sources

Data were obtained from primary and secondary sources. As mentioned above, 24 MSW samples were randomly obtained during a bi-monthly sampling campaign over 2016. Data on MSW composition, MSW generation rate and garbage transport were obtained from local primary sources, including laboratory analysis of MSW samples, environmental monitoring reports, landfill design documentation and operational procedures, and questionnaires/interviews to relevant stakeholders. Data on energy conversion efficiencies, and equipment technical specifications were obtained from technology suppliers. Air emissions and water discharges associated to WTE technologies were complemented with data obtained from Ecoinvent databases.

2.4 Environmental impact assessment models

There is a wide range of impact assessment models, including mid-point and end-point approaches [29]. In this study, the updated version of CML 2 Baseline 2000 v2.05/World, 1990 was used to describe the environmental impacts associated to each WTE scenarios [30]. This includes ten mid-point indicators that account for climate change, natural resources depletion, acidification and eutrophication potentials, toxicity, and emissions to soil, water, and air, among others.

Additionally, the Eco-indicator 99 end-point impact assessment model was used for comparison's sake. That model considers three end-point indicators related to damage to human health, ecosystem quality, and resources use, each related to a number of impact sub-categories [31]. The software package Simapro™ v.7.3.3 was used to model the systems and calculate environmental impacts, on the basis of primary data complemented with the Ecoinvent v. 2.2 database.

2.5 Waste-to-energy scenarios

Four alternative waste-to-energy scenarios are considered here, as described below.

- *Scenario 1:* Business as usual (BAU).
  All MSW are disposed in landfills without any energy and material resource recovery. However, for safety and environmental reasons, 60% of biogas is collected and burnt in torches, whereas the rest are non-point source emission to the atmosphere. Leachate are treated by physical–chemical methods and recycled to irrigation of internal green areas and dust roads. The average leachate generation rate in the landfill is 0.1 m^3/ton MSW, and nearly 80% is recycled within the landfill facility. This scenario represents the baseline scenario for most small and medium size landfill*s* in developing countries.
- *Scenario 2*: Sixty percent of generated biogas is recovered and used for electricity generation, using gas engines. Surplus electricity is sold to the public electricity network. The biogas CH_4 and CO_2 contents are assumed 54% and 41%, respectively, on dry mass basis,

featuring an energy potential around 1,877 MJ/ton MSW. According to design data from an existing project in Chile, the average electricity generation efficiency for this type of generation system is 42% at full load, with an overall biogas consumption around 250 m^3/MWh. This is a US$ 15 million project, involving 6 x 1.5 MW_e gas engine generators (General Electric-Jenbacher GmbH&Co model JMS420GS), with a nominal biogas consumption of 4,500 m^3/h [32]. The system includes biogas pre-treatment with activated carbon. Recovery of metals and glass for recycling in the local market.

- *Scenario 3*: Combustible fractions of MSW, namely food and other organic waste, paper and cardboard, and plastics, are incinerated to produce electricity and heat generation. Electricity if sold to the public electricity distribution network, whereas glass and metals are recovered and sold in the recycle market. Non-combustible residues, including ash and air pollution control (APC) residues, are landfilled. This scenario is based on a 240 ton MSW/day movable grate boiler. Overheated steam is fed to a steam turbine, providing nearly 12 MW electricity. Cyclones and bag filters are used for pollution control to meet local air emission regulations.
- *Scenario 4*: Combustible fractions of MSW, namely food and other organic waste, paper and cardboard, and plastics, are gasified to produce combustible gases (mainly, CO, CH_4 and H_2) for electricity and heat generation. Glass and metals are recovered and sold in the recycle market. MSW incineration data is obtained from a 240 ton MSW/day Mitsubishi MSW Gasification system operating at 950°C. Gases (mainly CO, H_2 and CH_4) are transferred to a fluidised bed adiabatic combustion chamber at 1100°C. Then, hot combustion gases are fed to a recovery boiler that generates 68 ton steam/h, at 45 bar and 400°C. Electricity is generated in a steam turbine with a rated output of 12 MW_e generation capacity, equipped with air pollution controls, heat recovery and water conditioning.

Both, Scenarios 3 and 4 include a MSW pre-treatment stage involving shredding, screening, sorting, thermal sanitation and drying. Thermal sanitation aims at removing pathogens by autoclaving treatment with 120 kg steam/1000 kg MSW, at 5 bar and 150°C for 20 min. A rotatory trommel is used to classify materials according to size. These materials undergo further separation processes in order to recover specific fractions. Indeed, ferrous metals are separated using electromagnetic separators, whereas non-ferrous materials are separated by eddy (Foucault) current separators. In turn, plastic agglomerates are separated using optical separators.

