Institute for Global Environmental Strategies

User Manual

Estimation Tool for Greenhouse Gas (GHG) Emissions from Municipal Solid Waste (MSW) Management in a Life Cycle Perspective

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This tool is developed under the project of Measurement, Reporting and Verification (MRV) for low carbon development in Asia (FY2013)

Note to User:

This is the version II of IGES GHG calculator. In this version, open burning and incineration are included. Some parts of the tool were revised based on feedbacks from the users.

We welcome any feedbacks from users to improve this model to best suit the requirements of local authorities and other users to facilitate sustainable waste management for climate change mitigation.

All feedbacks should be sent to Dr. Nirmala Menikpura (menikpura@iges.or.jp) and Dr. Janya Sang-Arun (sang-arun@iges.or.jp).

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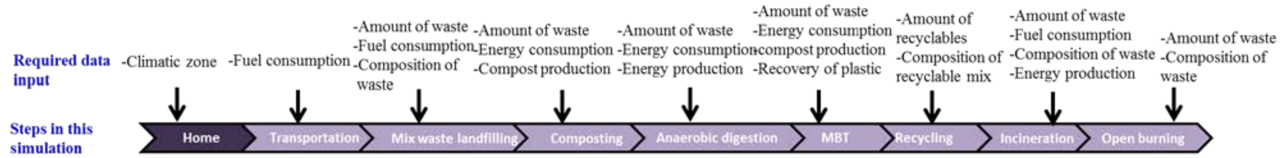
Executive Summary

Greenhouse gas (GHG) emissions from waste management activities and their contribution to climate change is one of the critical environmental concerns. Methane (CH_4) is the major GHG emitted from the waste sector, and open dumping and landfilling has been reported as the third highest anthropogenic CH_4 emission source. Climate pollutant including black carbon emission from open burning of waste which is practiced in many cities in developing countries is a critical concern. In addition, GHG emissions (e.g. CO_2, N_2O) from waste handling, transportation and operation of machinery are also significant especially due to the utilisation of fossil-based energy. Unfortunately, local authorities responsible for waste management do not clearly understand the linkage between waste management and climate change.

In 2011, IGES-Sustainable Consumption and Production (SCP) Group, in collaboration with local counterparts, conducted capacity building workshops for local governments to promote waste utilisation for climate change mitigation in Cambodia, Lao PDR and Thailand. Also, there was training on estimations of GHG emissions from waste management practices. However, it was difficult for personnel in local authorities since they are not familiar with the complex equations that are used for GHG estimation. Therefore, IGES developed a simple spreadsheet simulation to facilitate the decision-making of local governments on selection of appropriate technology and designing suitable waste management systems for climate change mitigation, as well as to evaluate their achievement/progress on GHG mitigation.

This GHG estimation model was developed to quantify the GHG emissions from individual treatment technologies as well as from integrated systems. Life cycle approach (LCA) has been adapted for developing this simulation. By using this model, the user can see the result of both direct emissions and GHG savings. This model can be applicable for countries across the Asia-Pacific region by selecting/entering country-specific or location specific parameters at the desired places.

This simulation consists of ten spreadsheets, which have been defined using the following names: User guidance, Home, Transportation, Mix waste landfilling Composting, Anaerobic Digestion, Mechanical Biological Treatment (MBT), Recycling, Incineration and Open burning. Except for the first two sheets (User guidance and Home), users are asked to enter the input data in all the other sheets and select the most appropriate conditions which are aligned with the waste-management practices of their local authority. Therefore, users should provide the required input data for each sheet in order to calculate GHG emissions from different aspects such as transportation, landfilling, composting, anaerobic digestion, MBT, recycling, incineration and open burning as shown in the chart below. If a municipality does not have all these technologies, they can enter the data in the corresponding sheets, specifically on available existing technologies or selected technology to be implemented.



IPCC 2006 guidelines have been adopted in this simulation to quantify GHG emissions from various waste management technologies. Therefore, this tool is useful for a bottom-up approach of national greenhouse gas inventory and for this objective the direct emission should be reported. Whenever other literature sources have been used for the estimation, it is clearly stated. Mathematical formulas have been assigned to the cells in the spreadsheets to quantify the GHG emissions from different phases of the life cycle. The detailed explanations on all the mathematical formulas which are used throughout the simulation have been described in the report under different technologies. The simulation calculates both the total GHG emissions and total GHG avoidance potentials of individual technologies. Based on the total GHG emissions and avoidance values, net GHG emissions are calculated from all the individual technologies. The net GHG emissions value reflects the overall climate impact/benefit of a particular technology taking into account the impact of all the possible resource and material recovery from the waste. Hence, the estimated net GHG emission values from an individual treatment method can be used as tangible figures in decision-making and policy recommendation processes.

If this simulation applies to quantifying climate benefits from an integrated waste management system, the net GHG emissions from individual technologies will further be aggregated based on the fraction of waste treated by those technologies. However, when technologies are aggregated to quantify GHG mitigation from the integrated system, GHG savings via avoided organic waste landfilling are excluded in order to avoid double counting. The estimated net GHG emissions from the integrated system indicate the overall progress of the systems. This kind of holistic approach would be very beneficial to provide systematic methodology and then to quantify potential GHG mitigation from an integrated waste management system. GHG emissions estimation results would be very useful for local governments to enable the decision-making process on selecting climate friendly waste management technologies.

It is important to identify the potential limitations of applying this simulation. Quantification based on life cycle assessment- users may find difficulty in gathering all the essential data required for this simulation (see Annex I). Furthermore, some assumptions have been made in the simulation that may influence the accuracy of the final result. For instance, as compared to other waste management technologies, GHG mitigation potential from an appropriate recycling scheme would be remarkable. Therefore, it is necessary to quantify GHG emissions more precisely and concisely from recycling business at the local authority level. However, due to lack of country-specific data, this simulation uses an inventory data which represents the situation of Thailand to quantify GHG emissions from all the included countries. In future, IGES will develop a more comprehensive simulation to overcome the problem and to quantify the overall climate benefits from particular recycling systems, taking into account the location-specific data.

Table of Content

Introduction

Greenhouse gas (GHG) emissions from conventional solid waste management in developing Asian countries contribute significantly to global climate change. Methane (CH_4) emission from open dumping and landfilling is the third highest anthropogenic methane emission source. These two methods are currently the most common waste treatment methods in Asian countries. In addition, GHG emissions (e.g. CO_2, N_2O) from waste handling, transportation and operation of machinery are also significant, especially due to the utilisation of fossil-based energy. However, there is a possibility for indirect GHG savings via materials and energy recovery from waste management. Unfortunately, local authorities responsible for waste management do not clearly understand the linkage between waste management and climate change.

The Sustainable Consumption and Production (SCP) Group at IGES has been conducted several capacity building workshops for local governments to promote waste utilisation for climate-change mitigation in Cambodia, Lao PDR and Thailand. There has also been a training programme on estimation of GHG emissions from waste management practices. However, it was difficult for personnel in local authorities to understand the complex procedure and the mathematical formula used in the estimation. Therefore, IGES developed a simple spreadsheet simulation to facilitate the local governments on estimating GHG emission from the current waste management practices, to support decision-making process of local governments on selection of appropriate technology for GHG mitigation, to evaluate progress made by adopting suitable waste management approaches, and to contribute to a bottom-up approach for national greenhouse gas inventory report.

This GHG estimation model can be applicable to quantify the GHG emissions from individual treatment technologies as well as from integrated systems. Life cycle approach (LCA) has been adapted for developing this simulation. By using this model, the user can see the result of both direct emissions (use for national greenhouse gas inventory and carbon market) and GHG savings (use for decision making). This model can be applicable for countries across Asia-pacific region by selecting/entering country-specific or location parameters at the desired places in each sheet.

This simulation consists of ten spreadsheets, which have been defined using the following names: User guidance, Home, Transportation, Mix waste landfilling, Composting, Anaerobic Digestion, Mechanical Biological Treatment (MBT), Recycling, Incineration and Open burning. Except for the first two sheets (User guidance and Home), users are asked to enter the input data in all the other sheets and select the most appropriate conditions which are aligned with the waste management practices of their local authority. Therefore, users should provide the required input data for each sheet in order to calculate GHG emissions from different aspects such as transportation, landfilling, composting, anaerobic digestion, MBT, recycling, incineration and open burning. If a municipality does not have all these technologies, they can enter the data in the corresponding sheets, specifically on available existing technologies or selected technology to be implemented.

The detailed explanation of individual sheet is described in the sections below.

1. User guidance page

The very first sheet of the simulation is designed to present the aim of developing the simulation, and useful guidelines to users for its application. By reading the "user guidance" sheet, users will understand the type of data required to quantify GHG emissions from the waste management system with respect to the existing technologies. The user guide page in the simulation is shown in Figure 1.

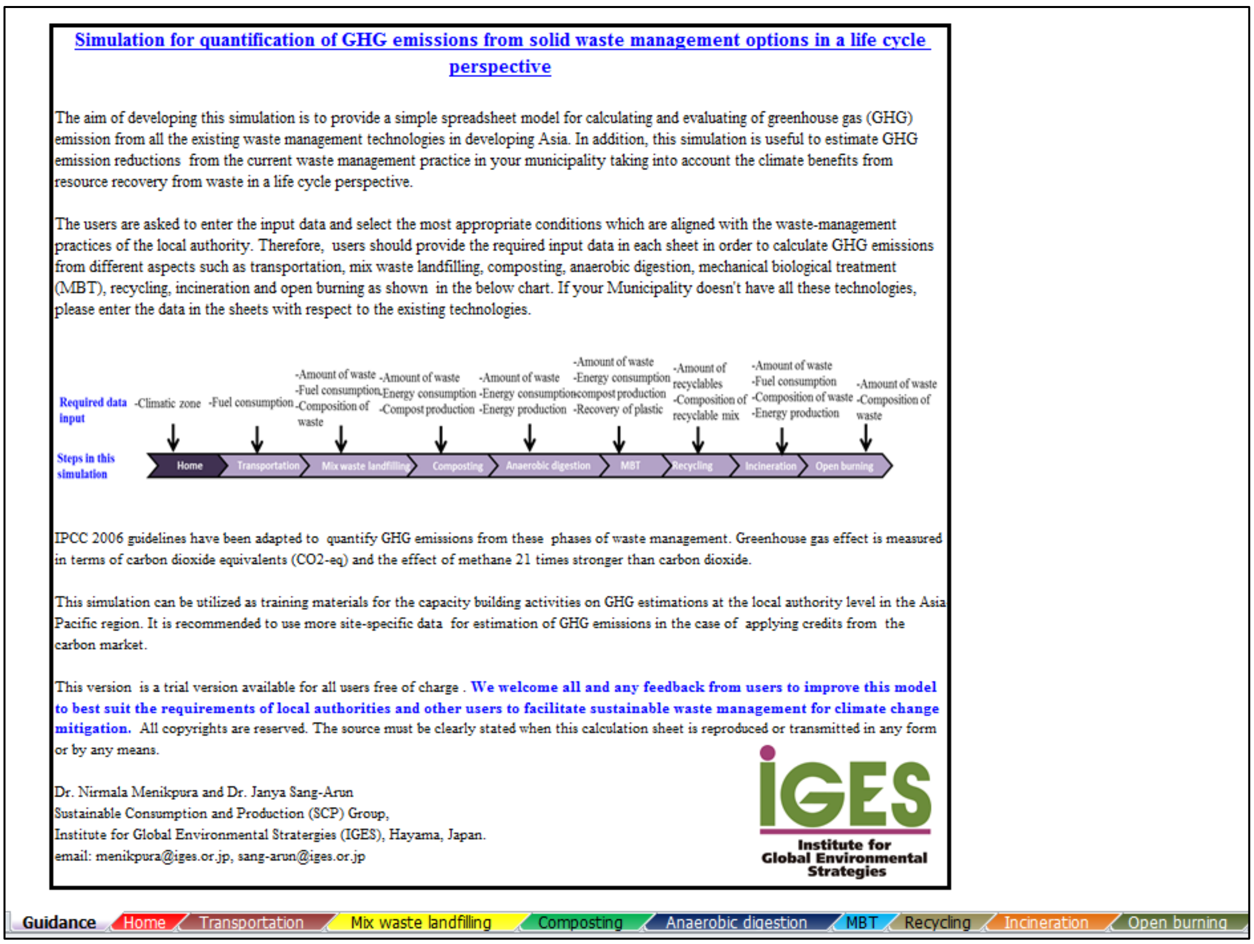
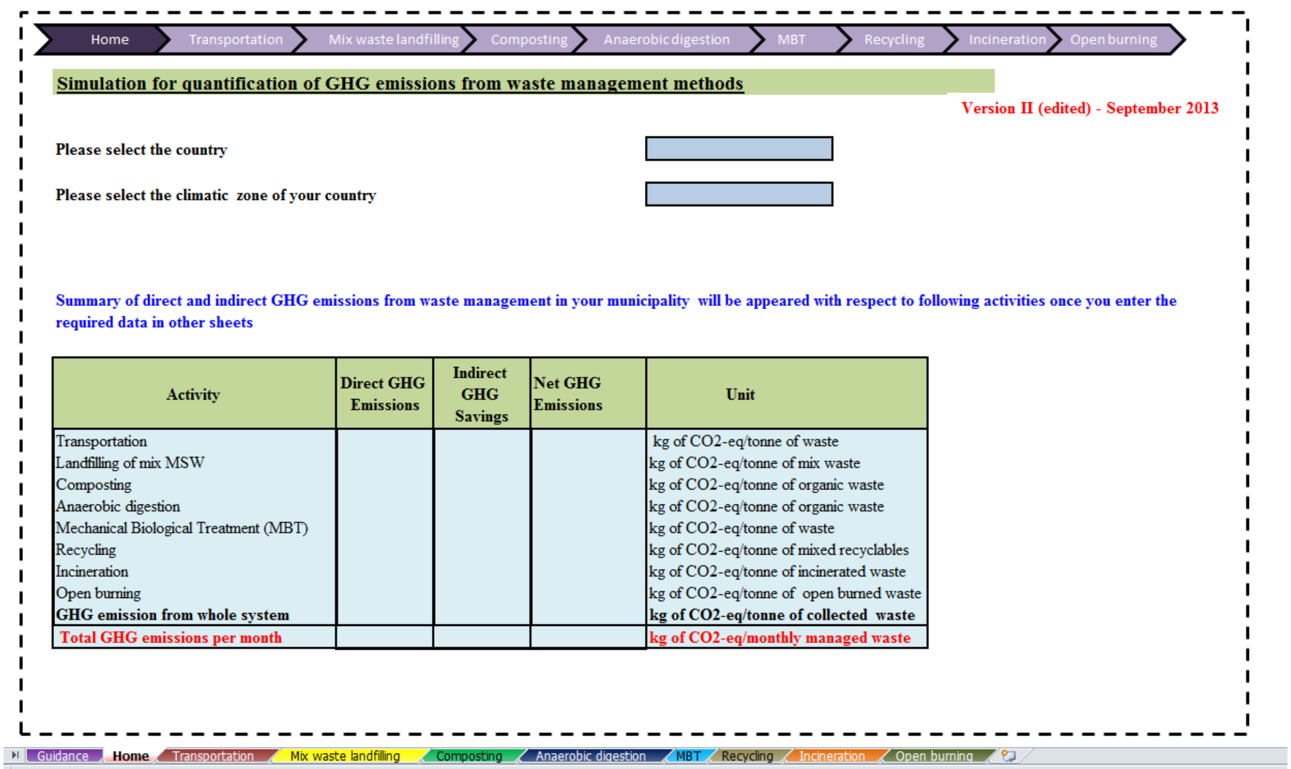


Figure 1: The user guidance page of the simulation

2. Homepage

On the homepage of this simulation, users are asked to select the country and the climatic zone of the country. Options have been given as a “drop-down list” as shown in Figure 2. Once users select a specific country (available in the simulation), all the country-specific data/information (e.g. GHG emissions from national grid electricity production, GHG emissions from fossil-fuel combustion) will be assigned automatically to the mathematical formulas throughout the spread sheet for quantifying GHG emissions from different phases of the life cycle.

