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Estimating the externalities of methane emission from municipal solid waste landfill: a case study[1]

Oszacowanie efektów zewnętrznych emisji metanu ze składowiska odpadów komunalnych – case study

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Abstract
The paper presents the estimate of externalities caused by methane emission from exploitation of the municipal solid waste landfill in the years 2002–2009. Methane emission was calculated according to the methodology recommended by the IPCC which is briefly presented in the paper. The following parameters were evaluated: mass of the landfilled wastes, correction coefficient for methane based on the landfill characteristics, content of biodegradable carbon based on waste morphology and mass of recovered methane. Based on these parameters, the amount of methane emitted from the landfill during 2002–2009 was estimated at 3.16 Gg.

Streszczenie
W artykule przedstawiono oszacowanie efektów zewnętrznych powodowanych emisją metanu ze składowiska odpadów komunalnych w latach 2002-2009. Emisja metanu została obliczona zgodnie z metodologią zalecaną przez IPCC, którą również przedstawiono. Na potrzeby obliczeń oszacowano następujące parametry: masa składowanych odpadów, współczynnik korekcyjny dla metanu w oparciu o charakterystykę odpadów, zawartość węgla w związkach organicznych w oparciu o morfologię odpadów, ilość odzyskanego metanu. Ilość metanu wyemitowanego ze składowiska odpadów w latach 2002-2009 oszacowano na 3.16 Gg.

1. INTRODUCTION

Global changes of anthropogenic origin are a vital problem of modern civilisation. One of the factors causing such changes is the emission of greenhouse gases (GHGs) among which landfill gas (LFG) emission from municipal solid waste (MSW) landfills plays a significant role. Emission of LFG into the atmosphere results in external effects (externalities) as it contributes to the greenhouse effect, particularly its methane (CH_4) component and to a lesser degree carbon dioxide (CO_2). This phenomenon is observed on a global scale. LFG is created as the result of anaerobic decay of organic matter within the landfill; its main products are CH_4 and CO_2, as well as other components, e.g. nitrogen, hydrogen sulphide, aldehydes, ammonium and mercaptanes. Favourable conditions for the formation of LFG with high CH_4 content occur in large municipal landfills located in depressions (regardless of the density of the landfilled waste) and in other landfills, in which wastes were compacted by heavy equipment and the landfills were closed down. CH_4 and CO_2 are produced in about an equal amount; however, CH_4 is of greater concern as a GHG: the 100-year global warming potential of CH_4 (i.e., its infrared absorption potential in the atmosphere) is about 21 times greater than that of CO_2 [FCCC/CP/1997/Add.1].
CH_4 emissions from managed landfills accounted for 1.8% of total EU-15 GHG emissions in 2011. Between 1990 and 2011, CH_4 emissions from managed landfills declined by 47% in the EU-15. A main driving force of CH4 emission reduction was the amount of biodegradable waste going to landfills which declined by 53% between 1990 and 2011. In addition, CH_4 emissions from landfills were influenced by the amount of CH_4 recovered and utilised or flared [EEA 2013].
The possible solution for the problem of LFG emission is either extraction and flaring or energy recovery. The recovered energy can displace energy generated from other sources using different fuels (coal, gas) and will thus displace the emissions from that of energy generation. The externalities associated with energy generation will be reduced in proportion to the energy saved by the use of LFG.
In Poland, the number of MSW landfills with LFG installations is steadily growing: from 23% of all active landfills in 2005 to 75% in 2011. Still, the recovery of LFG as an energy source is less common and the number of active landfills with LFG recovery amounted to 38 in 2005 and 69 in 2011 [GUS 2006, GUS 2012]. The primary use of the recovered energy in 2011 was the generation of electricity (13.5% of all landfills with LFG installations, 249 178 MWh produced) and heat (2.6% of all landfills with LFG installations, 73 244 GJ produced).

