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The Added Value of the Balance Method for Waste-to-Energy Operators and National Authorities

Therese Schwarzböck, Helmut Rechberger and Johann Fellner

Different directives of the European Union may require operators of Waste to Energy WTE plants to monitor the composition of their waste feed with respect to the content of biomass and fossil organic matter. The mass fractions of both materials are not only of relevance for the amount of fossil and thus climate relevant CO_2 emissions of the plant, but also for the ratio of renewable energy generated, as biomass in wastes is considered as renewable energy source [3, 4].

In recent years different methods, including manual sorting [15, 20], selective dissolution [2, 20], the radiocarbon method [12] and the Balance Method [6] have been developed to determine the biomass content of waste, and thus the fraction of renewable energy and fossil CO_2 emissions produced by WTE plants. Until now all of these methods have been applied to different WTE plants [7, 10, 12, 14] and different wastes [5, 11, 16] aiming at, on the one hand, the determination of characteristic values for the biomass content and fossil CO_2 emissions and on the other hand, at a comparison of the different analysis methods. With respect to the latter, results of the different studies indicate that methods requiring waste feed sampling – e.g. sorting analysis or selective dissolution method – are much more vulnerable to waste heterogeneity and temporal changes in waste composition as quantities of manageable waste samples (at maximum a few tons) are very small in comparison to the total amount thermally utilized.

The Balance Method as well as the radiocarbon method largely avoid problems associated with waste heterogeneity as the measurements or sampling take place in the highly homogeneous flue gas. Compared to the other methods, these two methods have additionally been proven to be practical for a continuous monitoring of the biomass content in the feed of WTE plants which provides the possibility to investigate temporal differences with a high resolution [14, 7, 13]. A further advantage of the Balance Method is the fact that it is based on routinely recorded operating data of WTE plants which usually avoids the need for additional sampling and measurement efforts. During the last years the concept of the Balance Method has been implemented in the software BIOMA (http://iwr.tuwien.ac.at/ressourcen/downloads/bioma.html), which enables a user-friendly application of the Balance Method.

In a recent research study [17] the BIOMA software has successfully been applied to 10 Austrian WTE plants to determine their fossil CO_2 emissions and also the ratio of energy from renewable sources. Despite the fact that the overall budget of the project was below 100 kEUR (and thus smaller than 10 kEUR per plant), it was possible to assess the waste composition of 10 plants with high accuracy – uncertainty below 5 percent relative – and to evaluate the overall climate impact of Austria´s waste incineration plants. The results of the study are given in detail in Schwarzböck et al. [17, 18].

Besides the evaluation of the waste feed composition and the therewith associated CO_2 emissions and energy production of the plants, the application of the software provided further benefits for the operators of the WTE plants and also for authorities. The aim of the present paper is to summarize the major outcomes of the study including the added values of the Balance Method. Therefore results and experiences gained throughout the application to the 10 Austrian WTE plants are described and evaluated.

1. Materials and methods

1.1. Balance Method

The Balance Method, applied in the present study, combines data on the elemental composition of moisture- and ash-free (maaf) biogenic and fossil organic matter with routinely measured operating data of the WTE plant in order to determine the composition of the waste feed. In principle the method utilizes one energy balance and five mass balances, whereby each balance describes a certain waste characteristic – e.g. content of organic carbon, lower calorific value, ash content. Each balance equation contains a theoretically derived term (left side of equations) that has to be attuned to measured data of the incineration plant (right side of equations). A simplified structure of the set of equations is illustrated in Figure 1. A detailed mathematical description of each equation is provided by Fellner et al. [6].

For setting up the 6 balance equations (Figure 1), the waste mass is virtually divided into four *material groups*: inert (m_I), biogenic and fossil organic materials (m_B, m_F) and water (m_W). Inert materials include all incombustible solid residues like glass, stones, ashes or other inorganic matter from biowaste and plastics – e.g. kaolin in paper or inorganic additives in plastics. Biogenic and fossil organic material groups refer only to the maaf organic matter (Figure 2). As the qualitative composition of organic materials in mixed wastes is usually well known – e.g. biogenic matter encompasses paper, wood, kitchen waste, etc. and fossil organic matter includes polymers, such as PP, PE, PET, PVC, etc. – the content of C, H, O, N, S and Cl of the maaf biogenic and fossil organic materials (m_B and m_F) can be derived.