In addition, the homepage has been designed to display a summary of the GHG emissions results from a particular waste management system. At the data-entering stage, users can see the message “Summary of GHG emissions from waste management in your municipality will appear with respect to the following activities once you enter the required data in other sheets”. Therefore, the users would be aware of checking the homepage again, in order to see the overall results of GHG estimations once they finish data entry. In the summary table, direct GHG emissions (e.g. GHG emissions due to fossil energy consumption, waste degradation, combustion of fossil based waste fractions etc.), total GHG savings (e.g. GHG avoidance via material and energy recovery and avoided organic waste landfilling) and net GHG emissions will be appeared with respect to individual treatment method and from the entire waste management system. In addition total GHG reduction/emissions from monthly managed waste is displayed which will be useful to identify the progress made.



Home | Transportation | Mix waste landfilling | Composting | Anaerobic digestion | MBT | Recycling | Incineration | Open burning

Simulation for quantification of GHG emissions from waste management methods

Version II (edited) - September 2013

Please select the country

Please select the climatic zone of your country

Summary of direct and indirect GHG emissions from waste management in your municipality will be appeared with respect to following activities once you enter the required data in other sheets

Activity	Direct GHG Emissions	Indirect GHG Savings	Net GHG Emissions	Unit
Transportation				kg of CO2-eq/tonne of waste
Landfilling of mix MSW				kg of CO2-eq/tonne of mix waste
Composting				kg of CO2-eq/tonne of organic waste
Anaerobic digestion				kg of CO2-eq/tonne of organic waste
Mechanical Biological Treatment (MBT)				kg of CO2-eq/tonne of waste
Recycling				kg of CO2-eq/tonne of mixed recyclables
Incineration				kg of CO2-eq/tonne of incinerated waste
Open burning				kg of CO2-eq/tonne of open burned waste
GHG emission from whole system				**kg of CO2-eq/tonne of collected waste**
Total GHG emissions per month				**kg of CO2-eq/monthly managed waste**

Guidance | Home | Transportation | Mix waste landfilling | Composting | Anaerobic digestion | MBT | Recycling | Incineration | Open burning

Figure 2: Homepage of the simulation

3. Estimation of GHG Emissions from Waste Transportation

MSW transportation consumed a significant amount of fossil fuel and led to GHG emissions due to fossil-fuel combustion. Therefore, the third sheet of the simulation has been developed for quantification of GHG emissions from waste transportation. Two major types of fossil fuel are used for waste transportation in developing Asia, namely diesel and natural gas. Therefore, users are asked to enter the amount of waste transport per month and the corresponding amount of fossil-fuel usage with respect to the two major types of fossil fuels, as shown in Figure 3.

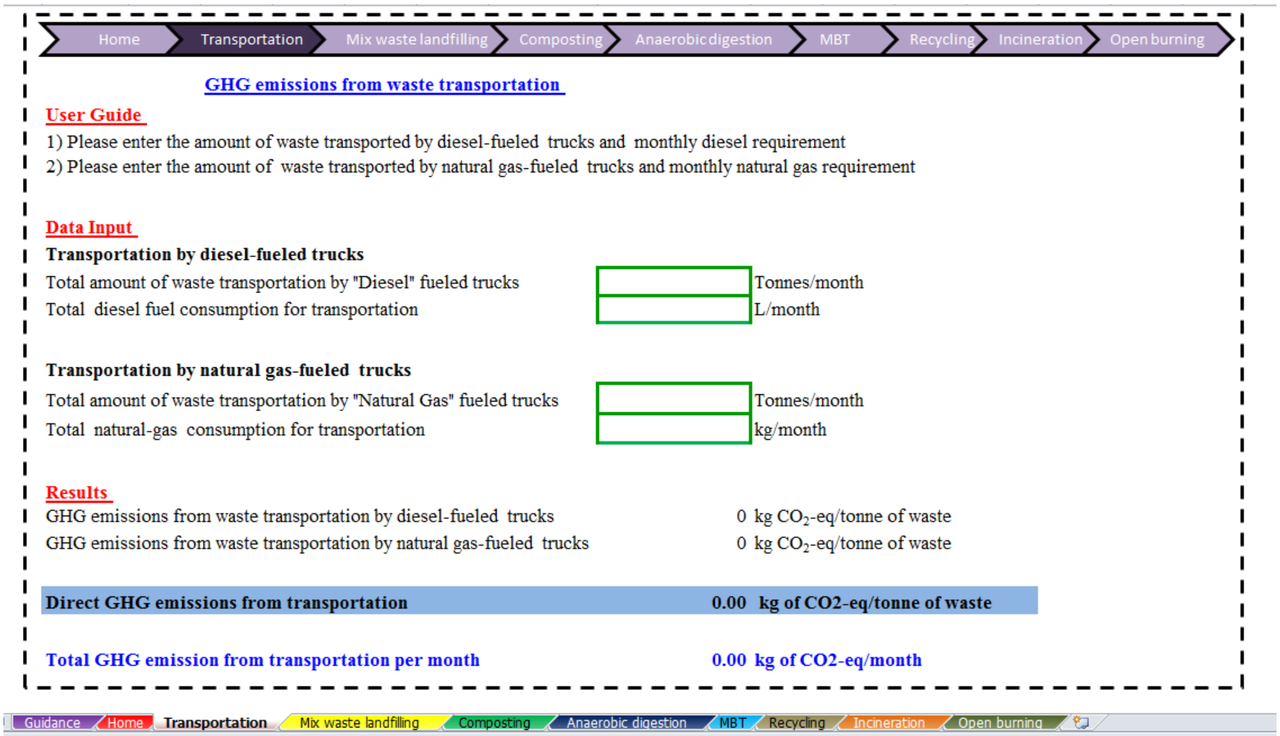


Figure 3: Page for quantification of GHG emissions from waste transportation

GHG emissions from extraction of crude oil, importation and the refining process are not included in this simulation since such emissions may not be significant (Menikpura, 2011). Also, CH_4 and N_2O emission from fossil fuel combustion is assumed to be negligible. Therefore CO_2 can be considered as the major component of GHG emissions from waste transportation. Mathematical formulas have been assigned to quantify CO_2 emissions from each type of fossil fuel.

Total GHG emissions from combustion of any kind of fossil fuel during waste transportation can be calculated as follows:

$$Emissions_T = \frac{Fuel(units)}{Waste(tonnes)} \times Energy(MJ/unit) \times EF(kgCO2/MJ)$$

$Emissions_T$ – Emissions from transportation (kg CO_2/tonne of waste transported)

Fuel (units) – Total amount of fossil fuel consumption per month, (diesel in Liters and Natural gas in kg)
Waste (tonnes) – Total amount of waste transported per month
Energy (MJ/unit) – Energy content of the fossil fuel (e.g. Diesel 36.42 MJ/L, Natural gas 37.92 MJ/kg)
EF – CO_2 emission factor of the fuel (e.g. diesel: 0.074 kg CO_2/MJ, Natural gas: 0.056 kg CO_2/MJ)

Some municipalities in developing Asia are trying to replace diesel fuel by using natural gas aiming to reduce GHG emissions from waste transportation. Therefore, this simulation shows the GHG emissions resulting from diesel-fueled trucks as well as natural gas-fueled trucks per tonne of waste transportation. If a municipality uses the both types of fuels, the results will show the aggregated effects due to the utilisation of diesel as well as natural gas, as shown in Figure 3. Furthermore, monthly GHG emissions from transportation can be estimated as follows:

Monthly GHG emissions (kg CO_2-eq/month) = GHG emissions per tonne × tonne of waste transported per month

4. Estimation of GHG emissions from landfilling

Landfilling is the most common waste disposal method throughout the world. Landfill technologies have developed drastically over the last few decades, but these developments have not yet reached all parts of the world (Manfredi et al., 2009). For example, most of the developing countries in Asia are still practicing open dumping and landfilling without gas recovery. Most of the time, waste is disposed in open dumps without a landfill cover, while the Government promotes development of on-land disposal towards sanitary landfill. Therefore, in some cases, sanitary landfill technology has been applied without a landfill gas recovery system so that most of the landfill gas is released into the atmosphere without any treatment or control. The anaerobic decomposition of MSW in open dumps and landfills eventually generates landfill gas (LFG) which contains approximately 60% methane (CH_4) and 40% carbon dioxide (CO_2). The CH_4 component of LFG contributes to global warming whereas the CO_2 component is generally regarded as being biogenic in origin and is thus not considered as GHG (CRA, 2010). The uncontrolled CH_4 emission from landfilling has been ranked as the third largest anthropogenic CH_4 emission source (IPCC, 2007).

The amount of methane generated at the disposal sites would depend on many factors such as quantity and composition of waste, moisture content, pH, and waste management practices. In general, methane production increases with higher organic content and higher moisture content in the disposal sites. A managed sanitary landfill has the potential of producing a greater methane yield than in an unmanaged disposal site (open dumps) where large amount of waste can decay aerobically in top layers. Deeper unmanaged solid waste disposal sites have greater methane emission than shallow unmanaged sites.

The IPCC 2006 Waste Model has the ability to calculate emissions from a variety of solid waste disposal site types, after deriving the default values considering country or region specific waste composition and climate information, and the situation of disposal sites. Therefore, to quantify the GHG emissions from normal waste management disposal practices in landfills, the IPCC 2006 waste model has been adopted in this simulation. The guidelines of IPCC strongly encourage the use of the First Order Decay (FOD) model, which produces more accurate emissions estimates since it reflects the degradation rate of wastes in a disposal site (IPCC 2006).

The following mathematical formula has been used in IPCC model to quantify GHG emissions from the landfilling or open dumping.

The basic equation for the first order decay model is:

(1) $DDOC_m = DDOC_{m(0)} \times e^{-kt}$

where $DDOC_{m(0)}$ is the mass of decomposable degradable organic carbon (DDOC) at the start of the reaction, when t=0 and $e^{-kt}=1$, k is the reaction constant and t is the time in years. $DDOC_m$ is the mass of DDOC at any time.

From equation (1) it is easy to see that at the end of year 1 (going from point 0 to point 1 on the time axis) the mass of DDOC left not decomposed in the SWDS is:

(2) $DDOC_{m(1)} = DDOC_{m(0)} \times e^{-k}$

and the mass of DDOC decomposed into CH_4 and CO_2 will be:

(3) $DDOC_{mdecomp(1)} = DDOC_{m(0)} \times (1 - e^{-k})$

In a first order reaction, the amount of the product (decomposed $DDOC_m$) is always proportional to the amount of reactant ($DDOC_m$). This means that it does not matter when the $DDOC_m$ was deposited. This also means that when the amount of $DDOC_m$ accumulated in the disposal site, plus last year's deposit, is known, CH_4 production can be calculated as if every year is year number one in the time series. Then all calculations can be done by equations (2) and (3) in a simple spreadsheet. The default assumption is that CH_4 generation from all the waste deposited each year begins on the 1st of January in the year after deposition. The assumption is that decomposition of first year can happen aerobically where methane generation is not taking place (the time it takes for anaerobic conditions to become well established). However, when the calculation includes the possibility of an earlier start to the reaction, in the year of deposition of the waste, this requires separate calculations for the deposition year.

To calculate mass of decomposable DOC ($DDOC_m$) from amount of waste material (W):

(4) $DDOC_{md(T)} = W_{(T)} \times DOC \times DOC_f \times MCF$

The amount of deposited DDOCm remaining not decomposed at the end of deposition year T:
(5) $DDOC_{mrem(T)} = DDOC_{md(T)} \times e^{(-k \cdot ((13-M)/12)}$

The amount of deposited DDOCm decomposed during deposition year T:
(6) $DDOC_{mdec(T)} = DDOC_{md(T)} \times (1 - e^{(-k \cdot ((13-M)/12))})$

The amount of DDOCm accumulated in the disposal site at the end of year T
(7) $DDOC_{ma(T)} = DDOC_{mrem(T)} + (DDOC_{ma(T-1)} \times e^{-k})$

The total amount of DDOCm decomposed in year T
(8) $DDOC_{mdecomp(T)} = DDOC_{mdec(T)} + (DDOC_{ma(T-1)} \times (1 - e^{-k}))$

The amount of CH_4 generated from DOC decomposed
(9) CH_4 $generated_{(T)} = DDOC_{mdecomp(T)} \times F \times 16/12$

The amount of CH_4 emitted from disposal site
(10) CH_4 emitted in year T = $(\Sigma CH_4 \text{ generated }_{(T)} - R_{(T)}) \times (1- OX_{(T)})$

Where:

T - the year of inventory
x - material fraction/waste category
$W_{(T)}$ - amount deposited in year T
MCF - Methane Correction Factor
DOC - Degradable organic carbon (under aerobic conditions)
DOC_f - Fraction of DOC decomposing under anaerobic conditions (0.0-1.0)
DDOC -Decomposable Degradable Organic Carbon (under anaerobic conditions)
$DDOC_{md(T)}$ - mass of DDOC deposited year T
$DDOC_{mrem(T)}$ - mass of DDOC deposited in inventory year T, remaining not decomposed at the end of year.
$DDOC_{mdec(T)}$ - mass of DDOC deposited in inventory year T, decomposed during the year.
$DDOC_{ma(T)}$ - total mass of DDOC left not decomposed at end of year T.
$DDOC_{ma(T-1)}$ - total mass of DDOC left not decomposed at end of year T-1.
$DDOC_{mdecomp(T)}$ - total mass of DDOC decomposed in year T.
CH_4 $generated_{(T)}$ - CH_4 generated in year T
F - Fraction of CH_4 by volume in generated landfill gas (0.0 – 1.0)
16/12 - Molecular weight ratio CH_4/C
$R_{(T)}$- Recovered CH_4 in year T
$OX_{(T)}$ - Oxidation factor in year T (fraction)

k - rate of reaction constant

M - Month of reaction start (= delay time + 7)

In order to calculate the methane emissions from landfill or open dump site, numerous default values are required and the amount of methane generation is highly dependent on the accuracy of these factors. The details explanations of the required default values are presented in Table 1.