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2. MATERIAL AND METHODS

2.1. Characteristics of the landfill

The landfill studied is the MSW landfill that belongs to the Regional Waste Treatment Plant in Machnacz. It is located 10 km west of Włocławek, a city in central Poland with a population of 116 000 inhabitants. The plant has a capacity of 30 000 Mg of municipal waste per year. Municipal waste is mechanically treated and the refuse is landfilled. The area of the landfill is 4.9 ha.

The operation of the landfill began in 1986 and was conducted till 1998 when the process of upgrade and enlargement of the landfill began. It included:

- sealing the top of the landfilled wastes with a HDPE (high density polyethylene) geo-membrane,
- construction of a gas collection system under the membrane,
- construction of drainage for leachates above the membrane,
- construction of gas extraction wells above the membrane.

An installation for LFG collection was constructed on the surface of the exploited landfill basin. Next, the landfill was sealed tightly with a synthetic, 2-mm thick HDPE geo-membrane. Two new waste cells were created on this basement, with 2-mm thick HDPE geo-membrane on the bottom, with leachate drainage and independent gas extraction wells. Presently, the landfill is a deep seated-surface type, and the working area comprises of two cells:

- cell I with an area of 1.80 ha and total capacity of 390 936 m^3,
- cell II with an area of 3.10 ha and total capacity of 450 000 m^3.

Upgrade and enlargement of the landfill was finished in 2001. The established Regional Waste Treatment Plant in Machnacz comprised of two basic technological objects, i.e. a waste sorting plant with a drum sieve and a picking table, and composting sheds. Additional buildings included two cells for storing ballast and auxiliary objects indispensible for the functioning of the plant.

Mechanical sorting of the wastes in a two-section sieve sub-divides them into the following fractions:

- fraction 0–20 mm including mineral wastes such as stones and sand used in the landfill as the cover material,
- fraction 20–80 mm including organic wastes which is composted in a composting pile,
- fraction larger than 80 mm which is sorted manually into recycled materials e.g., plastic (foil, PET, detergent bottles), paper, aluminium tins, steel scrap and dangerous wastes.

LFG collection from the installation in the sub-membrane parts of the landfill was activated in 2004. The collection system comprises of gas pipelines, an AC 100 kW electric power generator and a heat recovery block. The produced electricity and heat are utilised entirely by the facility.

Construction of the composting pile for wastes from the drum sieve and the fine mineral fraction began in 2005. The installation for degassing the composting pile was activated in 2006 and the installation for degassing the first cell of the landfill in 2010.

2.2. Quantification of CH_4 emission

Calculation of CH_4 emission from the landfill in Machnacz was based on data from the interval 2002–2009, i.e. the period from the next year after the upgrade and enlargement of the landfill (2001) till the activation of the gas collection and extraction system in the first landfill cell (2010). The emission of CH_4 from the exploited and sealed part of the landfill was excluded from the calculation, as there was no disorganised emission.

The estimate of CH_4 emission from the landfill has been carried out by means of empirical calculation according to the IPCC recommendations [IPCC 2000]. IPCC recommendations on the inventory of GHGs present a method of evaluating CH_4 emissions from landfill sites as the method of first-order decay. The first-order decay method supplies the magnitude of emission depending on time, which reflects the actual course of decay processes in time. The first-order decay (level 1) is expressed by two equivalent equations (1) and (2) presented below:

$$\textbf{CH}_4\textbf{ production in year t (Gg/year)} = \Sigma_x [(A \bullet k \bullet MSW_T(x) \bullet L0(x)) \bullet \exp(-k(t-x))] \quad (1)$$

where:

t – cataloguing year

x – years for which input data are introduced

$A - (1 - e^{-k})/k$ = coefficient correcting the sum

k – reaction constant expressing the speed of methane production, 1/year

$MSW_T(x)$ – total waste mass (MSW) landfilled in year x, Gg/year

$L_0(x) = MCF(x) \bullet DOC(x) \bullet DOC_F \bullet F \bullet 16/12$ – output of methane production, Gg_{CH4}/Gg_{waste}

$MCF(x)$ – methane correction factor for aerobic decomposition in the year of deposition, dimensionless

$DOC(x)$ – degradable organic carbon in the year of deposition, GgC/Ggwaste

DOC_F – fraction of DOC that can decompose, dimensionless

F – volumetric fraction of methane in the landfill gas, dimensionless

$16/12$ – molecular weight ratio CH_4/C, dimensionless.

