GREENHOUSE GAS EMISSIONS FROM INTEGRATED SOLID WASTE MANAGEMENT: A NEW MATHEMATICAL MODEL

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Keywords: Municipal Solid Waste Management; Greenhouse gases; Waste treatment; Mathematical model

Abstract. *Municipal solid waste management significantly contributes to the emission in the atmosphere of greenhouse gases (e.g.* CO_2*,* CH_4*,* N_2O*) and therefore the management process from collection to treatment and disposal has to be optimized in order to reduce these emissions. Many literature models developed for the evaluation of greenhouses gases emissions from the waste management system are based on the analysis of the life cycle. These models are not optimized for evaluation of emissions. The aim of this study is to overcome these limitations by proposing a mathematical model to estimate greenhouse gas emissions resulting from the integrated waste management. The model is aimed to be a verification tool for assessing the optimum system management in terms of greenhouse gas emissions. The model quantify the emissions associated with: heat treatment, landfill disposal, anaerobic digestion plants, recycling, composting. Different combinations of collection scenarios and disposal options have been considered in the Municipal Solid Waste management of the Province of Palermo. The obtained results applying the model show that limits to solid waste management must be clearly defined. In fact changing the limits, the emissions vary. The lower emissions are due to the use of different energy sources.*

1. Introduction

With global warming becoming an important environmental issue, many studies have investigated the topic of greenhouse gas emissions (GHG) from waste activities (Kennedy et al., 2009; Gentil et al., 2009; Friedrich and Trois, 2010). It is estimated that the waste sector contributes about 3–4% to the total global anthropogenic GHG emissions and for 2004–2005 (Bogner et al., 2008). Although this contribution is considered relatively small, the carbon reduction opportunities for the sector are still not fully explored (ISWA, 2009). A series of initiatives were highly successful and showed that large reductions in emissions are possible.

The European Union introduced policy and regulatory acts aimed at giving an impetus to effective management based principally on prevention and recovery and, only in the case that no treatment is possible, disposal of waste. An integrated management system is based on the use of complex technological and organizational solutions helping to prevent the production of waste and the recovery of materials and energy, leaving the landfill a marginal role (Direttiva1999/31/CE). An integrated management system should target not only the lower emissions in environmental systems associated with different processing, through new technologies, but also an overall improvement of the entire system by searching for the optimal solution for economy and environment, it is neither unique nor universally valid. The system changes in time and differs from site to site depending on the geographical, environmental and morphological situation of the installation. Ultimately the integrated waste is presented as a complex and multidisciplinary problem that must be considered in technical, economical, social and environmental terms (Banar et al., 2009).

In this context accurate measurements and quantification of greenhouse gas emissions is vital in order to set and monitor realistic reduction targets at all levels (ISWA, 2009).

In general, the majority of studies investigating the emissions of greenhouse gases from waste focused on individual waste management stages (especially waste disposal through landfilling) and other processes, in particular waste minimization and transport of waste, were not always included. As a result a more systemic and holistic approach is needed. In this context the entire waste management system needs to be considered to properly evaluate the best strategies to reduce greenhouse gases and to assess how different waste management processes can be combined and optimized for this purpose. This is of particular importance at local level, since local authorities are in charge of managing waste on a daily basis and they are the primary agents when planning and enforcing changes. Yet for local authorities there are no clear rules and/or guidelines on how to account and report greenhouse gases from waste. (Friedrich et all 2010). The amounts of waste generated, the composition of the waste (in particular the carbon content) as well as the technologies used for handling and disposing this waste will determine the final amount of greenhouse gases emitted from a waste management system.

Setting system boundaries for the waste sector is a very critical issue when establishing a GHG emission inventory (Cleary, 2009; Gentil et al., 2009; Jawjit et al., 2010; Scipioni et al., 2010). Three major boundaries can be defined: Material boundaries have to be set in order to specify which type of emissions should be accounted for; patial and temporal boundaries have to be delimited clearly, i.e. the geographic area, as well as the time horizon in which the GHG emissions originate; Functional and sectoral boundaries define areas and the functional units within those areas.

The aim of this study proposes to use a mathematical model to estimate greenhouse gas emissions resulting from the integrated waste management. A home-made model has been developed for quantifying the greenhouse gas emissions from solid waste management at an integrated scale (test /prevision).

The algorithms of the mathematical model have been drawn from the literature and are able to quantify the emissions associated with: heat treatment, landfill disposal, anaerobic digestion plants, recycling, composting. For each unit the model allows to estimate both direct emissions linked to physical or biological process and indirect associated with the consumption of energy and the lack of production of electricity from conventional energy sources. This should be the first step in the development of more holistic quantification models and overall strategies to reduce these emissions. As such it investigates individual processes in the waste management cycle, starting with the generation and composition of waste, followed by collection and transport, disposal processes and recovery and recycling.

Palermo City is selected as the location for the case study. It is the capital and the main urban centre of the

Sicily (Italy), with 674.742 inhabitants. The mathematical model was applied as a tool to evaluate GHG emissions caused by the present Municipal Solid Waste (MSW) management in the Province of Palermo (Italy). The model was also used as a tool to predict and estimate emissions determined by different hypothetical management scenarios, among which those considered by Solid Urban Waste Management Plan - June 2012. The data about waste production, the treatments and lastly the specific characteristics of every single plants were taken from Solid Urban Waste Management Plan – June 2012, of Regione Sicilia. Whereas the necessary information for the modelling were taken from previous studies.

