Greenhouse gas emission reductions through waste management and disposal planning

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The Third Conference of the Parties of the UN-FCCC (CoP-3) held in Kyoto in 1997 defined a Protocol with level of reduction of the Greenhouse Gasses (GHGs) overall emissions for Italy of 6.5% with respect to 1990 emissions. A mathematical model was created in order to evaluate the range of GHGs reduction effects obtained by upgrading waste collection, treatment and disposal system to new Italian regulation.

Keywords: waste system planning, greenhouse effect, waste disposal, CO_2 reduction

1. Introduction

Recent scientific hypotheses emphasize the existing relationship between the increment of anthropic emissions of some gasses and large scale climate modifications. The gaseous compounds on which attention has been focused are the so called greenhouse gasses: carbon dioxide (CO_2), methane (CH_4) nitrogen protoxide (N_2O) and CFCs, as emphasized in the Intergovernamental Panel on Climate Change (IPCC) (Houghton et al. [1,2]).

Recent scientific and political discussions about the problem of the greenhouse effect have led to the conclusion that an overall effort for limitation or reduction of anthropic emissions is necessary.

The Kyoto Protocol adopted at CoP-3 in 1997, defined the levels of reduction of the overall GHG emissions for all the different countries that signed the final document. For Italy a GHGs reduction of 6.5% (by 2010) in comparison with the 1990 emission estimations was proposed.

Greenhouse gasses (GHGs) level reduction has to be considered as one of the main aims in any territorial plane.

In Tuscany, in particular, the definition of the Energy Planning Act also took the effect of reduction of GHGs emissions into account for the definition of possible strategies or different future scenarios in addition to specific energy indicators (such as primary energy consumption reduction, increment of utilization efficiency, etc.).

In this way it is possible to evaluate how the energy strategy defined in the act of planning could be effective according to the objectives stated in the Kyoto Protocol.

In the present work, results are shown of the evaluation of GHGs overall emission reduction effect due to the different scenarios for waste management, treatment and disposal, also considering the possibility of energy recovery from waste.

2. Energy regional planning instrument (ERP)

In the first defining phase of the Tuscany Region Energy Planning Act, the state of the art of production, consumption and transport of the overall typology of energy sources was studied, using several energy and environmental indicators. In the second phase of the study the evaluation of possible alternatives was also carried out as support for future decision maker strategies.

In terms of environmental effects due to different energy planning scenarios, the GHGs overall emissions were selected as one of the main indicators, with reference to 1990 estimations. GHGs mass flow rates were referred to CO_2 equivalent mass flow rate, calculated using the Global Warming Potential (GWP) values reported in table 1.

Overall Tuscany Region emissions of GHGs (as CO_2 equivalent), estimated by the Italian New Technologies, Energy and Environment Agency (Ente per le Nuove tecnologie, l'Energia e l'Ambiente, ENEA), are reported in table 2 [4].

In table 3, emissions due only to management, treatment and disposal waste systems are reported, referring to 1990 [4].

The definition of the possible future scenarios concerning the overall regional future waste management and treatment plants system was carried out taking into account new Italian regulations (D.Lgs.22/97), the so called "Ronchi

Table 1
Global Warming Potential (GWP) factor. [a]

Pollutant	GWP (in mass)
CO_2	1
CH_4	21
N_2O	310

[a] Source: Houghton et al. [1,2].

Table 2
Overall and anthropic GHG emissions, Tuscany 1990. [a]

	Overall sources			Anthropic sources		
	Overall emissions (t/a)	Overall emissions (as CO_2 eq.) (t/a)	(%)	Overall emissions (t/a)	Overall emissions (as CO_2 eq.) (t/a)	(%)
CO_2	29,145,006	29,145,006	77.2	28,394,192	28,394,192	79.9
CH_4	228,173	6,845,193	18.1	196,816	5,904,477	16.6
N_2O	8,823	1,764,680	4.7	6,266	1,253,220	3.5
Overall	29,382,003	37,754,879	100.0	28,597,274	35,551,889	100.0

[a] Source: Regione Toscana data [4].