A 10% stoichiometric excess air both in the incinerator and in the gas combustion chamber is used here in mass and energy balance calculations. The overall biogenic carbon content in the energy feedstock is assumed 61% mass dry ash free basis.

Fuel consumption by MSW collection trucks was estimated on the basis of fuel inventory records kindly provided by the landfill operators, yielding a yearly average of 5.4 dm^3 Diesel/ton MSW transported from source to the landfill disposal site. Refuse collection lorries were modelled on the basis of 7.5–16 ton lorry, EURO4 /RER U from Ecoinvent.

In this LCA study, a mass-based cut off point of 2% was established to filter out minor material streams, and the total mass left out could not exceed 10% of total mass. Moreover, infrastructure and equipment construction and end-of-life were not considered here. Furthermore, chemical inputs included aluminium sulphate, phosphoric acid, and hydrogen peroxide associated to leachate treatment, as well as lubricants, refrigerants, urea, activated carbon and other materials used in thermo-electrical conversion processes.

3 RESULTS AND DISCUSSION

3.1 MSW physical–chemical characterization

Table 1 shows average MSW mass composition obtained from 24 samples over a 12 months period; corresponding standard deviations are also included. Complementarily, Table 2 summarises proximate and ultimate analysis of MSW major fractions. Values obtained here are comparable with MSW data reported elsewhere [33].

Table 1: MSW weight composition.

Waste category	*% weight composition, dry basis*
Organic matter	54 ± 5
Papers and cardboard	13 ± 2
Plastic	10 ± 2
Textile, leather	2 ± 1
Garden residues	2 ± 1
Glasses	3 ± 2
Metals	2 ± 1
Other inorganic residues	14 ± 3

Table 2: Main MSW fractions: Proximate and ultimate analysis.

Parameter	*Unit*	*Organic matter*	*Paper and cardboard*	*Plastics and fabrics*
Proximate analysis				
Moisture	%, dry basis	86 ± 5	39 ± 4	12 ± 2
Ash	%, dry basis	10 ± 1	13 ± 2	4 ± 1
HCV	MJ/kg	20 ± 3	18 ± 2	33 ± 4
LCV	MJ/kg	18± 2	16 ± 2	30 ± 3
Volatile Matter	%, dry basis	72 ± 5	81 ± 7	91 ± 8
Fixed Carbon	%, dry basis	3 ± 1	4 ± 1	4 ± 1
Ultimate analysis				
Carbon	%, ash free dry basis	42	41	72
Hydrogen	%, ash free dry basis	5	7	12
Oxygen	%, ash free dry basis	53	52	16
Nitrogen	%, ash free dry basis	<1	<1	<1
Sulfur	%, ash free dry basis	<0.1	<0.1	<0.1
Chloride	ppm	0.4	0.2	0.1

3.2 Impact assessment of WTE scenarios

Predictions of environmental impacts associated to WTE scenarios are presented in Tables 3 and 4, for mid-point and end-point impacts models, respectively.

Additionally, Figs. 1 to 4 illustrate the normalized impacts for each WTE scenario, using mid-point impact indicators (CML 2000) and end-point damage indicators (Ecoindicator 99). The use of biogas for electricity production (Scenario 2) leads to an environmental improvement compared to the baseline Scenario 1, due to avoided emissions and fossil fuel consumption as a result of the injection of electricity into the public grid.

In addition to electricity generation, Scenarios 3 and 4 include glass and aluminium recycling; therefore, further fresh minerals extraction and energy consumption are avoided due to recycle of those resources.

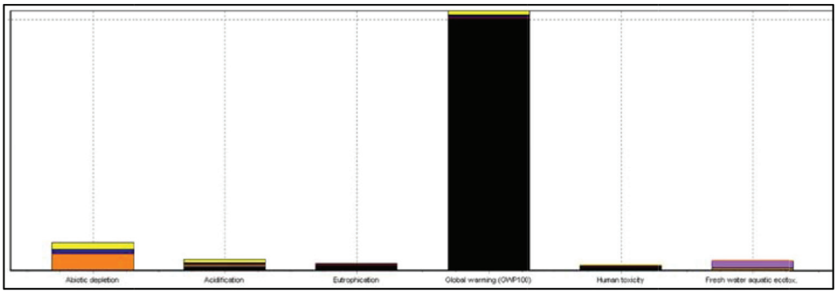
In the case of CML 2000 model, the GWP impact category is the main impact associated to landfill operation without energy recovery. Abiotic resources depletion related to fossil fuels usage in transport and grid electricity generation comes next, with less than 10% of the GWP effects. Moreover, the Ecoindicator 99 model predicts that human health damage constitutes the main end-point impact, followed by damage to natural resources.