2. Methods and data

2.1. Aims

The aims of this study are two-fold: to be a verification tool for assessing the optimum system management in terms of greenhouse gas emissions; and to investigate the potentials of GHG emission mitigation and trade-offs under different MSW management strategies through scenario studies.

2.2. Functional unit

The first component in any waste management system is the amount of waste generated and the nature of that waste. This is also important in terms of the quantities of greenhouse gases generated from that waste. The model considers two different waste streams, assessed on an annual basis: the unsorted waste and separate collection. Of particular interest regarding the potential for GHG generation has been the composition of the waste and in particular the biodegradable organic fraction which will ultimately give rise to greenhouse gases (Friedrich e Trois, 2011). Waste composition is one of the main factors influencing emissions from solid waste treatment, as different waste types contain different amounts of degradable organic carbon (DOC) and fossil carbon. Waste compositions, as well as the classifications used to collect data on waste composition in MSW vary widely in different regions and countries..

2.3. Model description

The management of solid waste causes emissions of greenhouse gases due both to biological processes, physical and chemical that develop in the various treatment units, and the indirect emissions, due to the energy consumption or energy production from each unit. To evaluate the best management strategy to avoid GHG is necessary to combine the different processes. This study develops a tool to compare various management scenarios, providing for each of them the amount of GHG produced. The tool proposed is a mathematical model for estimating greenhouse gas emissions from an integrated waste management. In figure 1 it is shown the conceptual schema of the model that shows the mass flows and energy considered. The proposed model can be used as a verification tool, for assessing the optimum system management in terms of greenhouse gas emissions. It can also be used as a predictive tool, to investigate the potentials of GHG emission mitigation and trade-offs under different MSW management strategies through scenario studies. The model has been divided into five sub-models in order to quantify the emissions associated with: heat treatment, landfill disposal, anaerobic digestion plants, recycling, composting. The algorithms of the mathematical model have been drawn from the literature

For each unit the model allows to estimate both direct emissions linked to physical or biological process and indirect associated with the consumption of energy and the lack of production of electricity from conventional energy sources.

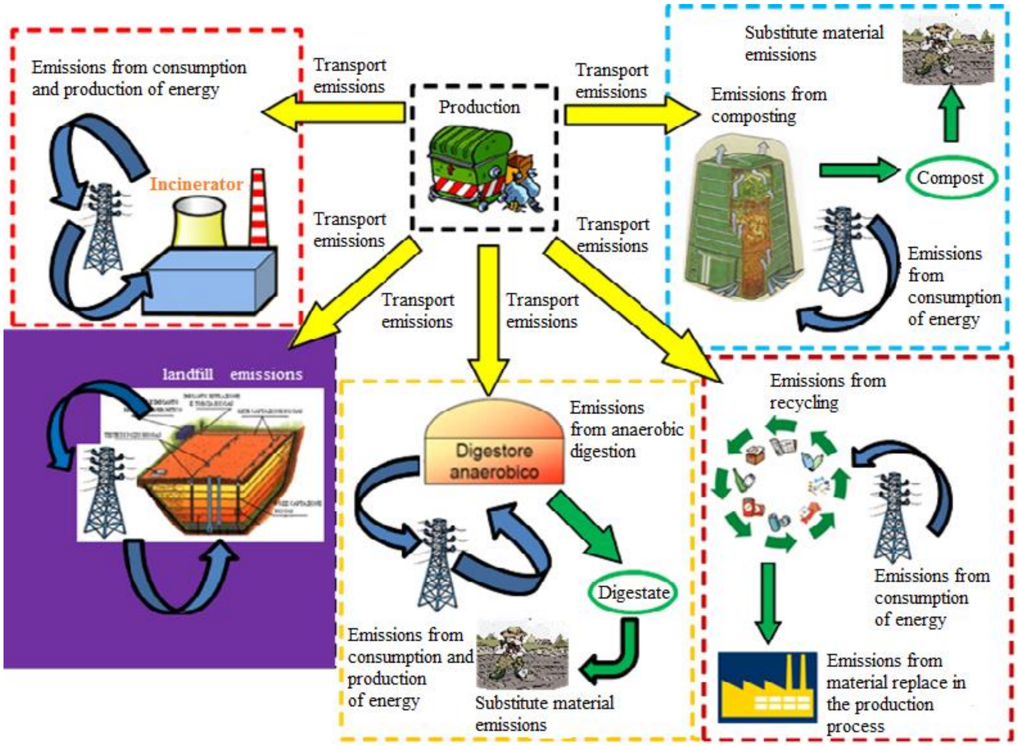

Figure 1. *Diagram of integrated emission simulation model*

This should be the first step in the development of more holistic quantification models and overall strategies to reduce these emissions. As such it investigates individual processes in the waste management cycle, starting with the generation and composition of waste, followed by collection and transport, disposal processes and recovery and recycling.

A home model has been developed for quantifying the greenhouse gas emissions from solid waste management at an integrated scale. The algorithms of the mathematical model have been drawn from the literature and are able to quantify the emissions associated with: heat treatment, landfill disposal, anaerobic digestion plants, recycling, composting.

For each unit the model allows to estimate both direct emissions linked to physical or biological process and indirect associated with the consumption of energy and the lack of production of electricity from conventional energy sources.

