European Journal of Sustainable Development (2018), 7, 3, 387-395 ISSN: 2239-5938
Doi: 10.14207/ejsd.2018.v7n3p387

Environmental Impact Assessment of Municipal Solid Waste (MSW) Management in Florence, Italy

Piernicola Masella[1], Lorenzo Guerrini[1], Giulia Angeloni[1], Alessandro Parenti[1]

Abstract

Facing the trouble of municipal solid waste (MSW) management is a rising challenge of urbanized areas. Yearly data of waste management from the city of Florence (Italy) and neighboring municipalities were gathered over 2015 year. About 412105 t of waste were collected, where 202794 t were mixed-waste and 72540 t were organic. Fractions were treated in a centralized selecting-composting plant. The outgoing materials were further treated in external plants for additional selection, composting, incineration, landfilling. The present study was aimed to assess the environmental impact of such waste management applying LCA technique. The functional unit was "one year mixed and organic waste treatment at Florence and neighboring municipalities". System boundaries included waste collection, final transport, working of the selecting-composting plant. System expansion was used to account for energy recovery (electricity) from waste. Background data were sourced from ELCD-core3-LCI database. Life cycle impact assessment (classification and characterization) was performed by ILCD midpoint method. Sixteen impact categories were computed. Focusing on global warming potential (GWP), the functional unit impacts for roughly 6.99E+8kgCO2eq. This figure drops to 0.212E+8kgCO2eq if urban collection was not considered and further to 0.186E+8kgCO2eq if final transportation was excluded. Results underline the potential benefit of on-site treatment of waste.

Keywords: urban waste, landfilling, biogas, incineration, LCA, global warming potential

1. Introduction

Municipal solid waste (MSW) management is a rising challenge of urbanized areas. The European Union called the imperative to follow hierarchical options for the management systems, moving from waste generation prevention to reuse preparing and recycling, to energy recovery, and only as a last option the waste disposal (Directive 2008/98/EC of the European Parliament and of the Council of 19th November 2008, on Waste). At the same time, public concerns still remain about the construction of new facilities and the adoption of new technologies. This main relies on the health matter, as consequences of direct and indirect effects of MSW management (Giusti, 2009). In this contest, Life Cycle Assessment (LCA) is an even more worldwide adopted technique to assess and compare the environmental burdens of MSW treatment strategies. Good examples are the works of Gunamantha and Sarto (2012), which study different options of MSW-to energy conversion in Indonesia, or that of Yay (2016) in Turkey. In the European contest, Jensen et al. (2016) focused on LCA of organic waste management, while Fernandez-Nava et al. (2014) compare alternatives for MSW management in Spain. At Italian level, Ripa et al. (2017) underline the importance of site-specific data for a

| [1]Department of Agricultural, Food and Forestry Systems Management (GESAAF) - Agricultural, Forest and Biosystem Engineering Section - Università degli Studi di Firenze, Piazzale delle Cascine 15, 50144 Florence, Italy

reliable application of LCA to MSW management, bringing as an example the city of Naples (case-study). Cherubuni et al. (2009), compare three different strategies (landfilling, sorting plant and incineration) for waste management in Rome.

The city of Florence (Tuscany region, 43°46'17" N 11°15'15"E, 47 m a.s.l.) is the eighth largest municipality in Italy (102.32 km², population of around 380000 inhabitants at 2015) (Comune di Firenze, 2015). Sustainability data (input and output materials, energy use, transport data, emissions) of waste management (collection and treatment) from Florence and 12 other neighboring municipalities are annually published and are freely available (Quadrifoglio spa, 2015). The present study was based on data from the 2015 report. Out of total waste collected in that year, about 50% were mixed waste and 18% were organic. Great parts of these two fractions were treated in a centralized selecting-composting plant. The outgoing materials (treated-MSW, organic stabilized fraction, secondary fuels, metals and leftovers) were further treated in external plants, following different fates, i.e. further selection and recovery, composting, incineration, landfilling. The study was aimed to assess the environmental impact of such waste management applying LCA technique.