Table 3
Greenhouse gas emissions from waste management, treatment and disposal, Tuscany 1990. [a]

	Overall emissions (t/a)	Overall emissions (as CO_2 eq.) (t/a)	(%)
CO_2	527,762	527,762	14.1
CH_4	106,860	3,205,809	85.5
N_2O	79	15,900	0.4
Total	634,701	3,749,471	100.0

[a] Source: Regione Toscana data [4].

Law" from the name of the Minister responsible for it, and the objectives indicated in this regulation in terms of waste fraction recovery and recycling, waste production reduction, conditions for plant utilization, etc.

Thus the main aim of the present work was to emphasize the possible effects, in terms of GHGs emission reduction, compared with the possible future scenarios for waste management and plant utilization treatment. The results obtained point to an additional strategy to be taken into account for the other anthropic sources of carbon dioxide emission for an overall reduction.

3. CO_2 reduction options from waste treatment systems

Municipal Solid Waste (MSW) collected can be sent, depending on previous planning decision making, to aerobic or anaerobic chemical degradation processes characterized by low or high temperatures (composting, landfilling, gassification or combustion). All these processes have some GHG emission outputs, depending on the overall flow rate of the different chemical compounds: some produce only small traces of methane, while others have high methane/carbon dioxide mass flow rate ratios.

On the other hand, thermal (combustion and gassification) processes have high efficiency in carbon content oxidation to CO_2 in comparison with nonthermal (composting and landfilling) processes. So a strategy of separating collection of refuse for recycling of different materials can influence the overall flow rate of GHGs due to waste management, treatment and disposal.

One of the main issues of the present work was to evaluate GHG overall production modification related to the fulfillment of new Italian regulations on waste management concerning waste production variation and waste fraction recovery percentage.

Due to the fact that serious doubts remain about the real possibility of complete fulfillment of regulations in the scheduled times, a series of different scenarios were evaluated, taking into account different conditions of management obtained within established times over the entire region. For this aim a specific evaluation model was developed using Matlab^{TM}.

The model developed allows calculation of the GHGs (in terms of CO_2 equivalent) overall mass flow rate due to waste management, depending on a series of established indicators, considered as waste market indicators:

– waste production growing rate;
– production growing rate for high Lower Heating Value (LHV) like plastic, paper, wood, textiles, etc. and production growing rate for lower LHV like biodegradables and organics in general;
– separated collection for recycling of the different materials;
– use of landfill as percentage of landfilled waste in comparison with the overall mass flow rate of treated waste;
– rate of mechanical separation for the different waste fractions obtained from pretreatment of wastes assigned to incineration as a way of separating lower LHV fractions for combustion and energy recovery optimization in compliance with present Italian regulations.

The model is based on a waste inventory database of 1997 waste production, collection and recycling in the 10 provinces of Tuscany and on a characterization of waste

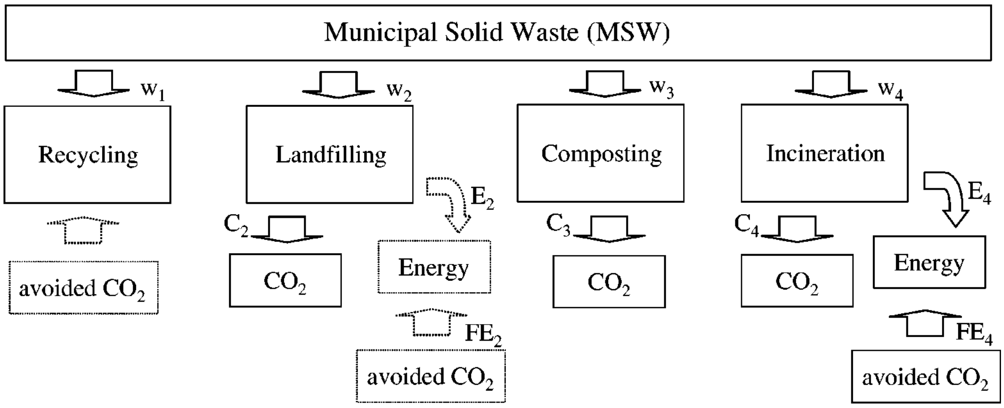

Figure 1. Evaluation of GHG (CO_2 equivalent) emission from waste management, treatment and disposal.

material composition based on 26 different fractions. Missing data about fraction composition of waste were replaced with average regional data.