2.3.1. GHGs emissions from the collection and transportation

Greenhouse gases are emitted in the collection and transport of waste from the combustion of fuel and mainly carbon dioxide, but also small amounts of other GHG (i.e. nitrous oxide and methane), are generated. Although these emissions are seldom included in GHG calculations for waste systems, it is necessary to acknowledge their contributions. GHG emissions from the waste collection and transport mainly came from the CO2 generated by the transport vehicles use of fuel. The actual emissions varied with the vehicles engine model, fuel type (petrol and diesel), size and load. The total emissions could also be derived from the total mileage or fuel usage. t

2.3.2. GHGs emissions from recycling

The model considers the use of recycled matter instead of virgin material in the manufacturing process. It not only greatly reduced the demand for energy but also reduced non-energy GHG emissions in the manufacturing process. The materials recovered from recycling operations, through the definition of appropriate substitution ratios, substitute in whole or in part, an equal amount of virgin materials.

2.3.3. GHGs emission from landfilling

Treatment and disposal of municipal solid waste produces significant amounts of methane (CH4). In addition to CH4, solid waste disposal sites (SWDS) also produce biogenic carbon dioxide (CO2) non-methane volatile organic compounds (NMVOCs) as well as smaller amounts of nitrous oxide (N2O) and carbon monoxide (CO). CH4 produced at SWDS contributes approximately 3 to 4 percent to the annual global anthropogenic greenhouse gas emissions (IPCC, 2001).

However the estimation of greenhouse gas emissions covered only CH_4, since the emitted carbon dioxide, of biological origin, is generally regarded as part of the natural decomposition cycle, while emissions of N_2O and CO are generally insignificant. In many industrialized countries landfill gas recovery has become more common as a measure to reduce CH_4 emissions from SWDS.

The model simulates the CH_4 emissions through the methodology proposed by IPCC that is based on the First Order Decay (FOD). This method assumes that the degradable organic component (degradable organic carbon, DOC) in waste decays slowly throughout a few decades, during which CH_4 and CO_2 are formed. If conditions are constant, the rate of CH_4 production depends solely on the amount of carbon remaining in the waste. As a result emissions of CH_4 from waste deposited in a disposal site are highest in the first few years after deposition, then gradually decline as the degradable carbon in the waste is consumed by the bacteria responsible for the decay.

2.3.4. GHGs emissions from composting

The model estimates the GHG emissions from the composting treatment using two different equations. The first refers to the IPCC guidelines while the second is used in EASEWASTE software.

Composting is an aerobic process and a large fraction of the degradable organic carbon (DOC) in the waste material is converted into carbon dioxide (CO_2). CH_4 is formed in anaerobic sections of the compost, but it is oxidised to a large extent in the aerobic sections of the compost. The estimated CH_4 released into the atmosphere ranges from less than 1 percent to a few per cent of the initial carbon content in the material. Composting can also produce emissions of N_2O. The range of the estimated emissions varies from less than 0.5 percent to 5 percent of the initial nitrogen content of the material (Beck-Friis, 2001; Detzel et al., 2003). Poorly working composts are likely to produce more both of CH_4 and N_2O (e.g., Vesterinen, 1996).

2.3.5. GHGs emissions from anaerobic digestion

Anaerobic digestion (AD) is considered as a sustainable option for the management of biomass wastes because the production of renewable energy and the recycling of nutrients. Additionally, MBW separated from MSW and treated with AD can significantly reduce the load of traditional disposal facilities, and subsequently prolong their service life. It also decreases the secondary pollutants originated from the biodegradation of organic wastes during landfill, incineration and composting.

The model estimates the GHG emissions from the anaerobic digestion treatment using two different equations. The first refers to the IPCC guidelines while the second is used in EASEWASTE software. Anaerobic digestion of organic waste expedites the natural decomposition of organic material without oxygen by maintaining the temperature, moisture content and pH close to their optimum values. Generated CH_4 can be used to produce heat and/or electricity. The CO_2 emission is of biogenic origin, and is generally regarded as part of the natural decomposition cycle. Emissions of CH_4 from such facilities due to unintentional leakages during process disturbances or other unexpected events will generally be between 0 and 10 percent of the amount of CH4 generated. In the absence of further information, the IPCC suggests to use as the default value 5%. N_2O emissions from the process are assumed to be negligible, however, the data on these emissions are very scarce.

2.3.6. GHGs emissions from incineration

Waste incineration is defined as the combustion of solid waste in controlled incineration facilities. Modern refuse combustors have tall stacks and specially designed combustion chambers, which provide high combustion temperatures, long residence times, and efficient waste agitation while introducing air for more complete combustion.

Incineration of waste are sources of greenhouse gas emissions, like other types of combustion. Relevant gases emitted include CO_2, methane (CH_4) and nitrous oxide (N_2O). Normally, emissions of CO_2 from waste incineration are more significant than CH_4 and N_2O emissions. Consistent with the 1996 Guidelines (IPCC, 1997), during incineration only CO_2 emissions resulting from oxidation of carbon in waste of fossil origin (e.g., plastics, certain textiles, rubber, liquid solvents, and waste oil), are considered net emissions and should be included in the national CO_2 emissions estimate. The CO_2 emissions from combustion of biomass materials (e.g., paper, food, and wood waste) contained in the waste are biogenic emissions and should not be included in national total emission estimates.

This study provides guidance on methodological choices for estimating emissions of CO_2 and N_2O fossil, assuming negligible methane emissions, as generated by incomplete combustion. CO_2 emissions are closely related to the amount of fossil carbon in the different fractions, while the N_2O emissions are more dependent on technology and on the combustion process conditions.

2.3.7. Consumption and production of energy

To estimate the greenhouse gas emissions it is necessary to consider the emissions directly associated with the treatment of waste, and also emissions indirect, determined on consumption or energy production.