The results for all years (x) should be summed up.

$$\textbf{CH}_4\textbf{ emission in year t (Gg/year)} = [\textbf{CH}_4\textbf{ production in year t} - R(t)] \bullet (1 - OX) \quad (2)$$

where:

$R(t)$ – amount of recovered methane in year t, Gg/year

OX – oxidation factor of methane in soil and other materials that cover the waste, dimensionless.

In these equations, three factors determine the emission rate – F, MCF and DOC – of which the last two are specific to the landfill. The amount of recovered CH_4, R(t), should be subtracted before introducing the oxidation factor of CH_4, because gas can be oxygenated during transmission through the mineral layer. The LFG productivity is expressed as a weighted unit.

The reaction constant expressing the speed of CH_4 production, k, which is used in the method of first-order decay, refers to the time in which half of the initial amount of carbon in organic compounds is decomposed (half-time or $t_{1/2}$) and is expressed by the following equation:

$$k = \ln 2 / t_{1/2} \quad (3)$$

The method of first-order decay requires historical data on waste production and management. The dataset should contain data from a time span of 3–5 decay half-times. Such dataset ensures the reliability of the calculations. During analysis of data from previous years, all changes in the waste management, such as landfill coverage, application of compactors or interdictions against depositing hazardous waste in municipal landfills should be taken into account.

3. RESULTS AND DISCUSSION

3.1. Production of wastes

Each year, 34 000–37 000 Mg of waste was received at the Regional Waste Treatment Plant in Machnacz. In figure 1, the amount of waste received yearly during 2002–2009 is presented.

During the period for which the calculation was made, a total of 285 712 000 tons of waste were managed at the facility.