2. Building the LCA model

According to ISO standards (International Standard Organization, ISO 14041-14042-14043), a LCA study should include the four steps of goal and scope definition, life cycle inventory (LCI) analysis, assessment of the potential impacts (Life Cycle Impact Assessment, LCIA) and interpretation. The most comprehensive framework of LCA is the so-called cradle-to-grave assessment, where the full life cycle of a product in considered, from resource extraction, to use and disposal phases. A variant of the latter is the gate-to-gate assessment, where a partial life cycle assessment is performed, looking at only one value-added process in the entire production chain. Moreover, LCA studies are generally product-oriented, meaning that the functional unit selected for the study and accounting for the computed environmental burdens is usually defined in terms of the system's output, i.e. the product. By contrast, dealing with waste management asks for defining the functional unit in terms of the input to the system. Roughly speaking, a useful trick is to consider the treated-waste as the product (output) of the treatment process.

In the present work, a gate-to-gate life cycle model has been built. The functional unit was "one year mixed and organic waste treatment at Florence and neighboring municipalities". Hence, the computed impact indicators (LCIA) refer to the treatment of waste other than pre-sorted and recycled wastes, produced, collected and treated in a specific geographical region (Florence plus 12 other neighboring municipalities) in a given time (i.e. 1 year). The work was based on data published in the "2015 Sustainability Balance" by Quadrifoglio Spa (Alia Servizi Ambientali SpA, 2015). Data are freely available on the web, and cover the annual flows of materials (waste, chemicals, water) and energy (electricity, fossil fuels) needed for MSW treatment. Tables 1-5 summarize the data extracted from the report. In 2015 year a total of 412105 t of waste were collected over the entire considered territory. Out of these, 202794 t were mixed waste and 72540 t were organic (Table 1).

Table 1: Waste amount and composition for year 2015

waste production			
item	**year**	**unit**	**amount**
mixed waste	2015	t	202794
pre-sorted and recycled wastes	2015	t	209311
total waste	2015	t	412105
pre-sorted waste glass	2015	t	21335
pre-sorted waste paper and cardboard	2015	t	69020
pre-sorted waste plastic, tin, etc	2015	t	16504
pre-sorted metals	2015	t	1118
pre-sorted organic and vegetal	2015	t	72540
other	2015	t	28794

Great parts of these two latter fractions were treated in an in-site centralized selecting-composting plant. The outgoing materials (treated-MSW, organic stabilized fraction, secondary fuels,) were further treated in external plants, following different fates, i.e. further selection and recovery, composting, incineration, landfilling (Table 2).

Table 2: Fate of waste

Fate	**in-site treatment (t)**	**out-site treatment (t)**	**total (t)**
selecting-composting plant/selection*	124950	38167	163117
landfilling*	0	16717	16717
incineration*	0	22960	22960
selecting-composting plant/composting**	61534	11006	72540
total (t)	186484	88850	275334

In short, about 50% of total wastes collected belong to pre-sorted and recycled wastes, with an organic fraction of about 18%. The latter undergoes in-site composting (75%) or outside composting (15%). The mixed waste (50% of the total) undergoes in-site selection/mechanical treatment for about 62%, while about 19% follows the same fate in external plants. The remaining 8% and 11% out of the mixed waste, are out-site landfilled or incinerated, respectively.

System boundaries included mixed wastes and organic fraction collection and transport, working of the selecting-composting plant and final transport to the out-site treatments. Working of the external plants (out-site treatments) was not included because environmental burdens will weigh on those specific plants, that is on other territories.

Wastes collection was considered in terms of fossil diesel consumption for the operation. The data of total consumption was extracted from the report and scaled to the unit mass of total collected wastes. Then, the unit value has been multiplied by the amount of mixed wastes plus the organic fraction. Annual working of the selecting-composting plant requires electricity, natural gas, water and chemicals (Table 3).