While the energy consumption determines an additional burden in terms of emissions associated with the system, energy production leads to a reduction of emissions, because the energy produced from the waste treatment replaces energy produced by traditional sources of energy. The model calculates the energy produced by the following waste treatment: incineration units; landfill; anaerobic digestion.

The energy produced by the thermal treatment of waste is closely related to their calorific value. It is defined as the amount of heat produced by the combustion of a unit quantity by weight of the waste and is generally expressed in kcal/kgRU.

The amount of energy produced from waste disposal, is a function of the amount of biogas recovered from the plant uptake, the percentage by volume of methane in the biogas and of its energy content.

The amount of energy produced by the anaerobic digestion, as for the disposal in landfills, is a function of the amount of biogas recovered from the plant uptake, the percentage by volume of methane in the biogas and of its energy content.

2.3.8. Replacement of fertilizers

The model considers the replacement of the recovered materials, with virgin ones used in conventional production processes. The model defines a replacement ratio for the kitchen and garden waste for which the treatment in composting units and anaerobic digestion produces compost and digestate. Compost and digestate are used as fertilizer. This substitution avoids the carbon dioxide emissions generated by the production process of fertilizers. The model then assesses the effect of compost or digestate replaced, on greenhouse gas emissions in terms of non-use of energy.

2.4. Case study

The mathematical model was applied as a tool to evaluate greenhouse gas emissions produced by the present Municipal Solid Waste (MSW) management in the Province of Palermo (Italy). The model was also used as a tool to predict and estimate emissions determinate by different hypothetical management scenarios, among which those considered by Solid Urban Waste Management Plan - June 2012.

The 2012 plan has three phases of implementation:

1. The present management (93,39% MSW , 6,61% Recycling);
2. The predictable management in a transitory phase (target: 45% Recycling within 2013);
3. The predictable management in a full-operating phase (target: 65% Recycling within 2015).

The predictable management scenarios have two main waste streams: the unsorted waste and separate collection. Unsorted waste will be initiated to treatment plants, able to separate the dry fraction from the wet fraction. The dry fraction, divided into paper, plastic, glass and metal, will go to recovery of materials or energy; the wet fraction will go to bio-stabilization, for the production of FOS. The kitchen waste of separate collection will go to composting plants; while the dry fraction of separate collection (paper, plastic, glass and metals) will go to CONAI spinneret for reuse.

2.4.1. Scenarios

The model was applied to seven different scenarios, two referring to the present management (one in force at present and one alternative), one for the predictable management in a transitory phase, while the other management options applied to the full operating phases.

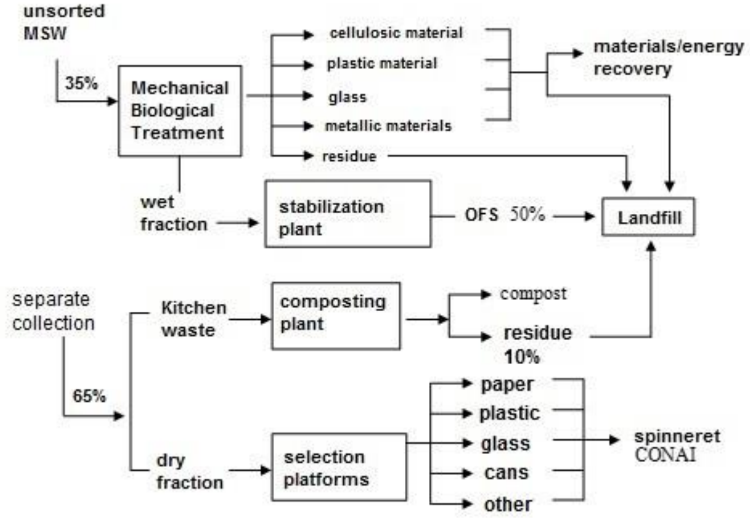

Figure 2. *System definition in a full operating phase*

- SC-1 baseline. This scenario corresponds to the current MSW management system where the 93.39 % of MSW is disposed of in landfills, and the remaining 6.61% is separated at source and treated in a material recycle facility(MRF) producing secondary materials while the Kitchen waste is collected to be composted
- SC-2 incineration. Compared to SC-1, the 93.39% of MSW is heat treated for energy recovery, the remaining 6.61% is treated in the same way as the previous scenario.
- SC-3 the predictable management in a transitory phase. 55 % of MSW will be disposed of in landfills, the remaining 45% will be treated with recycling and composting.
- SC-4 The predictable management in a full-operating phase with energy recovery. 65% will be treated with recycling and composting; cellulosic and plastic fractions of MSW will be heat treated with energy recovery
- SC-5 The predictable management in a full-operating phase as refuse-derived fuel in a cement plant. Cellulosic and plastic fractions from MSW are used to produce fuel from waste to be used in the cement plant Italcementi located in Isola delle Femmine.
- SC-6 The predictable management in a full-operating recycling phase. Solid urban waste is sent to recycling plants.
- SC-7 The predictable management in a full-operating phase with disposal in landfills. Entire disposal of Solid urban waste in landfills

2.4.2. Key assumptions

The key assumptions of this study are the following:

- Among the GHG, CO_2, N_2O, and CH_4 are included. Other GHGs are hardly emitted from the MSW management system and therefore ignored.