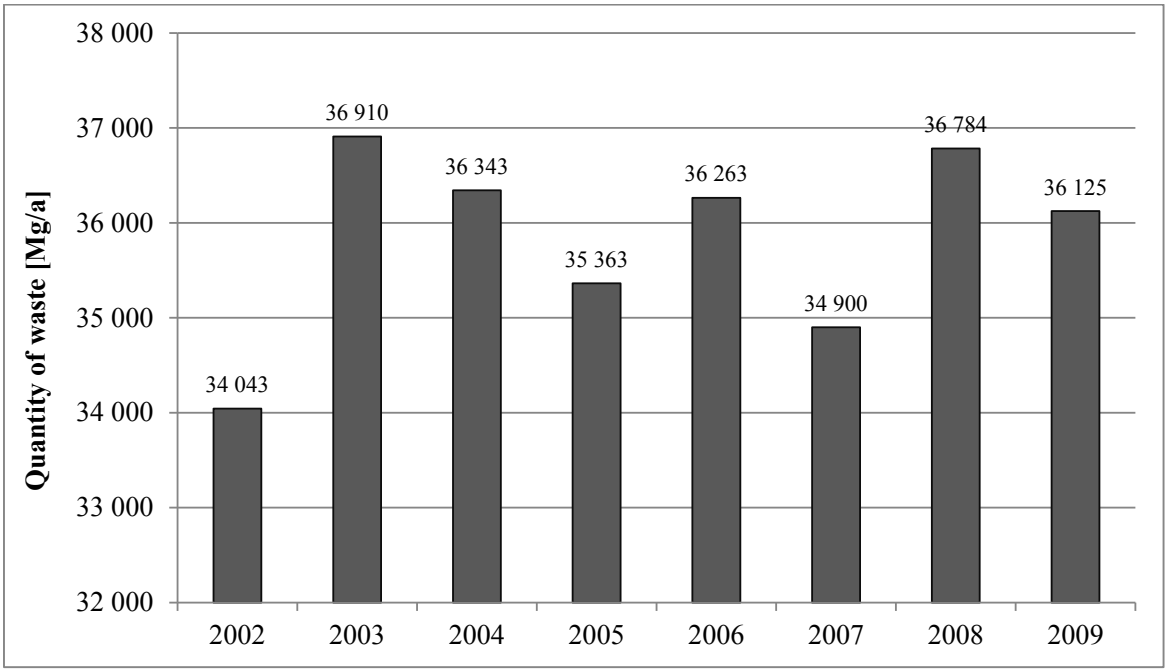

Fig. 1. Quantity of waste received annually at the facility.

3.2. Calculation of CH_4 emission

The effective emission of CH_4 from the landfill during 2002–2009 should be corrected assuming that in years 2007–2009, 65% of the total mass of waste was composted in the compositing pile that was subject to degassing.

x – years for which methane emission was calculated

Calculation of CH_4 emission from the municipal landfill in Machnacz was based on data from the interval between 2002 and 2009.

k – reaction constant expressing the speed of biodegradable organic matter decay (methane production)

The value of the constant applied for particular landfills is determined by indicators based on waste morphology and landfill conditions. Measurements made in the USA, Great Britain and the Netherlands have indicated that the value of this constant varies from 0.03 to 0.2 1/year. The fastest decay (k = 0.2 or the decay half-time of about 3 years) occurs at high humidity and in easily decaying waste such as food waste. The slowest decay (k = 0.03 or the decay half-time of about 23 years) occurs in low humidity conditions and in hardly decomposable wastes such as wood or paper waste.

In Polish conditions, the value of reaction constant is accepted at the level of k = 0.05 which is the value suggested in the IPCC recommendations.

$A = (1 - e^{-k})/k$ – correction coefficient of the summing

A = 0.975

$MSW_T(x)$ – mass of waste landfilled in individual years x

The amount of waste is presented in figure 1.

$\Sigma MSW_T(x)$ – total mass of waste landfilled at the end of year x

The total waste mass landfilled at the end of consecutive years is a cumulative sum from 2002 to 2009 as $\Sigma MSW_T(x)$ [Gg] and is presented in Table 1.

Actual CH_4 emission from the landfill during 2002–2009 should be corrected, taking into account that in the years 2007–2009, part of the wastes comprising 65% of the total landfilled waste was directed to the composting pile, which was next subject to degassing. Table 2 presents the total mass of the landfilled waste (MSW) in consecutive years from 2002 to 2009 after subtracting sorted wastes that were directed to the compositing pile during 2007–2009.

MCF(x) – methane correction factor for aerobic decomposition in the year of deposition

The CH_4 correction factor for CH_4 reflects the fact that non-managed landfills produce less CH_4 from a given amount of waste in comparison with managed landfills because a larger amount of wastes is decomposed in the presence of oxygen in the topmost parts of non-managed landfills. The MCF in relation to the management of solid wastes is specific and should be interpreted as the correlation coefficient taking into account the waste management practices. Table 3 shows IPCC recommendations on the default values of the MCF [IPCC 2006].

Based on the data on the technical conditions of the Machnacz landfill exploitation (regulated landfill, management following relevant recommendations, wastes landfilled with cover material, compressed with a compactor), it was assumed that MCF for the years 2002–2009 is equal to 1.

DOC(x) – degradable organic carbon in the year of deposition

The content of organic carbon present in compounds capable of biochemical decay is expressed in Gg of C per Gg wastes. The content of organic carbon in the waste, DOC, depends on the waste morphology and is calculated as a weighted average carbon content of the different components of the waste.