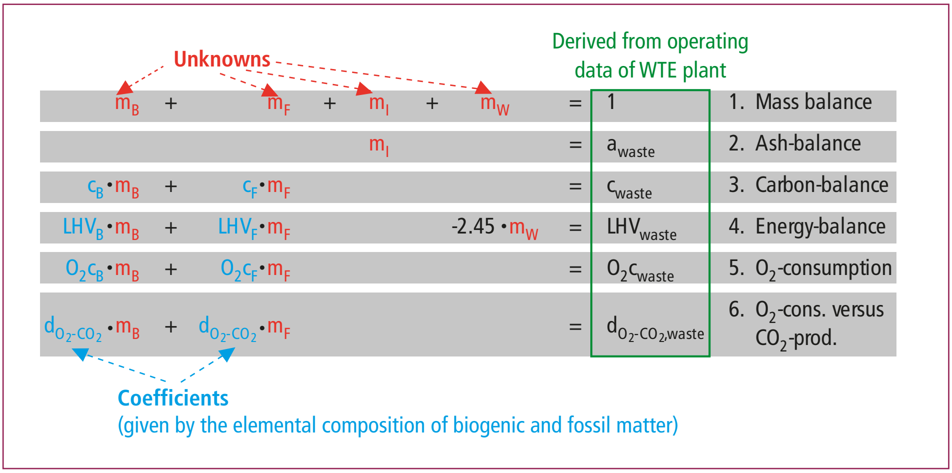


Figure 1: Set of equations (simplified) used by the Balance Method; the left side of the equations represent the theoretical balance (utilizing information on the elemental composition of maaf biogenic and fossil organic matter) that has to be attuned to the different waste characteristics derived from operation data of the WTE plant (right side of the equations)

based on Schwarzböck, T.; Van Eygen, E.; Rechberger, H.; Fellner, J.: Determining the amount of waste plastics in the feed of Austrian Waste to Energy facilities. Waste Management & Research (accepted for publication). 2016

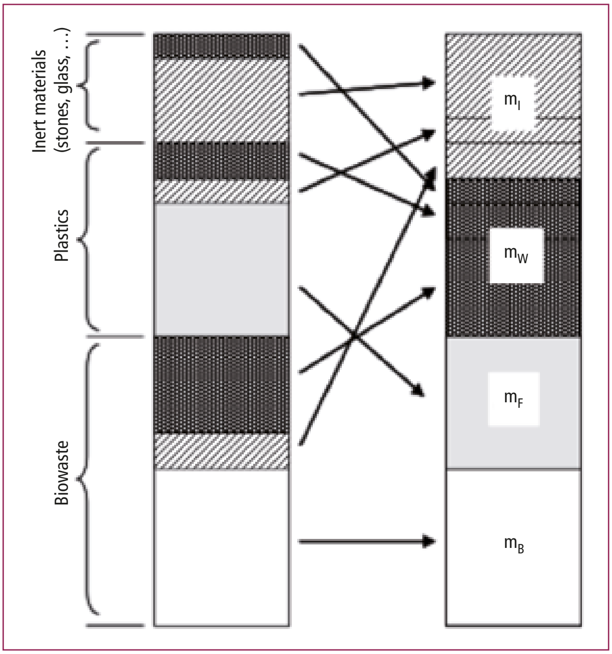


Figure 2:

Split-up of waste fractions into the four *material groups* (m_B, m_F, m_W, and m_I), which represent the unknowns in the set of 6 equations

based on Fellner, J.; Cencic, O.; Rechberger, H.: A new method to determine the ratio of electricity production from fossil and biogenic sources in waste-to-energy plants. Environ Sci Technol 41, 2007, pp. 2579-2586

The input data required for the Balance Method comprise information on the elemental composition of maaf biogenic and fossil organic matter present in the waste feed, information on the quantity of fuels incinerated (waste mass and auxiliary fuels), the amount of solid residues and steam produced, as well as data on the volume and composition (O_2 and CO_2 content) of the dry flue gas. A graphical overview of the required input data is provided in Figure 3.

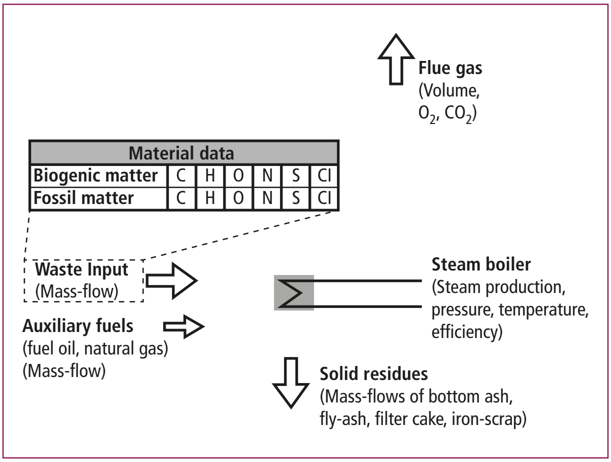


Figure 3:

Required input data for the Balance Method

based on Schwarzböck, T.; Van Eygen, E.; Rechberger, H.; Fellner, J.: Determining the amount of waste plastics in the feed of Austrian Waste to Energy facilities. Waste Management & Research (accepted for publication). 2016

Because the system of equations (set of constraints) used is over-determined (6 equations for 4 unknowns), data reconciliation has to be performed to eliminate data contradiction and to improve the accuracy of the results. The reconciled values are subsequently used to compute the unknown quantities (m_B, m_F, m_W, and m_I) including their uncertainties.

