EMISSIONS FROM WASTE INCINERATION

ACKNOWLEDGEMENTS

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ABSTRACT

The incineration of municipal waste involves the generation of climate-relevant emissions. These are mainly emissions of CO_2 (carbon dioxide) as well as N_2O (nitrous oxide), NO_x (oxides of nitrogen) NH_3 (ammonia) and organic C, measured as total carbon. CH_4 (methane) is not generated in waste incineration during normal operation. It only arises in particular, exceptional, cases and to a small extent (from waste remaining in the waste bunker), so that in quantitative terms CH_4 is not to be regarded as climate-relevant. CO_2 constitutes the chief climate-relevant emission of waste incineration and is considerably higher, by not less than 10^2, than the other emissions.

Formulas (1) and (2) are to be used for the purpose of compiling an inventory of greenhouse gas emissions, taking the following into account:

The incineration of 1 Mg of municipal waste in MSW incinerators is associated with the production/release of about 0.7 to 1.2 Mg of carbon dioxide (CO_2 output). The proportion of carbon of biogenic origin is usually in the range of 33 to 50 percent. The climate-relevant CO_2 emissions from waste incineration are determined by the proportion of waste whose carbon compounds are assumed to be of fossil origin. The allocation to fossil or biogenic carbon has a crucial influence on the calculated amounts of climate-relevant CO_2 emissions.

Annex 1 contains a description of a method to calculate the energy credit for the use of waste as a substitute for fossil fuel (MSW incineration plants with energy recovery). Formulas (3) and (4) are to be used for the purpose of a comparative evaluation of the climate-relevant emissions from waste incineration in relation to those of other types of energy production. A factor that has a decisive influence on the calculated amounts of climate-relevant emissions from waste incineration plants with energy utilisation is the credit allowed or allowable due to the substitution of energy from fossil fuels. The latter in turn is influenced by the energy carriers used as a basis to calculate the emission factor of the power plant mix.

An energy transformation efficiency equal to or greater than about 25 percent results in an allowable average substituted net energy potential that renders the emission of waste incineration plants (calculated as CO_2 equivalents) climate-neutral due to the emission credits from the power plant mix.

1 NATURE, MAGNITUDE AND DISTRIBUTION OF SOURCE

1.1 Waste incineration

The role of waste incineration differs in the countries of the world. While in the industrialised countries in Europe as well as in Japan, the USA and Canada the proportion of waste burned in waste incineration plants can be very high (up to 100 percent), in most developing countries landfilling is the more common waste management practice.

1.1.1 Status of waste incineration in the various EU member states

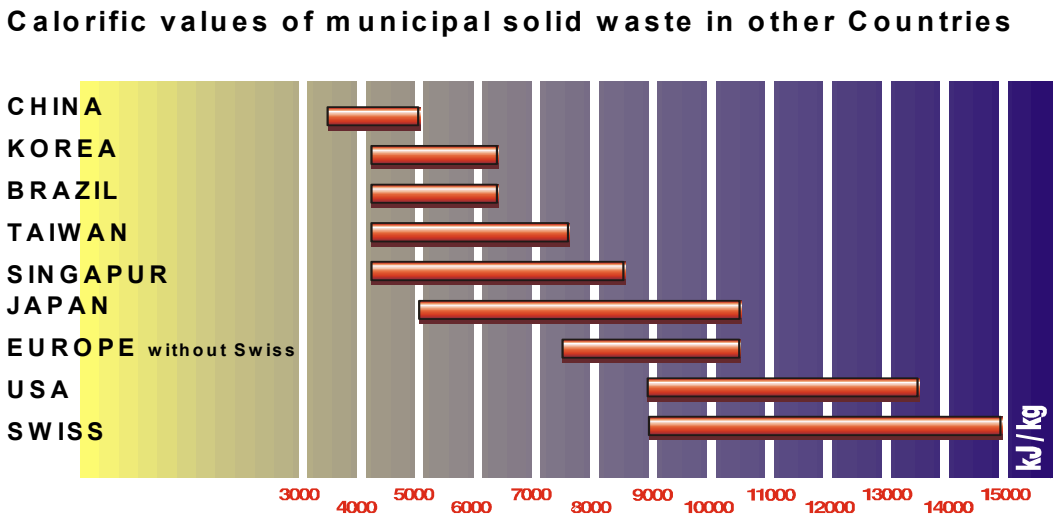
The role of municipal waste incineration in European countries varies from country to country. The compilation presented below (Table 1) shows the amounts of municipal waste incinerated in waste incineration plants of countries in western Europe. It has been taken from an EU report on waste incineration which has been prepared for the European Commission by the Netherlands-based TNO, with 1993 as the reference year. The figures for Germany, Portugal, Luxembourg and Austria have been updated to reflect the status in 1998.