Table 3: Environmental impacts associated to WTE scenarios. CML 2000 model.

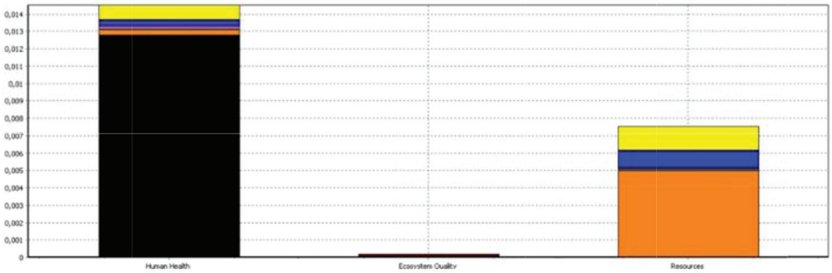
CML-2001 Environmental impact assessment					
Environmental impact categories		*WTE scenarios*			
	Unit	*1*	*2*	*3*	*4*
Electricity injected to grid	kWh	0	201	755	644
Global warming potential	kg CO_2 eq	516	413	−148	−135
Acidification	kg SO_2 eq	0.2	−0.4	−3.1	−2.9
Eutrophication	Kg PO_4^{-3}eq	0.1	0.1	0.9	0.2
Abiotic resource depletion	kg Sb eq	0.2	−0.5	−3.4	−3.4
Human toxicity	kg 1,4 DB eq	16	1	−15	−661
Fresh water toxicity	kg 1,4 DB eq	1	1	10	−30

Table 4: Environmental impacts associated to WTE scenarios. Ecoindicator 99 model.

Ecoindicador-99 Environmental impact assessment					
Environmental impact categories		*WTE scenarios*			
	Unit	*1*	*2*	*3*	*4*
Electricity injected to grid	kWh	0	201	755	644
Human Health	DALY	$1\ 10^{-4}$	$2\ 10^{-4}$	$-1\ 10^{-4}$	$-2\ 10^{-4}$
Ecosystem quality	PDF/m^2y	1	1	3	0.4
Resources	MJ surplus	57	−65	−621	−628



(a) Scenario 1. Normalized CML 2000, Mid point impacts



(b): Scenario 1. Normalized Ecoindicator 99, End point impacts

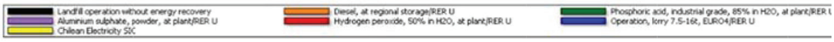


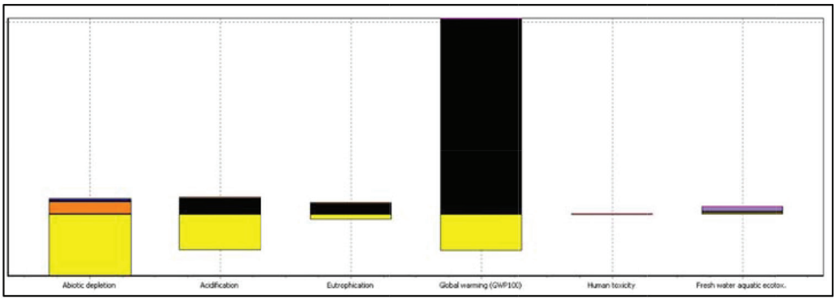
Figure 1: Scenario 1: Landfill without energy or material recovery.

Around 90% of human health could be attributed to gas emissions from landfill, whereas the remaining effects are related to fossil fuels consumption in transport and grid electricity generation.