Table 1: The required factors and default values for application of IPCC 2006 waste model

Factor	**Unit**	**Method of deriving**
Amount of mix waste disposal	Tonne/month	Amount/ description
Amount deposited	Gg/Year	MSW disposal (tonnes/month) ×12/1000
Degradable Organic Carbon(DOC)	DOC	Derived based on IPCC default DOC content values, DOC_{MSW} = % of food waste×0.15+ % of garden waste×0.43 + % of paper waste × 0.4 + % of textile waste × 0.24
Fraction of DOC decomposing under Anaerobic condition (DOCf)	DOC_f	IPCC default value is 0.5
Methane generation rate constant	k	k value will depend on waste composition of the location k_{MSW} =% of food waste×0.4+ % of garden waste×0.17 + % of paper waste × 0.07 + % of textile waste × 0.07 + % of disposal nappies × 0.17+ % of wood and straw × 0.035
Half- life time(t1/2, years)	h=In(2)/k	Can be calculated based on derived k value
exp1	exp(-k)	Can be calculated based on derived k value
Process start in decomposition year, month M	M	IPCC recommended value is after 12 months
Exp2	exp(-k((13-M)/12	Can be calculated based on derived k and M values
Fraction to CH_4	F	IPCC recommended value is 0.5
Methane Oxidation on Landfill cover	OX	IPCC recommended value for sanitary landfill with landfill cover is 0.1. for open dumpsites the OX value would be zero
MCF for the landfill/open dumpsite	MCF	According to the management practices, this value will be changed, IPCC recommended default MCF values for Managed (has landfill cover and liner), unmanaged-deep (> 5m waste), Unmanaged-shallow (<5m waste), Uncategorized are 1, 0.8, 0.4 and 0.6 respectively.

In this simulation, to calculate the total GHG emissions potential from a landfill or open dumpsite in a particular location, users are asked to enter the monthly average data such as amount mix waste landfilling, fossil fuel utilisation for operational activities at the landfill and the composition of mixed MSW. In addition, the user is asked to select the type of landfill from a drop-down list, as seen in Figure 4. The total value of the different fractions of waste of waste should be equal to 100 % in order to calculate the GHG emissions from the landfill, otherwise an error message would appear until the total value adjusts to the 100%.

The methane production per tonne of waste of degradation throughout the life cycle will be calculated and presented as kg of CH_4 production per tonne of waste. In addition, total GHG emissions from mixed waste will be calculated as follows:

GHG emissions from mixed waste landfilling/open dumping = CH_4 emissions per tonne of waste × GWP_{CH4} + GHG emissions from operation activities

Where; GWP_{CH4} - Global Warming Potential of CH_4 (The GWP of CH_4 was considered as 21 times higher than CO_2 on a time horizon of 100 years)

Based on this estimated value, the simulation calculates the monthly GHG emissions from mixed MSW landfilling can be calculated for a particular location.

Monthly GHG emissions (kg CO_2-eq/month) = GHG emissions per tonne of waste × Total amount of waste landfilled per month (tonnes)

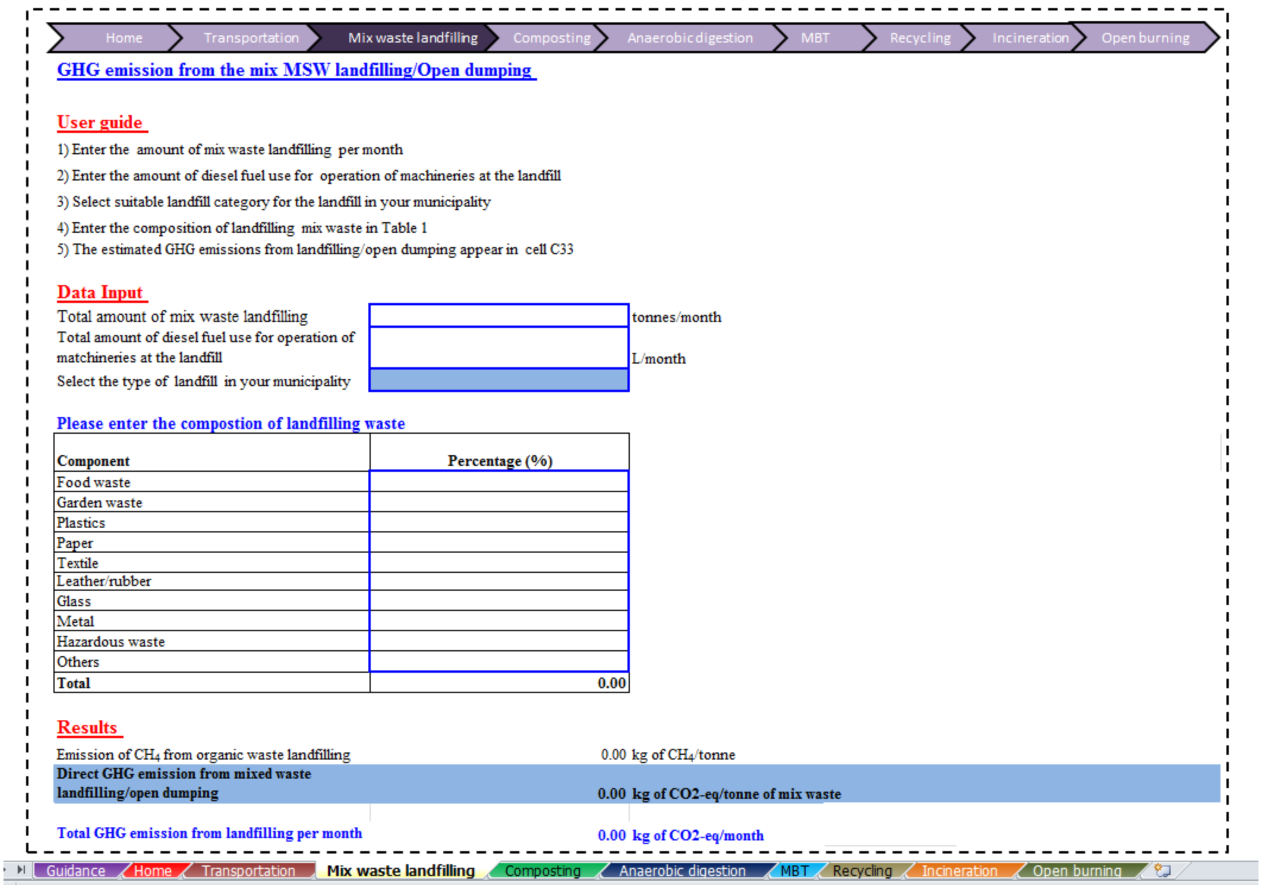


Figure 4: Page for quantification of GHG emissions from landfilling

5. Estimation of GHG Emissions from Composting

Importance of organic waste composting has been increasingly recognised in developing Asia. Amongst organic waste utilisation technologies, local governments prefer composting as it is simple, easier to manage and low cost. Therefore, composting is becoming one of the popular waste management options in Asia. In this simulation, the 4th excel sheet has been designed for quantification of potential GHG emissions from composting technology.

There are two major ways that composting could emit GHG: i) GHG emissions from utilisation of fossil energy (e.g. electricity and diesel) for operation of composting; and ii) GHG emissions from organic waste degradation.

As far as GHG emissions from organic waste degradation are concerned, composting is an aerobic degradation process whereby a large fraction of the degradable organic carbon in the waste material is converted into CO_2. Such CO_2 emissions have biogenic origin and would not be taken into account for GHG calculation. CH_4 can be formed due to anaerobic degradation of waste in deep layers of composting piles. However, such CH_4 is oxidised to a large extent in the aerobic sections of the compost piles. Composting can also produce emissions of N_2O in minor concentrations. In this study, IPCC published average default emission factors (e.g. 4 kg CH_4/tonne of organic waste in wet basis and 0.3 kg N_2O/tonne of organic waste in wet basis) were used to quantify the GHG emissions from composting (IPCC, 2006).

There is a potential for producing a significant amount of marketable compost from one tonne of organic waste. The produced compost can be used for agricultural purposes to replace conventional fertilizer. As reported in literature, one tonne of good-quality compost can be used to replace chemical fertilizer, since there is a possibility to supply the essential nutrients at the rate of 7.1 kg of nitrogen (N), 4.1 kg of phosphorus (P_2O_5) and 5.4 kg of potassium (K_2O) per tonne of compost (Patyk, 1996)[1]. Based on these figures, GHG mitigation potential from avoiding chemical fertilizer production is estimated in this model. However, in practice, this co-benefit should not be included in the calculation if farmers do not decrease the use of chemical fertilizer after application of compost. Furthermore, as a result of composting, disposal of organic waste at the landfill can be reduced. Therefore, this simulation will estimate the potential GHG avoidance by avoided organic waste landfilling.

In order to calculate all those potential emissions and avoidance, users are asked to enter the monthly average data such as the amount of organic waste use for composting, fossil-fuel utilisation for operational activities, the total amount of compost production and percentage of produce compost utilisation for agricultural activities, as shown in Figure 5.

The following mathematic formulas have been assigned to the spreadsheet cells in order to quantify the GHG emissions from composting.

[1] This figure can be changed if site specific or country's specific data is available.

GHG emission from operational activities due to fossil fuel combustions is calculated as follows. As mentioned earlier CH_4 and N_2O emissions from fossil fuel combustion assumed to be negligible, and thus it was not included in this equation.

$$Emissions_{Operation} = \frac{Fuel(L)}{Waste(tonnes)} \times Energy(MJ/L) \times EF(kgCO2/MJ)$$

$Emissions_{operation}$ – Emissions from Operational activities (kg CO_2/tonne of waste transported)
Fuel (L) – Total amount of fossil fuel consumption per month
Waste (tonnes) – Total amount of organic waste utilisation per month
Energy (MJ/unit) – Energy content of the fossil fuel (e.g. Diesel 36.42 MJ/L)
EF – CO_2 Emission Factor of the fuel (e.g. diesel: 0.074 kg CO_2/MJ)

GHG emission from waste degradation is calculated as follows:

$$Emission_{Degradation} = E_{CH4} \times GWP_{CH4} + E_{N2O} \times GWP_{N2O}$$

Where:
$Emissions_{Degradation}$ – Emissions from organic waste degradation (kg CO_2/tonne of organic waste)
E_{CH4}- Emissions of CH_4 during organic waste degradation (kg of CH_4/tonne of waste); in this model, the default value of 0.4 (average value given by IPCC (IPCC, 2006)) is used. This value should be changed if the site specific data is obtained.
GWP_{CH4} - Global warming potential of CH_4 (21 kg CO_2/kg of CH_4)[2]
E_{N2O} - Emissions of N_2O during waste degradation (kg of N_2O/tonne of waste); in this model, the default value of 0.3 (average value given by IPCC (IPCC, 2006)) is used. This value should be changed if the site specific data is obtained.
GWP_{N2O}- Global warming potential of N_2O (310 kg CO_2/kg of N_2O)[2]

Total GHG emissions from composting is calculated by adding GHG emissions from operation and waste degradation

Total GHG emissions from composting = $Emissions_{Operation} + Emission_{Degradation}$

Avoided GHG emission by replacing chemical fertilizer from compost is calculated as follows;

$$AvoidedGHG_{Compost} = AC \times PC_{Agriculture} \times A_{GHG}$$

$AvoidedGHG_{Compost}$ – Avoided GHG from composting due to avoidance of chemical fertilizer production (kg CO_2-eq/tonne of waste)
AC – Amount of Compost produced (tonne of compost/tonne of waste)
$PC_{Agriculture}$ – Percentage of compost use for agricultural and gardening purpose (%)

[2] In literature, there are different values of GWP for CH_4 and N_2O. However this model use value of 21 and 310 for CH_4 and N_2O respectively since those are the most widely used (including CDM calculation methodologies by UNFCCC) GWP values over 100 years timescale.

A_{GHG} – GHG Avoidance potential from chemical fertilizer production which is equivalent to one tonne of compost (kg CO_2-eq/tonne of compost)

However, A_{GHG} should be excluded if compost users do not reduce chemical fertilizer use even after application of compost.

In addition, as a result of initiating a composting facility, a significant amount of organic waste landfilling can be reduced and thereby GHG emissions from organic waste degradation in landfill can be avoided. The potential GHG mitigation from avoided organic waste landfilling was calculated by using IPCC 2006 waste model. Detailed information and calculation parameters of IPCC 2006 waste model can be seen in the "Mix waste landfilling" sheet in the simulation. Total avoided GHG emissions are calculated as follows:

$$\text{Total avoided GHG emissions (kg CO2} - \text{eq per tonne of organic waste)}$$
$$= \text{Avoided GHG from compost use and replacement of chemical fertilizer} + \text{Avoided GHG from landfilling}$$

In order to understand the overall climate benefit or the impact from composting technology, net GHG emission can be calculated as follows:

$$\text{Net GHG emissions from composting} = \text{Total GHG emissions} - \text{Total GHG avoidance}$$

If the estimated net GHG emissions remain as a positive value (e.g. due to consumption of excessive amount of fossil fuel or ineffective utilisation of produced compost for agricultural and gardening), users should understand that the current composting system is still contributing to climate impact and therefore further improvements are needed for mitigating GHG emissions. If it results in a net negative GHG emissions value, it indicates potential GHG savings from composting and possibility of compost use to act as a carbon sink.