TABLE 1
STATUS OF THE INCINERATION OF SOLID WASTE IN EUROPE

Country	Incineration capacity per country Mg • 10^6 /y	share of incineration	No of MSW incinerators
Austria	0.513	~20%	3
Belgium	2.24	~35%	24
Denmark	2.31	~75%	30
Finland	0.07	~4%	1
France	11.33	~45%	225
Greece	0	-	0
Germany	14	~32%	59
Ireland	0	-	0
Italy	1.9	~7%	28
Luxembourg	0.125	~95%	1
Netherlands	3.15	~27%	10
Norway	0.5	n.d.	18
Portugal	0.5	n.d.	2
Spain	0.74	~5%	14
Sweden	1.86	~40%	21
Switzerland	2.84	~100%	30
UK	3.67	~2%	31
West-Europe total	45.748	-	497
EU total	42.408	-	449

The compilation presented below (figure 1) shows that the calorific values of mixed municipal solid waste in other countries differ very much and range from 3,500 to 15,000 kJ/kg.

Figure 1 Compilation of calorific values from MSW in different countries



Source: Martin GmbH, München company brochure "Thermische Behandlung und energetische Verwertung von Abfall", page 5, 1997

1.1.2 MSW incineration in Europe (example Germany)

The thermal treatment of solid municipal waste mostly takes place in plants equipped with grate firing systems, in individual cases, in pyrolysis, gasification or fluidized bed plants or in plants using a combination of these process stages. Residual municipal waste (domestic refuse, commercial waste similar to domestic refuse, bulky waste, road sweepings, market waste, etc.) is delivered to grate furnaces as a heterogeneous mixture of wastes. Combustible components account for a content of about 40 - 60 wt. percentage. 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. The calorific value of mixed waste ranges from 7,500 to 11,000 kJ/kg. The waste's carbon content is generally in the range of 28 - 40 wt. percent (averages, related to dry matter).

Treatment in incineration plants is an output-controlled process (geared, as a rule, to steam output). The combustion temperature of the gases in the combustion chamber as measured for at least two seconds after the last injection of combustion air is usually at least 850°C. The oxygen necessary for incineration is supplied via ambient air, as primary, secondary and/or tertiary air. The volume of air supplied to the incinerator is between 3,000 and 4,500 m^3 (dry) per Mg of waste. This gives a waste gas volume of 3,500 - 5,500 m^3 (dry) per Mg of waste.

At almost all municipal waste incineration plants, the heat produced during incineration is utilised for steam generation. Upon reaching the end of the steam generator, the temperature of the waste gas has been reduced to 200° C. The steam produced in municipal waste incinerators exhibits pressures between 14 and 120 bar and temperatures between 196 and 525°C. Common steam parameters are 40 bar and 400°C. A high heat utilisation efficiency can only be achieved if incineration is controlled so that the produced amounts of steam can be made available continuously for direct supply of heat and electricity to an industrial plant or for use in a heating station or cogeneration plant.

1.1.3 Hazardous waste incineration in Europe (example Germany)

Hazardous waste is treated almost exclusively by incineration. Incineration must be understood here as an element of comprehensive logistics for the treatment of those wastes which due to their harmful nature have to be managed separately from municipal waste. Hazardous waste is waste requiring particular supervision, which by its nature, condition or amount poses a particular hazard to health, air and/or water or is particularly explosive, or may contain or bring forth pathogens of communicable diseases. Since hazardous waste is generated for the most part in industrial production, notably the chemical industry, it is also referred to as industrial waste or industrial residue.

Hazardous wastes occur, for example, as residues from petrochemical distillation processes, as undesirable by-products of syntheses processes of the basic organic chemical industry and the pharmaceutical industry as well

as in the recovery and disposal of contaminated or post-expiration-date products such as solvents, paints or waste oil. In addition, environmental protection measures such as regulations prohibiting PCBs, CFCs or halons may generate streams of hazardous waste. The waste going to incineration is usually a mixture of waste types which may differ in composition and be present in solid, semi-liquid or liquid form. Its chemical description differs from that of municipal waste. As hazardous wastes are of varying consistency, the rotary kiln is widely used as a universally applicable incineration process. Only in exceptional cases are hazardous wastes incinerated in a conventional combustion chamber, a muffle-type furnace or other type of incineration system. The rotary kiln operates according to the parallel-flow principle, in which the material being incinerated and the combustion gas are transported in the same direction, from the cold to the hot side. With combustion temperatures between 800 and 1200°C, the residence time of solids in the rotary kiln is up to 1 hour while for the combustion gases it is only a few seconds. The waste gas generated during the combustion process is fed to an after burning chamber, in which the minimum temperature of between 850 and 1200°C is maintained for a residence time of at least 2 seconds. The waste gas volume from this process is generally assumed to be about 7,000 m^3 (dry) per Mg of waste.

At nearly all hazardous-waste or residues incineration plants, the heat produced during incineration is utilised for steam generation downstream from the afterburner. Upon reaching the end of the steam generator, the temperature of the waste gas has been reduced to 200-300°C. The steam from hazardous-waste incineration exhibits pressures between 17 and 30 bar and temperatures between 250 and 300°C.

1.1.4 Mono-incineration of sewage sludge in Europe (example Germany)

The system mainly used for the incineration of sewage sludge is fluidized-bed combustion. Most plants are stationary fluidized-bed furnaces, but there are also multiple-hearth furnaces and multiple-hearth fluidized-bed furnaces in use. Fluidized-bed furnaces for the incineration of sewage sludge are usually operated at combustion temperatures in the range of 850°C and 900°C. The waste gas volume from this process is generally assumed to be about 8,000 m^3 (dry) per Mg. of sewage sludge (dry matter). Modern plants are equipped with a steam generator downstream from incineration, producing wet steam with a pressure of 10 bar and a temperature of 180°C. Most plants use the produced steam to meet in-plant requirements (e.g. for sludge drying).