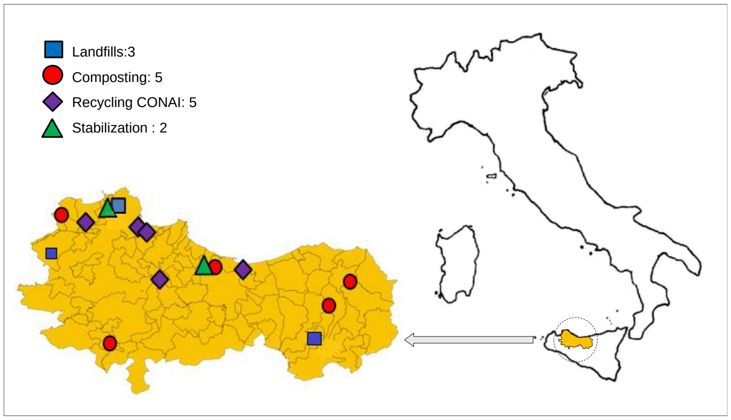

Figure 3. *Treatment plants in the territory of the Province of Palermo in a full-operating phase*

- The collection of biogas in landfills is set equal to 50% and the efficiency of electricity production to 30%.
- The incinerator of SC-2 and SC-4 is located at Bellolampo and has an efficiency of energy production equal to 20%.
- In all scenarios the energy produced replaces an equal amount of energy produced by the national energy mix.
- In scenarios SC4, SC5, SC6, SC-7 (full-operating phase) the only landfill in the service of the Province is located in Bellolampo
- The emissions from energy consumption of the plant selection and the use of FOS for environmental restoration are insignificant.
- In the scenario SC-5 the cement plant of Isola delle Femmine uses petcoke.

2.4.3. Data issues

The data about waste production, the treatments and lastly the specific characteristics of every single plants were taken from Solid Urban Waste Management Plan – June 2012, of Regione Sicilia. Whereas the necessary information for the modelling were taken from previous studies.

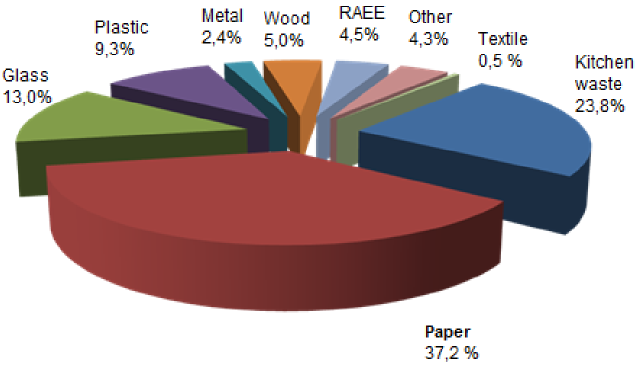

Figure 4. *Fraction composition of MSW in Sicilia - collection of 2009*

The amount of waste considered in all scenarios is the production per head in 2009: 527 kg/ inhabitant per annum, and Solid Waste Characterization taken as reference is that of the collection of 2009.

3. Results

Figure 5 shows gas emissions from all treatments considered, for every single scenario indicating those which determine lower total emissions and those which, on the other hand, are characterized by higher levels. In scenario 6 where MSW is recycled entirely, there are the lowest emissions of CO_2. This scenario compared to the baseline has a reduction of 67% of CO_2 emission. Then the scenario 7 (Sc.7), where all the dry fraction from the residual waste is disposed of in landfills, this scenario compared to the baseline has a reduction of 53% of CO_2 emission.

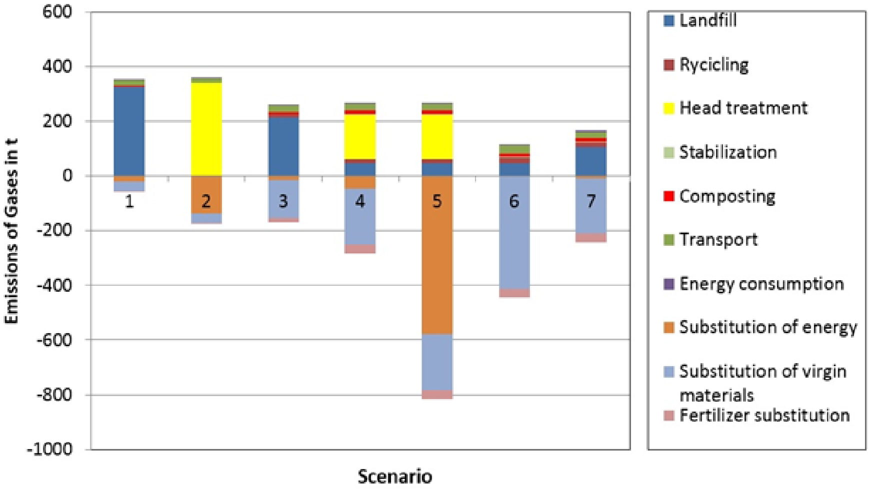

Figure 5. *Results of the model application for the different simulated scenarios*

In SC-4 and SC-5, GHG emissions are almost the same, because the model uses the same algorithm for calculating the emissions caused by the incinerator and by the cement plant. In both scenarios, the GHG emissions are reduced by approximately 24% compared to the baseline scenario. In SC-3 the reduction of the GHG emissions is slightly greater, equal to approximately 25%. Finally, in SC-2, the GHG emission is approximately equal to that estimated for the baseline scenario (Sc.1).

Figure 5 also shows the avoided emissions. The greater avoided emissions are attributed to the SC-5, where the CDR was used in the cement plant. This result was expected because CDR, replaces an equal amount of petroleum coke, which is associated with a high CO_2emission factor. Among Scenarios that produce electricity, the major emissions are avoided in the SC-2. The Electricity Production refers to the national energy mix. By comparing the emissions avoided in SC- 5 and SC-4, it is evident that the replaced energy source, must be clearly defined. It is also important to define the limits of MSW. In fact, if one includes the emissions avoided, due to the recovery of material or the production of energy, one can get a significant change in results. Figure 6 shows, for the various scenarios, the net emissions of greenhouse gases, determined considering the avoided emissions.