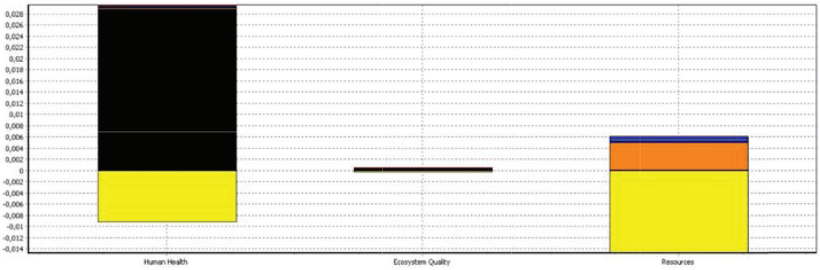
Injection of electricity to the public grid in Scenario 2 results in a positive effect on damage to resources, due to avoided consumption of fossil fuels for electricity generation. GWP is the main mid-point impact category; however, this is somewhat compensated by avoided emissions derived from the injection of electricity to the public grid. Additional positive effects due to avoided impacts related to abiotic depletion and acidification, where a net positive impact is attained. Human health damage from respiratory inorganics and climate change are the most important end-point impact category, as predicted by the Ecoinvent 99 model, followed by damage to natural resources. Damage to resources is fully offset by avoided fossil fuel consumption due to injection of electricity to the public grid.

Scenario 3 features both energy recovery by incineration of combustible waste, and glass and aluminium recovery for recycling. Fresh water aquatic ecotoxicity is drastically reduced when considering the avoided emissions associated to aluminium production. Similar offsets could be seen for damage to human health and natural resources, where large offsets are attained in respiratory inorganics, climate change and fossil fuel consumption, due to aluminium recovery and electricity injection to the public grid.

The use of gasification technology for electricity generation in Scenario 4 yields similar impacts as those observed in Scenario 3. However, offsets in human toxicity impact category



(a) Scenario 2. Normalized CML 2000, Mid point impacts



(b): Scenario 2. Normalized Ecoindicator 99, End point impacts

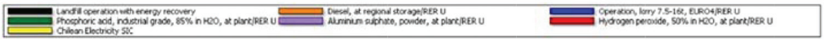
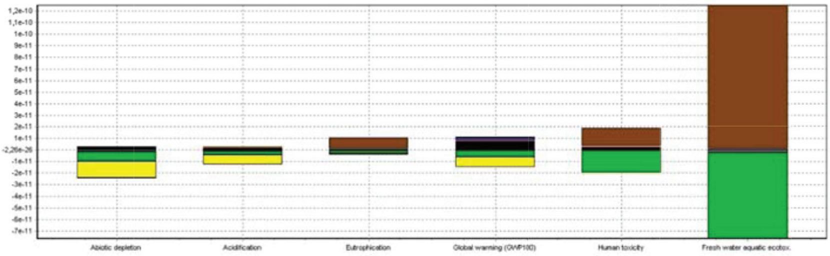
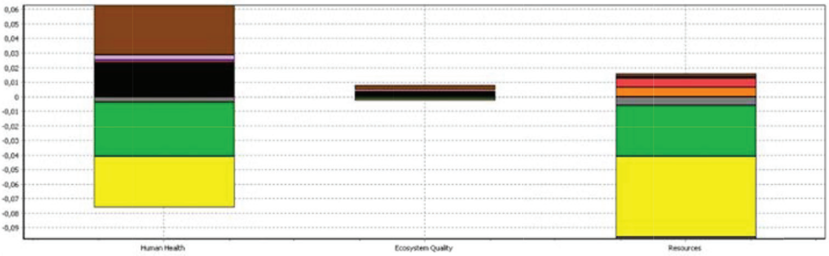


Figure 2: Scenario 2: Landfill with biogas recovery for electricity generation.



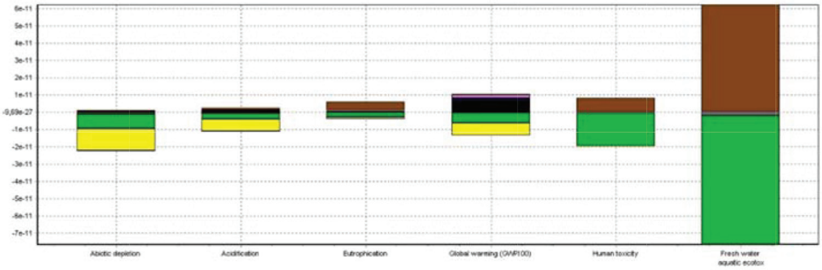
(a) Scenario 3: Normalized CML 2000, Mid point impacts

Figure 3: Scenario 3: MSW incineration for electricity generation and materials recovery.