Furthermore, monthly GHG emissions from composting can be estimated as follows:

Monthly GHG emissions (kg CO_2-eq/month) = GHG emissions per tonne × Total amount of waste use for composting per month

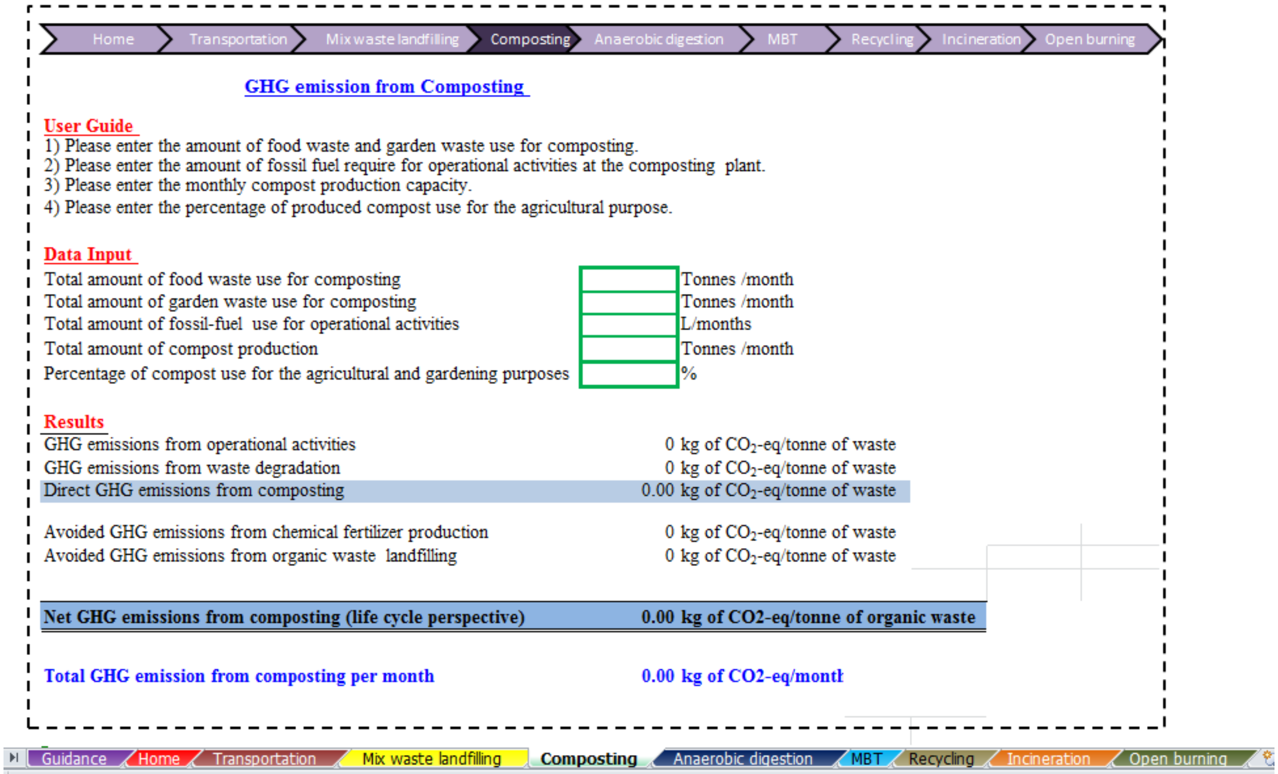


Figure 5: Page for quantification of GHG emissions from waste composting

6. Estimation of GHG Emissions from Anaerobic Digestion

There is a growing interest in developing Asia for application of anaerobic digestion as one of the potential technologies for organic waste treatment. Among the biological treatment methods, anaerobic digestion would be the most cost-effective, due to the potential of high-energy recovery linked to the process and its limited environmental impact.

In order to quantify overall GHG emissions from anaerobic digestion, a spreadsheet has been designed for quantification of both GHG emissions and GHG avoidance. There are two major ways that anaerobic digestion could emit GHG: i) GHG emissions from fossil fuel (e.g. electricity and diesel) utilisation for operation; and ii) GHG emissions from the reactor due to unavoidable leakages. This model uses the average default value (2 kg of CH_4/tonne of dry organic waste; IPCC, 2006) for methane emissions due to unavoidable leakages. This value should be changed if the site specific value is available.

There is a potential for producing a significant amount of energy from anaerobic digestion. Biogas is the major output from anaerobic digestion, which has a calorific value of 20-25 MJ/m^3. Biogas can be converted to thermal energy (heat) or electricity by using various kinds of technologies. For instance, burning of biogas in small engines (<200kW) and large internal-combustion engines (up to 1.5 MW) can generate a significant amount of electricity (Pöschl et al., 2010). The produced electricity or the thermal energy could be used to replace fossil-fuel-based conventional electricity and thermal energy production and thereby reduce the GHG emissions from those conventional processes.

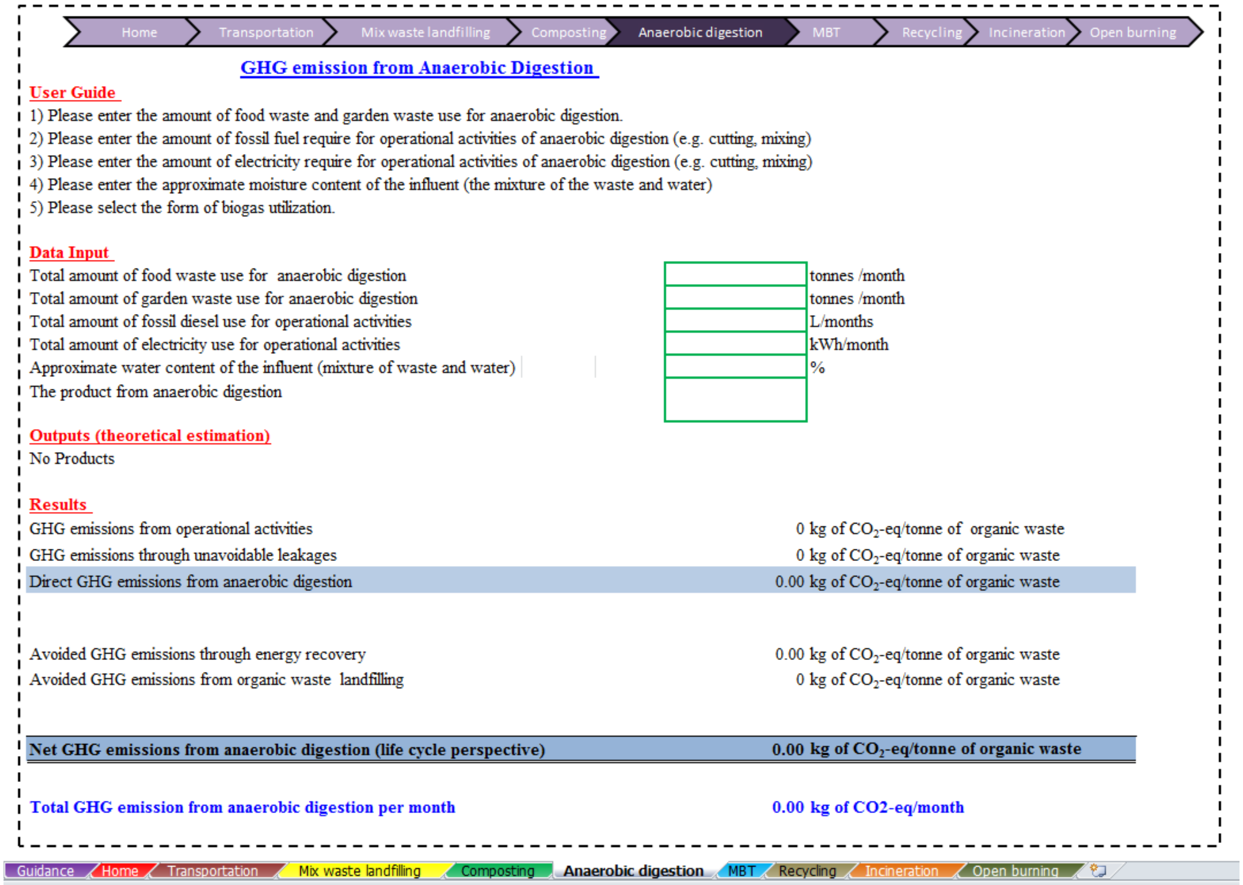
Similar to the outcome of composting technology, anaerobic digestion is also contributing to the avoidance of organic waste landfilling in developing Asia and thereby avoiding GHG emissions that would otherwise occur during the degradation of organic waste in the landfills.

In order to calculate all those potential emissions and avoidance from a particular anaerobic digestion facility, users are asked to enter the monthly average data such as the amount of organic waste use for anaerobic digestion, fossil-fuel utilisation for operational activities, electricity utilisation for operational activities, approximate moisture content of the influent (the mixture of waste and water), the type of output production from anaerobic digestion (electricity or thermal energy), as shown in Figure 6.

At the local authority level, finding the accurate water content of the influent can be a challenging issue since it is required to dry the sample for 24 hours in a 105-110^{0}C oven. However, it can be estimated approximately based on the mixing ratio of waste and water. For instance, if 1 tonne of vegetable waste mix with 1 tonne of water to make the influent, the total moisture in it would be 1.6 tonnes (approximate moisture content of vegetable waste is 60%). Therefore, moisture content of the influent would be 80% (1.6 tonnes/2tonnes x100).

The following mathematic formulas have been assigned to the spreadsheet cells in order to quantify the GHG emissions and GHG avoidance from anaerobic digestion with respect to the data entered by the users.

Users are asked to select the product from anaerobic digestion. For instance, if they select the option “electricity”, the potential electricity production will be automatically calculated under the “outputs” corresponding with the data input, as can be seen in Figure 6. In order to calculate this figure, several literature figures have been used. A detailed quantification approach has been shown under the down part of the same spreadsheet for so-called “calculation of biogas and electricity”.


Home | Transportation | Mix waste landfilling | Composting | Anaerobic digestion | MBT | Recycling | Incineration | Open burning

GHG emission from Anaerobic Digestion

User Guide
1) Please enter the amount of food waste and garden waste use for anaerobic digestion.
2) Please enter the amount of fossil fuel require for operational activities of anaerobic digestion (e.g. cutting, mixing)
3) Please enter the amount of electricity require for operational activities of anaerobic digestion (e.g. cutting, mixing)
4) Please enter the approximate moisture content of the influent (the mixture of the waste and water)
5) Please select the form of biogas utilization.

Data Input

Total amount of food waste use for anaerobic digestion		tonnes /month
Total amount of garden waste use for anaerobic digestion		tonnes /month
Total amount of fossil diesel use for operational activities		L/months
Total amount of electricity use for operational activities		kWh/month
Approximate water content of the influent (mixture of waste and water)		%
The product from anaerobic digestion		

Outputs (theoretical estimation)
No Products

Results

GHG emissions from operational activities	0 kg of CO_2-eq/tonne of organic waste
GHG emissions through unavoidable leakages	0 kg of CO_2-eq/tonne of organic waste
Direct GHG emissions from anaerobic digestion	0.00 kg of CO_2-eq/tonne of organic waste
Avoided GHG emissions through energy recovery	0.00 kg of CO_2-eq/tonne of organic waste
Avoided GHG emissions from organic waste landfilling	0 kg of CO_2-eq/tonne of organic waste
Net GHG emissions from anaerobic digestion (life cycle perspective)	**0.00 kg of CO_2-eq/tonne of organic waste**
Total GHG emission from anaerobic digestion per month	**0.00 kg of CO2-eq/month**

Guidance | Home | Transportation | Mix waste landfilling | Composting | Anaerobic digestion | MBT | Recycling | Incineration | Open burning

Figure 6: Page for quantification of GHG emissions from anaerobic digestion

Emissions of CO_2 owing to fossil fuel combustion and utilisation of electricity for operating machines can be calculated as follows. As mentioned earlier, CH_4, N_2O emissions from fossil fuel combustion considered to be negligible.

$$Emissions_{Operation} = (FC \times NCV_{FF} \times EF_{CO2}) + (EC \times EF_{el})$$

$Emissions_{Operation}$ – Emissions from operational activities (kg CO_2/tonne of organic waste)
FC - Fuel consumption apportioned to the activity type (mass or volume/tonne of organic waste)
NCV_{FF} - Net calorific value of the fossil fuel consumed (MJ/unit mass or volume)
EF_{CO2}- Emission factor of CO_2 by combustion of fossil fuel (kg of CO_2/MJ)
EC - Electricity consumption for operation activities (MWh/tonne of organic waste)
EF_{el} - Emission factor of country grid electricity production (kg CO_2.eq/MWh)

GHG emissions (mainly CH_4) due leakages from the anaerobic digestion system can be calculated as follows:

$$Emissions_{Treatment} = E_{CH4} \times DM \times 1000 \times GWP_{CH4}$$

$Emissions_{Treatment}$ – Emissions from treatment of organic waste (kg CO_2/tonne of organic waste)

E_{CH4} – Emissions of CH_4 due to leakages (kg of CH_4/kg of dry matter)
DM – Dry matter percentage in the influent (%) (DM =100 - % of water in the influent)
1000 – Conversion factor to calculate dry matter content per tonne of organic waste
GWP_{CH4} – Global warming potential of CH_4 (21 kg CO_2/kg of CH_4)

Total GHG emissions from anaerobic digestion can be calculated by adding GHG emissions from operational activities and GHG emissions due to leakages.

Total GHG emissions = $\text{Emissions}_{\text{Operation}}$ + $\text{Emissions}_{\text{Treatment}}$

In addition, mathematical formulas were derived to estimate the potential avoidance of GHG emissions due to electricity production or use of biogas as a thermal energy. If a municipality develops an anaerobic digestion facility for electricity production from biogas, the contribution for potential GHG avoidance can be calculated as follows:

$$AvoidanceGHG_{Electricity} = C_{Biogas} \times P_{CH4} \times E_{CH4} \times \frac{1}{CF_{Energy}} \times E_{Powerplant} \times EF_{el}$$

Avoidance $GHG_{Electricty}$ –Total GHG avoidance due to electricity production (kg CO_2 –eq/tonne of organic waste
C_{Biogas} – Used amount of Biogas (m^3/tonne of organic waste)
P_{CH4} – Percentage of CH_4 in biogas (%)
E_{CH4} – Energy content of CH_4 (MJ/m^3)
CF_{Energy} – Conversion Factor of Energy (3.6 MJ/kWh)
$E_{Powerplant}$ – Efficiency of the Power plant (%)
EF_{el} - Emission factor of country grid electricity production (kg CO_{2}-eq/kWh)

If a municipality develops an anaerobic digestion facility to use biogas as a thermal energy source, GHG avoidance potential can be calculated as follows:

$$AvoidanceGHG_{Thermal} = C_{Biogas} \times P_{CH4} \times E_{CH4} \times EF_{CO2}$$

Avoidance $GHG_{Thermal}$ –Total GHG avoidance due to thermal energy production (kg CO_2 –eq/tonne of organic waste
C_{Biogas} – Collected amount of biogas (m^3/tonne of organic waste)
P_{CH4} –Percentage of CH_4 in biogas (%)
E_{CH4} –Energy content of CH_4 (MJ/m^3)
EF_{CO2-} Emission factor of CO_2 by combustion of liquid petroleum gas (LPG) (kg of CO_2/MJ) (in this model, it was assumed that LPG consumption can be substituted by using biogas)

In addition, as a result of using organic waste for anaerobic digestion, organic waste landfilling can be reduced. Avoided GHG emissions from avoided organic waste landfilling should be accounted for, in order to calculate total avoidance. In this simulation, the IPCC 2006 waste model was used to estimate GHG mitigations via avoided organic waste landfilling. Detailed information and calculation parameters of the IPCC 2006 waste model can be seen in the "Mix waste landfilling" sheet in the simulation.