The equation below shows how to estimate its content (weighted fraction) using default values of its content in particular elements of the wastes [IPCC 2000].

$$\mathbf{DOC = (0.4 \cdot A) + (0.17 \cdot B) + (0.15 \cdot C) + (0.3 \cdot D)} \quad (4)$$

where:

A – waste comprising of paper and textiles

B – waste from parks, gardens and other organic waste excluding food waste

C – food waste

D – waste comprising of wood and straw.

Sub-division into such waste groups is usually not used in waste management programmes and schedules. According to the commonly applied classification, the percentage contribution of

Table 1. Total mass of municipal solid waste landfilled in the Machnacz landfill during 2002–2009

No.	Year [x]	Total waste landfilled at year x [Gg]
1	2002	34.043
2	2003	70.953
3	2004	107.296
4	2005	142.659
5	2006	178.922
6	2007	213.822
7	2008	250.606
8	2009	286.731

particular fractions in the total amount of wastes landfilled in Machnacz is presented in Table 4.

Based on the classification and results presented in Table 4, in Table 5 the most probable composition of wastes according to IPCC terminology is presented.

Based on the IPCC recommendations, the carbon content was calculated in decomposable organic wastes and is equal to 0.1243.

DOCF – fraction of DOC that can decompose

DOCF estimates the contribution of carbon which is definitely biodegradable and is emitted from the landfill. The coefficient reflects the fact that part of the organic carbon is not biodegraded or its decay is very slow. IPCC recommendations [IPCC 2000] suggest a default value of 0.77 for the DOCF coefficient. Accepting this value is necessary due to the lack of relevant literature data.

F – volumetric fraction of methane in the landfill gas

Analysis of the process of decay of organic substances from wastes indicates that in anaerobic conditions the content of CH_4 should reach 65%. The process of waste decomposition in actual landfilling conditions is much more complicated and the composition of the resulting gas differs in time. Generally, the composition of the main gas components depends on their contribution in aerobic and anaerobic decay reactions. The F fraction of the CH_4 content has values between 0.4 and 0.6, also depending on waste morphology. According to IPCC recommendations, the mole fraction in LFG is accepted as 0.5.

R(t) – methane recovery in the individual year t

Between 2002 and 2005, there was no CH_4 recovery from the landfill. Between 2007 and 2009, CH_4 was recovered from the compositing pile. Between 2007 and 2008, about 23 500 Mg of wastes (fraction 20–80 mm) were annually directed for recovery (on the compositing pile), which gives a recovery level of 65% for biodegradable waste. This means that from the beginning of 2007, the emission from the landfill decreased by ca. 65%. After 2010 (activation of the second degassing installation above the membrane), disorganised emission significantly decreased.

In determining the amount of CH_4 emission when the LFG is collected and flared, the fact that it is not possible to collect all of the biogas and that some of it is released into the atmosphere must be taken into account. In the case of passive degassing, the coefficient of the biogas collection equals to 0.25, with the active degassing to 0.5 [Czurejno, Gaj 2005]. In the case of properly designed and built system of biogas collection and extraction, the coefficient could reach 0.7 [Dudek, Rachwalski 1998]. However, the composting pile, where some of the waste amount was directed, was closed and it could be assumed that disorganised emission was negligible.

R (2002–2006) = 0

R (2007–2009) = 0.65 • CH4 emitted during 2007–2009 = 0.41982 Gg

OX – oxidation factor

During diffusion of gas from the deeper parts of the landfill towards the surface, CH_4 passes through layers rich in oxygen closer to the surface and may be oxidised to CO_2. The exothermic process of CH_4 oxidation takes place with the contribution of methanotrophic bacteria. The oxidation processes cause that the mol ratio of CH_4 to CO_2 decrease in the gas migrating beyond the landfill area.

The oxidation coefficient (OX) reflects the content of CH_4 formed in landfills, which is oxygenated according to the presented procedure. Studies show that in regulated landfills, the degree of oxygenation is higher in comparison with non-regulated landfills. For example, the value of the oxygenation coefficient in landfills covered by a thick layer of material may significantly differ from its values in landfills without a cover, where a large contribution of CH_4 may be released through fissures formed due to fracturing. The default value of the oxygenation coefficient according to IPCC recommendations [IPCC 2000] equals zero and this value was used in the calculations.