The GHGs evaluation model output and input refer to the 9 different Territorial Waste Management Authorities (Ambiti Territoriali Ottimali, ATO).

Varying the input of the waste management overall scenario using the previously described indicators, the model calculates GHG (CO_2 equivalent) emission mass flow rates, using different models for specific treatment chemical degradation (figure 1).

The calculation process can be summarized as

$$\mathrm{GHG} = \sum_i Q_i \sum_j W_{i,j}(C_{i,j} - E_{i,j}\mathrm{FE}_{i,j}), \qquad (1)$$

where GHG is greenhouse gasses production mass flow rate, Q_i ith specific ATO waste mass flow rate, $W_{i,j}$ jth specific treatment waste mass flow rate, $C_{i,j}$ GHG emission factor for the jth specific treatment system, $E_{i,j}$ energy production factor related to the jth specific treatment system, $\mathrm{FE}_{i,j}$ GHG emission factor related to conventional energy conversion national system, i = specific ATO number (overall number equal to 9), j = specific treatment system number (overall number equal to 4).

The calculation model developed at this stage does not take into account avoided emissions due to recycling of waste material in spite of unused resources in terms of energy and resource saving.

Emissions from transport were not evaluated owing to the specific aim of the present research, which is to evaluate different scenarios of waste management and treatment as a support for planning decision makers, and also considering the lower influence to the overall effect already shown [5]. So any considerations were made about specific locations of technological plants needed for transport flux definition.

Consumption of energy, materials and reagents was not evaluated as an indirect source of GHG emissions.

A description of the 1997 plant situation concerned waste treatment systems in Tuscany as reported by Beone et al. [6], considering that no variation occurred from that time in terms of new waste treatment system implementation or notable existing plant process modifications. Referred data are reported in table 4.

Table 4
Technological plant situation for 1997 waste management scenario. [a]

Province	Separation and composting plants (t/a)	Incineration plants (t/a)
Firenze	46,500 [b]	11,000
		43,200
Grosseto		14,000
Livorno	31,000	36,832
	26,600	
	62,000	
Lucca		10,850
Massa	62,000	
Pistoia	28,830	37,200 [c]
Siena		27,000
Pisa		62,000 [c]
Prato	–	–
Arezzo	–	–

[a] G. Beone et al. [6].
[b] Refuse Derived Fuel (RDF) production.
[c] Energy recovery by electrical energy production.

Starting from the existing system situation (in 1997), the model evaluates the effects of CO_2 overall production for the different scenarios taken into account.

2001 was considered for the evaluation of possible GHG emission modifications related to new waste regulation fulfillment for the overall territory of Tuscany.

Italian waste regulations in terms of material recycling considered two different hypotheses of level of fulfillment by 2001. Two scenarios for the two different regulation fulfillments were considered, as reported in table 5.

4. Estimation models of waste treatment system GHG production

GHG emissions from different waste treatment systems are evaluated by the model as the overall mass flow rate produced within the duration of chemical degradation reactions that take place for the specific system and for the specific waste fraction considered.

Table 5
Separate waste collection objectives in 2001. [a]

	Minimum objective overall recycling rate in 2001 of about 25%	Maximum objective overall recycling rate in 2001 of about 35%
Organic fraction	33%	48%
Paper and cardboard	40%	60%
Plastic packing	15%	15%
Glass	60%	75%
Wood and textiles	10%	20%
Ferrous and nonferrous metal packing	15%	15%

[a] Italian Waste regulation D.Lgs.22/97.

In this way results of GHG emissions are unable to estimate the real mass flow rate per time unit well, depending on the specific parameter of chemical reactions such as temperature, reaction kinetic, overall waste already landfilled and time of landfilling, etc.

For waste combustion CO_2 production and emission model the net combustion of 95% of the overall nonfixed carbon mass burning present in chemical bonds of every fraction considered, represents the loss of combustible mass because of uncompleted reactions or overall mass losses in the combustion section.

For the future scenarios of waste incineration systems the presence for all plants was considered of an energy recovery section able to guarantee an overall net electrical conversion efficiency of about 18%.