Prior to solving the set of equations for calculating the unknown mass fractions (m_F, m_B, m_W, and m_I) the input data (operating data of the WTE plant) are checked regarding their plausibility. Thereto, correlations between the flue gas and its composition and the steam production are used – e.g., during the combustion of organic matter the consumption of 1 mole O_2 corresponds to an energy generation of 360 to 400 kJ; and the combustion of 1 g organic carbon produces a heat amount of 34 up to a maximum of 44 kJ. The calculations according to the Balance Method (solving the set of 6 equations) are only performed with plausible data, whereby the temporal resolution of the data used is preferably in the range of hourly averages for most input data.

1.2. Austrian Waste-to-Energy plants investigated

The feed of 10 Austrian WTE plants, which represents 91 percent of the waste incinerated in Austria in 2014, has been investigated with respect to the composition of the waste feed, the climate relevant CO_2 emissions and the ratio of energy generated by renewable sources. Three facilities could not be included in the study as they did not provide all operating data required for the Balance Method or were under reconstruction in the respective time period.

In Table 1 and Figure 4 an overview of the 10 Austrian waste incineration plants investigated is given. The annual capacity of these plants amounts to about 2.3 million tons of waste [1], whereby different types of combustion technologies (grate incineration GI or fluidized bed combustion FBC) are utilized. The plants mainly combust municipal solid waste, commercial and industrial waste, sewage sludge and refuse derived fuels (Table 1), whereby the share of the different wastes may vary significantly during the investigated time period of one year.

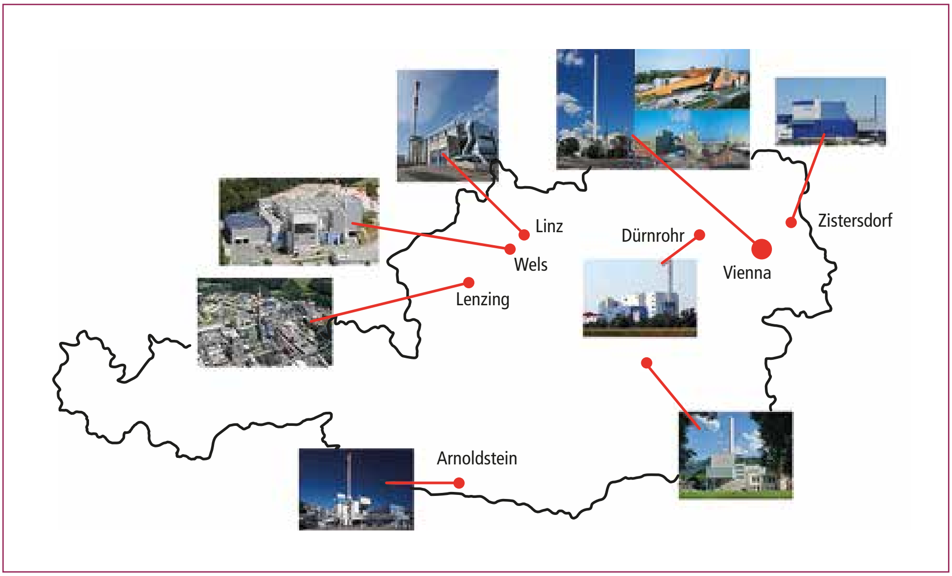


Figure 4: Location of Austrian Waste-to-Energy plants investigated

Table 1: Summary of the WTE plants including information about the combustion technology utilized and the type of waste incinerated

WTE plant	Combustion technology	Waste combusted
A	Grate incinerator (GI)	MSW
B	Grate incinerator (GI)	MSW and CW and IW
C	Fluidized bed combustion (FBC)	RDF and SS
D	Fluidized bed combustion (FBC)	RDF and SS
E	Fluidized bed combustion (FBC)	RDF and SS
F	Grate incinerator (GI)	CW and IW and minor amounts of MSW
G	Stationary fluidized bed combustion (FBC)	RDF and minor amounts of SS
H	Grate incinerator (GI)	MSW, CW and IW & minor amounts of SS
I	Grate incinerator (GI)	MSW
J	Grate incinerator (GI)	MSW, CW and IW & minor amounts of SS

MSW = Municipal solid waste, CW and IW = commercial and industrial waste, SS = sewage sludge, RDF = refuse derived fuels

based on Schwarzböck, T.; Van Eygen, E.; Rechberger, H.; Fellner, J.: Determining the amount of waste plastics in the feed of Austrian Waste to Energy facilities. Waste Management & Research (accepted for publication). 2016

2. Results

In the subsequent chapters various results obtained by the application of the Balance Method to different Austrian WTE plants are summarized and highlighted.