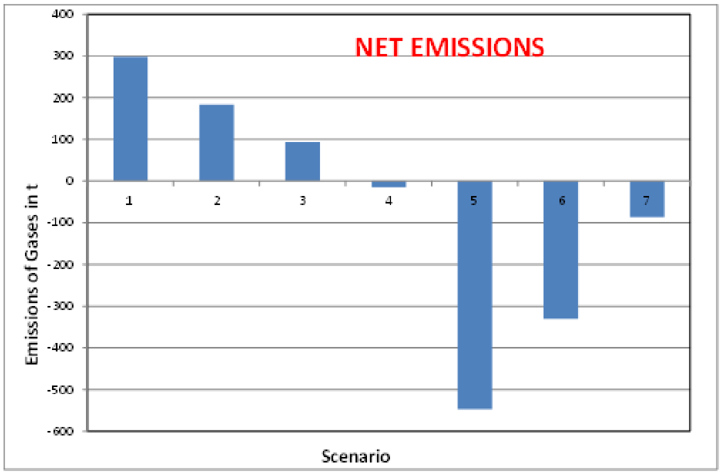

Figure 6. *CO_2 net emissions equivalent for the different scenarios Management*

Figure 6 shows that the best scenario in terms of greenhouse gas net emissions is the SC-5. This result confirms the importance of the system limits accepted for the waste management system. In fact excluding or including the avoided emissions from the system, determines a difference among the modelled scenarios.

As the combination of energies is variable from place to place, the predicted greenhouse gases are specific to every single case study. The emissions from waste transport and energy consumption are shown in fig.5. It has been observed that the waste transport emissions change according to the scenario. For this reason they must be included to estimate total greenhouse gases emissions (Friedrich e Trois, 2011). Conversely, it comes up that the emissions due to energy consumption can be neglected.

4. Conclusion

This study was conducted to evaluate the most appropriate municipal solid waste management scenario regarding greenhouse gas emissions. This was completed by using the mathematical model to compare different management options. The mathematical model developed can be used for the estimation of greenhouse gas emissions from the integrated waste management. The model was applied, as a verification tool for the estimation of GHG emissions from the current solid waste management system in the province of Palermo. It was also applied as a forecasting tool, to determine the goodness in terms of GHG emissions, of the forecast systems provided for the Municipal Solid Waste Management Plan - June 2012.

The results of the study draw some conclusions as follows:

- The baseline scenario (collection + landfilling) was the major contributor of GHG emissions.
- Scenario 6 (where solid urban waste is sent to recycling plants) seemed to be very environmentally appealing as it avoided the maximum amount of CO2 equivalents.
- It is important to clearly define the limits of the system considered for the solid waste management system, to consider all that happens downstream of the waste management system, in terms of replacement energy or matter, as a significant effect on the final results (Gentil et al. 2010).
- Emissions avoided through the energy exchange are directly related to the replaced energy source. Also because the energy mix used varies depending on the country concerned.

- The estimated emissions of greenhouse gases, are specific to the case study considered and the combination of energies is variable from place to place, the predicted greenhouse gases are specific to every single case study.

Table 1. *In table 1 are reported the algorithms used by the integrated model for simulation of emissions from integrated waste management.*

N°	Simulated process	Algorithms	Variabile simulata	Rif. bibliogr.
1	Collection and transportation waste	$E_{t,j} = F_{ic,j}\ x\ H_i\ x\ C_{ig}\ x\ GWP_g$	Emission of carbon dioxide	Chen e Lin, 2008
2	Collection and transportation waste	$F_{ic,j} = 2 \times \frac{d_{j,tot}}{c_i}$	Amount of Fuel consumed	-
3	Collection and transportation waste	$d_{j,tot}\ \frac{(Q_{tot,j} \times d_j)}{(capacity \times load\ factor)}$	Total distance from the point of collection to the treatment unit	-
4	Recycling	$E_{CO_2,i} = (Q_{sost,i} \times F_{em,recycling,i}) + (Q_{virgin,i} \times F_{em,virgin,i})$	Emission of carbon dioxide fraction	-
5	Recycling	$Q_{sost,i} = Q_{recycling,i} \times rs_i$	Quantity of recycled material which enters the manufacturing process of the i material	-
6	Recycling	$Q_{virgin,i} = Q_{recycling,i} \times (1 - rs_i)$	Quantity of virgin material used in the production process of the i material	-
7	Landfilling	$CH_4\ emitted = \left[\sum_i CH_4\ generated_i \times (1-R)\right] \times (1-OX)$	CH4 emitted	IPCC, 2006b
8	Landfilling	$DDOCmd_i = W_i \times DOC_i \times DOC_{f,i} \times MCF$	Mass of Decomposable Degradable Organic Carbon deposited	IPCC, 2006b
9	Landfilling	$DDOCma_{i,t} = DDOCmd_{i,t} + (DDOCma_{i,t-1} \times e^{-k_i})$	Mass of Decomposable Degradable Organic Carbon accumulated	IPCC, 2006b
10	Landfilling	$DDOCm\ decomp_{i.t} = DDOCma_{i,t-1} \times (1 - e^{-k_i})$	Mass of Decomposable Degradable Organic Carbon decomposed	IPCC, 2006b
11	Landfilling	$CH_4\ generated_i = DDOCm\ decomp_i \times F \times 16/12$	Amount of methane produced by the anaerobic decomposition of the waste category fraction i	IPCC, 2006b
12	Composting	$CH_4\ emitted = \sum_i (M_i \times EF_{CH_4}) \times 10^{-3}$	CH4 emitted	IPCC, 2006c
13	Composting	$N_2O\ emitted = \sum_i (M_i \times EF_{N_2O}) \times 10^{-3}$	N2O emitted	IPCC, 2006c
14	Composting	$CH_4 emitted = C_{air} \times CH_{4,degr} \times (1 - CH_{4,remov}) \times \frac{16}{12}$	CH4 emitted	Boldrin, et al., 2011
15	Composting	$NH_3 emitted = N_{air} \times NH_{3,degr} \times (1 - NH_{3,remov}) \times \frac{17}{28}$	NH_3emitted	Boldrin, et al., 2011
16	Composting	$N_2O\ emitted = N_{air} \times N_2O_{degr} \times (1 - N_2O_{remov}) \times \frac{44}{28}$	N_2O emitted	Boldrin, et al., 2011
17	Anaerobic digestion	$CH_4\ emitted = \sum_i (M_i \times EF_{CH_4}) \times 10^{-3} - R$	CH_4 emitted	IPCC, 2006c
18	Anaerobic digestion	$CH_4\ produced = \sum_i M_i \times L_i$	CH_4 produced	
19	Anaerobic digestion	$L_i = DOC_i \times DOC_f \times F \times 16/12$	Generating potential of methane in the waste	IPCC, 2006c