Table 2. Total mass of municipal solid waste landfilled in the Machnacz landfill during 2002–2009 after subtracting sorted wastes directed to the compositing pile

No.	Year [x]	Total waste landfilled at year x without composted waste [Gg]
1	2002	34.043
2	2003	70.953
3	2004	107.296
4	2005	142.659
5	2006	178.922
6	2007	191.109
7	2008	204.255
8	2009	216.917

Table 3. Landfill classification and methane correction factor (MCF) according to IPCC recommendations

No.	Type of landfill	MCF default values
1	Managed – anaerobic[a]	1.0
2	Managed – semi-aerobic[b]	0.5
3	Unmanaged 3 – deep (>5 m waste) and/or high water table[c]	0.8
4	Unmanaged 4 – shallow (<5 m waste)[d]	0.4
5	Uncategorised SWDS[e]	0.6

[a] *Anaerobic managed solid waste disposal sites: These must have controlled placement of waste (i.e., waste directed to specific deposition areas, a degree of control of scavenging and a degree of control of fires) and will include at least one of the following: (i) cover material; (ii) mechanical compacting; or (iii) levelling of the waste.*
[b] *Semi-aerobic managed solid waste disposal sites: These must have controlled placement of waste and will include all of the following structures for introducing air to waste layer: (i) permeable cover material; (ii) leachate drainage system; (iii) regulating pondage; and (iv) gas ventilation system.*
[c] *Unmanaged solid waste disposal sites – deep and/or with high water table: all SWDS not meeting the criteria of managed SWDS and which have depths of greater than or equal to 5 m and/or high water table at near ground level. Latter situation corresponds to filling inland water, such as pond, river or wetland, by waste.*
[d] *Unmanaged shallow solid waste disposal sites; all SWDS not meeting the criteria of managed SWDS and which have depths of less than 5 m.*
[e] *Uncategorised solid waste disposal sites: Only if countries cannot categorise their SWDS into above four categories of managed and unmanaged SWDS, the MCF for this category can be used.*

L_0 (x) – output of methane emission

L_0 (2002–2009) = MCF(2002–2009) • DOC(2002–2009) • DOC_F • F • 16/12 [Gg_{CH4}/Gg_{wastes}]

L_0 (2002–2009) = 0.06381 [Gg_{CH4}/Gg_{wastes}]

Calculations of the theoretical mass of CH_4 emitted from waste landfilled during 2002–2009 are presented in Table 6.

Total mass of CH_4 generated in the landfill during 2002–2009 amounted to 3.57598 Gg.

The actual emission of CH_4 from the landfill in the years 2002–2009 should be corrected taking into account that in the period 2007–2009, 65% of the total mass of wastes were directed to the compositing pile that was subject to degassing.

The results of the calculations of CH_4 emission from the Machnacz landfill in years 2002–2009 are given in Table 7.

The diversion of part of the waste to the composting pile with biogas collection and recovery has led to decrease of CH_4 emission of 0.41982 Gg.

During the studied interval, 216 000 Mg of wastes were landfilled. The total mass of CH_4 produced from the landfilled wastes amounted to 3.57598 Gg and the calculated productivity was equal to 0.06381 Gg of CH_4 per Gg of waste. This emission is an equivalent of a volume of ca. 5 mln m^3 of CH_4. In a relevant installation, this would result in a capacity of 73 m^3/h.

CH_4 belongs to GHGs whose global warming potential is 21 times greater than that of CO_2 over a time span of 100 years. This means that the negative effects caused by LFG emission from the Machnacz landfill corresponded to the emission of 75.1 Gg of equivalent CO_2. The CO_2 emission resulting from decomposition of organic material derived from biomass sources (e.g., crops, wood) is not included because the carbon is of biogenic origin.