2.1. Detection of errors in the plant operating data recorded

Prior utilizing the operating data of the WTE plants for determining the waste feed composition plausibility checks are conducted. Thereto hourly values of the operating data are aggregated to 6-hour averages (in order to account for the fact that there is obviously a temporal difference between certain input and output flows of the facility – Figure 3), which are subsequently tested for their correlation between oxygen consumption, carbon content and lower calorific value of the waste.

Results of the plausibility tests are exemplary given for the operating data of plant F (Figure 5). From the relations in Figure 5 it can be seen that a large share of the data points displayed are outside the theoretically plausible band. Based on the fact that for both figures (O_2 vs. calorific value and C-content vs. calorific value) a similar pattern for the data points outlying the theoretical band is observable, it can be concluded that the flue gas volume measurements at plant F are implausibly high and very likely defective. Furthermore the results of the plausibility check even allow valuing that the measured flue gas volume is about 20 percent above the plausible level.

By conducting control measurements at the respective plant, the error in flue gas volume detected via the Balance Method could be proven and could subsequently be corrected. The observed implausible data sets could be attributed to a significant amount of leak air entering the plant between the measuring points for the flue gas volume and for the O_2 and CO_2 content of the flue gas.

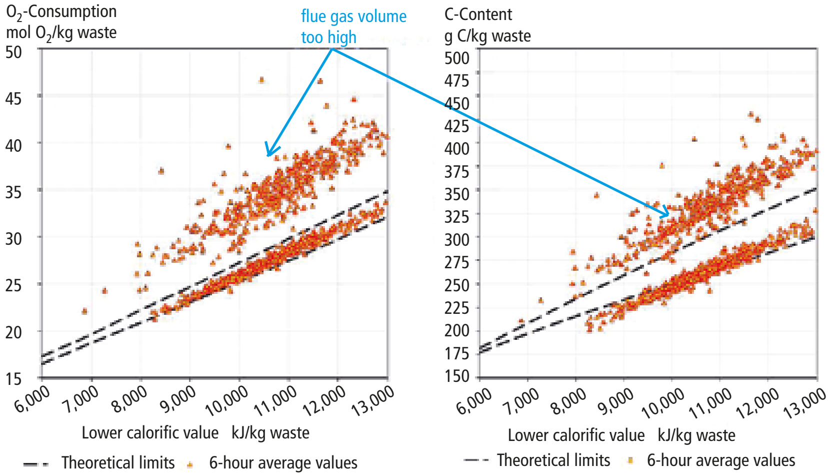
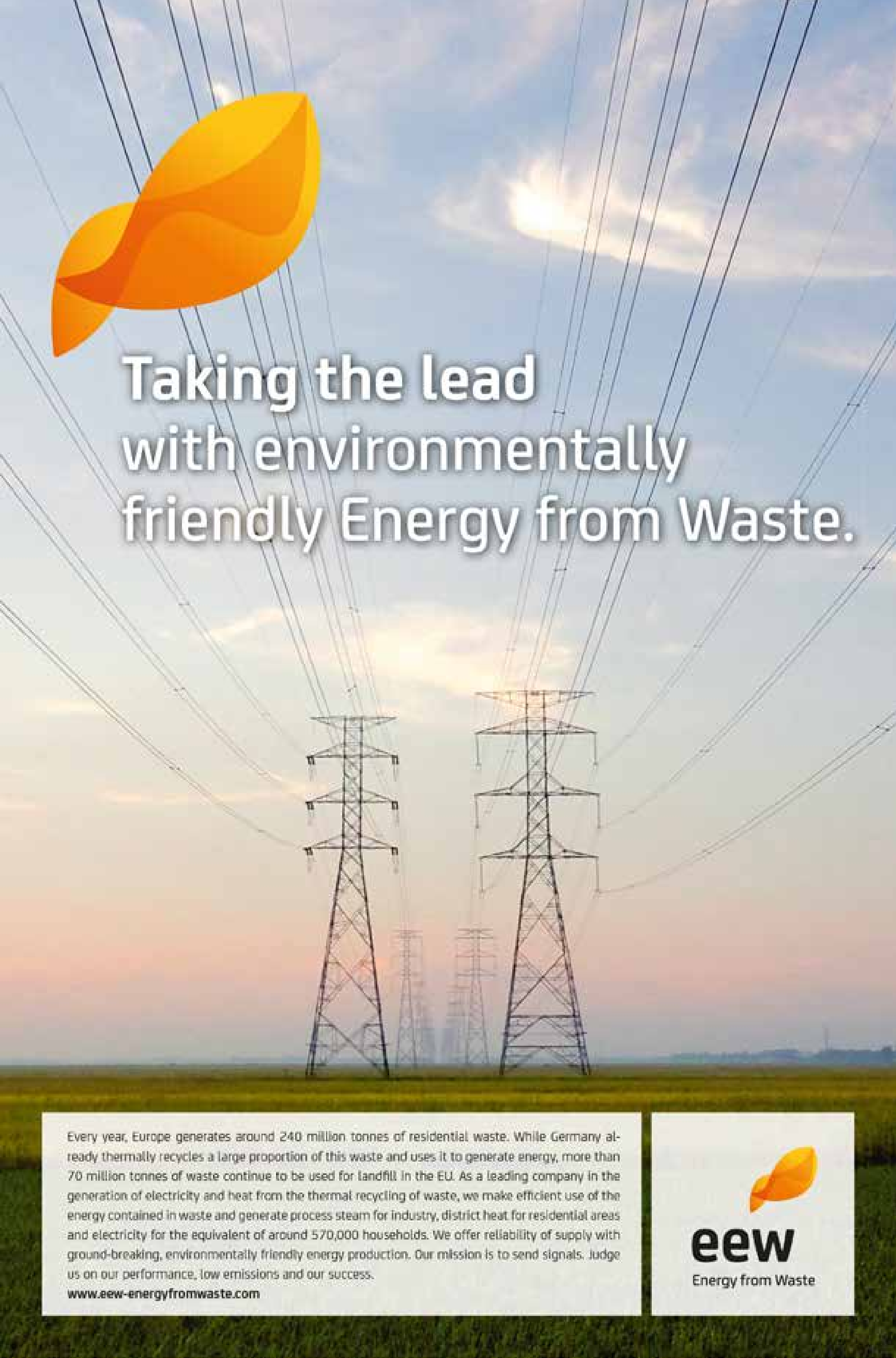


