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LCA Analysis of Different MSW Treatment Approaches in the Light of Energy and Sustainability Perspectives

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This study concerns with a theoretical investigation on the disposal and valorisation of Municipal Solid Waste (MSW) through a challenging approach, based on the separation of MSW into two different fractions: Refuse Derived Fuel (RDF) and Organic Fraction Municipal Solid Waste (OFMSW). Both fractions are energetically valorised through gasification and anaerobic digestion (AD) processes respectively, in both cases gas streams were burned to produce electrical and thermal energy. The sustainability of the processes from the environmental as well as the energetic point of view, has been pursued, to find out if it can represent a viable alternative to the problem raised by the management of MSW and their landfill containment. Following the Life Cycle Analysis (LCA) approach, each stream of the processes has been analyzed in order to evaluate the environmental performances. On the other hand, the energy sustainability analysis has been carried out following the evaluation of two indexes: the Energy Sustainability Index (ESI) and the Energy Return of Investment (EROI). Results highlight that this process is more sustainable than landfill technology, in particular for *"global warming", "photochemical oxidation"* and *"eutrophication"* impact parameters of CML2001, and categories connected with *"Human Heath"* of Eco-indicator99 method; the comparison with traditional landfill option shows that the environmental impacts are less than 10%. The proposed MSW treatment approach is less sustainable than landfill for only two categories: *"acidification/eutrophication"* and *"minerals".* In merit to the energy sustainability analysis, the system results to have a positive merit: it produces a surplus of "Useful Energy".

1. Introduction

The MSW management represents one of the major issues in the present civilization era. Even if the significant achievement of the separate refuses collection systems aimed to the production of secondary materials, an important flow of undifferentiated waste, ranging in (70–25) % of MSW production, still justifies the continuous search for more environmentally suitable treatment technologies. Today the most studied alternative processes are aimed to energy recovery and the contemporary limitation of the confinement in the landfill. However, given the recent growing needs of environmental sustainability linked with the social acceptability of incinerators, research has focused on the development of new technologies such as the gasification of RDF (Malkow, 2004) that seems to be a competitor to the incineration, as showed by several studies (Angelova et al., 2014). In the same time in the recent years, the coupling between the AD and composting of OFMSW has been the choice of several Municipalities, thanks to the production of electricity, heat or biomethane and fertilizers. This study is aimed to evaluate the environmental and energy sustainability of an integrated process able to treat the MSW residue after the differential collection, via gasification and AD. Environmental sustainability of the process is assessed by the LCA methodology (Azapagic, 1999) by using as impact categories the more frequently considered for this type of system, and taking as "reference scenario" the landfill treatment option. The energy sustainability evaluation was carried out by the quantification of two indexes: Energy Sustainability Index (ESI) (Di Addario et al., 2016) and Energy Return On Investment (EROI) (Mulder and Hagens, 2008) in order to quantify the actual amount of energy useful to sustain the society.

2. Waste treatment plant considered

The object of the present study deals with the disposal of MSW products in a city of about one million of inhabitants. Considering a pro capita production of MSW in Italy equal to 488 kg per year and the average percentage of recycling equal to 45.2 %, the residue has been considered as representative of the feed to the virtual plant under investigation. As shown in Figure 1, in the analysis it has been included a first treatment step able to separate the inorganic fraction, as RDF, from the organic one, as OFMSW, and iron, as recycled material and some residue conveyed to the landfill. The two main streams are then valued separately in order to increase the energy efficiency of the overall process. The RDF section provides a shed used for the accumulation of the material and to assure a continuous feeding in the gasification section constituted by a fluidized bed gasifier followed by gas treatment section where the syngas produced passes through several apparatuses to remove ashes, tar and acid gases using sodium hydroxide. Finally, a cogeneration system (CHP) fueled by syngas produces electricity and heat. The OFMSW section, includes an accumulation basin from where the OFMSW is fed to the pulper where it is mixed with the recirculated water to obtain a homogeneous flow feeding of the digesters at adequate concentration of total solid (TS). The digestate output is separated into its liquid component, which constitutes the water recirculated (no purification section is necessary), and the solid fraction, sludge, which is sent to the composting section for the production of compost. The biogas, containing at least 60%*w/w* of CH_4, without any treatment of purification is burned (as occurs in full plant applications) in a cogeneration system that produces electricity and heat.