The electrical efficiency was estimated considering an energy recovery system composed of a water-jacket, and water wall irradiation boiler with a tail-end recovery realized with a Heat Recovery Steam Generator (HRSG) operating from flue gas temperatures of 650 and 280 °C for the production of reheated steam at a pressure level of 40 bar and a temperature of 400 °C.

These conditions correspond to a conventional technology recovery system level, that could be upgraded to a maximum value of about 25% of net electrical conversion efficiency, lowering flue gas HRSG output temperature (down to 170–180 °C) and increasing steam pressure level (up to 50–60 bar).

None of the existing regional waste incinerator plants equipped with energy recovery section has been able to guarantee these levels of energy conversion up to now, so that for the modeling of the present scenario the supplied data of overall annual energy production were considered.

Estimation of the avoided GHG emissions from substitution of conventional national conversion system electrical energy with energy produced from waste to energy systems, was made referring to an average value of energy conversion efficiency for Italian generated electricity equal to 37.4% and to fossil fuels mix supplied by the Italian National Electricity Board (ENEL) [7].

For estimation of GHG production from aerobic and anaerobic organic waste fermentation and chemical degradation, occurring in landfilling and composting plants, a simplified chemical model based on the Organic Biodegradable carbon presence in waste compounds (OBC) was used (Pizullo et al. [3]).

Overall organic biodegradable carbon (OBC) present in the waste can be evaluated using the following equation:

$$\mathrm{OBC} = \sum_i \mathrm{OBC}_i = \sum_i \mathrm{C}_i f_{bi} \big[(1 - u_i) p_i\big], \qquad (2)$$

where C_i organic carbon fraction in the ith component, referring to dry mass of waste ($\mathrm{kg\,C/kg}_i$), $f_{bi}\mathrm{C}_i$ fraction that is biodegradable, u_i wet fraction of the ith component, p_i mass fraction referring to wet compounds of the ith component ($\mathrm{kg}_i/\mathrm{kg}$ MSW wet).

Produced gas mass from fermentation of the overall waste mass flow rate is calculated on the basis of the following equation:

$$\mathrm{Biogas} = \mathrm{OBC}\, Q_{\mathrm{MSW}} \mathrm{Eff}. \qquad (3)$$

The biodegradation efficiency parameter (Eff = fermented mass on biodegradable mass ratio) for the obtained value of OBC, is evaluated to be equal to 0.77 in the case of landfilling reactors (Pizzullo et al. [3]) and is estimated to be 0.95 in case of composting reactors.

The flue gasses obtained from the fermentation reactors were evaluated to be a mixture of CO_2 and CH_4, with a mass fraction of the two compounds depending on the specific reactor system. For landfilling a mixture of 55% of CH_4 and 45% of CO_2 was considered in comparison with the 95% of CO_2 and 5% of CH_4 considered in the case of composting reactors, where a prevalence of aerobic reactions takes place (Pizzullo et al. [3]).

The overall balance of GHG emitted from "cold" waste treatment (landfilling and composting mainly) is also dependent on the use of the gasses produced. In the case of landfilling in particular, the presence of a biogas collection system inside the reactor enables the reduction of partially uncontrolled biogas emissions. Collected biogas may be used for energy recovery aims or simply flare burned.

In the case of energy recovery (conventional fossil fuel substitution or cogeneration gas engine feeding) an additional beneficial effect obtained is derivation from avoided emissions for substituted conventional energy cycles, while in the case of flare burning the only positive effect is the oxidation of the CH_4 present in the mixture with a higher GWP than CO_2.

The mass fraction of landfill biogas collected with respect to the overall production is a modifiable parameter inside the model; for estimations from Tuscany landfills, an average value of collecting capacity equal to 0.13 was considered (Pizzullo et al. [3]); this data was validated using data from some specific plants.

For collected biogas end use, in the present study no consideration was made of the possibility of a connected energy recovery system, so that all the biogas collected is considered to be flare burned. This consideration reflects the actual situation in Tuscany, with a negligible energy recovery from landfill biogas.