Figure 5: Results of plausibility checks (correlation between lower calorific value and O_2 consumption and carbon content of the waste, respectively) for the operating data of WTE plant F (data points represent 6-hourly averages)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Besides *wrong* flue gas volume measurements, also data transfer errors and conversion errors – e.g., related to 11 percent O_2 or dry vs. wet flue gas – have been identified at different plants and could subsequently be corrected.

After obtaining different additional information from the plant operators on e.g. the calibration practices, the combustion process or experiences with measurement devices, the plausibility tests finally showed that all plant operators (with the exception of two) were able to provide operating data with a plausibility of more than 95 percent, meaning that more than 95 percent of the 6-hourly averages were assessed as plausible and thus utilized for the analyses according to the Balance Method.

2.2. Climate relevant (fossil) CO_2 emissions from Austrian WTE plants

All plausible operating data of the WTE plants were used for the analysis according to the Balance Method. By inserting the calculated composition of the waste feed (content of m_B, m_F, m_I and m_W) into the carbon balance, it was possible to determine the content of fossil carbon and thereon based the amount of fossil CO_2 emissions for any time period of interest.

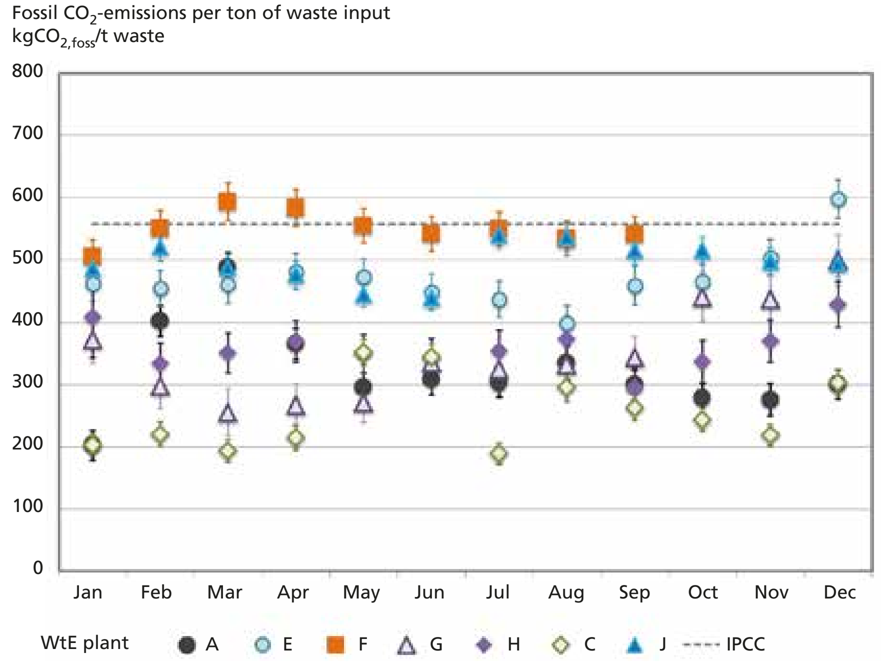

Figure 6: Monthly averages (incl. standard deviation) of specific fossil CO_2 emissions (given in kg CO_2 per ton of waste) for 7 Austrian WTE plants in comparison to the default value recommended

by IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories - Chapter 5 -Waste http://www.ipcc-nggip.iges.or.jp/public/gp/english/, p. 32