Table 3: Requirements for one-year working of the selecting-composting plant

item	**unit**	**amount**
total electricity	kWh	6704368
electricity from biogas	kWh	2014214
electricity from grid	kWh	4395086
electricity from photovoltaic	kWh	295068
natural gas	m^3	9850
water	m^3	11772
sodium hydroxide	kg	10000
hydrogen peroxide	kg	250
output waste water	m^3	22260

The main waste of the plant is waste water, which requires a further treatment (Table 4)

Table 4: Requirements and emissions for the treatment of waste water outgoing the selecting-composting plant

Item	**unit**	**amount**	**emissions**		
waste water	m^3	21812	NO3	kg	1.06
electricity consumption	kWh	271691	Cd	kg	0.01
emissions			Cr	kg	0.16
COD	kg	425.31	Cu	kg	0.05
BOD	kg	15.87	Pb	kg	0.01
NH3	kg	0.26	Ni	kg	0.05
NO2	kg	0	Zn	kg	0.13

Annual materials flows of the plant are further detailed in Table 5. The main output (40% of total) is a refuse derived fuel destined to be burned for electricity recovery. The Non-reusable fraction (20% of total), the treated-MSW (18% of total) and the stabilized organic fraction (9% of total) are destined for landfill, with recovery of electricity by biogas production. The undersized fraction is destined to a further selection/mechanical treatment. All these treatments are carried out in external plants.

Table 5: Mass balance of one-year working of the selecting composting plant.

input	**unit**	**amount**	**fate**
total waste	t	186484	in-site treatment
mixed waste to sorting	t	124950	in-site treatment
organic fraction to composting	t	61534	in-site treatment
output			
treated-MSW	t	21921	Out-site landfilling
Non-reusable fractions	t	24573	Out-site landfilling
stabilized organic fraction	t	11364	Out-site landfilling
Undersized fraction to recovery	t	13966	Out-site mechanical biological treatment
refuse derived fuel		53127	Out-site incineration
soil improver	t	9231	market
other	t	3269	unknown
total output materials	t	137450	
losses, stock and leftovers	t	49034	

Data about final transport of wastes to the external plants have been extracted from the report on the base of total amount of waste transported (about 200000 t) during the year, the average number of travel (about 8650), the total amount of kilometers traveled (about 2000000 km). This gives a final figure of roughly 50000000 t*km of transport.

The report also specifies annual requirements (materials and energy carriers) for infrastructure management, intended as yearly working of the registered/main office, operational headquarters and special waste collection centers (Table 6).

Table 6: Annual requirements (materials and energy carriers) for infrastructure management

Urban infrastructures management	
total electricity (kWh)	1683379
total natural gas (mc)	172218
total water (mc)	41913

The total amounts of Table 5 were scaled to the unit amount of yearly waste collected and then multiplied by the amount of wastes corresponding to the functional unit.

The LCA model has been built in openLCA software (v. 1.5.0), a free and open source Life Cycle and Sustainability Modeling Suite by GreenDelta GmbH (Germany). Background data were sourced from ELCD core 3 LCI database (Joint Research Centre, EC). Specifically, the main following unit or system processes have been used: fuels combustion (diesel, natural gas, coal); electricity mix, Italian grid; electricity from landfill; electricity from waste incineration; electricity from photovoltaic; chemicals production (hydrogen peroxide, sodium hydroxide); articulated lorry transport (25 t payload).

Foreground data about wastes production and treatment, were extracted from the cited "2015 Sustainability Balance" by Quadrifolgio spa, as detailed above. System expansion was used to account for energy recovery (electricity) from treated wastes. In detail, the system has been credited for the displacement of electricity grid production of the specific Italian mix, both for the electricity from landfill biogas and for electricity from waste incineration.

Life cycle impact assessment (LCIA, classification and characterization) was performed according to the ILCD2011 impact assessment method at midpoint level, as developed by Joint Research Centre (JRC) of the European Commission. Figure 1 gives an outline of the system model.