5. Results

Using the developed GHG estimation model, an evaluation of the possible scenario for GHG emission reductions depending on waste management, treatment and disposal strategies in Tuscany was made. The evaluations were carried out referring to a waste system scenario in 2001. All the results obtained were compared with data estimated for the year 1997 and with data estimated by ENEA for the year 1990. The comparison with 1990 GHG emission data is particularly important since it allows an evaluation of the reduction effects with respect to the Kyoto Protocol objectives of 6.5% proposed for Italy.

Concerning GHG data for different years it should be remembered that the estimations of 1990 were made taking into account different models, so that values are not directly comparable. Moreover, data for 1990 also consider industrial and commercial wastes. Thus the evaluation of GHG reduction was made, considering the variation between 1997 and 2001 estimated data with respect to the overall production estimated in 1990.

The dependence of waste system planning and fulfillment on regulation was studied concerning an optimum scenario and a series of different scenarios with different grades of unfulfillment.

The optimum scenario considered is an integrated waste management system as described in figure 2 and consists of a reduction to zero of unstable waste landfilled, an overall 25% of separate collection and recycling of materials, and a mechanical separation phase for reducing the organic compound fraction in the incinerated wastes (80% of the mass flow rate).

For the evaluation of different scenarios of unfulfillment with respect to regulation objectives, the parameter value variation below was considered:

- MSW production growth varying from 0 to +5% in 2001 with respect to 1997 reported data;
- separated collection and recycling obtained in 2001 always equal to 25% of the overall MSW production mass flow rate;
- landfill use for unstable MSW varying from an optimum value (regulation objective) of 0% to a maximum value of 60% with respect to the 1997 value of 79.96% of MSW landfilled as unstable.

In table 6 more significant results are reported among the different scenarios evaluated. In particular, in table 6 the estimation data for referring the existing situation (1997) in comparison with the minimum and maximum 2001 GHG emission scenarios obtained from different cases evaluated are reported.

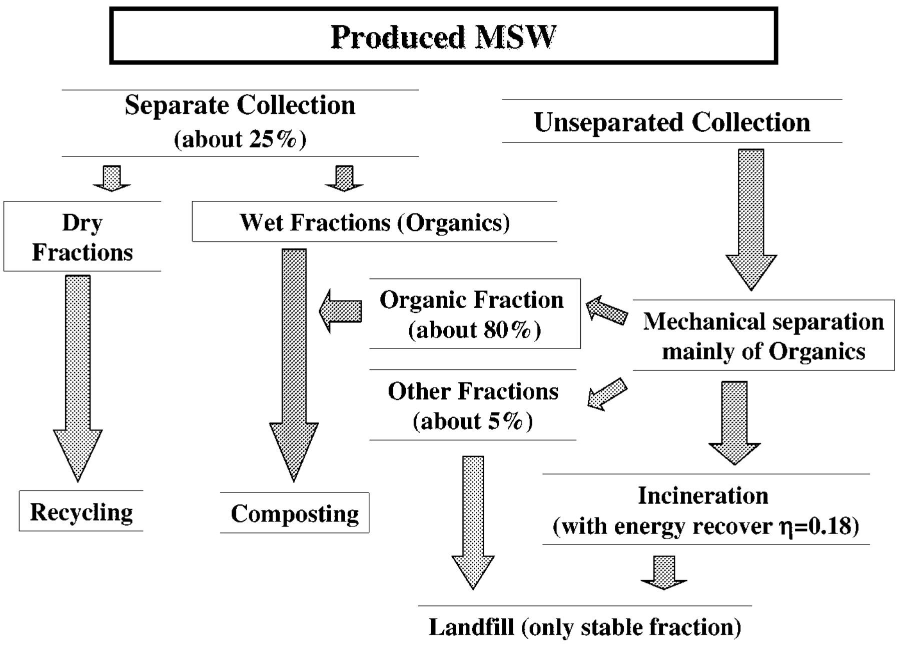

Figure 2. Sketch of the integrated waste management and treatment system considered as 2001 optimum scenario.

Table 6
GHG emission reduction results.