The sewage sludge delivered to the incineration plants in de-watered and/or partially dried condition usually has a water content of 50-70 percent. The calorific value of de-watered sludge averages 3,500 kJ/kg in the case of raw sludge (25 percent dry matter) and 2,500 kJ/kg in the case of digested sludge (25 percent dry matter). The content of mineral and inorganic components in sludge can be as high as 30 percent. The carbon content of sludge is generally about 30 percent.

1.1.5 Co-incineration in Europe

In the future, the use of waste in plants other than waste incineration plants will be gaining in importance as a waste management option. The object of co-incinerating high-calorific waste as substitute fuel (so-called waste for energy recovery) in production (e.g. cement works, brick manufacture, blast furnace), power plants (e.g. use of sewage sludge in coal-fired power plants) and industrial boilers is the substitution of regular fuel (coal, fuel oil, etc.) and to reduce energy costs.

The climate-relevant emissions of a waste incineration plant are made up of a proportion to be allocated to the waste's contribution to the thermal output and that of the remaining regular fuel. Therefore, a proportions calculation has to be carried out to determine the proportion of those climate-relevant emissions which result from the co-incineration of the waste.

1.1.6 Other kinds of waste incineration

In most European countries, the use of incineration plants for medical waste or as crematoria is for the combustion capacity and the climate-relevant emission of flue gas stream not so relevant. For that reason this kind of incineration will not be considered in this paper.

(From a waste management perspective, merely dividing the total CO_2 load produced by a waste incineration plant into carbon compounds of biogenic and carbon compounds of fossil origin is too simple a view. It fails to take into account that waste of biogenic origin. It includes a fossil component from the product life-cycle. That component stems from manufacture and transport (e.g. of textiles, paper and cardboard, composites, wooden furniture $\Rightarrow$ bulky waste) and needs to be allocated and charged to the product/waste fraction as climate-relevant. When reporting emissions according to the Revised 1996 IPCC Guidelines for National Greenhouse Gas for National Inventories (IPCC Guidelines) however, these emissions are included in the energy sector and should therefore not be included in the waste emission.)

2 METHODOLOGICAL ISSUES

2.1 Proposed methodology to calculate the emissions from waste incineration

(The values of the calculation shall be standardised on the following conditions: dry gas, 11 percent O_2, 273 K, 1013 hPa).

Equation 1 calculates the emissions from waste incineration plants:

EQUATION 1

Emissions i [Mg] = emission concentration i [Mg ● $10^{-9}/m^3$]
● exhaust gas volume (dry) [m^3/Mg waste]
● amount of incinerated waste [Mg waste]

Where:

Emission i in [Mg emission]

i ≅ CO_2, N_2O, CH_4, NOx, CO, TOC, NH_3

emission concentration i [Mg • 10^{-9}/ m^3] of the climate-relevant emission according to chapter 2.2

i ≅ CO_2, N_2O, CH_4, NOx, CO, TOC, NH_3

exhaust gas volume (dry) [m^3/Mg waste] of the incineration plant according to chapter 2.4

amount of incinerated waste [Mg waste] of a country per year.

Equation 2 calculates the emissions in CO_2-equivalent:

EQUATION 2

Emissions in CO_2-equivalent i [Mg CO_2] = Emission i [Mg emission]
● GWP [Mg CO_2/Mg emission]

Where:

Emissions in CO_2-equivalent i [Mg CO_2]

Emission i [Mg emission] of Formula (1)

i ≅ CO_2, N_2O, CH_4, NOx, CO, TOC, NH_3

global warming potential GWP in [Mg CO_2/Mg emission] according to chapter 2.3

2.2 Choice of emission factor and activity data

Carbon Dioxide CO_2

The incineration of 1 Mg of municipal waste in MSW incinerators is associated with the production/release of about 0.7 to 1.2 Mg of carbon dioxide CO_2. Although this carbon dioxide is directly released into the atmosphere and thus makes a real contribution to the greenhouse effect, only the climate-relevant CO_2 emissions from fossil sources are considered for the purposes of a global analysis. 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. In the literature, the proportion of CO_2 assumed to be of fossil origin (e.g. plastics) and consequently to be considered as climate-relevant, is given as 33 to 50 percent.

Assuming that carbon dioxide emissions from MSW incineration average 1 Mg per Mg of waste, then of these CO_2 emissions 0.33 (0.50) Mg are of fossil and 0.67 (0.50) Mg are of biogenic origin. In subsequent calculations, the proportion of climate-relevant CO_2 is figured out as an average value of 0.415 Mg of CO_2 per Mg of waste. The measured CO_2 output content of the exhaust gas (dry) in MSW incineration plants is round about 10 Vol. percent multiply with 5,500 m^3 exhaust gas volume (dry) per Mg waste multiply with 1.9768 kg/ m^3 density of CO_2 result in 1087 kg CO_2 per Mg waste. The content of C in CO_2 is round about 27.3 percent resulting in 297 kg C per Mg waste.