Total avoided GHG emission from anaerobic digestion can be calculated as follows:

$$\text{Total avoided GHG emissions (kg CO2} - \text{eq per tonne of organic waste)}$$
$$= \text{Avoided GHG from energy recovery} + \text{Avoided GHG from landfilling}$$

In order to understand the overall climate benefit or the impact from anaerobic digestion as an organic waste management option, net GHG emissions are calculated as follows:

$$\text{Net GHG emissions from anaerobic digestion (kg CO2} - \text{eq per tonne of organic waste)}$$
$$= \text{Total GHG emissions} - \text{Total GHG avoidance}$$

Similar to the composting technology, if the estimated net GHG emissions remain as a positive value, it means that the anaerobic digestion technology is still contributing to climate impact and therefore efficiency of energy recovery should be further improved for mitigating GHG emissions. If the result is a net negative GHG emission value, it indicates the potential GHG savings from anaerobic digestion and the possibility to be a carbon sink. Furthermore, monthly GHG emissions/savings from a particular municipality can be calculated by using the estimated results of GHG emissions/ savings per tonne of organic waste.

Monthly GHG emissions/savings (kg CO_2-eq/month) = GHG emissions per tonne of organic waste × Total amount of organic waste use for anaerobic digestion per month (tonnes).

7. Estimation of GHG Emissions from Mechanical Biological Treatment (MBT)

Generally, Mechanical Biological Treatment (MBT) is used as a pre-treatment either before thermal treatment or as the final disposal of solid waste. MBT can reduce the volume of waste through the decomposition of organic substances prior to landfilling, minimise GHGs emissions (methane) from landfill sites, and enhance separating different material fractions, such as compost-like materials and high-energy fractions after stabilisation of waste prior to final disposal. MBT facilitates organic waste to be degraded rapidly under optimised conditions (homogenisation, ventilation, irrigation). The total mass loss during the MBT process would be as high as 50%. The stabilised material can be screened into three parts such as compost-like materials, waste plastics (use to produce Refuse-derived fuel (RDF)) and inert materials.

As far as GHG emissions from MBT process are concerned, the major cause for GHG emissions is utilisation of fossil fuel, grid electricity for operational activities in the various stages, and degradation of organic waste. Under good management, there is considerably less possibility for production of GHG from waste piles if organic waste degradation occurs under aerobic conditions. If CH_4 production may take place in the bottom layer of MBT piles, most of the CH_4 can be oxidised to a large extent in the aerobic sections of the piles. Thus, the possibility of releasing CH_4 into the atmosphere would be very small. Generally, MBT is an aerobic process and therefore, a large fraction of the degradable organic carbon in the waste material is converted into CO_2. CO_2 emissions have biogenic origin and would not be taken into account for GHG calculations. According to IPCC guidelines, MBT process also produces N_2O in minor concentrations. In this simulation, IPCC published the average values of 4 kg CH_4/tonne of organic waste on a wet basis (range of 0.03-8 kg CH_4/tonne of waste) and 0.3 kg N_2O/tonne of organic waste on a wet basis (range of 0.06-0.6 kg N_2O/tonne of waste) and these values were used to quantify the GHG emissions from degradation of organic waste in MBT piles.

Similar to composting or anaerobic digestion technology, MBT process can contribute to minimizing organic waste landfilling in developing Asia and thereby avoiding GHG emissions that would otherwise occur during the degradation of organic waste in the landfills. In addition, there is a possibility for utilisation of degraded organic waste as compost and consequently, a reduction in the amount of chemical fertilizer used. Avoidance of chemical fertilizer utilisation would greatly contribute to GHG reduction. However, there is concern about heavy metal contamination in the compost-like product from MBT of mixed waste. Levels of heavy metal contamination should be measured prior to decision-making on whether this material should be applied as compost.

Furthermore, there is growing interest in developing Asia on the recovery of the plastic fraction from degraded mixed waste for RDF production or for extraction of crude oil via pyrolysis process. Even though, there is an additional energy requirement for production of RDF or crude oil, energy recovery from plastic via both processes would contribute for further GHG reduction. Taking into account all the potential GHG avoidance, overall contribution of MBT process for climate impacts can be estimated.

In order to quantify overall GHG emissions from MBT, a spreadsheet has been designed in this simulation. This would calculate both GHG emissions and GHG avoidance potentials from MBT processes. Similar to other spreadsheets, users are asked to enter the monthly average data of MBT processes such as the amount of total waste for MBT, the amount of fossil fuel required for operational activities at the MBT plant, and the amount of electricity required for the operational activities at the MBT plant. In addition, if users select the option of “Utilisation of degraded materials as compost” as “Yes”, and then the users should enter the data related to compost production such as the amount of compost production per month and the percentage of produced compost used for soil amendment. If the answer to the above option is “No” there is no data entry requirement with respect to compost production.

The next step is selecting the answer to the option of “Separation of plastic at the end of MBT” from the drop-down list. If users select the options either “Yes-for RDF production” or “Yes-for crude oil production," they are asked to enter such data as the amount of recovered waste plastics for crude oil/RDF production, the amount of diesel required for crude oil/RDF production, the amount of electricity required for crude oil/RDF production and percentage of produced crude oil/RDF use for energy production. If the answer to the above option is "No" there is no data entry requirement with respect to production of RDF/crude oil.

If users enter all the required data, the amount of compost use for crop production and amount of RDF/crude oil use for energy purpose per tonne of waste input in MBT plant will be displayed in the output. Furthermore, this simulation would calculate GHG emissions, GHG avoidance and net GHG emissions from the entire MBT process per tonne of waste input.

Emissions of CO_2 owing to fossil-fuel combustion and utilisation of electricity for operating machines at MBT plant can be calculated as follows. As mentioned before, in this simulation, CH_4, N_2O emissions from fossil-fuel combustion are considered to be negligible.

$$Emissions_{Operation} = (FC \times NCV_{FF} \times EF_{CO2}) + (EC \times EF_{el})$$

$Emissions_{Operation}$ – Emissions from operational activities (kg CO_2/tonne of waste)
FC – Fuel consumption apportioned to the activity type (mass or volume/tonne of waste)
NCV_{FF} –Net calorific value of the fossil fuel consumed (MJ/unit mass or volume)
EF_{CO2} – Emission factor of CO_2 by combustion of fossil fuel (kg of CO_2/MJ)
EC – Electricity consumption for operation activities (MWh/tonne of waste)
EF_{el} – Emission factor of country grid electricity production (kg CO_{2}-eq/MWh)

GHG emission from waste degradation in MBT piles is calculated as follows:

$$Emission_{Degradation} = E_{CH4} \times OW_{Percentage} \times GWP_{CH4} + E_{N2O} \times OW_{Percentage} \times GWP_{N2O}$$

Where:
$Emissions_{Degradation}$ – Emissions from organic waste degradation (kg CO_2/tonne of organic waste)
E_{CH4}- Emission of CH_4 during organic waste degradation (kg of CH_4/tonne of organic waste)
$OW_{Percentage}$- Percentage of Organic Waste in the mixed waste (%)
GWP_{CH4}- Global warming potential of CH_4 (21 kg CO_2/kg of CH_4)
E_{N2O}- Emission of N_2O during waste degradation (kg of N_2O/tonne of waste)
GWP_{N2O}- Global warming potential of N_2O (310 kg CO_2/kg of N_2O)

Total GHG emissions from MBT would be calculated by adding GHG emissions from operational activities and GHG emissions from degradation of organic waste under the anaerobic condition in the deep layers of the piles.

Total GHG emissions = $Emissions_{Operation}$ + $Emissions_{Treatment}$

Furthermore, if the recovered plastic fraction is used for the production of RDF or crude oil, the GHG emissions from those processes is estimated in this simulation by using the mathematical formula below:

$$Emissions_{RDF\,/\,crudeoil\,production} = (FC \times NCV_{FF} \times EF_{CO2}) + (EC \times EF_{el})$$

$Emissions_{Operation}$ – GHG Emissions from RDF and crude oil production (kg CO_2/tonne of waste)
FC – Fuel consumption apportioned to the operational activities (mass or volume/tonne of waste)
NCV_{FF} – Net calorific value of the fossil fuel consumed (MJ/unit mass or volume)
EF_{CO2} – Emission factor of CO_2 by combustion of fossil fuel (kg of CO_2/MJ)
EC – Electricity consumption for operation activities (MWh/tonne of waste)
EF_{el} – Emission factor of country grid electricity production (kg CO_2-eq/MWh)

As mentioned before, there are several ways that initiation of MBT process could contribute to GHG mitigation. GHG avoidance by utilising the degraded organic materials as compost can be estimated as follows:

$$AvoidedGHG_{Compost} = AC \times PC_{Agriculture} \times A_{GHG}$$

$AvoidedGHG_{Compost}$ – Avoided GHG from composting due to avoidance of chemical fertilizer production (kg CO_2-eq/tonne of waste)
AC – Amount of Compost produced (tonne of compost/tonne of waste input)
$PC_{Agriculture}$ – Percentage of produce Compost use for agricultural purpose (%)
A_{GHG} – GHG avoidance potential from chemical fertilizer production which is equivalent to one tonne of compost (kg CO_2-eq/tonne of compost)

In addition, as a result of operating a MBT plant, a significant amount of organic waste landfilling can be avoided and thereby GHG emissions from organic waste degradation under anaerobic condition can be minimised. The potential GHG mitigation from avoided organic waste landfilling is calculated by using IPCC 2006 waste model. Detailed information and calculation parameters of IPCC 2006 waste model can be seen in the "Mix waste landfilling" sheet in this simulation.

It should be noted that production of energy using RDF or crude oil would not greatly contribute as a climate friendly solution since this energy production has a fossil-fuel-based origin (waste plastic originated as a product of virgin crude oil). In other words, emissions from combustion of RDF and crude oil would be equivalent to the emissions of virgin fossil fuel combustion. Therefore, GHG avoidance due to combustion of produced RDF or crude oil has not been accounted for in this simulation. However, GHG emissions related to virgin oil extraction, transportation and processing of fuel are included since utilisation of RDF/crude oil may indirectly influence avoidance in the virgin fuel production chain. Also it is noteworthy to identify that the produced RDF or crude oil can be substituted to replace the virgin crude oil production process so that it would contribute to fossil-fuel savings and thus avoid abiotic resource depletion.

Total avoided GHG emissions from MBT can be calculated as follows:

$$\text{Total avoided GHG emissions (kg CO2} - \text{eq per tonne of waste)}$$
$$\begin{aligned} = {} & \text{Avoided GHG from replacement of chemical fertilizer using compost like product} \\ & + \text{Avoided GHG from organic waste landfilling} \\ & + \text{Avoided GHG emissions from virgin fossil fuel production} \end{aligned}$$

In the next step, estimation of net GHG emissions is important in order to understand the overall climate benefit or the impact from the MBT process. The net GHG emissions are calculated as follows:

$$\text{Net GHG emissions from MBT (kg CO2} - \text{eq per tonne of waste)}$$
$$= \text{Total GHG emissions} - \text{Total GHG avoidance}$$

If the estimated net GHG emissions remain as a positive value, it does mean that MBT process is still contributing to climate impact. However, significant GHG reduction can be expected as compared to the 100% of generated waste landfilling without prior treatment. If the result is a net negative GHG emissions value, this indicates the potential GHG saving potential from MBT and the possibility to be a carbon sink.

Furthermore, monthly GHG emissions/savings from a particular municipality/location can be calculated by using the estimated results of GHG emissions or savings per tonne of waste management by means of MBT.