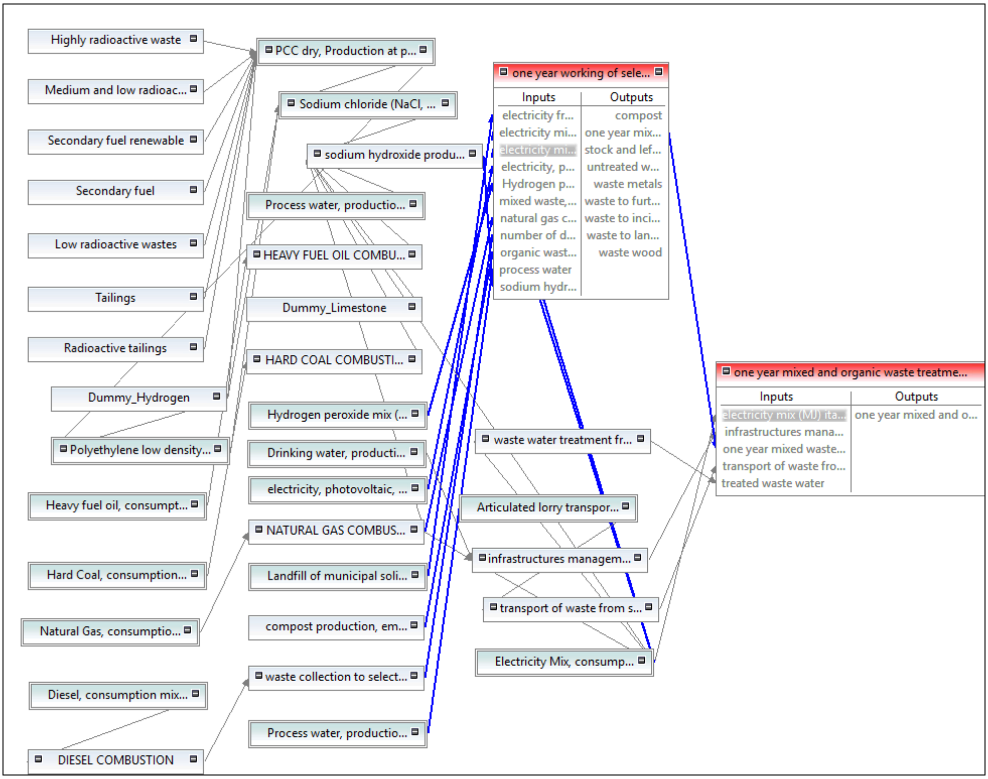


Figure 1: Structure of LCA model.

3. Results and Interpretation

Table 7 gives the results of LCIA for the sixteen impact indicators computed according to the ILCD2011 method. We can pay special attention on climate change by the global warming potential indicator (GWP, kgCO$_2$eq/FU). The indicator roughly amounts to 6.99E+08 kgCO2eq/FU, corresponding to about 2500 kgCO2eq per ton of treated wastes. This figure is about thirty times lower than the value reported by Ripa et al. (2017). Probably, both the different assumptions used for the construction of the model (e.g. system boundaries, allocation choices) and the different impact methods, contribute to this discrepancy. By contrast, our result is consistent with findings of Cherubini et al. (2009), where a very similar scenario (mixed wastes and organic fraction treated in a selecting/composting plant) gives a GWP of 7.04E+8 kgCO2eq on yearly base. The magnitude of our GWP is also consistent with the range computed by Fernandez-Nava et al. (2014), varying between about 30 and 4600 kgCO2eq/t of treated waste. A useful benchmark to understand the scale of the our result is the Italian Greenhouse Gas Inventory 1990 - 2015, National Inventory Report 2017 (ISPRA 2017), where the Italian waste sector has been accounted for a total equivalent emission of 1.88E+10kgCO2eq for the 2015 year. Our GWP for the same year represents about 3.7% of this figure. Moreover we can crosscheck our finding by computing the per capita GWP potential due to the waste sector, via dividing the total equivalent emission of the sector (1.88E+10kgCO2eq) by the Italian population of 2015 year (60.73E+6 inhabitants). The resulting per capita amounts of 3.09E+02 kgCO2eq/inhabitant, can be multiplied by the population of the territory under study (6.54E+05), thus obtaining a final estimate of 2.02E+08 kgCO2eq/FU, which represent an average indirect estimate of GWP imputable to our functional unit. This latter figure is about 3.5 times lower than the GWP computed in our study, indicating that our assessment may be overestimated. However, it should be noted that the Italian waste management strongly differs among territories, either on regional scale or national scale.