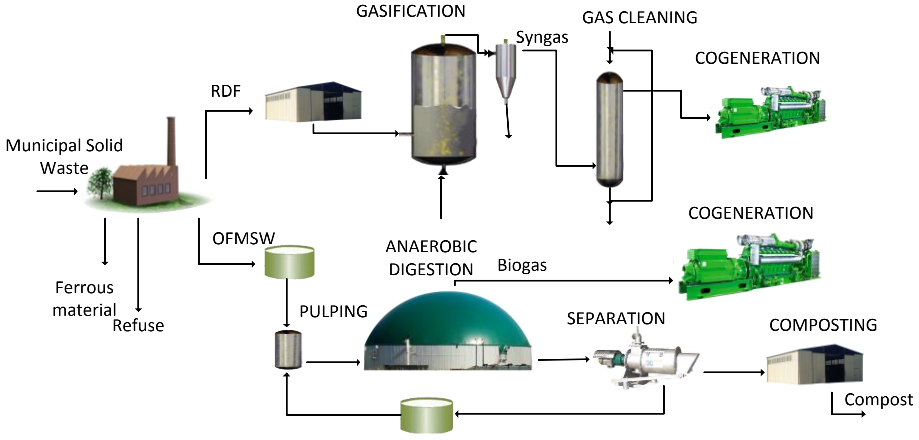

Figure 1. Main apparatus of the analysed plant for the treatment of MSW via RDF and AD valorisation approach

The plant has been firstly designed by recognition of scientific literature data for the gasification section and acquiring information available from existing plants for the OFMSW line. Technical calculations and simulations has been carried out by using the Aspen Plus software, for the mass and energy balances of the plant and to evaluate the mass flow rate of the streams leaving the process. Major efforts have been devoted to the design of the gasifier to find the optimal operating conditions and to obtain the composition of the syngas; a search of optimal running conditions such as gasification temperature, oxygen flow rate and the maximum energy efficiency (ratio between the calorific value of the syngas and the calorific value of the RDF), has been conducted. The simulation has been carried out by assuming the thermodynamic equilibrium for the gasifier outlet gas stream, as often reported in similar studies (Puig-Arnavat et al., 2010, Ramzan et al., 2011) in order to evaluate the syngas composition. The best operating conditions for the gasifier have been stated in order to guarantee a high efficiency and proper working temperature, and have been identified as the equivalence ratio (ER) equal to 0.41 by preheating the air at 600° C. The physical and chemical characterization of RDF, including its Low Heating Value (LHV), have been experimentally evaluated on real samples of RDF produced in a Southern Italy plant, chosen as representative matter for this study.

As regards the OFMSW treatment section, the starting point to design has been the identification of the percentage of dry (57.5%) and volatile substances (60% dry matter) present in the OFMSW, the amount of produced biogas (375 Nm^3/t_{tq}) and its methane content (55% *v/v*). All the data are a mean value of an existing AD plant treating the OFMSW in Northern of Italy. In addition, the following operating conditions have been considered: mesophilic conditions (35 °C), retention time of the substrate in the digesters of about 35 days, percentage of the dry matter in bioreactors equal to 15% (wet digestion). Other information needed to carry out the mass balance of the section are: the efficiency of the digestate solid/liquid separation and the percentage of dry substance in sludge considered 80% and 40% respectively; the electrical and thermal efficiency of internal combustion engine were assumed to be 44% and 40% respectively; all the data taken from commercial catalogues of the devices.

3. Environmental and energetic sustainability theoretical backgrounds

The LCA is an operational tool aiming at the evaluation of the potential environmental impacts of a product, a process or a service, on human health, ecosystems and the depletion of natural resources. The term "life cycle" indicates that, in order to make an objective assessment of the environmental consequences of human activity, it is a must to conduct a comprehensive investigation of the problem taking into account the entire life cycle from “cradle to grave” (Singh et al., 2013). In the present study, the LCA has been performed by means of the SimaPro 7.2.4 software. The assessment of environmental impacts has been carried out through two methods: CML 2001 and Ecoindicator99. The CML2001 method contains several impact categories, those considered in this analysis are: *"Global warming": "Acidification", "Eutrophication", “Ozone layer depletion”, “Photochemical oxidation", “Human toxicity"*. On the other hand, the peculiarity of the Ecoindicator99 method is that it evaluates the environmental damage by grouping the impact in three major categories : *"Human Health-HH"* (which considers damage to health caused by carcinogenic substances, by organic and inorganic substance, climate change, ionizing radiation and ozone layer depletion), *"Ecosystem Quality-EQ"* (that takes into account three types of impact: toxic emissions, compounds that affect the acidity and nutritional levels and the use and transformation of the territory), and *"Resources-R"* (that consider the additional surplus energy needed in the future to extract minerals and fossil resources).