Monthly GHG emissions/savings (kg CO_2-eq/month) = GHG emissions per tonne of waste × Total amount of waste use for MBT per month (tonnes)

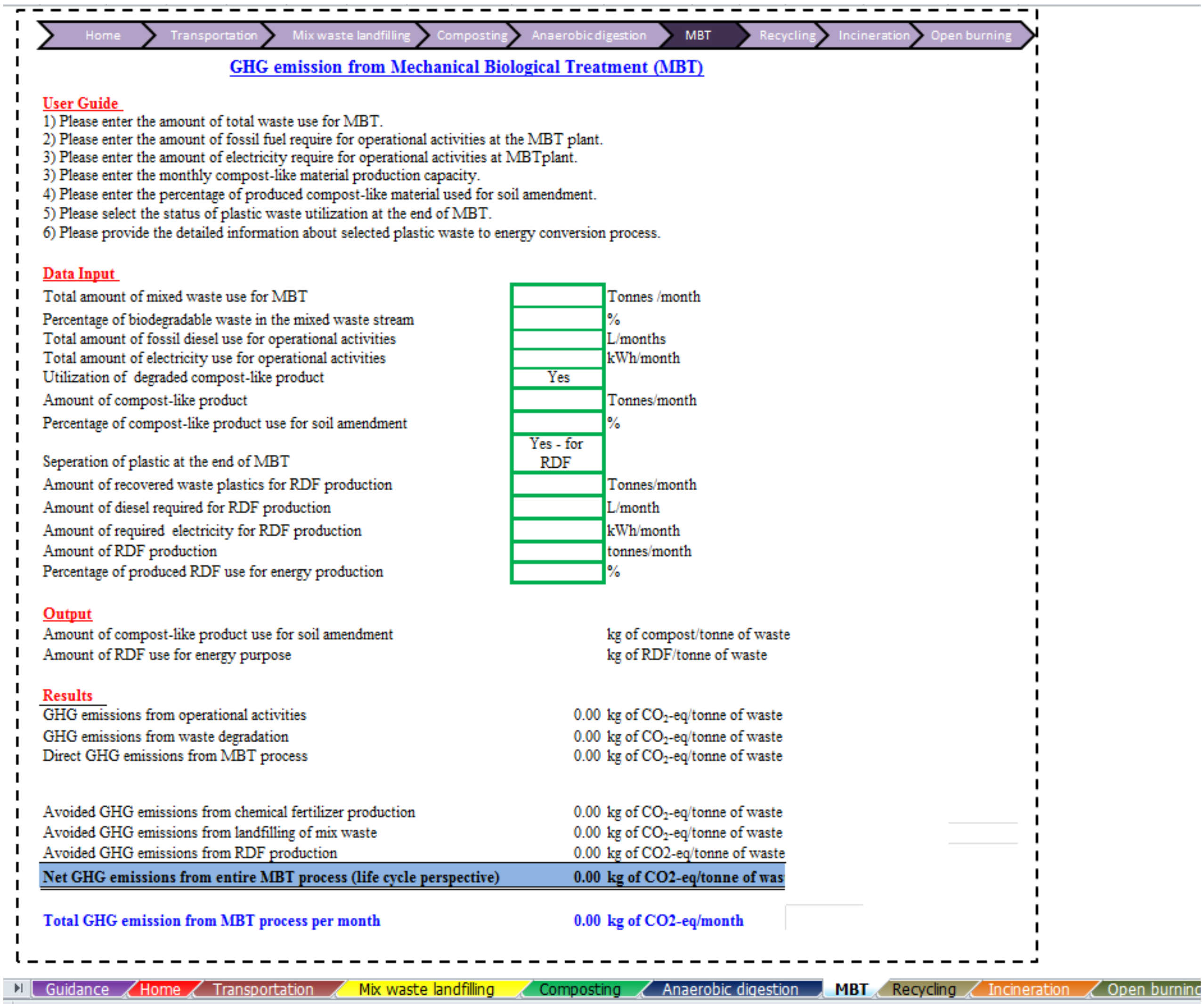


Figure 7: Page for quantification of GHG emissions from MBT

8. Estimation of GHG Emissions from Recycling

It has been convincingly argued and proved that recycling is an extremely sustainable option since a significant amount of valuable materials can be recovered from the recycling process. Consequently, this would create tremendous outcomes in the environmental, economic and social fields. One of the key environmental benefits from recycling is its significant contribution to GHG mitigation. Thus, incorporating recycling into integrated waste management would be the most valuable action to drive the entire system towards sustainability.

Similar to any other technology, the recycling process also contributes to significant GHG emissions. Recycling is not a simple process, and it requires a great deal of energy for pre-processing at the sorting facility, transportation of pre-processed recyclables to the recycling facilities by heavy-duty trucks, as well as recycling processes of different type of recyclables at various recycling facilities. All these activities would emit a considerable amount of GHG. On the other hand, material recovered from the recycling processes can be used to replace the virgin production of an equivalent amount of materials, thereby avoiding a massive amount of GHG emissions that would otherwise occur through the production of the virgin resource. Therefore, estimation of net GHG emissions from a recycling scheme would be very important to make the decision on overall climate impacts.

Recycling entails more than a one-stage process. Sorted recyclables in a particular municipality might have to be sent to various recycling facilities, which are located in different provinces. Therefore, obtaining site-specific data related to recycling of different types of recyclables is a challenging issue. Due to this reason, it would be difficult to find more country-specific GHG emissions from recycling. In order to do a detailed assessment on GHG emissions reduction from recycling activities in a particular location, data are required related to the composition of recyclables, operation activities in pre-processing facilities, total fossil fuel and electricity requirement for pre-processing activities (cleaning, particle size reduction, baling etc), transportation distance to the recycling facilities, fossil energy and electricity consumption data for recycling, country-specific emissions factors from fossil energy combustion and grid electricity production, recyclability of different recyclables, as well as calculating the amount of recovered materials. This makes recycling quite a complex process, and it requires the involvement of different levels of stakeholders. For instance, at the municipal level, the availability of data will be limited to the amount of monthly generated recyclables and composition of the recyclables. Numerous types of other data need to be collected from transportation companies and recycling companies. Due to the unavailability of these data at the local authority level, it would be difficult to calculate life cycle GHG emissions overall recycling process more precisely. Therefore, development and handling of a reliable database on the recycling process chain is an urgent issue in most developing countries.

Despite these difficulties, this simulation quantifies the GHG emissions from recycling based on country specific information in Thailand. This simulation uses the inventory data presented by Menikpura (2011) on both GHG emissions from recycling as well as virgin production process chain of different type of recyclables in Thailand. In the spread sheet, users are asked to enter basic data such as amount of separated recyclables per month and the composition of recyclables, as shown in Figure 8. It should be noted that, GHG emissions from each type of recyclable will be calculated based on the country-specific information in Thailand and location-specific information in Nonthaburi (e.g. average transportation distance is 30km, coal and diesel fuel use for thermal energy is 566 kg of CO_2-eq/MWh emissions from the grid electricity production (DEDE, 2008)).

GHG emissions from recycling have been calculated based on emissions of CO_2 owing to fossil fuel combustion and utilisation of electricity for operating machines at sorting plants and recycling facilities. As mentioned earlier, in this simulation, CH_4, and N_2O emissions from fossil fuel combustion is considered to be negligible. GHG emissions from each type of waste recycling can be calculated as follows:

$$Emissions_{\mathrm{Re}\,cycling} = (FC \times NCV_{FF} \times EF_{CO2}) + (EC \times EF_{el})$$

$Emissions_{Recycling}$ – Emissions from recycling (kg CO_2/tonne of recyclables)
FC – Fuel consumption apportioned to the activity type (mass or volume/tonne of recyclables)
NCV_{FF} –Net calorific value of the fossil fuel consumed (MJ/unit mass or volume)
EF_{CO2} – Emission factor of CO_2 by combustion of fossil fuel (kg of CO_2/MJ)
EC – Electricity consumption for operation activities (MWh/tonne of recyclables)
EF_{el} – Emission factor of country grid electricity production (kg CO_{2}-eq/MWh)

In order to quantify the GHG avoidance potential materials recovery from each type recyclables should be accounted. The recovered materials from each type of recyclable can be estimated as follows;

Recovery of materials (kg/tonne of recyclable) = Amount of recyclables (kg/tonne) × Recyclability (%)

According to the literature, recyclability of major recyclables such as paper, plastic, aluminium, metal and glass would be 90-95%. The amount of recovered materials would be equal to the amount of potential avoidance of virgin resources. Therefore, GHG avoidance from equivalent amount of virgin resource production should be calculated.

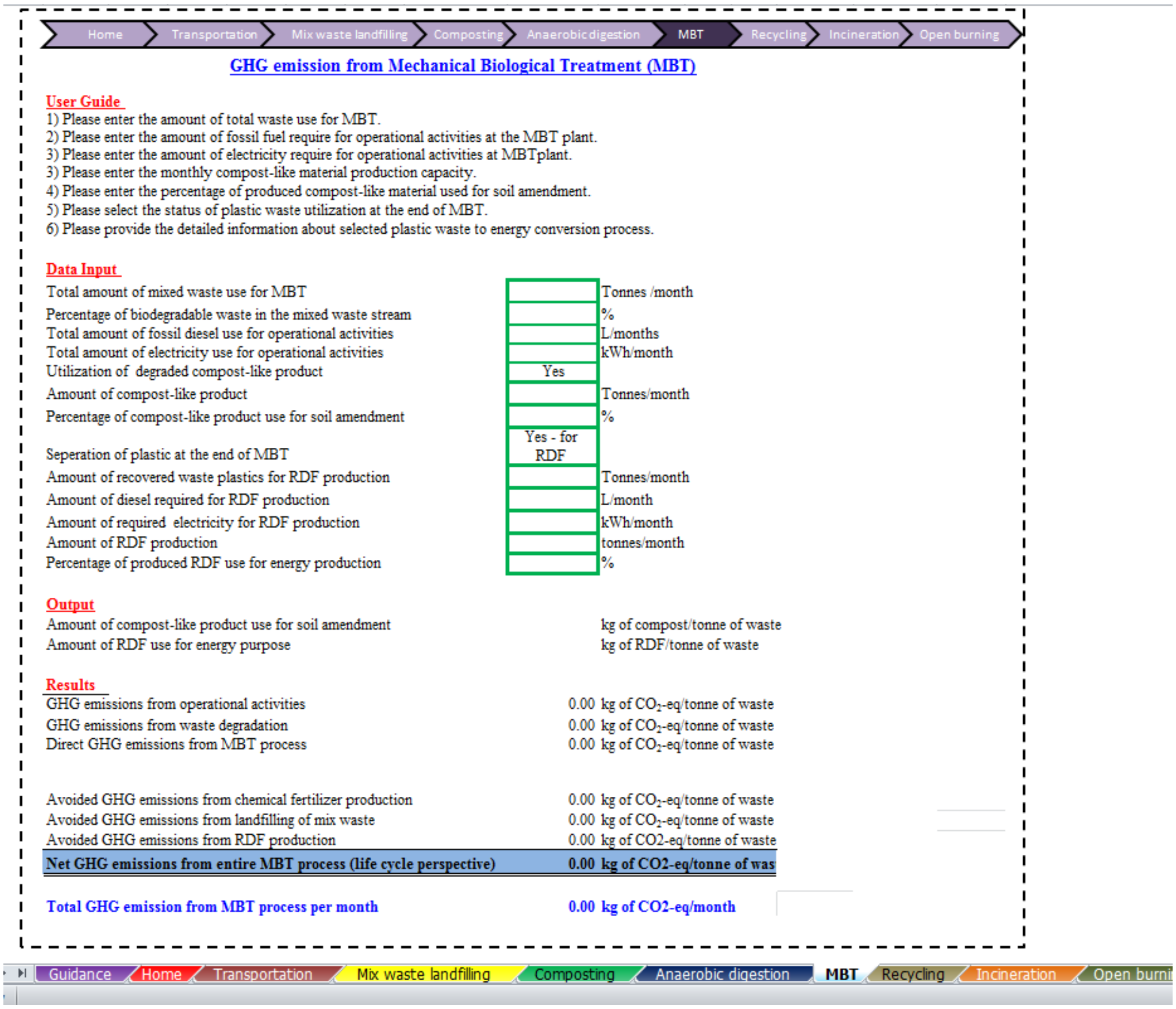
In order to calculate the GHG emissions from the virgin resource production, Eco-invent and SimaPro LCA databases have been used, mainly for collecting basic information on thermal energy, electricity requirements and material requirements for a unit process of recycling of each type of materials. Then those inputted data have been adjusted to suit the Thailand situation in order to improvise a data set which represents the local situation. For instance, the recommended type of fuel sources for heat energy supplement, fuel sources used in grid electricity production and efficiencies of furnace and power plant have been taken into consideration to adjust the Eco-invent/SimaPro databases to the local situation. In fact, as reported by DEDE (2008), Thailand paper industry used 96.2% of thermal energy from imported coal and coal products and the remaining 3.8% from fuel oil and diesel. The authors have considered the emissions from these energy sources to replace the emissions from equivalent amount of energy that have been presented in Eco-invent database (this database focus in energy consumption in European Countries) to supply the same amount of thermal energy for unit weight of paper recycling. The relative electricity requirement for recycling in Thai recycling facilities, energy sources and emission from grid electricity production are also taken into account in the inventory analysis.

In addition, as a result of recycling, landfilling of recyclables can be eliminated. As far as methane emissions from landfilling of recyclables are concerned, GHG emissions from paper waste landfilling can be avoided since this is the only degradable fraction of recyclables. Therefore, GHG avoidance potential from paper waste landfilling has been accounted for by using IPCC 2006 model. As mentioned earlier, based on the country specific information of Thailand (Menikpura, 2011), GHG emissions from each type of recyclable as well as GHG avoidance from equivalent amount of materials production from virgin processes and avoided landfilling of organic waste (paper waste) is presented as below.

Table 2: GHG emissions/avoidance from recycling (Based on country specific information in Thailand)

Type of recyclables	(A) GHG emissions from recycling	(B) Avoided GHG emissions from equivalent amount of materials production from virgin process	(C)Avoided GHG emissions from landfilling	(D) Net GHG emissions (D) = (A)-(B)-(C)
Paper	1,266	971	2,383	-2,088
Plastic	2,148	1,899	0	249
Aluminium	393	12,486	0	-12,093
Steel	1,102	2,949	0	-1,847
Glass	569	1,024	0	-454

Source: Menikpura, 2011


Home | Transportation | Mix waste landfilling | Composting | Anaerobic digestion | MBT | Recycling | Incineration | Open burning

GHG emission from Mechanical Biological Treatment (MBT)

User Guide
1) Please enter the amount of total waste use for MBT.
2) Please enter the amount of fossil fuel require for operational activities at the MBT plant.
3) Please enter the amount of electricity require for operational activities at MBTplant.
3) Please enter the monthly compost-like material production capacity.
4) Please enter the percentage of produced compost-like material used for soil amendment.
5) Please select the status of plastic waste utilization at the end of MBT.
6) Please provide the detailed information about selected plastic waste to energy conversion process.