Table 7: Impact indicators coming from LCIA computation (ILCD2011 midpoint method)

Impact category	**with collection**	**without collection**	**Reference unit**
Acidification	1.671E+07	6.86E+06	Mole H+ eq.
Climate change	6.996E+08	2.12E+07	kg CO2 eq.
Freshwater ecotoxicity	1.265E+07	-4.20E+05	CTUe
Freshwater eutrophication	1.435E+03	1.28E+03	kg P eq.
Human toxicity - carcinogenics	1.186E-01	2.31E-02	CTUh
Human toxicity - non-carcinogenics	1.059E+00	-2.65E-01	CTUh
Ionizing radiation - ecosystems	6.000E+00	-1.04E+01	CTUe
Ionizing radiation - human health	6.787E+05	-9.85E+05	kg U235 eq.
Land use	2.144E+09	2.14E+09	kg SOC
Marine eutrophication	5.365E+06	1.20E+06	kg N eq.
Ozone depletion	3.669E-01	-1.00E+00	kg CFC-11 eq.
Particulate matter/Respiratory inorganics	3.892E+05	2.19E+05	kg PM2.5 eq.
Photochemical ozone formation	1.422E+07	3.29E+06	kg C2H4 eq.
Resource depletion - mineral, fossils and renewables	1.109E+02	2.76E+01	kg Sb eq.
Resource depletion - water	-4.104E+06	1.32E+07	m3
Terrestrial eutrophication	6.175E+07	1.61E+07	Mole N eq.

Contribution analysis reveals that over 95% of total GWP comes from the waste collection process. Data about the latter process have been extracted from the report with some uncertainty. In fact, the report gives the total amount of diesel consumed (about 2421341kg) for waste collection plus the processes entailed in the urban cleaning, without discrimination among the two operations. By analyzing the composition of machineries available for the two processes (waste collection and urban cleaning), a reasonable share of 0.68 for collection out of the total consumption, has been assumed. This gives about 4.73E+07 kg/FU of diesel. Obviously, GWP is extremely sensitive to diesel consumption, so much so that if collection is excluded from the system boundaries, GWP drops to 0.212E+8kgCO2eq/FU (Table 7), while a decreasing sharing of diesel consumption gives intermediate results (Figure 2). Interestingly, by halving the diesel share (i.e. from 0.68 to 0.34) the computed GWP approach the value reported by ISPRA (2017). As expected, all the indicators are sensitive to the waste collection via the diesel combustion process (Table 7 and Figure 2). Once the collection process is excluded, contribution analysis reveals that the main contributing processes are the waste transport to the out-side treatments and, above all, the infrastructure management (Figure 3). This pattern is almost common to most of the indicators. For the categories

Freshwater ecotoxicity, Human toxicity – carcinogenics, Human toxicity - non-carcinogenics, Ionizing radiation – ecosystems, Ionizing radiation - human health, Marine eutrophication, Ozone depletion, Particulate matter/Respiratory inorganics, Photochemical ozone formation, Resource depletion - mineral, fossils and renewable, and Terrestrial eutrophication, the most impacting process is the infrastructure management. Specifically for acidification and Particulate matter/Respiratory inorganics, the infrastructure management account for over 90%, while about 10% is due to emissions from compost production. For Freshwater ecotoxicity, Human toxicity - non-carcinogenics, Photochemical ozone formation, and Resource depletion - mineral, fossils and renewable, final transport to the out-side treatments is the most relevant process. For freshwater eutrophication, the most significant process is landfilling. The latter is also important for Human toxicity – carcinogenics, while for Ionizing radiation – ecosystems and Ozone depletion, the waste water treatment from the selecting-composting plant is significant via the grid electricity consumption. Finally, the importance of the transport process is also detectable by excluding the final transportation of waste to the out-site treatments, i.e. assuming that all the treatments may be carried out in-site. In this case, the GWP drops to 0.186E+8kgCO2eq/FU, with a potential saving of about 10%.