Another way to develop the estimate of climate-relevant CO_2 emission from the input, was to estimate the amount of non-biogenic carbon in the waste. Usually, three waste categories contain non-biogenic carbon: plastics, textiles, and a combined category for rubber and leather (U.S. EPA 1997).But it is a problem to determine the real

content of carbon in the heterogeneous MSW, because it is variable from day to day. The waste's carbon content of German MSW is generally in the range of 28 - 40 wt .percent (averages, related to dry matter) or 280 - 400 kg C per Mg waste.

Calculation example (Germany MSW incinerated 14 ● 10^6 Mg waste/ year):

Equation 1:

Total Emission CO_2 = 0.415 Mg CO_2 /Mg waste ● 14 ● 10^6 Mg waste/ year

Total Emission CO_2 = 5.81 ● 10^6 Mg/year

Equation 2:

Total emission CO_2 = 5.81 ● 10^6 Mg CO_2 /year

For the incineration of sewage sludge in fluidized-bed plants, an emission of 1 Mg of CO_2 per Mg of incinerated sludge (dry matter) is assumed.

Nitrous Oxide N_2O

As well as the above nitrogen oxide compounds NO and NO_2, nitrous oxide N_2O is of relevance from a climate perspective. Emission levels of 1 to 12 mg/m^3 have been determined in individual measurements at MSW incineration plants, with an average of 1 - 2 mg/m^3. From hazardous waste incineration plants the emission levels of 30 to 32 mg/m^3 have been determined in individual measurements.

NO_2 emission levels (individual measurements) are markedly higher in the incineration of sewage sludge in fluidized-bed plants. An average of 100 mg N_2O/m^3 was used for the calculations presented here.

Calculation example:

Equation 1:

Total Emission N_2O = 2 mg/m^3 ● 5,500 Nm^3 /Mg waste ● 14 ● 10^6 Mg waste/year

Total Emission N_2O = 154 Mg/year

Equation 2:

Total emission CO_2-equivalent = 154 Mg N_2O/y ● 310 Mg CO_2 /Mg N_2O

Total emission CO_2-equivalent N_2O = 0.04774 ● 10^6 Mg CO_2 /year

Methane CH_4

It can be assumed that under the oxidative combustion prevailing in waste incineration in MSW incinerators, methane is not present in the waste gas and consequently is not emitted. Although methane emissions may form in the waste bunker, the underpressure in the waste bunker causes them to be transported with the bunker air to the combustion chamber as primary air, to be converted there.

Calculation example:

Equation 1:

Total Emission CH_4 = 0

Equation 2:

Total emission CO_2-equivalent CH_4 = 0

2.2.1 Other climate-relevant emissions from MSW incineration (NOT relevant for IPCC methodology)

Carbon Monoxide CO

During the incineration of municipal waste in MSW incinerators carbon monoxide is formed as the product of incomplete combustion. CO is an indicator substance for the combustion process and an important quality criterion for the level of combustion of the gases. As a rule, CO is measured continuously in the plants. Average CO emissions, as daily means, are below 50 mg/ m^3. Plants reflecting BAT (Best Available Techniques) have daily means in the range of <10 mg/ m^3.

Calculation example:

Equation 1:

Total Emission CO = 50 mg/m^3 ● 5,500 Nm^3 /Mg waste ● 14 ● 10^6 Mg waste/year

Total Emission CO= 3.85 ● 10^3 Mg/year

Equation 2:

Total emission CO_2-equivalent = 3.85 ● 10^3 Mg CO/y ● 3 Mg CO_2 /Mg CO

Total emission CO_2-equivalent CO = 0.01155 ● 10^6 Mg CO_2 /year

Nitrogen Oxides NO_x

In the incineration of municipal waste in MSW incinerators nitrogen oxides NOx (NO, NO_2) arise, which are formed essentially from the nitrogen contained in the waste, from the combustion process itself and from spontaneous reaction (so-called prompt NOx). As a rule, nitrogen oxide concentrations in waste gas are measured continuously at these plants. If no measures were performed at MSW incinerators for nitrogen removal, the emissions would be between 350 and 400 mg/m^3. An emission level of 200 mg/m^3 can safely be attained if selective waste gas treatment measures are carried out (SNCR, SCR). Plants reflecting BAT (best available techniques) attain emission levels in the range of 100 to 150 mg NOx/m^3 when using SNCR technology and <70 mg NOx/m^3 when using SCR technology.

Hazardous waste incineration plants reflecting BAT attain emission levels in the range of 40 to 50 mg NOx/m^3 when using SCR technology.

Calculation example:

Equation 1:

Total Emission NO_x = 0.2 ● 10^3 mg/m^3 ● 5,500 Nm^3 /Mg waste ● 14 ● 10^6 Mg waste/year

Total Emission NO_x = 15.4 ● 10^3 Mg/year

Equation 2:

Total emission CO_2-equivalent = 15.4 ● 10^3 Mg NO_x/y ● 8 Mg CO_2 /Mg NO_x

Total emission CO_2-equivalent NO_x = 0.123 ● 10^6 Mg CO_2 /year

Ammonia NH_3

In MSW combustion, emissions of ammonia NH_3 arise in particular from the use of ammonia (and also ammonia water) as an additive in waste gas treatment measures for nitrogen removal (SNCR, SCR). As a rule, emissions (determined in individual measurements) are in the range of 1-10 mg/m^3; the average is assumed to be 4 mg NH_3/m^3.