In Figure 6 the specific fossil CO_2 emissions (given as monthly averages in kg CO_2 per ton waste) of different plants are summarized. The results clearly indicate large temporal variations in the waste composition and thus also in CO_2 emissions. Furthermore, significant differences in the waste feed of the plants are observable, resulting in specific CO_2 emissions ranging from 200 (plant C) to almost 600 kg $CO_{2,\,foss}$/t waste (plant F). These significant differences further indicate that the usage of generic emission factors – e.g., 557 kg$CO_{2,foss}$/t waste as default given by the IPCC [8] – may result in considerable overestimations (or in some cases also underestimations) of fossil CO_2 emissions. Thus, a plant-specific and continuous evaluation of the waste composition is considered mandatory as it constitutes the only reliable means for quantifying fossil CO_2 emissions. These emissions are of particular interest for WTE plants already participating in greenhouse gas emissions trading schemes but also for authorities reporting overall national greenhouse gas emissions.

2.3. Ratio of energy from biogenic (renewable) sources

Besides the fossil CO_2 emission also the ratio of energy from biogenic sources have been determined by the software BIOMA. Thereto the energy balance has been utilized in conjunction with the outcomes of the waste composition (m_B, m_F, m_W, and m_I). The results of these calculations are summarized in Figure 7, which displays the annual averages for the ratio of energy produced out of biogenic sources in different plants. This information is of particular interested for incineration plants producing electricity, as they are on the one hand obligated to label the electricity put on the market (quantifying the energy carriers used for electricity generation) and on the other hand they may acquire a higher feed-in tariff – e.g. green electricity certificate – for electricity produced out of biogenic and thus renewable sources.

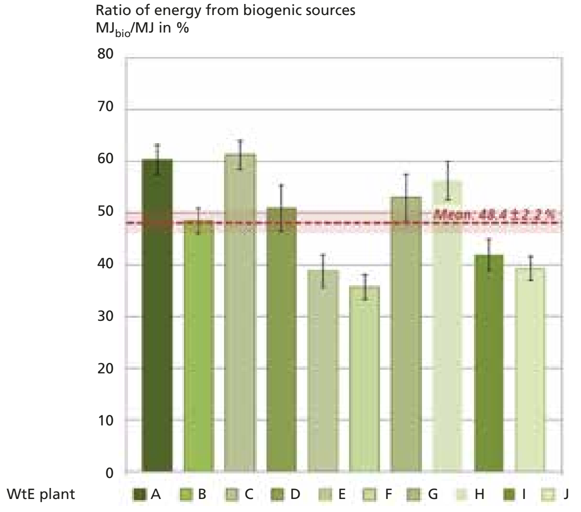

Figure 7:

Annual averages (incl. standard deviation) and weighted means for the ratio of energy produced out of biogenic sources (given in MJ of energy produced out of biogenic sources referred to MJ of total energy generated) for the 10 Austrian WTE plants investigated

In analogy to the specific CO_2 emissions also for the ratio of energy produced out of biogenic sources large difference between the plants can be observed. Plant C shows the highest ratio of renewable energy (61 percent), whereas plant F is characterized by the lowest share of renewables (36 percent). This might be explained by the fact that plant F almost exclusively utilizes commercial and industrial waste.

2.4. Content of plastics in the feed of Austrian WTE plants

In addition to the determination of fossil CO_2 emissions and the energy carriers utilized, which are both of interest for the plant operators, the Balance Method also allows assessing the amount/content of plastics in the waste feed. Thereto results about the mass fraction of fossil matter m_F in the feed have to be combined with data about the average content of inorganic plastics additives.

Information about the plastics content in the feed of waste incineration plants might be of interest for waste authorities for different reasons: First of all, these data allow evaluating the performance of different waste plastics collection schemes in place by simply comparing the amount of plastics separately and not separately collected. Secondly, continuous information about the plastics amount in the feed of WTE plants enables to analyse the trend of waste plastics generation. And thirdly, the overall potential for plastics recycling becomes evident.

