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Allocation Analysis of Waste Treatment Nodes for Economic Optimisation Considering Reduced Greenhouse Gas Emissions

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The paper has analysing factors having a significant impact on greenhouse gas emissions (GHG) in the handling and processing residual waste. A present trend has been updating and modernising the waste treatment infrastructure. The proposed system has been following the waste management (WM) hierarchy. A software tool NERUDA was developed for the allocation design of newly built waste processing capacities. NERUDA serves as an optimiser of waste treatment strategy in a specific region from a waste producer point of view. The present version of NERUDA focuses on the economic aspects only. Besides the economic also the environmental aspects play an important role. For the environmental assessment of waste management processes, the GHG emissions are one of the most common and discussed environmental impact indicator. A global warming potential (GWP) is used as a unit to measure and standardise the GHG emissions. The next step in the development of NERUDA is the implementation of GWP parameter as environmental criteria. This paper results are a summary and an analysis of important factors, which have a significant effect on GHG emissions in WM. Waste to energy (WTE), landfilling and mechanical-biological treatment (MBT) are disposal processes considered in this analysis. The main factors for each of these waste treatment processes are analysed. The emphasis has been on WTE plants and consequences to allocation planning considering reduced GHG emissions. The main parameters that influence GHG emissions from a WTE are analysed and influence of waste input and heat utilisation strategy is quantified. GHG emissions of landfilling are mainly affected by the collected and diffused landfill gas. The MBT is characterised by the refuse derived fuel (RDF) utilisation (incineration and heat and power production). Transportation is also taken into account. These issues have been formulated and proposed for the implementation of an extended objective function of NERUDA tool. In conclusions, the availability of the necessary inputs for the calculation is discussed.

1. Introduction

Most Central and Eastern European countries have been undergoing changes in the waste management (WM). The goal of modernization is to reorganise the WM to the fashion according to waste hierarchy, as stated in EC (2008). Environmental questions are more and more frequent in the modern world. This has been influencing progress in the sector of WM. E.g. Rigamonti et al. (2016) presented a composite indicator for the assessment of the environmental and economic sustainability of integrated MSW management systems. Tascione et al. (2016) analysed the environmental impact of waste management based on LCA. An interesting assessment of economics versus carbon emissions footprint for waste to energy projects substituting fossil fuels in small cities was presented by Ng et al. (2013). A system used for planning of modern WM is a computational tool NERUDA presented by Šomplák et al. (2014). The NERUDA tool has been developed for the purpose of the optimisation of WM strategy in selected region from the waste producer point of view. It integrates WTE facilities within

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energy concepts of cities and analyses various waste treatment technologies (WTE plants, mechanical-biological treatment plants with subsequent RDF utilisation). Then it looks for the optimal solution for the question where to treat the waste. NERUDA so far focused only on the economic aspects - the cheapest solution was proposed not putting the prize for environmental issues. Residual waste has been the most discussed and consequently processes related to residual waste treatment are focused on by this work. The result of the analysis will be addressed to extend NERUDA. Various techniques are used for the assessment of environmental impact. Arushanyan et al. (2017) considered 18 different impact indicators for the environmental assessment of waste management scenarios. Čuček et al. (2012) presented an overview of footprints as defined indicators. The GHG emissions are one of the most common and discussed environmental impact indicators. The global warming potential (GWP) (Stocker et al., 2013) is a relative measure, that allows comparisons of the global warming impacts of different gases. The GWP is standardised by using carbon dioxide as a base unit (GWP of CO_2 = 1). Specifically, it measures the amount of heat trapped by the emissions of 1 t of a gas over a given period of time, relative to the emissions of 1 t of CO_2. The time periods used for GWPs are 20, 100 and 500 years. In this paper, the values from the 100 y time horizon will be used. The three main gases in the field of waste management and their GWP values are GWP_{CO2} = 1, GWP_{CH4} = 28 and GWP_{N2O} = 265 as it is stated in (Stocker et al., 2013). On the basis of these values the GWP, measured in kg of CO_2 equivalents, is calculated for residual waste disposal processes in the next sections of this paper. The GWP parameter was selected by the authors for simplified ecological assessment in NERUDA tool. The main goal of this analysis is the identification of parameters (waste and process specific) that are important to the GWP of disposal processes for residual waste. For this purpose the following treatment methods are considered in this analysis:

- Waste-to-energy treatment in a municipal incineration plant (WTE)
- Landfilling
- Mechanical-biological treatment (MBT aerobic processing) with subsequent processing of the outputs (e.g. refused-derived fuel RDF utilisation, landfilling).