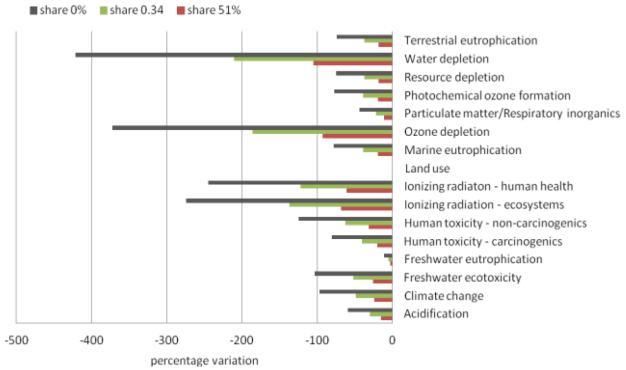
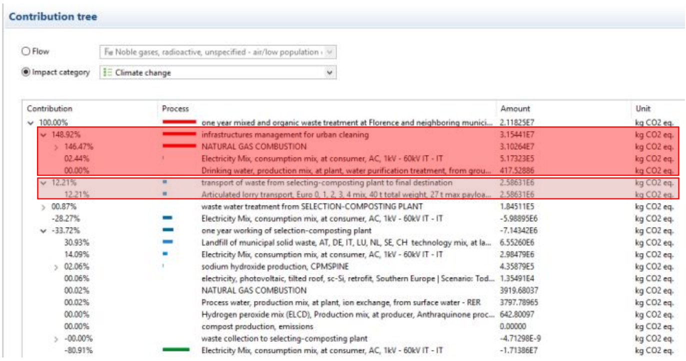


Figure 2: Sensitivity of indicators to the waste collection process. Variations refer to a diesel consumption share of 0.68 among collection and urban cleaning operation.



Contribution tree

○ Flow Noble gases, radioactive, unspecified - air/low population

● Impact category Climate change

Contribution	Process	Amount	Unit
100.00%	one year mixed and organic waste treatment at Florence and neighboring munici...	2.11825E7	kg CO2 eq.
148.92%	infrastructures management for urban cleaning	3.15441E7	kg CO2 eq.
146.47%	NATURAL GAS COMBUSTION	3.10264E7	kg CO2 eq.
02.44%	Electricity Mix, consumption mix, at consumer, AC, 1kV - 60kV IT - IT	5.17323E5	kg CO2 eq.
00.00%	Drinking water, production mix, at plant, water purification treatment, from grou...	417.52886	kg CO2 eq.
12.21%	transport of waste from selecting-composting plant to final destination	2.58631E6	kg CO2 eq.
12.21%	Articulated lorry transport, Euro 0, 1, 2, 3, 4 mix, 40 t total weight, 27 t max payloa...	2.58631E6	kg CO2 eq.
00.87%	waste water treatment from SELECTION-COMPOSTING PLANT	1.84511E5	kg CO2 eq.
-28.27%	Electricity Mix, consumption mix, at consumer, AC, 1kV - 60kV IT - IT	-5.98895E6	kg CO2 eq.
-33.72%	one year working of selection-composting plant	-7.14342E6	kg CO2 eq.
30.93%	Landfill of municipal solid waste, AT, DE, IT, LU, NL, SE, CH technology mix, at la...	6.55260E6	kg CO2 eq.
14.09%	Electricity Mix, consumption mix, at consumer, AC, 1kV - 60kV IT - IT	2.98479E6	kg CO2 eq.
02.06%	sodium hydroxide production, CPMSPINE	4.35879E5	kg CO2 eq.
00.06%	electricity, photovoltaic, tilted roof, sc-Si, retrofit, Southern Europe | Scenario: Tod...	1.35491E4	kg CO2 eq.
00.02%	NATURAL GAS COMBUSTION	3919.68037	kg CO2 eq.
00.02%	Process water, production mix, at plant, ion exchange, from surface water - RER	3797.78965	kg CO2 eq.
00.00%	Hydrogen peroxide mix (ELCD), Production mix, at producer, Anthraquinone proc...	642.80097	kg CO2 eq.
00.00%	compost production, emissions	0.00000	kg CO2 eq.
-00.00%	waste collection to selecting-composting plant	-4.71298E-9	kg CO2 eq.
-80.91%	Electricity Mix, consumption mix, at consumer, AC, 1kV - 60kV IT - IT	-1.71386E7	kg CO2 eq.