Calculation example:

Equation 1:

Total Emission NH_3 = 4 mg/m^3 ● 5,500 Nm^3 /Mg waste ● 14 ● 10^6 Mg waste/year

Total Emission NH_3 = 308 Mg/year

Equation 2:

Total emission CO_2-equivalent NH_3 = n.d.

Non-Methane Volatile Organic Compounds (NMVOCs)

Organic compounds (organic C) in the waste gas of MSW incineration plants are measured continuously as sum parameter Total Carbon. This parameter constitutes an indicator of the level of combustion achieved in an incineration process. The emissions are subject to a limit of 10 mg/ m^3, but BAT plants attain, as a rule, emission levels of 1 mg/ m^3.

Calculation example TOC:

Equation 1:

Total Emission TOC= 5 mg/ m^3 ● 5,500 N m^3 /Mg waste ● 14 ● 106 Mg waste/year

Total Emission TOC= 385 Mg/year

Equation 2:

Total emission CO_2-equivalent = 385 Mg TOC/y ● 11 Mg CO_2 /Mg TOC

Total emission CO_2-equivalent TOC = 0.004235 ● 106 Mg CO_2 /year

2.3 Estimation of the specific emissions of a power plant mix per kWh Net (related to total electricity consumption) and the global warming potential (GWP)

The specific emissions data, in mg/kWh, refer to the total amount of electricity produced in all public power plants, based on a power plant mix consisting of fossil-fuelled power plants (gas, oil, coal), nuclear power plants and power plants operated with renewable energy sources (hydro, wind, solar). They are used to make a global estimate at country level (in the present case, Germany) of the specific climate-relevant emissions from the power plant sector. For local-level analyses, instead of the electricity-related power plant mix more specific emission factors (related to the energy carrier actually being replaced) should be used in the calculations to determine the substitution effect of energy produced in waste incineration (Table 2).

TABLE 2
EMISSION FACTORS FOR POWER PLANT MIX

Emission	Emission factor (power plant mix) [mg/kWh]	GWP (100 years) [kg CO_2/kg emission]
CO_2	690,000	1
N_2O	32	310
CO	235	3
NMVOC	13	11
NH_3	7	not defined
NO_x	660	8
CH_4	13	21

2.4 Exhaust gas volumes in waste incineration

Waste incineration plants have different exhaust gas volumes. This depends on the kind of the process and the composition of waste. Table 3 shows the usual exhaust gas volumes in MSW incineration plants, hazardous waste incineration plants and mono-sewage sludge incineration plants.

TABLE 3
DIFFERENT EXHAUST GAS VOLUMES IN WASTE INCINERATION PLANTS

	Exhaust gas volume (dry)
Municipal solid waste incineration	5,500 m^3/Mg waste
Hazardous waste incineration	7,000 m^3/Mg waste
Mono sewage sludge incineration	8,000 m^3 /Mg sewage sludge dry matter

3 REPORTING AND DOCUMENTATION

Transparency will be improved if all countries report estimates for their waste incineration activities separately, and indicate whether they use Tier 1, Tier 2, or Tier 3 methods.

4 INVENTORY QA/QC

4.1 Internal inventory QA/QC systems

Quality of the data used to calculate climate-relevant emissions:

Tier 1 Emissions data for the waste gas parameters NO_x, CO, Total Organic Carbon are determined by continuous measurements in the waste incineration plants, monitored by the competent licensing authorities and published on a yearly basis.

Municipal solid waste is heterogeneous (a composite of many waste components). A determination of the climate-relevant chemical substances contained in the waste input, cannot be specifically stated, due to the fact that MSW analysis can only make individual conclusion and not general statements (due to their permanent changing as non-homogenous composition). The method proposed here for estimation of the climate-relevant total emissions is therefore based on exhaust gas measurements. These output measurements can be more exactly defined as the waste input analysis.

Tier 2 Emissions data for the waste gas parameter CO_2 are calculated on the basis of waste analyses, and emissions data for NH_3 and N_2O are determined by individual measurements.

Tier 3 The specific emissions factors, related to electricity consumption, for climate-relevant emissions of the power plant mix have been calculated on the basis of energy statistics and annual reports of the energy industry.

The specific waste gas volumes generated in the various treatment processes have been calculated from the operators' data on waste gas volume and the associated waste throughputs. Uncertainty is involved in determining the proportion of climate-relevant CO_2 from waste incineration for the purpose of calculating total climate-relevant CO_2 emissions, since the range of variation in the proportion of CO_2 from waste of biogenic origin leaves ample scope for subjective judgement. One has to largely draw upon literature data from analyses for the carbon content in waste, its distribution among the various waste fractions, associated assumptions with respect to waste composition, and estimates based thereon.

The results of the calculation in Annex 1 shows, that the determination of the energy actually substituted in a country by waste incineration is likewise subject to a great deal of uncertainty. Energy-related data (calorific value of the waste, utilisation of waste-derived energy) and possible efficiencies vary widely. They are determined by the site conditions and the geographical location, and have a considerable influence on the energy credits to be deducted from the total emissions determined.