	1997 estimation	2001 – minimum GHG emission scenario (MSW growth 0%) (0% MSW landfilled)	2001 – maximum GHG emission scenario (MSW growth 5%) (60% MSW landfilled)
Electrical energy produced (MWh)	38,441	597,192	250,821
Energy saving (TEP/a)	3,306	137,322	57,675
Composted MSW (t/a)	126,116	568,404	364,103
Landfilled MSW (t/a)	1,468,926	0	836,255
Incinerated MSW (t/a)	242,082	957,890	402,356
GHGs from incineration (CO_2 eq.) (t/a)	235,397	1,069,690	449,270
GHGs avoided for E.E. produced (t/a)	10,314	428,445	179,947
GHGs from composting (CO_2 eq.) (t/a)	88,586	377,623	244,884
GHGs from landfilling (biogas recovery rate 13%) (CO_2 eq.) (t/a)	1,862,886	0	1,010,516
Overal GHGs (CO_2 eq.) (t/a)	2,186,869	1,447,313	1,704,669
GHG reduction (%)		33.8	22.1
GHG 2001/1990 reduction (MSW = 3,749,471 t/a CO_2 eq.) (%)		19.7	12.9
GHG 2001/1990 reduction (Global = 3,749,471 t/a CO_2 eq.) (%)		2.08	1.36

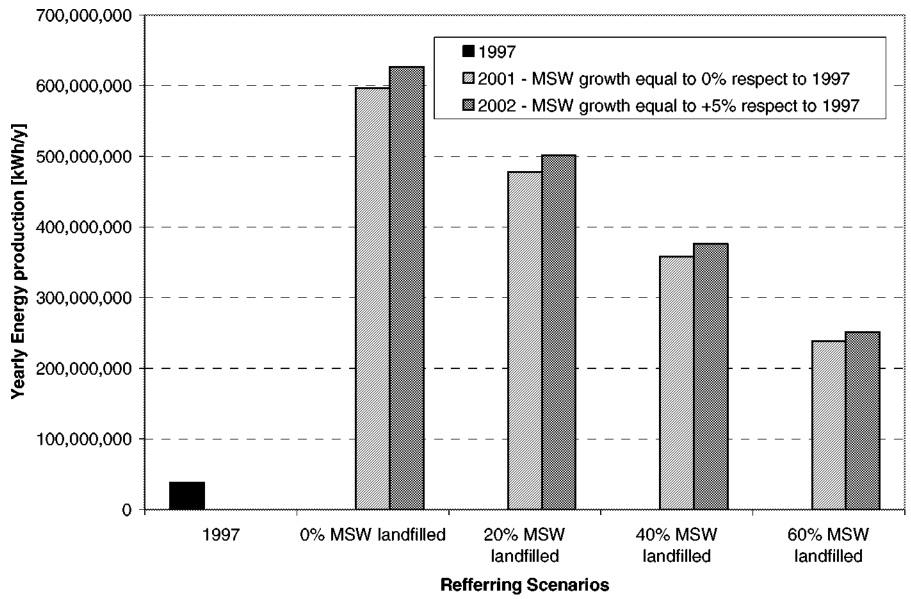

Figure 3. Electrical energy from waste overall year production (kWh/y).

The high increment of number and potentiality of the waste to energy plants, in addition to a more rationally utilized system (higher energy recovery and conversion efficiency coupled with a separation of lower LHV fraction from incineration feeding) allow a qualitative improvement in the anthropic contribution due to incineration:

– in terms of GHG specific emissions per TOE (tons oil equivalent) unit feed to incineration it is possible to verify an estimated value in 2001 of about 7.79 t_{CO_2}/TOE to be compared with 2.35 t_{CO_2}/TOE for natural gas and 4.23 t_{CO_2}/TOE for coal;
– even if in terms of GHG specific emissions per mass unit of incinerated MSW we observe an increment from the present situation (0.97 t_{CO_2}/t_{MSW} estimated for 1997 to be compared with 1.12 t_{CO_2}/t_{MSW} in 2001), with future scenarios it will be possible to obtain a considerable reduction of GHG specific emissions per energy unit produced: from 6.12 kg_{CO_2}/kWh to 1.79 kg_{CO_2}/kWh.

In terms of energy production from waste a wide range of increment rates were evaluated with respect to the existing situation (figure 3) with a maximum value of about 627 GWh/y estimated in 2001.