20	Anaerobic digestion	$N_2O\ emitted = \sum_i (M_i \times EF_{N2O}) \times 10^{-3}$	N_2O emitted	IPCC, 2006c
21	Anaerobic digestion	$CH_4 emitted = CH_4\ produced \times CH_{4,not\ recovered}$	CH_4emitted	Boldrin, et al., 2011
22	Incineration	$CO_2\ emitted = RSU \times \sum_i (WF_i \times dm_i \times CF_i \times FCF_i \times OF) \times 44/12$	CO_2 emitted	IPCC, 2006d
23	Incineration	$N_2O\ emitted = \sum_i (IW_i \times EF_i)$	N_2O emitted	IPCC, 2006d
24	Consumption and production of energy	$CO_2 emitted/avoided = Energy_{consumed/produced} \times percentage_i \times EF_i$	CO_2emitted	
25	Energy produced	$Energy\ produced = \frac{Efficiency}{3600} \times \sum_i (Q_i \times dm_i \times PCIS_i)$	Energy produced by incineration	
26	Energy produced	$Energia\ produced = \frac{Efficiency}{3600} \times CH_4\ produced \times R \times Energy_{CH_4}$	Energy produced from disposal in landfill	
27	Energy produced	$Energy\ prod_{dig.an.} = \frac{Effic.}{3600} \times CH_4\ prod \times \left(1 - CH_{4,non\ recov}\right) \times Energy_{CH_4}$	Energy produced by the anaerobic digestion	
28	Energy consumed	$Energy\ consumed_i = Q_i \times Cs_i$	Energy consumed by the plants (composting, incineration)	
29	Energy consumed	$Energy\ consumed_i = Energy\ produced_i \times Cs_i$	Energy consumed by the plants (landfill, anaerobic digestion)	
30	Replacement of fertilizers	$Energy\ saved = Fs \times Cs_i$	Energy saved which is not consumed to produced the fertilizer	
31	Replacement of fertilizers	$Fs = \sum_i (Q_i \times dm_i \times rs_i)$	Amount of fertilazer the twill be replaced by compost or digestate	

Table 2. *In table 2 are reported the parameters used by the integrated model for simulation of emissions from integrated waste management.*

N°	Model parameter	Description	Variation range	Fitted value	Bibliographic reference.
1	Input parameter	Hi = the fuel heating value of Fuel i	-	0.038136 (GJ/l)	Chen e Lin, 2008
		Cig = GHGs emission coefficient	-	72.098 gCO_2/MJ; 0.003 gCH_4/MJ; 0.002 gN_2O/MJ;	Chen e Lin, 2008
2	Input parameter	c_i = Fuel used	-	3 km/l	Diaz e Warith, 2006
3	Calibration parameter	load factor = load factor of the truck	0 – 1	0.7	Zhao et al., 2009