The comparison of the total emissions calculated according to formulas (1) and (3) allows a criterion to be obtained for the assessment of modern waste incineration with and without energy use which takes into account the substituted primary energy potential.

Using the climate-relevant CO_2 equivalents calculated according to formulas (2) and (4), the climate-relevant emissions of waste incineration plants can be added up as CO_2 equivalents to enable an overall assessment.

CO_2 constitutes the chief climate-relevant emission of waste incineration and is considerably higher, by not less than 10^2, than the other emissions.

An energy transformation efficiency equal to or greater than about 25 percent results in an allowable average substituted net energy potential that renders the emission of waste incineration plants (calculated as CO_2 equivalents) climate-neutral due to the emission credits from the power plant mix.

5 CONCLUSIONS

The incineration of municipal waste involves the generation of climate-relevant emissions. These are mainly emissions of CO_2, but also of N_2O, NO_x, NH_3, and organic C, measured as total carbon. CH_4 is not generated in waste incineration during normal operation. It only arises in particular, exceptional, cases and to a small extent (from waste remaining in the waste bunker), so that in quantitative terms CH_4 is not to be regarded as climate-relevant.

In waste incineration plants, CO_2 constitutes the chief climate-relevant emission and is considerably higher, by not less than 10^2, than the other climate-relevant emissions.

In Germany the incineration of 1 Mg of municipal waste in MSW incinerators is associated with the production/release of about 0.7 to 1.2 Mg of carbon dioxide (CO_2 output). The proportion of carbon of biogenic

origin is usually in the range of 33 to 50 percent. The climate-relevant CO_2 emissions from waste incineration are determined by the proportion of waste whose carbon compounds are assumed to be of fossil origin. The allocation to fossil or biogenic carbon has a crucial influence on the calculated amounts of climate-relevant CO_2 emissions.

In Germany, every waste incineration plant is equipped with facilities to utilize energy. A factor that has a decisive influence on the calculated amounts of climate-relevant emissions from waste incineration plants with energy utilisation is the credit allowed or allowable due to the substitution of energy from fossil fuels. The latter in turn is influenced by the energy carriers used as a basis to calculate the emission factor of the power plant mix.

An energy transformation efficiency equal to or greater than about 25 percent results in an allowable average substituted net energy potential that renders the emission of waste incineration plants (calculated as CO_2 equivalents) climate-neutral due to the emission credits from the power plant mix.

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ANNEX 1 METHOD FOR CALCULATION OF ENERGY CREDIT FOR USE OF MSW AS A SUBSTITUTE FOR FOSSIL FUELS

Discription of a method to calculate the energy credit for the use of waste as a substitute for fossil fuel (MSW incineration plants with energy recovery)

A 1.1 Formulas to calculate the energy credit for the use of waste as a substitute for fossil fuel (MSW incineration plants with energy recovery)

Equations 3 and 4 are to be used for the purpose of a comparative evaluation of the climate-relevant emissions from waste incineration in relation to those of other types of energy production. A factor that has a decisive influence on the calculated amounts of climate-relevant emissions from waste incineration plants with energy utilisation is the credit allowed or allowable due to the substitution of energy from fossil fuels. The latter in turn is influenced by the energy carriers used as a basis to calculate the emission factor of the power plant mix.

Equation 3 corrects the total emissions from Equation 1 for the use of waste as substitute fuel (for incineration plants with energy recovery):

EQUATION 3

$$\text{Total emission}_{i\ cor}\ [\text{Mg emission}] = \text{total emission}_{i}\ [\text{Mg emission}] - \text{usable/used energy [kWh]} \bullet \text{emission factor (power plant mix) [Mg emission} \bullet 10^{-9}/\text{kWh}]$$

Where:

Total emission $_{i\ cor}$ in [Mg emission] for incineration plants with energy recovery

i ≅ CO_2, N_2O, NOx, CO, TOC, CH_4, NH_3, etc.

total emission $_i$ [Mg emission] of Formula (1)

i ≅ CO_2, N_2O, NOx, CO, TOC, CH_4, NH_3, etc.

usable/used energy [kWh] different for every country according to A 1.2 and A 1.3 in this annex.

emission factor (power plant mix) [Mg emission ● 10^{-9}/kWh] for the climate-relevant emissions of substituted energy from fossil fuel according to chapter 2.3

Equation 4 adds the calculated correct climate-relevant total emission as CO_2-equivalent (for incineration plants with energy recovery):

EQUATION 4

$$\text{Total emission } CO_2\text{-equivalent}_{i\ cor}\ [\text{Mg } CO_2] = \text{total emission}_{i\ cor}\ [\text{Mg emission}] \bullet \text{GWP [Mg } CO_2/\text{Mg emission}]$$

Where:

Total emission CO_2-equivalent $_{i\ cor}$ [Mg CO_2]

total emission $_{i\ cor}$ [Mg emission] from Formula (3)

global warming potential (GWP) [Mg CO_2/Mg emission] according to chapter 2.3

<u>Calculation example CO_2</u> :

Equation 3:

Total Emission $CO_{2\ cor}$ = 5.81 ● 10^6 Mg /year - 8.75 ● 10^9 kWh/year ● 690,000 mg CO_2 /kWh