The LCA approach is also used for the energy sustainability analysis of the process to evaluate if the suggested technologies are valid candidates for the production of *“Useful energy”* for the society (Malave et al., 2014). A first level of energy sustainability analysis can be performed by the evaluation of the Energy Sustainability Index (ESI); it is calculated according to the equation:

$$ESI = \frac{Produced\ energy}{Direct\ energy\ spent} \tag{1}$$

where *“Produced energy”* is the total energy produced by the process and *“Direct energy spent”* is the direct energy spent to run the process. If ESI is greater than one, the process produces more energy than it directly consumes, so it is a candidate to be energetically sustainable (Ruggeri et al., 2015). According to the LCA approach, in addiction to the direct energy, it is necessary to calculate the indirect energy consumed to cover all other needs of the technology. This step includes the evaluation of Energy Return On Investment (EROI). The EROI is the ratio between the total amount of net energy produced on the indirect energy spent by the process, during the technological life of the plant (here considered 20 years), expressed by the equation:

$$EROI = \frac{Net\ energy}{Indirect\ energy} \tag{2}$$

As seen for the ESI parameter, when the EROI is greater than one, the process is energetically sustainable, since it necessarily produces a positive *“Useful energy”*.

To evaluate the indirect energy, various contributions are added together:

$$E_{ind} = E_{chem} + E_{mat} + E_{main} + E_{constr} + E_{decom} + E_{amort} - E_{avoided} + E_{already} \tag{3}$$

The terms E_{chem} and E_{mat} represent the indirect energy used to produce the chemicals used in the process and the materials that make up the machinery and infrastructure. E_{main} is the indirect energy consumed in maintenance operations. Indirect energy for the construction of the plant and for decommissioning are respectively E_{constr} and E_{decom}. E_{amort} is the energy necessary to reconstruct a new plant. The avoided energy $E_{avoided}$ is the avoided energy consequentially due to not disposing the waste; finally, $E_{already}$ is the energy spent to produce the energy resource, in the present case the energy spent to produce the RDF and OFMSW at the separation section. The energy spent to collect the waste have not been considered because the finality of the study is to compare different technologies, hence the boundary of the system starts with MSW feed and ends with outputs: electrical, thermal energy and compost (Figure 1).

3.1 Main assumption to conduct the LCA

The analysis of the environmental impact life cycle of the plant considered has been carried out by following the ISO 14040. The boundaries of the system under LCA analysis include the production of syngas and biogas as well as the production of electricity and thermal energy. The analysis includes materials of construction of the main equipment, previously designed in a proper way to quantify the necessary materials, and their disposal at end of life, the chemicals used and the emissions that result from the process. In the inventory phase of the LCA all the materials placed in the plant have been considered (Table1). In order to get the inventory data, it has been necessary to size the main equipment units. The gasifier has been sized through the scale-up of a pilot gasifier (Arena et al., 2010), considering as scale-up parameter the fluidization velocity. Details can be found in Lombardelli (2016). The AD section has been dimensioned by considering the residence time for each tank: 3 hours and 35 days for the pulper and digester, respectively; tanks and storage warehouses of feeds by considering 2 days of storage; bio-cells and maturation stalls present in composting section establishing the duration of the aerobic digestion process: 9 days for the bio-oxidation, 35 days for the primary maturation and 27 days for the secondary maturation. The data relating to separator and cogeneration systems are taken from the catalogues of companies (410 kg of steel which constitutes the separator and 74400 kg of steel for the cogeneration system).