	Input parameter	capacity = capacity of the truck	5 – 10 t	5 t	Zhao et al., 2009
4	Input parameter	$F_{emission, recycling,i}$ = emission factor of the recycled material i	9.23 – 1507 [kg CO_2/t]	According to waste fraction	Diaz e Warith 2006
		$F_{emission, virgin,i}$ = emission factor of virgin material i	14.1 – 2900 [kg CO_2/t]	According to waste fraction	Diaz e Warith 2006
5	Calibration parameter	rs_i = fraction of recycled material that replaces the virgin material in the production process of the i material	0 – 1	According to waste fraction	Zhao et al., 2009
6	Calibration parameter	rsi = fraction of recycled material that replaces the virgin material in the production process of the i material	0 – 1	According to waste fraction	Zhao et al., 2009
7	Calibration parameter	OX = oxidation factor	0 – 1	0.1	IPCC, 2006b
		R = recovered CH4	0 – 1	0.5	IPCC, 2006b
8	Calibration parameter	DOCf = fraction of DOC that can decompose (fraction)	0 – 1	0.5	IPCC, 2006b
	Input parameter	MCF = CH4 correction factor for aerobic decomposition in the year of deposition (fraction)	0 – 1	1	IPCC, 2006b
		DOC = degradable organic carbon in the year of deposition, fraction	0 – 1	According to waste fraction	IPCC, 2006a
9	Input parameter	k_i reaction constant	0.01 – 0.08	According to waste fraction	IPCC, 2006b
10	Input parameter	k_i reaction constant	0.01 – 0.08	According to waste fraction	IPCC, 2006b
11	Parametro di calibrazione	F = the fraction of CH4, by volume, in generated landfill gas (fraction)	0 – 1	0.5	IPCC, 2006b
12	Parametro di calibrazione	EF_{CH_4} = emission factor for treatment	0.03 – 8 kg CH_4/t waste	4 kg CH_4/t waste	IPCC, 2006c
13	Parametro di calibrazione	EF_{N2O} = emission factor for treatment	0.06 – 0.6 kg CH_4/t waste	0.3 kg CH_4/t waste	IPCC, 2006c
14	Parametro di calibrazione	$CH_{4,degr}$ = fraction of C_{air} emitted as CH4	0 – 1	0.2	Boldrin, et al., 2011
	Parametro di calibrazione	$CH_{4,remov}$ = efficiency of the biofilter, if provided, to remove the methane	0 – 1	0.5	Diaz e Warith 2006
15	Parametro di calibrazione	$NH_{3,degr}$ = fraction of N_{air} emitted as NH_3	0 – 1	0.98	Beck-Friset et al. 2001a
		$NH_{3,remov}$ = efficiency of the biofilter, if provided, to remove the NH_3	0 – 1	0.991	Diaz e Warith 2006
16	Parametro di calibrazione	N_2O_{degr} = fraction of N_{aria} emitted as N_2O	0 – 1	0.02	Beck-Friset et al. 2001a
		$N_2O_{,remov}$ = efficiency of the biofilter, if provided, to remove the N_2O	0 – 1	0.9	Diaz e Warith 2006
17	Parametro di calibrazione	EF_{CH_4} = emission factor for treatment	0 – 8	1	IPCC, 2006c
19	Parametro di calibrazione	F = fraction of CH_4, by volume, in the biogas	0 – 1	0.5	IPCC, 2006b
		$DOC_{f,i}$= fraction of DOC that can decompose	0 – 1	0.5	IPCC, 2006b
	Input parameter	DOC_i = fraction of degradable organic carbon present in the waste	0 – 1	According to waste fraction	IPCC, 2006a
20	Parametro di calibrazione	EF_{N2O} = emission factor of nitrous for the anaerobic digestion treatment	-	0	IPCC, 2006c
21	Parametro di calibrazione	$CH_{4,not\ recovered}$ = percentage of methane that is not recovered	0 – 0.1	0.1	IPCC, 2006c
22	Parametro di calibrazione	OF = oxidation factor	0 – 1	1	IPCC, 2006d
	Input parameter	dm_i = dry matter content in the component i of the MSW incinerated (fraction)	0 – 1	According to waste fraction	IPCC, 2006a

		CF_i = fraction of carbon in the dry matter (i.e., carbon content) of component i	0 – 1	According to waste fraction	IPCC, 2006a
		FCF_i = fraction of fossil carbon in the total carbon of component i	0 – 1	According to waste fraction	IPCC, 2006a
23	Parametro di calibrazione	EF_i = N2O emission factor (g N2O/t of waste) for waste of type i	50 – 150 gN_2O/t waste	50	IPCC, 2006d
24	Input parameter	$percentage_i$ = percentage fraction of the energy source used in the energy mix	0 – 1	0.126 coal; 0.034 oil products; 0.43 natural gas; 0.015 nuclear; 0.395 renewable sources	GSE
	Parametri di calibrazione	EF_i = emission factor of the energy source	0 – 1.121 kg CO_2/kWh	-	Diaz e Warith, 2006
25	Parametri di calibrazione	Efficiency = efficiency of energy recovery	0.18 – 0.85	0.2	Diaz e Warith, 2006
	Input parameter	dm_i = dry matter content of the waste	0 – 1	According to waste fraction	IPCC, 2006a
26	Parametri di calibrazione	Efficiency = efficiency of energy recovery	0.2 – 0.85	0.3	Zhao et al., 2009
		R = percentage of uptake	0 – 1	0.5	IPCC, 2006b
		Energy CH_4 = methane energy content	49 – 55 GJ/tCH_4	51 GJ/tCH_4	Diaz e Warith, 2006
27	Parametri di calibrazione	Efficiency = efficiency of energy recovery	0.2 – 0.85	0.3	Zhao et al., 2009
		$CH_{4\ \text{not recover}}$= percentage of non-recovered gas	0 – 0.1	0.1	IPCC, 2006c
		Energy CH_4 = methane energy content	49 – 55 GJ/tCH_4	51 GJ/tCH_4	Diaz e Warith, 2006
28	Input parameter	Cs_i = specific consumption of system energy per ton of waste treated	21.4 – 30 kWh/t waste for composting; 4.03 kWh/t refusal to the incinerator	30 kWh/t waste for composting; 4.03 kWh/t refusal to the incinerator	Ham et Komilis,2003; Diaz e Warith, 2006
29	Input parameter	Cs_i = percentage of energy produced by the plant consumed	15 – 25 %	20%	Di Stefano et al., 2009
30	Input parameter	Cs_i = specific energy consumption for the production of fertilizer	4 – 39 MJ/kg fertilizer	4 MJ/kg fertilizer	
31	Parametro di calibrazione	rs_i =percentage of the fertilizer replacement for the refusal	0 – 1	1	Zhao et al., 2009

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