In the years 2007–2009, CH_4 was recovered from the compositing pile, which gathered about 65% of the wastes received at the facility. This means that during this period, ca. 0.42 Gg of CH_4 was recovered and utilised and the CH_4 release to the atmosphere was reduced to 3.15616 Gg. The negative effects caused by LFG emission were reduced to 67.4 Gg of CO_2 (66.3 Gg of equivalent CO_2 and 1.1 Gg of CO_2 from burning of LFG).

The energy from recovered and utilised LFG (containing ca. 0.42 Gg of CH_4) replaced the energy from other sources. The calorific value of LFG depends on the CH_4 content. On average, the calorific value of LFG is estimated as 22 MJ/m^3 (30.8 MJ/kg) which is lower than the calorific value of natural gas (min. 32 MJ/m^3) [Dudek, Rachwalski 1998]. The theoretical total calorific value of the LFG produced during 2002–2009 in Machnacz landfill reached ca. 110 000 GJ. The theoretical calorific value of the LFG recovered and utilised during 2007–2009 reached ca. 12 900 GJ. It corresponds to the energy obtained from burning of ca. 0.6 Gg of coal with a mean heating value of 21.75 GJ/Mg [KOBIZE 2011].

In terms of CO_2 emission, utilisation of LFG during the period 2007–2009 resulted in CO_2 emission of ca. 0.7 Gg whereas the emission from burning the coal would be ca. 1.2 Gg [KOBIZE 2011]. The avoided emission of CO_2 could be assessed as 0.5 Gg.

4. CONCLUSIONS

During exploitation of the MSW landfill in Machnacz in the period 2002–2009, disorganised emission of CH_4 to the atmosphere amounted to 3.58 Gg. It corresponded to total emission of 75.1 Gg of CO_2 eq. The recovery of LFG during 2007–2009 reduced the emission of CH_4 to 3.16 Gg. The energy from recovered and utilised LFG corresponds to the energy obtained from burning of ca. 0.6 Gg of coal with a mean heating value of 21.75 GJ/Mg. The avoided emission of CO_2 resulting from recovery and utilisation of LFG could be assessed as 0.5 Gg.

Table 4. Percentage contribution of particular fractions of biodegradable wastes in the total amount of the landfilled wastes

No.	Waste source	Contribution of particular wastes [weighted %]
1	Organic waste of plant origin	19.9
2	Organic waste of animal origin	1.1
3	Other organic wastes	1.1
4	Garden wastes[1]	1.9
5	Paper and board (non-packaging)	8.4
6	Paper and board (packaging)	11.0
7	Multimaterial packaging	1.1
8	Textiles	3.0

[1] *Contribution without wastes recycled in a separate composting device and picking, table no. 2*

Table 5. Percentage contribution of particular fractions of biodegradable waste in the total amount of the landfilled waste according to IPCC terminology

No.	Waste category according to IPCC	Source of municipal waste	Content in weighted %
1	A – paper and textiles	Paper and board (non-packaging) Paper and board (packaging) Textiles	8.4 11.0 3.0
2	B – garden waste from parks and other decomposable non-food organic wastes	Garden wastes	1.9
3	C – food wastes	Decomposable kitchen wastes	19.9 + 1.1 = 21.0
4	D – wood, straw		0

Table 6. Theoretical production of methane from landfill during 2002–2009

No.	End of year	Theoretical production of methane [Gg/year]
1	2002	0.10591
2	2003	0.21558
3	2004	0.31812
4	2005	0.41262
5	2006	0.50528
6	2007	0.58919
7	2008	0.67492
8	2009	0.75436
	Total:	**3.57598**

Table 7. Emission of methane from the Machnacz landfill during 2002–2009

No.	End of year	Mass of emitted methane in particular years [Gg/year]
1	2002	0.10591
2	2003	0.21558
3	2004	0.31812
4	2005	0.41262
5	2006	0.50528
6	2007	0.51862
7	2008	0.53336
8	2009	0.54667
	Total:	**3.15616**

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