Lower values of energy recovery from waste incineration are obtainable with reference to 60% of untreated MSW landfilled in 2001; in this case, also considering an upgrade of waste to energy plants with respect to the existing situation an overall value of 239 GWh/y could be obtained.

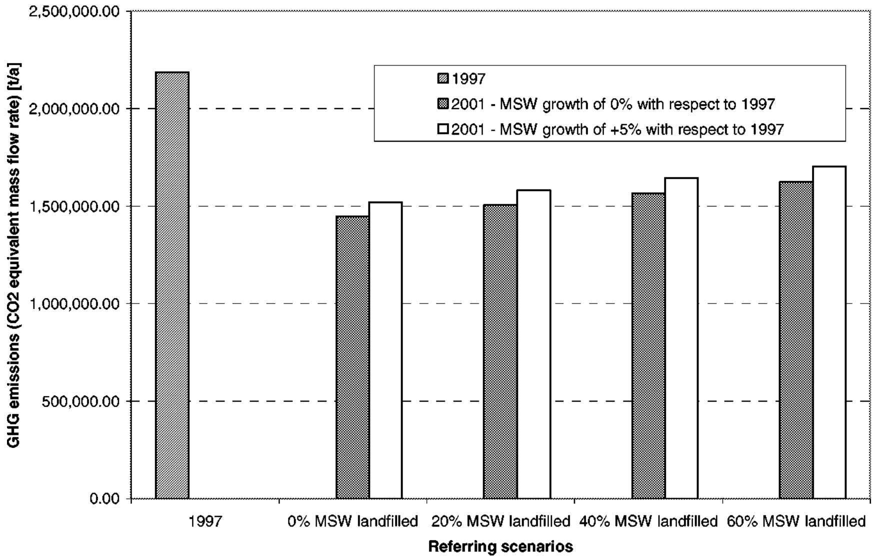

Figure 4. Overall GHG emission (as CO_2 eq.) for referring scenarios considered.

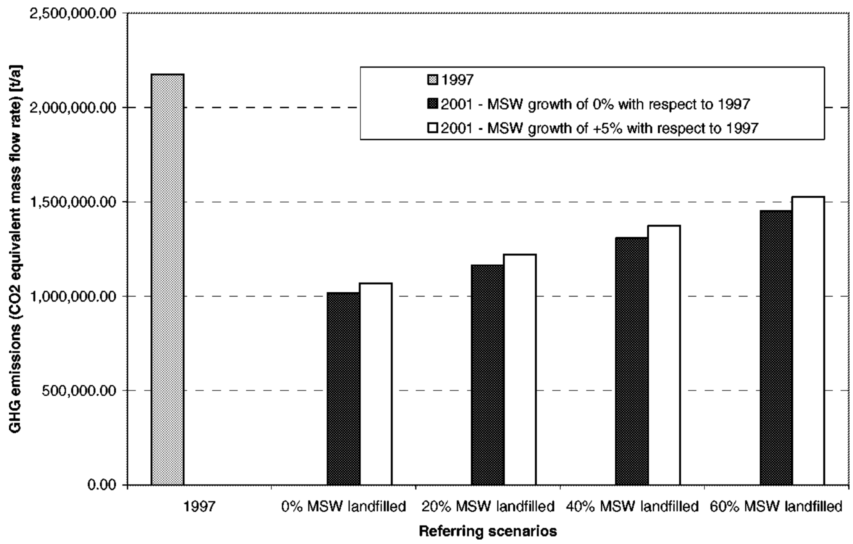

Figure 5. Overall GHG emission (as CO_2 eq.) for referring scenarios considering avoided from produced energy.

In terms of net GHG emissions, results obtained show the high levels of reductions that could be obtained with the complete fulfillment of the regional management, treatment and disposal system with reference to the new Italian waste regulation (D.Lgs.22/97). This effect could reduce the magnitude of modification needed for the other anthropic sectors in order to fulfill the overall 6.5% of GHG emission reduction.

Maximum value of GHG reduction (concerning the cases of future scenarios) in 2001 with respect to calculated emissions for the existing situation (1997) of 33.8% can be obtained if no landfilled MSW mass flow rate is reached. Considering the additional contribution of avoided GHG emissions due to conventional electrical energy substitution, an overall reduction of 53.2% could be the maximum reduction value for GHG emissions from the overall regional waste management system.