Data Input

Total amount of mixed waste use for MBT		Tonnes /month
Percentage of biodegradable waste in the mixed waste stream		%
Total amount of fossil diesel use for operational activities		L/months
Total amount of electricity use for operational activities		kWh/month
Utilization of degraded compost-like product	Yes	
Amount of compost-like product		Tonnes/month
Percentage of compost-like product use for soil amendment		%
Seperation of plastic at the end of MBT	Yes - for RDF	
Amount of recovered waste plastics for RDF production		Tonnes/month
Amount of diesel required for RDF production		L/month
Amount of required electricity for RDF production		kWh/month
Amount of RDF production		tonnes/month
Percentage of produced RDF use for energy production		%

Output

Amount of compost-like product use for soil amendment	kg of compost/tonne of waste
Amount of RDF use for energy purpose	kg of RDF/tonne of waste

Results

GHG emissions from operational activities	0.00	kg of CO_2-eq/tonne of waste
GHG emissions from waste degradation	0.00	kg of CO_2-eq/tonne of waste
Direct GHG emissions from MBT process	0.00	kg of CO_2-eq/tonne of waste
Avoided GHG emissions from chemical fertilizer production	0.00	kg of CO_2-eq/tonne of waste
Avoided GHG emissions from landfilling of mix waste	0.00	kg of CO_2-eq/tonne of waste
Avoided GHG emissions from RDF production	0.00	kg of CO2-eq/tonne of waste
Net GHG emissions from entire MBT process (life cycle perspective)	**0.00**	**kg of CO2-eq/tonne of was**

Total GHG emission from MBT process per month **0.00** **kg of CO2-eq/month**

Guidance | Home | Transportation | Mix waste landfilling | Composting | Anaerobic digestion | MBT | Recycling | Incineration | Open burni

Figure 8: Page for quantification of GHG emissions from Recycling

In order to quantify the total GHG emissions from a recycling scheme, the following formula can be adopted:

GHG emissions from Recyclable mix (kg of CO_2-eq/tonne of recyclables) = GHG emission from paper (kg CO_2-eq/tonne) × Percentage of paper waste (%) + GHG emission from plastics (kg CO_2-eq/tonne) × Percentage of plastics (%) + GHG emission from glass (kg CO_2-eq/tonne) × Percentage of Glass (%) + GHG emission from Aluminium (kg CO_2-eq/tonne) × Percentage of Aluminium (%) + GHG emission from metal (kg CO_2 -eq/tonne) × Percentage of Metal (%)

A similar approach can be followed to quantify the GHG avoidance potential per tonne of mixed recyclables. Once the quantification is done for GHG emissions and GHG avoidance per tonne of mixed recyclables, net GHG emissions can be estimated as follows:

$$\text{Net GHG emissions from Recycling (kg CO2} - \text{eq per tonne of mixed recyclables)}$$
$$= \text{Total GHG emissions} - \text{Total GHG avoidance}$$

If the estimated net GHG emissions remain as a positive value, it implies that the recycling process is still contributing to climate impact. In most cases, a net negative GHG emissions value may be expected due to the avoidance of a massive amount of GHG emissions that would occur from virgin resource production chains. If the result is a net negative GHG emission value, it indicates the potential GHG saving potential from recycling process chain and the possibility to be a carbon sink. Furthermore, based on the estimated net GHG emissions value from recycling of per tonne of mixed recyclables, monthly GHG emissions/savings from the particular municipality/location can be calculated. This estimation will show the overall climate impacts from recycling.

Monthly GHG emissions/savings (kg CO_2-eq/month) = GHG emissions per tonne of mixed recyclables × Total amount of waste recycled per month (tonnes)

It is important to mention that, as compared to other waste management technologies, GHG mitigation potential from appropriate recycling schemes would be remarkable. Therefore, it is necessary to quantify GHG emissions more precisely and concisely from recycling businesses in developing Asia. IGES will develop more comprehensive simulations to quantifying overall climate benefits from particular recycling systems taking into account the location specific data. This kind of holistic approach would be very useful to provide systematic methodology and then to quantify potential GHG mitigation from recycling businesses. The results would be useful for applying carbon credits under the new market mechanisms.

9. Estimation of GHG emissions from Incineration

Initially, waste incineration has been commissioned with the main goal of decreasing the waste mass by 75%, volume by up to 90%. Nowadays there is a big interest for energy recovery from waste as a solution for the energy crisis and also it enables financial benefits via energy recovery. Due to these reasons, there is a growing interest in the application of incineration as a near-term solution to tackle the growing waste management problems in developing Asia. As far as climate impact is concerned, incineration technology would directly eliminate methane emissions from anaerobic degradation at the landfill site (which is the normal practice in developing Asia) and also displace fossil fuel-based electricity generation.

In general, the application of waste-to-energy technologies which are well-designed to suit the local situation would significantly contribute to GHG mitigation and energy recovery. However, inefficiencies can be noticed as a common obstacle to most of the existing incineration plants in developing Asia which has been influenced for the failure cases. For instance, the composition and moisture content of the waste have a great effect on the efficiency of the incineration plant.

According to the information obtained from the Phuket incineration plant in Thailand, even after draining off part of the moisture by leaving waste some days in the waste pit, the moisture content of the combustibles remained at 40-42%. This high moisture content leads to more energy being consumed to produce power from waste. In addition the majority of combustibles in Asia consist of organic waste which has less calorific value. These reasons have an effect on the overall energy conversion efficiency and similar problems may be experienced in incineration plants in tropical Asia due to the weather pattern and the high organic content of the waste streams. All in all low efficiencies of incineration may result higher GHG emissions from overall combustion process.

In order to do a detailed assessment on GHG emissions from incineration in a particular location, data are required related to the composition of combustibles, total fossil fuel and grid electricity requirement for on-site operational activities and total electricity and heat recovered from incineration process.

Incineration process is releasing a significant amount of CO_2 into the atmosphere and thus makes a real contribution to the greenhouse effect. However, as recommended in the IPCC guidelines, only the climate-relevant CO_2 emissions from the combustion of fossil based waste are considered for GHG emissions estimation (IPCC, 2006). Since the municipal waste incinerated is a heterogeneous mixture of wastes, in terms of sources of CO_2 a distinction is drawn between carbon of biogenic and carbon of fossil origin. Only CO_2 emissions resulting from oxidation, during incineration of waste containing fossil origin such as plastics, certain textiles, rubber, liquid solvents, and waste oil) are considered. The CO_2 emissions from the combustion of biomass materials (e.g. paper, food, and wood waste) contained in the waste are biogenic emissions and should not be taken to account in GHG emission estimation (IPCC, 2006). IPCC default values of dry matter content of different type of waste, total carbon content, fossil carbon fraction and oxidation factors have been used in this tool in order to quantify GHG from incineration process.

In addition, as stated in IPCC guidelines, there is a possibility to emit CH_4 and N_2O like GHG during the combustion process. However, the magnitude of such emissions depends on the type of the incinerator and the management practices. Therefore, in this simulation an option as given to choose the type of the incineration technology and the default values of CH_4 and N_2O emission will be automatically selected with respect to the selected option.

GHG emissions due to utilization of fossil fuel and grid electricity for plant operation can be quantified as explained in the following formula.

$$Emissions_{Operation} = (FC \times NCV_{FF} \times EF_{CO2}) + (EC \times EF_{el})$$

$Emissions_{Operation}$ – Emissions from operation (kg CO_2/tonne of combustables)
FC – Fuel consumption for on-site activities (mass or volume/tonne of combustibles)

NCV_{FF} –Net calorific value of the fossil fuel consumed (MJ/unit mass or volume)
EF_{CO2} – Emission factor of CO_2 by combustion of fossil fuel (kg of CO_2/MJ)
EC – Electricity consumption for on-site activities (MWh/tonne of combustibles)
EF_{el} – Emission factor of country grid electricity production (kg CO_{2}-eq/MWh)

IPCC recommended Tier 2 approach was adapted (IPCC, 2006) in this simulation to quantify the fossil CO_2 emissions from combustion of one tonne of wet MSW.

$$CE = \sum_i (SW_i \times dm_i \times CF_i \times FCF_i \times OF_i) \times \frac{44}{12}$$

CE - Combustion Emissions kg CO_2/tonne of waste)
SW_i-total amount of solid waste of type i (wet weight) incinerated (kg/tonne of waste)
dmi - dry matter content in the waste (partially wet weight) incinerated
CF_i -fraction of carbon in the dry matter (total carbon content), (fraction; 0.0-1.0)
FCF_i - fraction of fossil carbon in the total carbon, (fraction; 0.0-1.0)
OF_i - oxidation factor, (fraction; 0.0 – 100%)
44/12 - conversion factor from C to CO_2
i - type of fossil based waste incinerated such as textiles, rubber and leather, plastics

When waste is incinerated, most of the carbon in the combustion product oxidises to CO_2. However, a minor fraction may oxidise incompletely due to the inefficiencies in the combustion process, which leave some of the carbon unburned or partly oxidised. However, for waste incineration, it was assumed that the combustion efficiencies are close to 100 percent so that OF_i can be assumed as 1.

Once the quantification was done for CO_2 emissions from the above phases, life cycle GHG emissions from incineration can be calculated as follows;

Total GHG emissions from incineration (kg of CO_2-eq/tonne) = OE + CE

TE – Operation emissions (kg CO_2-eq/tonne of combustibles)
CE – Combustion Emissions (kg CO_2-eq/tonne of combustibles)

Furthermore, total GHG avoidance potential from incineration can be calculated as follows;

$$\begin{aligned}&\text{Total avoided GHG emissions (kg CO2} - \text{eq / tonne of combustibles)}\\&= \text{ Avoided GHG from replacement of equivelent amount of conventional electricity}\\&+ \text{Avoided GHG from replacement of equivelent amount of heat which is produced via fossil fuel}\\&+ \text{Avoided GHG emissions from landfilling (BAU)}\end{aligned}$$

Please note that, landfilling without a gas recovery system has been considered as the business as usual (BAU) practice since which is the most common waste disposal method in many developing Asian countries.

In the next step, estimation of net GHG emissions can be done in order to understand the overall climate benefit or the impact from the incineration process. Net GHG emission from incineration can be estimated as follows;

$$\text{Net GHG emissions from incineration (kg CO2} - \text{eq per tonne of combustibles)} = \text{Total GHG emissions} - \text{Total GHG avoidance}$$

Similar to any other technology, if the estimated net GHG emissions from incineration remain as a positive value, it implies that the incineration is contributing to climate impact. If the incineration is resulted, a net negative GHG emissions value that may be expected due to the avoidance of a massive amount of GHG emissions that would occur from conventional production of electricity and heat and landfilling of organic waste. Furthermore, if the result is a net negative GHG emission value, it indicates the potential GHG saving potential from incineration. Based on the estimated net GHG emissions value from incineration of per tonne of combustibles, monthly GHG emissions/savings from the particular municipality/location can be calculated. This estimation will show the overall climate impacts from incineration.

Monthly GHG emissions/savings (kg CO_2-eq/month) = GHG emissions per tonne of wet waste combustion × Total amount of waste combusted per month (tonnes)

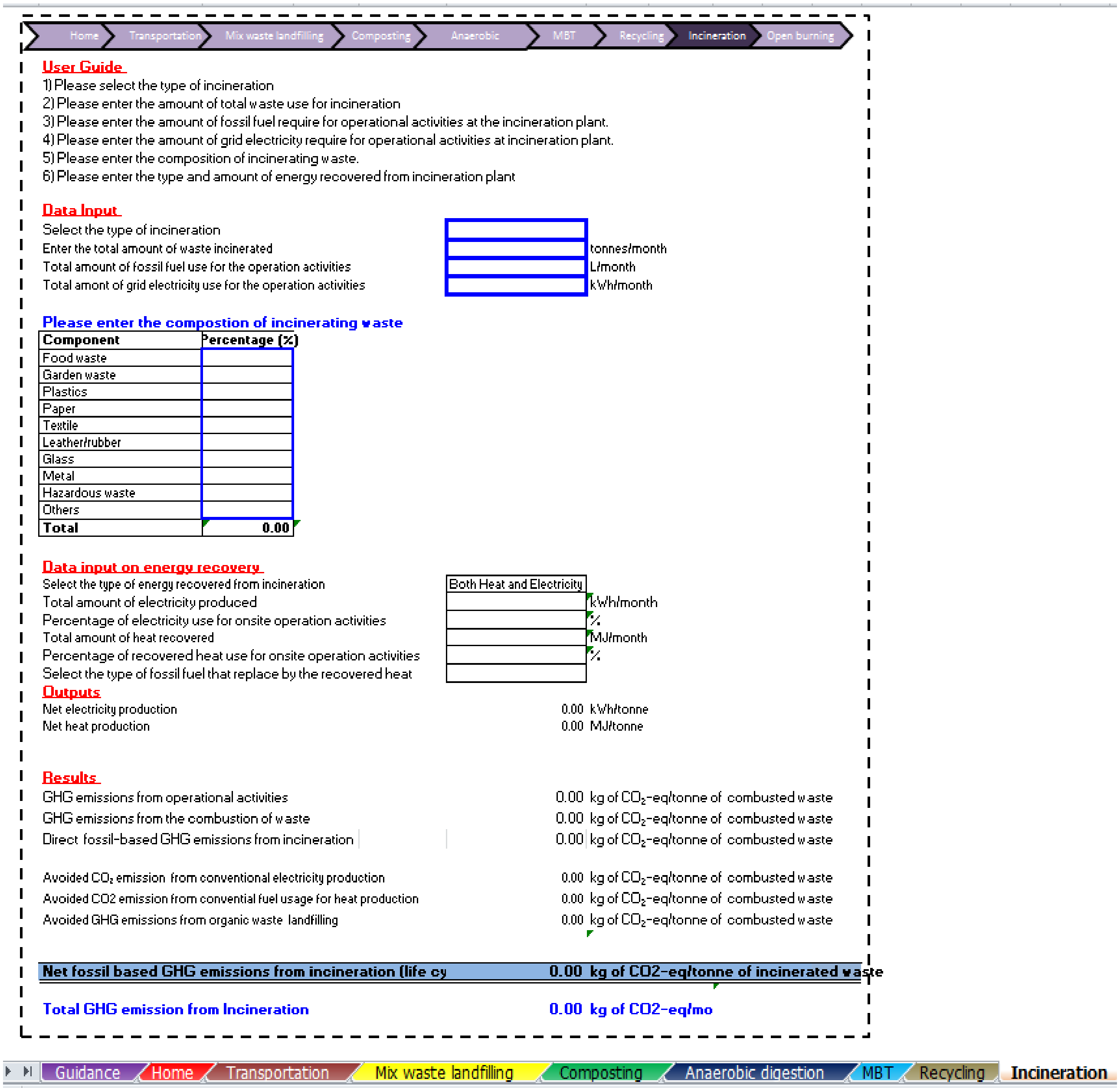


Figure 9: Page for quantification of GHG emissions from incineration

10. Estimation of GHG emissions from open burning

There is an increasing trend in uncontrolled burning a massive amount of waste in the open dump sites and landfill sites as people believe that it is the cheapest, easiest means of volume reduction for saving the land and disposal of combustible materials. However, this kind of primary methods cannot be accepted any longer due to its serious threats to the environment as well as to the local community. Regulations are needed to prohibit such unacceptable practices.

Beside fossil based CO_2 emission from combustion, open burning is responsible for generation of various kind of toxic by-products from incomplete combustion such as hydrocarbons, particulate matter and black carbon, benzene and carbon monoxide. Recent research has shown that black carbon is the second largest contributor to global temperature increases, with CO_2 remaining as the number one contributor to global warming. However, still there are no published default values from IPCC or any other international organization to quantify the climate impact from black carbon. Therefore, in this version, only fossil based CO_2 emissions from open burring has been considered to quantify the climate impact.

Unlike in landfill management, fossil fuel is not required to do any operational and maintenance activities and therefore there is no any GHG emission with respect operational activities.