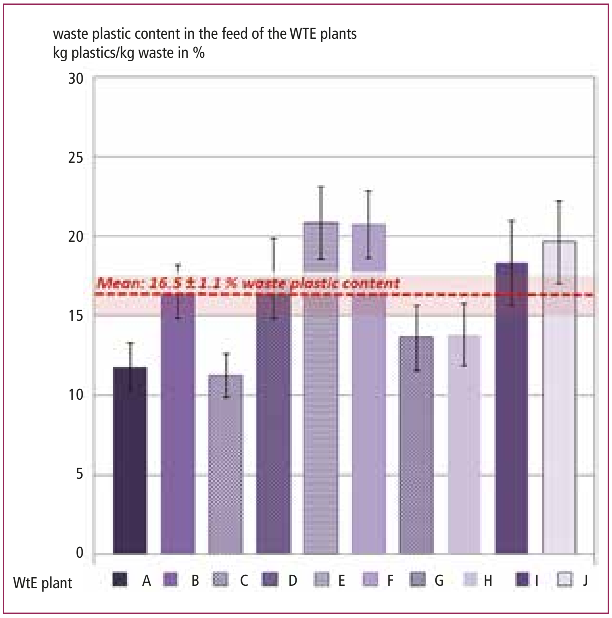

Figure 8:

Annual averages (incl. standard deviation) and overall annual mean of the plastics content in the feed of 10 Austrian WTE plants investigated (figures given in kg plastics per kg waste)

based on Schwarzböck, T.; Van Eygen, E.; Rechberger, H.; Fellner, J.: Determining the amount of waste plastics in the feed of Austrian Waste to Energy facilities. Waste Management & Research (accepted for publication). 2016

From the results presented in Figure 8 it can be concluded that also the content of plastics in the waste feed of the different plants varies significantly. The average plastics content of the waste thermally utilized in Austria in 2014 was determined to 16.5 percent (per weight) and is thus significantly higher than results obtained via waste sorting campaigns – e.g. 12.3 percent found by IUT&SDAG [9] or 9.7 percent given in [1]. This discrepancy can be explained by the fact that sorting analyses always generate sorting fractions – e.g. composite materials, hygienic products, textiles – that contain both plastics and biogenic matter, whereby the plastics content of these fractions is difficult to assess and hence usually not considered in the final results about the plastics content in waste. Thus, the herein applied Balance Method represents the only practical approach that allows assessing the *total* content of plastics in wastes.

2.5. Mixing of the waste feed and its impact on steam production and auxiliary fuel consumption

In addition to information about the plausibility of the plant operating data, the amount of fossil CO_2 emission generated, the ratio of energy from renewable sources, or the plastics content in the waste feed, the Balance Method also allows assessing the performance of the waste crane operator with respect to the mixing of the waste (in the receiving bunker) prior its feeding into the shut of the incinerator.

In Figure 9 the results of such analysis are summarized. In particular the steam production (tons/hour), the consumption of auxiliary fuel oil (tons/hour) as well as the water content of the waste feed (%-mass) and the ratio between fossil matter and biogenic matter m_F/m_B are displayed for an exemplary period of 12 days for plant B. The data are given as hourly averages. The first two parameters are obtained from the operating data of the plant, whereas the latter two have been determined via the software BIOMA. The temporal trend of the 4 parameters clearly indicates that within the time period 30/05/2014 until 01/06/2014 the plant yields the most constant and thus also the highest rate of steam production. During these 2 days the water content and also the ratio of fossil and biogenic matter in the waste feed show comparatively small variations, indicating a well mixing of the waste prior its combustion. In contrary, the time periods before 30/05 and also after 01/06 are characterized by significant changes in waste composition. This variation in waste composition is most probably a consequence of insufficient mixing of the waste received, which would per se not be a problem. However, as it can be seen in Figure 9, insufficient mixing of the waste goes along with strongly varying and thus reduced steam (energy) production of the plant. Furthermore, the consumption of auxiliary fuels is increased during these times of variable waste composition.

In Table 2 the average values for the period of well and insufficient waste mixing are summarized. Thereby it becomes obvious that despite the fact that the average water content of the waste feed was higher in times of well waste mixing (35.5 vs. 32.7 percent), the steam production was significantly higher during this time (52.0 vs. 49.6 t/h). Besides an increased steam production also a lower consumption rate of fuel oil is observable (1.8 vs. 40 kg/h). The average ratio of fossil matter and biogenic matter in the waste feed appears to be the same for both presented periods in Table 2. This indicates that the evaluation based on hourly mean values provides much more valuable information on the actual process conditions than for example daily values.