Table1. Material considered in the inventory analysis

Operation	Inventory
Gasification	Structure: steel Inner lining: Inconel
Gas cleaning	Structure: steel Solvent: sodium hydroxide
Cogeneration	Structure: steel Emission: NO, CO_2, NMVOC, SO_2, N_2O
Pulping	Structure: steel
Anaerobic digestion	Structure: reinforced concrete Thermal insulator: polystyrene Coverage: PVC
Separation	Structure: steel
Aerobic Digestion	Structure: reinforced concrete Emission: CO_2, NH_3
Storage tanks/sheds	Structure: reinforced concrete

4. Results

4.1 Environmental impacts

As regards the LCA of the global plant (gasification plus AD) all the values of the categories of impacts have been assessed related to 1 ton of MSW as functional unit. Figure 2 shows the comparison between the waste treatment investigated and the more "traditional" method of waste disposal, landfill, through: a) CML2001 method and b) Ecoindicator99 method. The impacts connected to the proposed approach are reported as a percentage of the impacts related to the landfill. The values of environmental impact carried out by CML2001 method, show that the impacts associated with the plant investigated are smaller than those of the landfill for all categories analyzed. The only category for which the process analyzed has an impact close to that of the landfill is the *“acidification”*, since it is roughly equal to 90% of that of the landfill. For all other categories analyzed by CML2001 method the impact is less than 25% of that of the landfill. Even for the most part of the categories of the method Eco-indicator99 the impact connected with the studied system is less than 35% of the impact given by the landfill. Exception are: the category *"respiratory inorganics"*, for which the impact, albeit less than that of the landfill, is relevant as equal to its 94%, and the categories *"acidification / eutrophication"* and *"minerals"*, for which the environmental impact of the process studied is greater than that of a landfill of 26 % and 37%, respectively.

4.2 Energy sustainability analysis

As concerns the energetic sustainability, three scenarios were analyzed (see Figure 1): *i)* the entire system of treatment of MSW constituted by the RDF and OFMSW production plus the gasification and AD lines, also including the purification section of the syngas, the treatment of digestate and the internal combustion engines to produce electricity and heat; *ii)* the gasification line alone till the energy production; *iii)* the AD line till the electricity and heat productions. Three functional units for each scenario, *i)*1 ton of MSW, *ii)*1 ton of RDF, *iii)*1 ton of OFMSW, were selected because they permit the comparison of different technologies, gasification and AD and the propose approach (gasification plus AD) with different MSW treatments. Energy sustainability has been assessed by quantifying the ESI referred to electrical and thermal energy. Table 2 shows the result of the calculation. For the sake of clarification in Table 2 all energy terms are reported too.

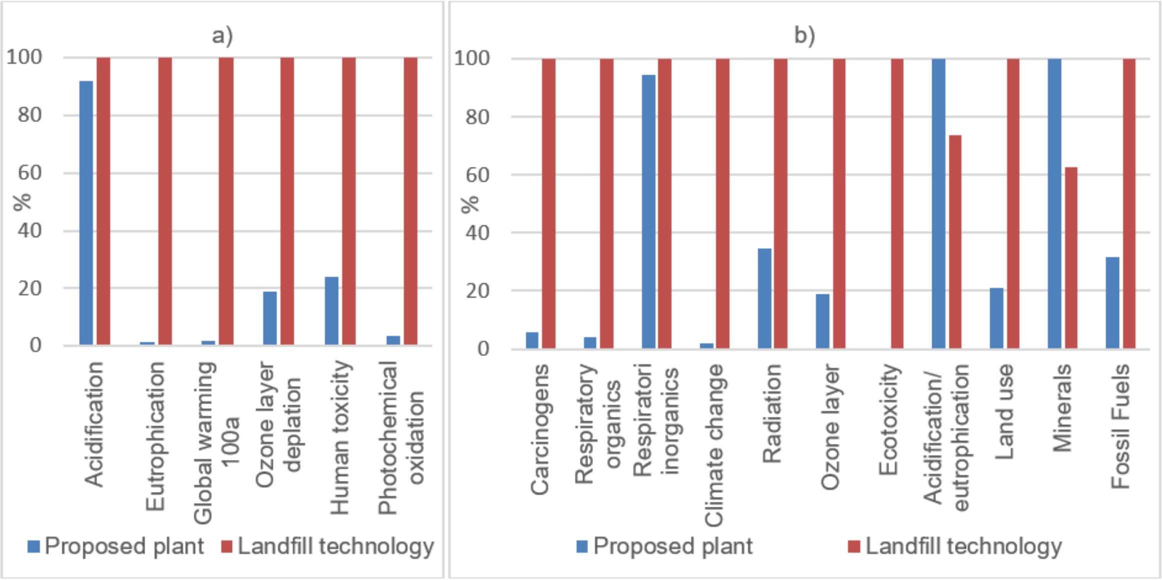

Figure 2. LCA impact assessment comparison between the proposed plant and landfill technology: a) CML2001 method b) Ecoindicator99 method.