Figure 3: Contribution tree of aggregated processes to GWP indicator, as extracted from the software.

Conclusions

The built LCA model allows an estimate of potential environmental impact of waste management sector in Florence (Italy). The greater uncertainty belongs to the assessment of waste collection and transport process. This confirms that a substantial reduction of environmental burdens may be achieved by moving towards increased efficiencies of transports in the urban area, such as lighter vehicles, more efficient engines, improved fuels or increasing degree of hybridization (electricity) and cleaner/more-sustainable biofuels. At the same time, environmental impact may be reduced by planning the implementation of new local plant for in-site treatment of waste. Finally, the present work also showed that an important part of the impact is due the infrastructure management, thus underlining the need of an in-depth revision/audit of the organization and management of these structures.

References

Cherubini, F., Bargigli, S., & Ulgiati, S. (2009). Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. Energy, 34(12), 2116-2123. doi:10.1016/j.energy.2008.08.023

Comune di Firenze (2015). Retrieved from http://statistica.fi.it/opencms /opencms/MenuPrincipale/Dati/Popolazione_Firenze/index.html?comune=firenze

Fernández-Nava, Y., Río, J. D., Rodríguez-Iglesias, J., Castrillón, L., & Marañón, E. (2014). Life cycle assessment of different municipal solid waste management options: A case study of Asturias (Spain). Journal of Cleaner Production, 81, 178-189. doi:10.1016/j.jclepro.2014.06.008

Giusti, L. (2009). A review of waste management practices and their impact on human health. Waste Management, 29(8), 2227-2239. doi:10.1016/j.wasman.2009.03.028

Gunamantha, M., & S. (2012). Life cycle assessment of municipal solid waste treatment to energy options: Case study of KARTAMANTUL region, Yogyakarta. Renewable Energy, 41, 277-284. doi:10.1016/j.renene.2011.11.008

ISPRA. Italian Greenhouse Gas Inventory 1990 - 2015, National Inventory Report 2017 (Rep. No. 261).

Jensen, M. B., Møller, J., & Scheutz, C. (2016). Comparison of the organic waste management systems in the Danish–German border region using life cycle assessment (LCA). Waste Management, 49, 491-504. doi:10.1016/j.wasman.2016.01.03

Quadrifoglio Spa (by Alia Servizi Ambientali SpA) (2015) Bilancio di sostenibilità 2015. Retrieved from http://www.quadrifoglio.org/

Ripa, M., Fiorentino, G., Vacca, V., & Ulgiati, S. (2017). The relevance of site-specific data in Life Cycle Assessment (LCA). The case of the municipal solid waste management in the metropolitan city of Naples (Italy). Journal of Cleaner Production, 142, 445-460. doi:10.1016/j.jclepro.2016.09.149

Yay, A. S. (2015). Application of life cycle assessment (LCA) for municipal solid waste management: A case study of Sakarya. Journal of Cleaner Production, 94, 284-293. doi:10.1016/j.jclepro.2015.01.089