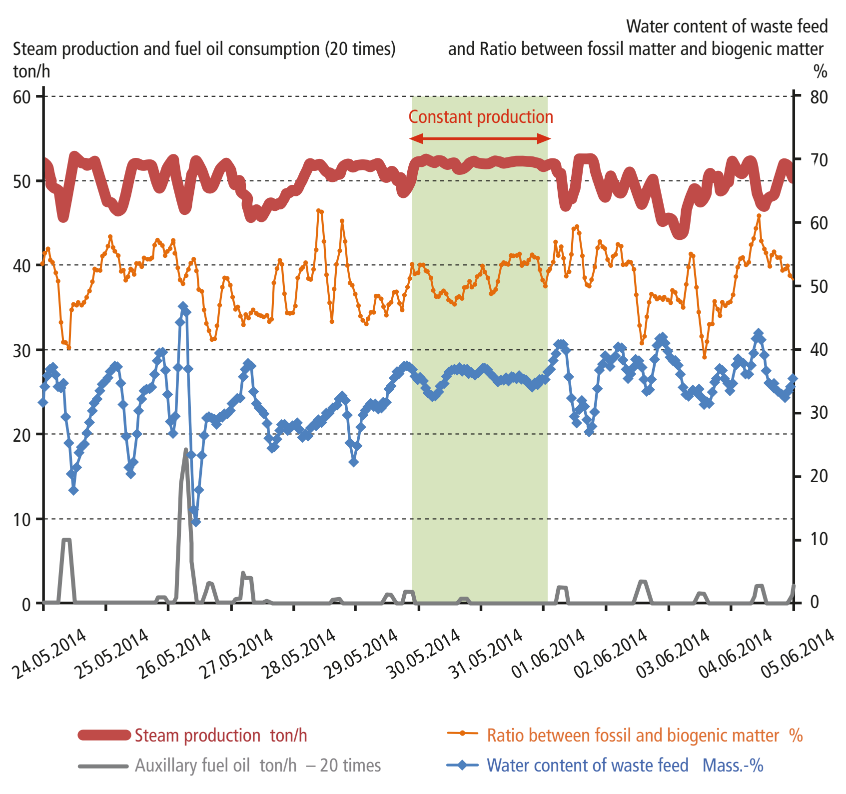

Figure 9: Hourly averages for steam production, fuel oil consumption, water content and ratio between fossil and biogenic matter m_F/m_B in the waste feed of plant B for a period of 12 days

The higher steam production and the lower fuel oil consumption can also be expressed in economic terms. Considering the enthalpy difference of feed water and the steam and assuming an electrical efficiency of 30 percent for converting steam into electricity, the electricity generation rate amounts to 0.21 MWh_{elec}/t steam. The average market price for electricity is about 35 EUR/MWh in 2014. So the financial losses due to insufficient waste mixing for plant B amounts to almost 18 EUR/h or more than 4,000 EUR for the considered period of 10 days. In addition also costs for increased fuel oil (market price of approximately 500 EUR/t heavy fuel oil in 2014) consumption of 38 kg/h and the thereby induced reduction of waste throughput – the combustion of 1 ton fuel oil reduces the waste throughput by almost 4 tons – need to be accounted for, whereby a gate fee for the waste of 90 EUR/tons is assumed. Based on these figures the increased fuel oil consumption during times of insufficient waste mixing causes energy costs of about 20 EUR/h and reduces the waste throughput by 0.15 t/h, which lowers the income via gate fees by almost 14 EUR/h. For the time period of almost 10 day the overall income losses and additional costs induced by increased fuel oil consumption can be expected to amount to more than 7,600 EUR.

Hence, all in all the economic losses caused by insufficient waste mixing (over the considered period of 10 days) can be estimated to almost 12,000 EUR.

The utilization of the software BIOMA at the WTE plant could provide a possibility to control the mixing of the waste in the receiving bunker. Insufficient mixing could immediately be detected and avoided/corrected by monitoring parameters like the ratio between fossil and biogenic matter or the water content. Furthermore, the performance of the personal operating the waste crane could be evaluated and benchmarked.

The overall annual economic benefits of a controlled and improved waste mixing prior combustion are estimated to a few hundred thousand Euros per plant.

Table 2: Averages for steam production, fuel oil consumption, water content and ratio between fossil and biogenic matter in the waste feed of plant B during times of well and insufficient waste mixing

Averages for	Steam production	Auxiliary fuel oil consumption	Water content of waste feed	Content of fossil matter vs. content of biogenic matter
	t/h	kg/h	kg H_2O/kg waste	m_F/m_B
Period of insufficient waste mixing (9.7 days)	49.6	40	0.327	0.51
Period of well waste mixing (2.3 days)	52.0	1.8	0.355	0.51

3. Conclusions

The results presented demonstrate the various potentials and benefits of the Balance Method in general and the BIOMA software in particular. Information of direct interest for the operators of WTE plants can be derived: plausibility checks of operating data, ratio of energy from biogenic sources, or control of waste mixing in the receiving bunker. Additionally, general information which is relevant for waste authorities can be generated at comparatively low costs: e.g., the amount of plastics in the waste feed or fossil CO_2 emissions. Finally it was demonstrated that the economic benefits generated by the application of the Balance Method outpaces by far the costs of its application, which are in the range of about EUR 10,000 per plant and year.

Acknowledgements

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