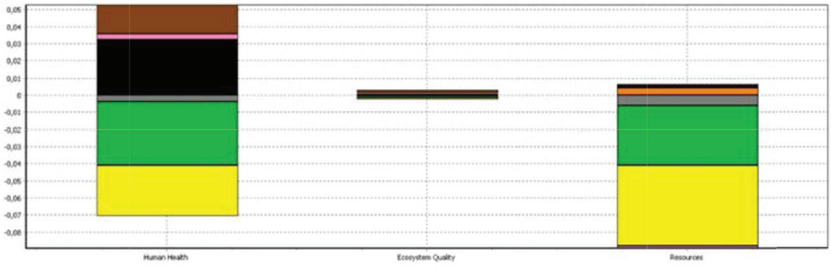


(b) Scenario 3: Normalized Ecoindicator 99, End point impacts

Figure 3: (*Contined*)



(a) Scenario 4: Normalized CML 2000, Mid point impacts



(b) Scenario 4: Normalized Ecoindicator 99, End point impacts

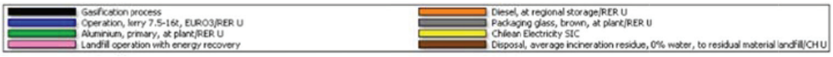


Figure 4: Scenario 4: MSW gasification for electricity generation, and materials recovery.

are much higher in the case of gasification as compared with incineration, as a consequence of much lower emissions of respiratory inorganics in Scenario 4.

Those positive environmental effects could increase if energy conversion efficiency associated to incineration and gasification are improved.

4 CONCLUSIONS

This study compares the environmental performance of three alternative WTE scenarios under typical conditions of a mid-sized town in a developing country.

Energy recovery, either from biogas or MSW incineration or gasification, results in a significant reduction in global warming potential, acidification, human toxicity and abiotic resources impact categories.

The positive contributions of material and energy recovery to overall environmental performance are clearly shown here, particularly in the case of aluminium recycling that results in a direct positive impact on human health, fresh water ecotoxicity and natural resources.

Positive impacts due to avoided fossil fuel and mineral consumptions, as a result of electricity injection to the public grid and aluminium recycling, are sufficiently large to generate offsets in various impact categories.

Finally, results obtained here highlight the value of life cycle assessment to identify the environmental attributes of WTE alternatives in the context of decision making concerning circular economy scenarios.

REFERENCES

[1] Palmiotto, M., Fattore, E., Paiano, V., Celeste, G., Colombo, A. & Davoli, E., Influence of a municipal solid waste landfill in the surrounding environment: toxicological risk and odor nuisance effects. *Environment International*, **68**, pp. 16–24, 2014.

[2] Fernandez-González, J.M., Grindlay, A.L., Serrano-Bernardo, F., Rodriguez-Rojas, M.I. & Zamorano, M., Economic and environmental review of waste-to energy systems for municipal solid waste management in medium and small municipalities. *Waste Management*, **67**, pp. 360–374, 2017.

[3] Arafat, H.A., Jijakli, K. & Ahsan, A., Environmental perdormance and energy recovery potenctial of five processes for municipal solid waste treatment. *Journal of Cleaner Production*, **105**, pp. 233–240, 2015.

[4] Bosmans, A. & Helsen, L., Energy from Waste: Review of thermochemical technologies for refuse derived fuel (RDF) treatment. *Proceedings Venice 2010, Third International Symposium on Energy from Biomass and Waste,* Venice, Italy, pp. 8–11, November 2010.

[5] Leckner, B., Process aspects in combustion and gasification Waste-to-Energy (WtE) units. *Waste Management*, **37**, pp.13–25, 2015.

[6] Panepinto, D., Tedesco, V., Brizio, E. & Genon, G., Environmental performances and energy efficiency for MSW gasification treatment. *Waste Biomass Valor*, **6**, pp. 123–135, 2015.

[7] Lee, U., Chung, J.N. & Ingley, H.A., High-temperature steam gasification of municipal solid waste, rubber, plastic and wood. *Energy Fuels,* **28(7)**, pp. 4573–4587, 2014.

[8] Chen, D., Yin, L., Wang, H. & He, P., Pyrolysis technologies for municipal solid waste: A review. *Waste Management*, **37**, pp. 116–136, 2015.

[9] Wang, H., Wang, L. & Shahbazi, A., Life cycle assessment of fast pyrolysis of municipal solid waste in North Carolina of USA. *Journal of Cleaner Production*, **87**, pp. 511–519, 2015.

[10] Akolkar, A.B., Choudhury, M.K. & Selvi, P.K. Assessment of methane emission from municipal solid wastes disposal sites. *Research Journal of Chemistry and Environment*, **24(4)**, pp. 49–55, 2008.