The novel implementation into NERUDA introduces a new term into the objective function. It is a product of CO_2 allowance price in the market (European Emission Allowances traded at European Energy Exchange) multiplied by aggregated GWP contributions of every allocated technology in every possible locality of an assessed region. The GWP of various disposal processes has been performed by LCA. First Step of an LCA was to provide an in-/output inventory of the treatment. Based on this inventory an environmental impact assessment was carried out. The environmental burdens and credits of separate disposal processes parts were evaluated (see section 2 and 3). The specification of residual waste treatment processes is based on average data from Czech Republic (CZE) and Germany. The environmental burdens and credits of transport were dealt separately from the waste treatment processes, see section 3. As a reference unit, the disposal of 1 t of residual waste was set. However, the effect of scaling up with capacity is important and was included too (see section 2). The resulting specific GWP is either a constant (landfilling, MBT, transport) or a function of capacity (WTE, RDF utilisation). This means that the GWP is a function of a variable obtained by NERUDA, i.e. of capacity. Residual Waste is a mixture of various waste fractions. There are potential recyclable fractions like plastic, paper and cardboard, metals, etc. Additionally, there is always a significant portion of the organic material. Other important fractions as minerals, hygienic products and small-scale waste fractions are present as well. Average composition of residual waste for the Czech Republic used is in Table 1. It is a result of calculations carried out in JUSTINE tool (Zavíralová et al., 2015). Waste characteristics have a significant influence on the GWP – especially for WTE plant. The most relevant characteristics for particular fractions of residual waste are the lower heating value (LHV), the content of fossil carbon and content of biogenic carbon. Due to the assumption of zero climate change potential of biogenic carbon (or biomass) combustion, the methods for assessing its global warming impact usually do not include the biogenic CO_2 emission and even treat biogenic CO_2 emission as a negative impact (Stocker et al., 2013).

Table 1 Average composition of residual from JUSTINE calculation

Waste fraction	Share in residual waste [%]	Waste fraction	Share in residual waste [%]
Bio	27	Textile	4.5
Fine fraction	22	Mineral	3.5
Other Combustible	14	Composite packaging	3
Plastic	9.5	Metals	2.5
Paper	7.5	Electronic waste	0.5
Glass	5.5	Hazardous	0.5

2. GWP of WTE

A comprehensive description of WTE plant principle was introduced by Stehlík (2016). In this article, only the basic assumption for WTE plant related to GWP are shortly summarised.

During incineration, all combustible contents of the waste are oxidised with energy release. CO_2 from oxidising the carbon content of the residuals waste is emitted to the environment. Only the part that comes from fossil carbon is taken into account in the GWP assessment. Utilising released heat the steam is generated and used for the production of electricity and heat. The energy production means that the corresponding amounts of energy do not need to be produced in a conventional way from primary sources. CO_2 is "saved" or "avoided". To determine the substitutional effect of energy produces the emission factors of replaced energy sources should be used. For this paper, the authors used a CZE national mix for electricity produced in all power plants. A CZE national mix for heat produced in all heating plants was used as well. Only in Figure 2 different emission factors were used for substituted heat production. This is used for local-level GWP analyses opposed to the national mixes which are used for a country-level GWP evaluation. Similar locality-sensitive curves like in Figure 2 may be obtained for each of localities and serves as input for NERUDA.

Solid residues of a municipal incineration plant are slags and waste from flue gas cleaning. After metal separation slags are landfilled or recycled (filling material e.g. in road construction). Residues from the flue gas cleaning are deposited underground.

The simplified LCA methodology to divide the whole WTE process into basic activities was used. These activities describe the main parametrization of the material flow and can be summarised into several sub-systems the WTE plant consists of. The environmental burdens are almost exclusively due to the incineration itself. Subtle role as the burden has additional energy supply for the WTE plant and residues treatment. Environmental benefits are mostly from electricity and heat production in WTE plant. Other credits with low impact on the GWP are recycling of metals and possible usage of secondary materials (for example slag as building material). This means the relevant sectors with a view to burdens respective credits with a common share of more than 90 % of the GWP are incineration and credits from energy utilisation. Only those 3 sub-systems were used by authors for the calculation of a simplified environmental criterion for the implementation into NERUDA.

The following Figure 1 and Table 2 show the relation between the identified relevant sub-systems and the resulting GWP burdens and/or credits. The burdens are expressed with positive numbers = CO_2 production. The credits are expressed in negative numbers since CO_2 is avoided. The main burdens and credits are mainly affected by waste composition. The two main parameters dependent on waste composition are the fossil carbon content and lower heating value (LHV). The fossil carbon content of waste is proportional to the GWP-burden from incineration. The plastic content in the residual waste determines the fossil carbon content the most. In Figure 1 the three different curves represent three different waste compositions – A) the one mentioned in Table 1 (9.5 % of plastic), next B) with 2 % less of plastic (7.5 % of plastic) and last C) with 2 % more of plastic (11.5 % of plastic) with other fractions adjusted accordingly. LHV is a parameter that influences the energy production (GPW-credit). Heating value can be approximately calculated from the waste fractions. Large shares of waste fractions with high heating value (e.g. plastic, paper) increase GWP-credits. The bigger share of plastic thus higher LHV and more energy produced (GWP-credit) goes slightly against the abovementioned increase of fossil carbon content (GWP-burden). This feature lowers the gap between the three curves in Figure 1. The LHV of the three curves are A) 9.3 GJ/t, B) 8.8 GJ/t and C) 9.8 GJ/t.