Total Emission $CO_{2\ cor}$ = 5.81 ● 10^6 Mg CO_2 /year - 6.0375 ● 10^6 Mg CO_2 /year (energy credit)

Total Emission $CO_{2\ cor}$ = - 0.2275 ● 10^6 Mg CO_2 /year

Equation 4:

Total emission $CO_{2\ cor}$ = - 0.2275 ● 10^6 Mg CO_2 /year

Calculation example NO_x :

Equation 3:

Total Emission $NO_{x\ cor}$ = 15.4 ● 10^3 Mg/year - 8.75 ● 10^9 kWh/year ● 660 mg NO_x/kWh

Total Emission $NO_{x\ cor}$ = 15.4 ● 10^3 Mg /year - 5.775 ● 10^3 Mg/year (energy credit)

Total Emission $NO_{x\ cor}$ = 9.625 ● 10^3 Mg NOx/year

Equation 4:

Total emission CO_2-equivalent $NO_{x\ cor}$ = 9.625 ● 10^3Mg NOx/year ● 8 Mg CO_2 /Mg NOx

Total emission CO_2-equivalent $NO_{x\ cor}$ = 0.077 ● 10^6 Mg CO_2 /year

Calculation example N_2O :

Equation 3:

Total Emission $N_2O_{co\ r}$ = 154 Mg /year - 8.75 ● 10^9 kWh/year ● 32 mg N_2O /kWh

Total Emission N_2O_{cor} = 154 Mg /year - 280 Mg /year (energy credit)

Total Emission N_2O_{cor} = -126 Mg/year

Equation 4:

Total emission CO_2-equivalent N_2O_{cor} = - 126 Mg N_2O /year ● 310 Mg CO_2 /Mg N_2O

Total emission CO_2-equivalent N_2O_{cor} = - 0.03906 ● 10^6 Mg CO_2 /year

Calculation example CO :

Equation 3:

Total Emission CO_{cor} = 3.85 ● 10^3 Mg/year - 8.75 ● 10^9 kWh/year ● 235 mg CO/kWh

Total Emission CO_{cor} = 3.85 ● 10^3 Mg/year - 2.05 ● 10^3 Mg/year (energy credit)

Total Emission CO_{cor} = 1.8 ● 10^3 Mg/year

Equation 4:

Total emission CO_2-equivalent CO_{cor} = 1.8 ● 10^3Mg CO/year ● 8 Mg CO_2 /Mg CO

Total emission CO_2-equivalent CO_{cor} = 0.0054 ● 10^6 Mg CO_2 /year

Calculation example TOC:

Formula (3)

Total Emission $TOC_{co\ r}$ = 385 Mg /year - 8.75 ● 10^9 kWh/year ● 13 mg TOC/kWh

Total Emission TOC_{cor} = 385 Mg /year - 113.75 Mg /year (energy credit)

Total Emission TOC_{cor} = 271.25 Mg/year

Formula (4)

Total emission CO_2-equivalent TOC_{cor} = 271.25 Mg TOC/year ● 8 Mg CO_2 /Mg TOC

Total emission CO_2-equivalent TOC_{cor} = 0.002983 ● 10^6 Mg CO_2 /year

Calculation example NH_3 :

Equation 3:

Total Emission $NH_{3\ cor}$ = 308 Mg /year - 8.75 ● 10^9 kWh/year ● 7 mg NH_3/kWh

Total Emission $NH_{3\ cor}$ = 308 Mg /year - 61.25 Mg /year (energy credit)

Total Emission NH_{3cor} = 246.75 Mg/year

Formula 4:

Total emission CO_2-equivalent NH_{3cor} = n.d.

Calculation example CH_4 :

Equation 3:

Total Emission CH_4 = 0 - 8.75 ● 10^9 kWh/year ● 13 mg CH_4/kWh

Total Emission CH_4 = 0 - 113 Mg/year

Total Emission $CH_{4\ cor}$ = - 113 Mg/year

Equation 4:

Total emission CO_2-equivalent $CH_{4\ cor}$ = - 113 Mg CH_4/year ● 21 Mg CO_2 /Mg CH_4

Total emission CO_2-equivalent $CH_{4\ cor}$ = - 0.002373 ● 10^6 Mg CO_2 /year

A1.2 Energy utilisation efficiency of (energy supplied by) different MSW incineration plants

In general, about 300 to 600 kWh of electricity can be produced in a MSW incineration plant from 1 Mg of municipal waste, depending on plant size, steam parameters and steam utilisation efficiency. In the case of the co-generation of electricity and heat, about 1,250 kWh of heat per Mg of waste can be produced in addition and supplied to external users, depending on the incineration plant's site-dependent heat supply opportunities as well as the geographical location of the country and the (long-distance) heat utilisation periods usual for that country (e.g. in Germany, 1,300-1,500 hrs/year out of a possible 8,760 hrs/year). Given ideal site conditions with favourable opportunities for utilisation and supply in the form of steam, electricity and hot water or exclusively steam, the transformation/recovery efficiency of an incineration plant operating at base load can be increased to a maximum of 75-83 percent of the energy input (calorific value). In this energetically favourable case, about 2 MWh, as energy mix (electricity and heat), per Mg of waste can be produced and supplied to external users.