[11] Ahmed, S.I., Johari, A., Hashim, H., Lim, J.S., Jusoh, M., Mat, R. & Alkali, H., Economic and environmental evaluation of landfill gas utilisation: A multi-period optimisation approach for low carbon regions. *International biodeterioration & biodegradation*, **102**, pp. 191–201, 2015.

[12] Broun, R. & Sattler, M., A comparison of Greenhouse Gas Emissions and potential electricity recovery from conventional and bioreactor landfills. *Journal of Cleaner Production*, **112**, pp. 2664–2673, 2016.

[13] Gökçek, M. Waste to energy: exploitation of landfill gas in micro turbines. *Journal of Engineering Sciences*, **6(2)**, pp. 710–716, 2017.

[14] Astrup, T.F., Tonini, D., Turconi, R. & Boldrin, A., Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. *Waste Management*, **37**, pp. 104–115, 2015.

[15] Ayodele, T.R., Ogunjuyigbe, A.S.O. & Alao, M.A., Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. *Applied Energy*, **201**, pp. 200–218, 2017.

[16] Lee, U., Han, J. & Wang, M. Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways. *Journal of Cleaner Production*, **166**, pp. 335–342, 2017.

[17] Karlsson, J., Brunzell, L. & Venkatesh, G., Material flow analysis, energy analysis, and partial environmental LCA of a district heating combined heat and power plant in Sweden. *Energy,* **144**, pp. 31–40, 2018.

[18] Bidart, C., Fröhling, M. & Schultmann, F., Municipal solid waste and production of substitute natural gas and electricity as energy alternatives. *Applied Thermal Engineering*, **51(1–2)**, pp. 1107–1115, 2013.

[19] ISO 14.040. Environmental management—Life cycle assessment—Principles and framework. *International Organization for Standardization*, Geneve, Switzerland, 2006.

[20] ISO 14.044. Environmental management—Life cycle assessment—Requirements and guidelines. *International Organization for Standardization*, Geneve, Switzerland, 2006.

[21] NCh. 3321. Norma Chilena 3321: Caracterización de residuos sólidos municipales. *Instituto Nacional de Normalización*, Santiago, Chile. 2012.

[22] ASTM D5231-92(2008). Standard test method for determination of the composition of unprocessed municipal solid waste. *ASTM International*, West Conshohocken, PA, 2008.

[23] ASTM E790-87(2004). Standard test method for residual moisture in a refuse-derived fuel analysis sample. *ASTM International*, West Conshohocken, PA, 2004.

[24] ASTM E830-87(1996). Standard test method for ash in the analysis sample of refuse-derived fuel. *ASTM International*, West Conshohocken, PA, 1996.

[25] ASTM E897-88(2004). Standard test method for volatile matter in the analysis sample of refuse-derived fuel. *ASTM International*, West Conshohocken, PA, 2004. www.astm.org

[26] BS EN 14918. Solid biofuels. Determination of calorific value, 2009.

[27] BS EN ISO 16948: 2015 Solid biofuels. Determination of total content of carbon, hydrogen and nitrogen, 2015.

[28] EPA. *Landfill Gas Emissions Model (LandGEM) Version 3.02. EPA-600/R-05/047*. U.S. Environmental Protection Agency. Office of Research and Development, Washington, DC 20460, 2005.

[29] Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R. & Hellweg, S., Recent developments in life cycle assessment. *Journal of Environmental Management*, **91(1)**, pp. 1–21, 2009.

[30] Guinée, J.B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R. & Koning, A.D., *Handbook on life cycle assessment. Operational guide to the ISO standards. I: LCA in perspective. IIa: Guide. IIb: Operational annex. III: Scientific background*. Kluwer Academic Publishers, ISBN 1-4020-0228-9, Dordrecht, 2002.

[31] PRé Consultants. SimaPro 7.3.3. Pré Consultants, Amersfoort, the Netherlands. 2009.

[32] Environmental Impact Declaration. Planta Bio Energia Los Pinos. Presented to the Chilean Environmental Impact Assessment Service in August 2017. http://seia.sea.gob.cl/documentos/documento.php?idDocumento=2132658505 (accessed 12 September 2017).

[33] Tchobanoglous, G., Theisen, H. & Vigil, S., *Integrated Solid Waste Management Engineering Principles and Management Issues*, McGraw-Hill, Inc.: Singapore, 1993.