IPCC recommended Tier 2 approach was adapted (IPCC, 2006) in this simulation to quantify the fossil CO_2 emissions from open burning of wet MSW. As explained in IPCC guidelines, for open burning, all the default values are similar to the incineration except the oxidation factor. In open burning process higher fraction of waste oxidize incompletely due to the inefficiencies in the combustion process, IPCC recommended oxidation factor (OF) for open burning is 58%.

$$CE = \sum_i (SW_i \times dm_i \times CF_i \times FCF_i \times OF_i) \times \frac{44}{12}$$

CE - Combustion Emissions kg CO_2/tonne of waste)
SW_i-total amount of solid waste of type i (wet weight) open burning (kg/tonne of waste)
dmi - dry matter content in the waste (partially wet weight) incinerated
CF_i - fraction of carbon in the dry matter (total carbon content), (fraction; 0.0 – 1.0)
FCF_i - fraction of fossil carbon in the total carbon (fraction; 0.0 – 1.0)
OF_i - oxidation factor (0.0 – 100%)
44/12 - conversion factor from C to CO_2
i - type of fossil based waste open burnt such as textiles, rubber and leather, plastics

Once the quantification was done for fossil based CO_2 emissions from open burning process, it can be considered as the gross GHG emissions. Unlike other treatment methods, open burning has no any possibility for avoidance of GHG emissions process. Therefore, net GHG emission would be equal to the gross GHG emission process.

It should be noted that in order to quantify to overall climate impact from open burning, the impact from black carbon emission should be taken into account. Such improvements will be made in the next version of the tool.

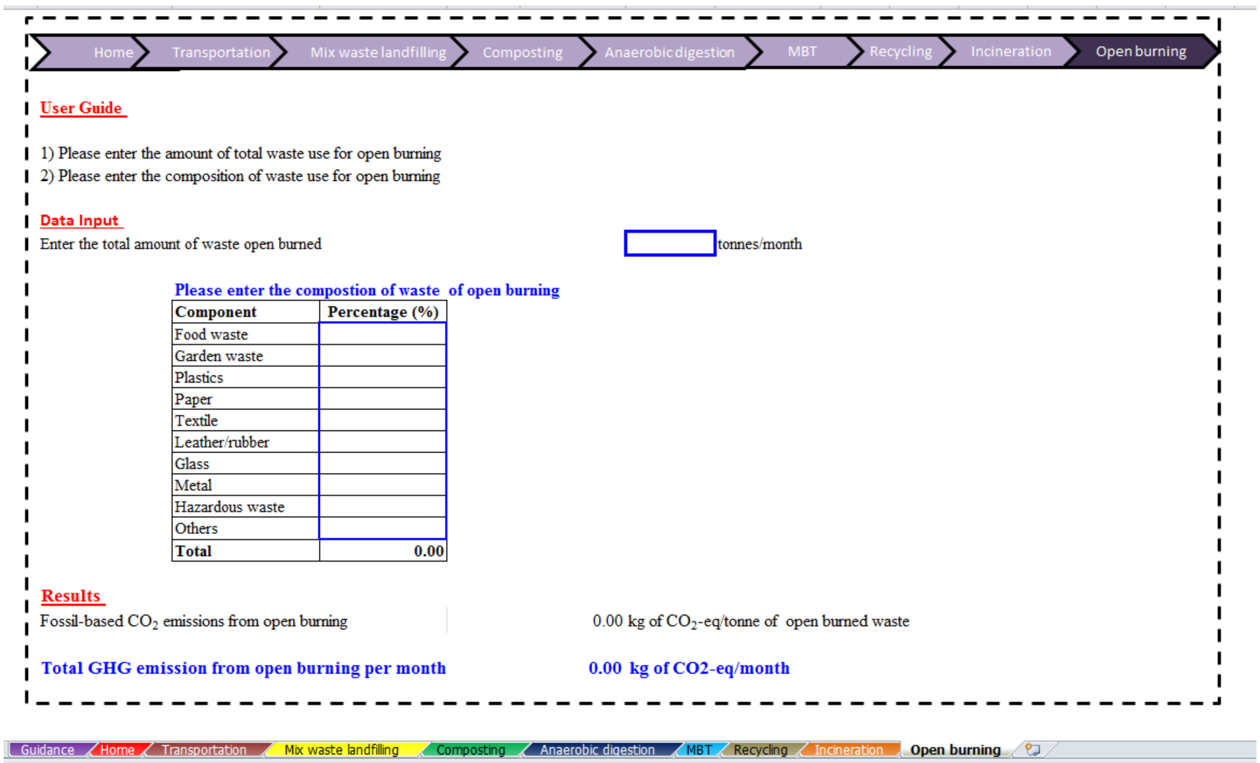


Figure 10: Page for quantification of GHG emissions from open burning

Estimation of GHG Emissions from an Integrated Solid Waste Management System

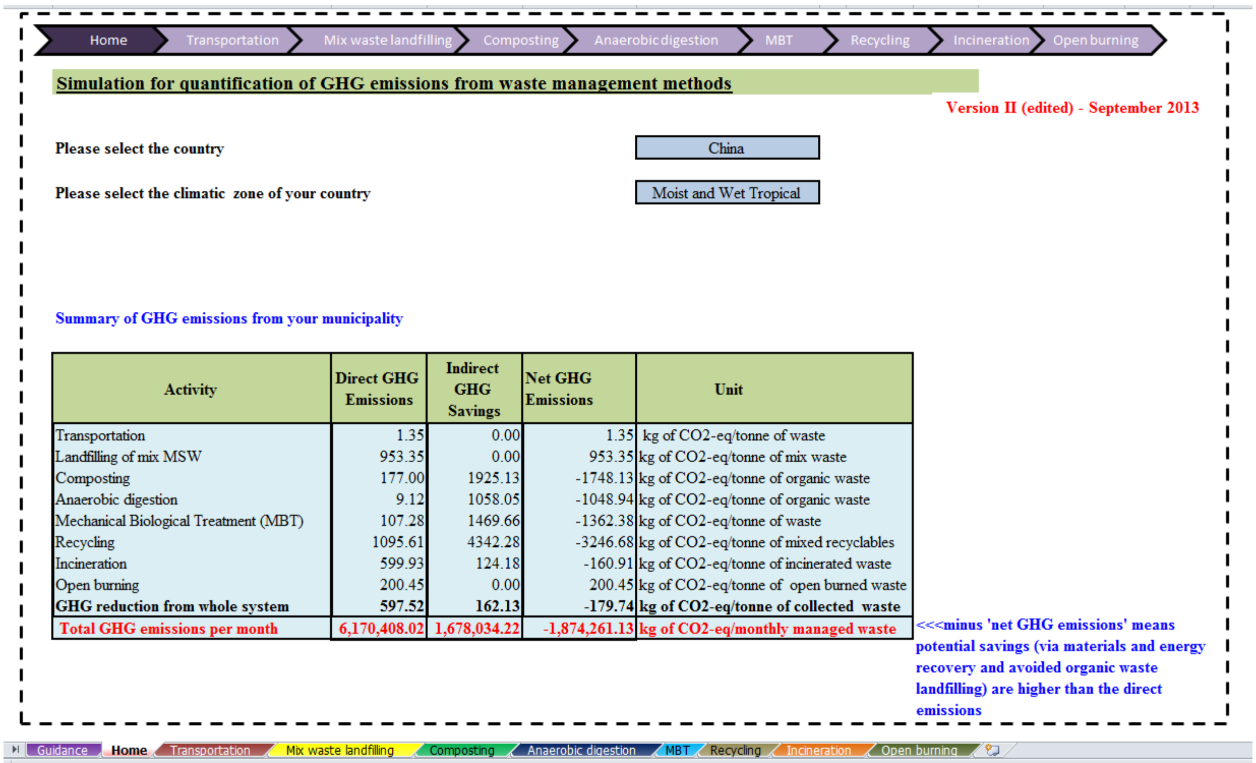
This simulation can be applied to quantify the climate benefits from individual treatment technologies as well as from integrated waste management systems. In order to estimate the net GHG emissions from an integrated system, the net GHG emissions from individual technologies will further be aggregated based on the fraction of waste treated by those technologies. By aggregating different type of waste, such as organic waste, recyclables, combustibles and mixed MSW, GHG emissions can be estimated “per tonne of collected waste” in a particular location. The following mathematical formula is used for this estimation in the “home” sheet.

Net GHG emissions from the integrated system (kg CO_2-eq/tonne of collected waste) =

Net GHG emissions from landfilling (kg CO_2-eq/tonne of mix waste landfilling) × Percentage of waste use for landfilling + Net GHG emissions from composting (kg CO_2-eq/tonne of organic waste) × Percentage of waste use for composting + Net GHG emissions from anaerobic digestion (kg CO_2-eq/tonne of organic waste) × Percentage of waste use for anaerobic digestion

+ Net GHG emissions from MBT (kg CO_2-eq/tonne of organic waste) × Percentage of waste use for MBT + Net GHG emissions from recycling (kg CO_2-eq/tonne of sorted recyclables) × Percentage of waste use for recycling + Net GHG emissions from incineration (kg CO_2-eq/tonne of combustibles) × Percentage of waste use for incineration + Net GHG emissions from open burning (kg CO_2-eq/tonne of waste) × Percentage of waste use for open burning

It is important to mention that when aggregating technologies to quantify GHG mitigation from an integrated system, GHG savings via avoided organic waste landfilling should be excluded from organic waste treatment technologies in order to avoid double counting since that effect has resulted in fewer GHG emissions from the existing landfill. The estimated net GHG emissions from the integrated system indicate the overall progress of the systems. The summary of the GHG emissions from individual treatment method as well as the integrated system will be displayed in the "home page" as shown in Figure 11.



Activity	Direct GHG Emissions	Indirect GHG Savings	Net GHG Emissions	Unit
Transportation	1.35	0.00	1.35	kg of CO2-eq/tonne of waste
Landfilling of mix MSW	953.35	0.00	953.35	kg of CO2-eq/tonne of mix waste
Composting	177.00	1925.13	-1748.13	kg of CO2-eq/tonne of organic waste
Anaerobic digestion	9.12	1058.05	-1048.94	kg of CO2-eq/tonne of organic waste
Mechanical Biological Treatment (MBT)	107.28	1469.66	-1362.38	kg of CO2-eq/tonne of waste
Recycling	1095.61	4342.28	-3246.68	kg of CO2-eq/tonne of mixed recyclables
Incineration	599.93	124.18	-160.91	kg of CO2-eq/tonne of incinerated waste
Open burning	200.45	0.00	200.45	kg of CO2-eq/tonne of open burned waste
GHG reduction from whole system	**597.52**	**162.13**	**-179.74**	**kg of CO2-eq/tonne of collected waste**
Total GHG emissions per month	**6,170,408.02**	**1,678,034.22**	**-1,874,261.13**	**kg of CO2-eq/monthly managed waste**

Figure 11: The view of summary of GHG emissions in Home page

This kind of holistic approach would be very beneficial to provide systematic methodology and then to quantify potential GHG mitigation from an integrated waste management system. GHG emissions estimation results would be very useful for the local governments for enabling the decision-making process on selecting climate friendly waste management technologies.

Limitations of the simulations and possible improvements

As mentioned earlier, there are various kinds of advantages that can be clearly seen with respect to development of simple spreadsheet simulation to quantify GHG emissions at the local authority level. However, it is also important to identify the potential limitations of developing/applying this life cycle assessment tool. . Some specific data e.g. waste composition data, may not available at the local authority level. Even though the authors made every effort to produce a user-friendly simulation, users may still find some difficulty in gathering some of the essential data which are required in this simulation.

In this version, the simulation includes all waste treatment technologies. However, the authors are considering further improvements of this simulation in order to improve the user friendliness. Furthermore, some assumptions have been made in the simulation that may influence the accuracy of the final result. For instance, as compared to other waste management technologies, GHG mitigation potential from an appropriate recycling scheme would be remarkable. Therefore, it is necessary to quantify GHG emissions more precisely and concisely from recycling businesses at the local authority level. However, due to lack of country-specific data, this simulation uses an inventory data of recycling which represents the situation in Thailand to quantify GHG emissions from all the included countries. In the future, IGES will develop a more comprehensive version to overcome this problem and to quantify the overall climate benefits from particular recycling systems taking into account location-specific data.

In this simulation, landfilling and open dumping have been considered as the base scenario for the comparison purpose since most of the developing Asian countries are practicing those primary disposal methods. However, in some cases, other kinds of technologies such as incineration or MBT would be the base scenario in some cities or municipalities. Authors do understand these issues and would improve the simulation in the future in order to include the different type of base scenarios.

Comments and suggestions from users would be greatly appreciated for further improvement of this simulation.

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Annex I: List of data requirement

Step/treatment	Type of data required	Unit
Transportation	Amount of waste transported diesel-fueled trucks	Tonnes/month
	Monthly diesel requirement	L/Month
	Amount of waste transported by natural gas-fueled trucks	Tonnes/Month
	Monthly natural gas requirement	Kg/Month
Mix waste landfilling	Amount of mix waste landfilling per month	Tonnes/month
	Amount of diesel fuel use for operation of machineries at the landfill	L/Month
	Composition of waste	%
Composting	Amount of food waste and garden waste use for composting	Tonnes/Month
	Amount of fossil-fuel use for operational activities	L/Month
	Total amount of compost production	Tonnes/Month
	Percentage of compost use for the agricultural and gardening purposes	**%**
Anaerobic digestion	Amount of food waste and garden waste use for anaerobic digestion	Tonnes/Month
	Amount of fossil diesel use for operational activities	L/Month
	Amount of electricity use for operational activities	kWh/month
	Approximate water content of the influent (mixture of waste and water)	%
Mechanical Biological Treatment (MBT)	Amount of waste use for MBT.	Tonnes/month
	Amount of fossil fuel require for operational activities	L/Month
	Amount of electricity require for operational activities	kWh/month
	Amount of compost-like material production capacity	Tonnes/Month
	Approximate percentage of produced compost-like material used for soil amendment	%
Recycling	Amount of separated recyclables	Tonnes/Month
	Composition of the recyclable mix	%
Incineration	Amount of total waste use for incineration	Tonnes/Month

	Amount of fossil fuel use for the operation activities	L/Month
	Amount of grid electricity use for the operation activities	kWh/Month
	Composition of combustibles	%
	Amount of electricity produced	kWh/Month
	Percentage of electricity use for on-site activities	%
	Amount of heat recovered	MJ/Month
	Percentage of recovered heat use for onsite activities	%
Open Burning	Amount of waste open burned	Tonnes/month
	Composition of waste	%