The direct energy expenditure consists of the following terms: heat spent to warm-up the air flow for gasification and the feed of digester from ambient temperature (mean value 10 °C for the entire year) to 35 °C, which is the working temperature; the electrical energy spent to feed the RDF and OFMSW and sodium hydroxide, the electrical energy for mixing in the pulper, in order to mix the digesters, to separate the digestate and to ventilate the composting section (for details refers to Lombardelli, 2016). The indirect energy includes the energy expenditure for the construction of materials and plants, to produce the necessary chemicals, the necessary energy for maintenance during the life of the plant and finally the amortization energy to rebuild the plant at the end of production time. It should be noted that the ESI calculation considers the energy already spent or the avoided energy, i.e. the energy to produce RDF and OFMSW and energy for landfilling.

Table2. Energy Sustainability analysis results

	Produced E. (electricity)	Produced E. (heat)	Direct E.	ESI el.	ESI th.	Net E.	Indirect E.	EROI
i)Whole plant	2639 [MJ/t_{MSW}]	2399 [MJ/t_{MSW}]	977 [MJ/t_{MSW}]	3.06	2.81	4061 [MJ/t_{MSW}]	209 [MJ/t_{MSW}]	19
ii)Gasification section	5760 [MJ/t_{RDF}]	5236 [MJ/t_{RDF}]	1325 [MJ/t_{RDF}]	4.03	3.63	9671 [MJ/t_{RDF}]	955 [MJ/t_{RDF}]	10.13
iii)AD section	1254 [MJ/t_{OFMSW}]	1132 [MJ/t_{OFMSW}]	307 [MJ/t_{OFMSW}]	2.68	2.32	2085 [MJ/t_{OFMSW}]	470 [MJ/t_{OFMSW}]	4.40

The values of ESI and EROI are greater than 1 for all the scenarios analyzed, thus demonstrating the energy sustainability of the processes. It is important to calculate the value of *"Useful energy"* since it is indicative of how the system is energetically sustainable. It is considered by evaluating the difference between the net energy and the indirect spent energy, for the entire system, is equal to 4201 MJ/t_{MSW}. In Figure 3 all terms of energy calculated for the whole process case *i)*, are represented through a Sankey diagram, which clarifies the contribution of the various energy terms; the available energy is the LHV of the MSW.

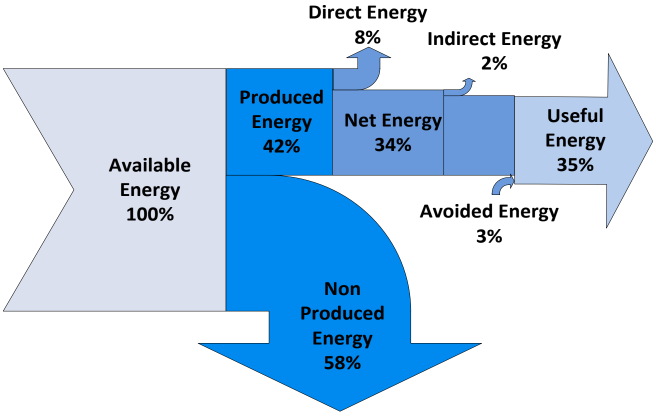

Figure 3. Sankey diagram for the whole process of MSW treatment.

5. Conclusion

The present results show that the suggested plant for almost all the environmental impacts, is more sustainable than landfilling. Although it is not possible the direct comparison between the Eco-indicator99 and CML2001 methods there is consistency between them: in both cases the main impacts associated with the process studied derive from the emissions. In the OFMSW section they are produced at steel production step and as lesser extent, for sodium hydroxide production used for the purification of the syngas. As concern the cogeneration systems the quantity of steel for their construction represent the highest percentage to total steel present in the plant, hence the highest impacts. Another factor that attests that the process studied is a good alternative for the disposal of MSW in landfill is its energy sustainability. The energy analysis shows that the process is sustainable either considering the system as a whole or considering the two section of RDF and OFMSW separately. In the case of the whole system a 35% of the energy present in the MSW is converted in "*Useful Energy*" with an EROI of about 20. Lastly, as concerns the comparison of gasification and AD from an energetic point of view, the first produces more *"Useful energy"* than the second one: EROI =10.13 and EROI=4.40, respectively.

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