In figures 4 and 5 GHG overall emissions from waste management systems are reported for all considered main cases of future scenarios. While in figure 4 the reduction of net overall production of GHG mass flow rate is emphasized, in figure 5 the same results are reported also considering the contribution due to conventional electrical energy substitution.

In figure 6 the modification of specific relative contributions to GHG overall emissions from the different treatment systems are compared taking into account the existing 1997 scenario and the 2001 future minimum and the maximum impact scenarios. As emphasized in the figure, changing the overall waste system from the existing one it is possible to obtain a high reduction of the relative contribution due to landfilling from the present 85.2% to a zero percentage in case of full regulation fulfillment.

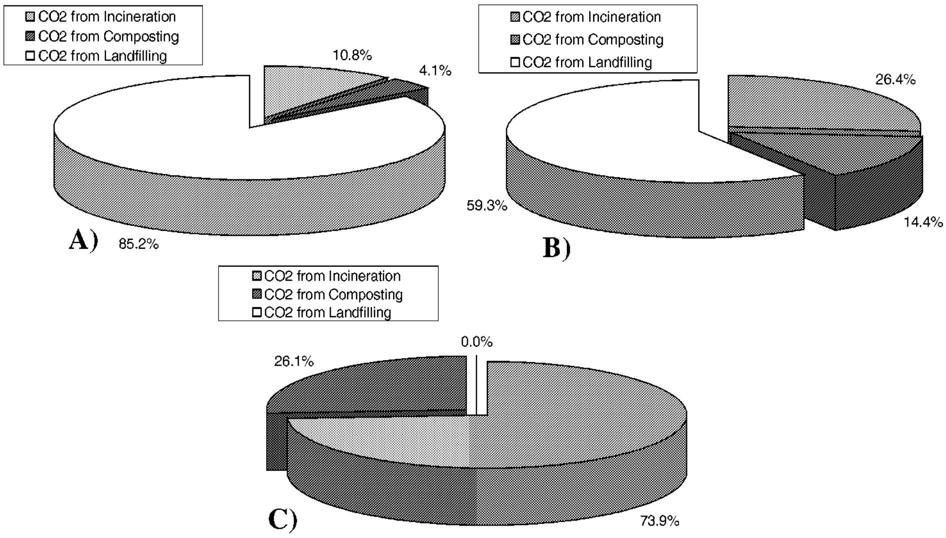

Figure 6. Percentage contribution to GHG (as CO_2 eq.) for different treatment and disposal systems for existing 1997 situation scenario (A) and future 2001 minimum (C), and maximum (B) impact scenarios.

On the contrary, an increment of "warm" waste treatment processes is obtained with a maximum value of relative weight up to 73.9%.

The overall possible contribution from waste modified system to greenhouse gas emissions as estimated by the developed GHG production model with respect to 1990 estimated emissions was evaluated as decision making planning for Kyoto Protocol objective fulfillment.

Considering the range of different cases previously defined in terms of overall net emissions a range of GHG reductions varying from 2.08 to 1.36% was calculated. Considering the additional contribution due to conventional electrical energy substitution, a GHG reduction rate varying from 3.26 to 1.83% is estimated from our model calculations. Higher reduction rates are obtained in case of fulfillment of waste separate recovery higher than 25% and waste overall production reductions.

6. Conclusions

The developed model represents a good compromise for a simple and quick instrument as support for decision makers on planning strategies to be compared with more accurate but also more complicated Life Cycle Assessment instruments.

The model was applied to a case study of energy planning decision making that needs to be in compliance with new objectives of greenhouse gas reduction based on the Kyoto Protocol adopted at CoP-3. The scenario considered is also in compliance with the objectives of the Energy and Environment Italian Pact signed during the Italian Conference on Energy and Environment in November 1998.

The case study here reported shows how, starting from an overall waste management, treatment and disposal system practically without integrated and optimized technological plants, also with an uncompleted fulfillment to new Italian waste regulation objective high reduction of overall GHG mass flow rates able to considerably affect the overall reduction to be obtained, up to a maximum value of 30–50% of the objective can be reached.

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