Actual energy transformation efficiencies are shown in the Table 4 below, ranging from a site with minimum supply of energy (electricity only) to sites with normal or optimised power/heat co-generation or exclusively supplying heat. This broad range of variation among existing plants illustrates that the energy transformation efficiency as well as the proportion of energy actually supplied by waste incinerators to substitute for fossil energy sources, as estimated on the basis of it, and the resultant emissions, are of major importance to the calculation of climate-relevant emissions.

TABLE 4
ENERGY TRANSFORMATION/RECOVERY EFFICIENCIES (W) OF THE GROSS ENERGY INPUT OF MSW INCINERATORS

	minimum energy recovery	normal energy recovery	optimised energy recovery	optimised energy recovery
W thermal (%)	<1	11	15 - 55	70-83
W electrical (%)	13	14	20	0
W total (%)	13	25	35 - 75	70-83

A1.3 Status of Waste Incineration and Energy Use in Germany

In Germany an amount of approx. 14 ● 10^6 Mg/a of residual waste is subjected to thermal treatment (status: 1999). For waste incineration plants in Germany, a theoretical gross energy content in municipal waste, in kJ/a, can be specified by multiplying an assumed average calorific value of about 9 ●10^6 kJ per Mg of waste, roughly reflecting as a rule the calorific value of low-quality lignite, by the amount of waste incinerated annually. From this, the

energy made available by waste incineration can be calculated as a function of the assumed energy transformation and utilisation efficiency (the average from all plants in Germany is in the range of 20 to 35 percent) to derive conclusions as to the relevance of waste-derived energy for the substitution of climate-relevant emissions from fossil energy sources. The waste incineration plant's own energy (electricity, etc.) requirements (e.g. for waste gas treatment) are considered to be external energy which in the ideal case would be met through in-plant electricity production.

Taking Germany as an example, the credit for energy from waste incineration is calculated as follows:

Amount of residual waste subjected to thermal treatment: approx. 14 ● 10^6 Mg/a,

multiplied by an average calorific value of approx. 9 ● 10^6 kJ/Mg waste

gives 126 ● 10^{12} kJ, or 126 ● 10^6 GJ/a;

divided by 3.6 GJ/MWh

gives 35 ● 10^6 MWh/a.

Of this amount, an average of 35 ● 10^6 MWh/a ● 0.25 total energy transformation efficiency is utilised, which brings the average allowable substituted net energy potential to 8.75 ● 10^6 MWh/a (normal energy recovery).

Based on 1992 operating data taken from the ISWA's data compilation "Energy from Waste Plants 1994", the energy supplied to external users in the form of heat and electricity by waste incineration plants in Germany (incineration capacity 7.3 ● 10^6 Mg/a) can be calculated at approx. 4.8 ● 10^6 MWh/a.

If the total emission of the non-biogenic CO_2 is estimate with 0.414 Mg CO_2 per Mg waste and the average total energy transformation efficiency of all waste incineration plants with energy recovery were optimised to reach a value equal to or greater than about 0.25, the allowable substituted net energy potential would increase to 8.75 ● 10^6 MWh/a (normal energy recovery), leading to neutrality in climate-relevant emissions from waste incineration due to the emission credits from the power plant mix.

A 1.4 Comparison example of the climate-relevant total emission from MSW Incineration in Germany with or without energy recovery

Results of the amount of calculation from Equations 1, 2, 3, and 4 - Table 5

CO_2 constitutes the chief climate-relevant emission of waste incineration and is considerably higher, by not less than 10^2, than the other emissions.

TABLE 5
SW INCINERATION IN GERMANY (THROUGHPUT 14 ● 10^6 MG/YEAR)

Emission	W = 0	W = 25%	W = 0	W = 25%
	Total Emission (1) [Mg/year]	Total Emission $_{cor}$ (3) [Mg/year]	Total Emission (2) [Mg CO_2/year]	Total Emission $_{cor}$ (4) [Mg CO_2/year]
CO_2	5.81 ● 10^6	- 0.2275 ● 10^6	5.81 ● 10^6	- 0.2275 ● 10^6
NOx	0.0154 ● 10^6	0.009625 ● 10^6	0.123 ● 10^6	0.077 ● 10^6
N_2O	0.000154 ● 10^6	0.000126 ● 10^6	0.0477 ● 10^6	- 0.039 ● 10^6
CO	0.00385 ● 10^6	0.0018 ● 10^6	0.0115 ● 10^6	0.0054 ●10^6
TOC	0.000385 ● 10^6	0.00027125 ● 10^6	0.0042 ● 10^6	0.0029 ● 10^6
NH_3	0.000308 ● 10^6	0.00024675 ● 10^6	not defined	Not defined
CH_4	0	0.000113 ● 10^6	0	- 0.00237 ● 10^6
Amount of total emission as CO_2 equivalent from MSW Incineration			5.99 ● 10^6 Mg CO_2 per year	-0.18 ● 10^6 Mg CO_2 per year

An energy transformation efficiency equal to or greater than about 25 percent results in an allowable average substituted net energy potential that renders the emission of waste incineration plants (calculated as CO_2 equivalents) climate-neutral due to the emission credits from the power plant mix.