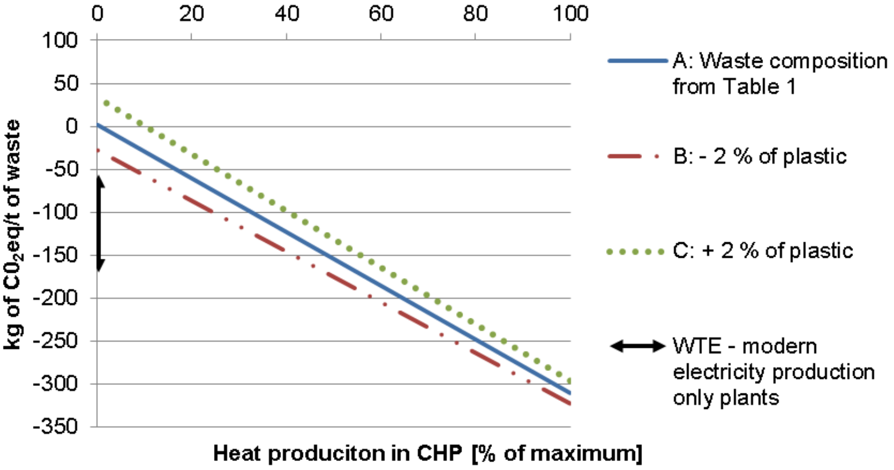


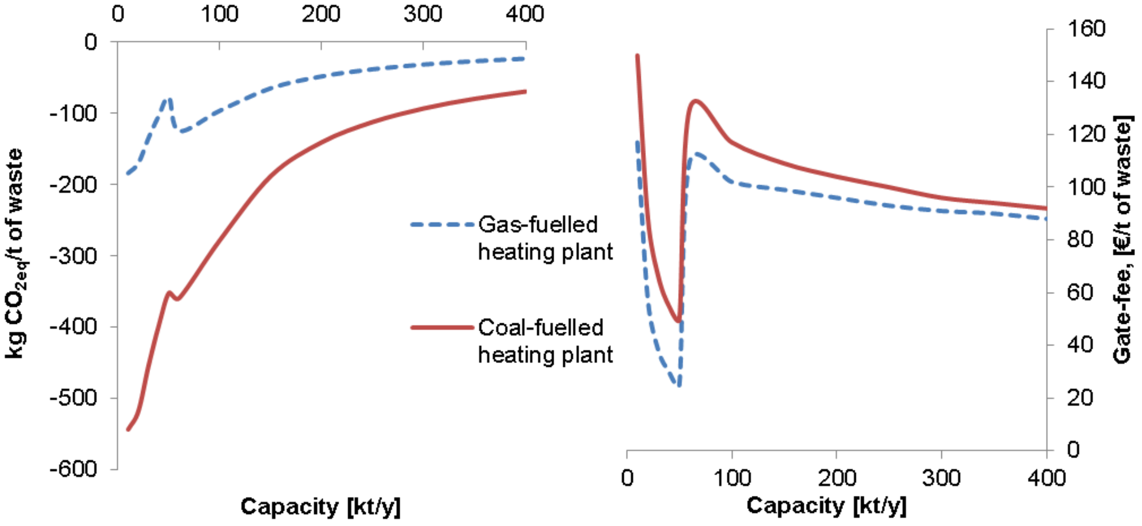
Figure 1: WTE: GWP as a function of heat utilisation percentage in CHP

The next parameter that highly affects the GWP-credit connected to energy production is the power to heat ratio. The power to heat ratio can be described using the percentage of utilised heat in CHP sub-system. This is shown in Figure 1 where an average plant with an extraction (condensing) steam turbine was used. The value 0 on the horizontal-axis represents the power plant operating with no heat export and the value 100 on the horizontal-axis represent full usage of extraction with a minimum steam flow needed for the condensing part of the turbine. As the Figure 1 shows the more heat is produced the more kg of CO_2 equivalents are saved. Concrete values of relevant sub-systems for the limit points are stated in Table 2. A specific example of modern WTE plants that produce mainly electricity is illustrated in Figure 1, too. The specific energy recovery rate for these plants varies for the electricity production from 0.6 to 0.8 MWh_e/t_{waste} and for the heat production only for self-consumption.

Table 2 GWP of relevant subsystems in power and heat operated points corresponding with Figure 1

	GWP [kg of $C0_{2eq}$/t of waste]					
	Power operated			Heat operated		
Waste composition	A	B	C	A	B	C
Burden: incineration	366	317	417	366	317	417
Credit: Electricity prod.	-343	-325	-361	-145	-138	-152
Credit: Heat prod.	-21	-20	-22	-531	-502	-560
Resulting GWP	2	-28	34	-310	-322	-296

Applying finding from Figure 1 to a particular locality, characterised by a fixed heat demand profile during the year and current utility system, it is possible to show the impact of the increasing capacity on the resulting GWP. Two in-house developed techno-economic models of WTE plants were built. First is relevant for the small-sized capacity WTE plants (10 to 50 kt/y) equipped with back-pressure turbines. More details on this concept can be found in Stehlík 2016. The second model was dedicated to WTE plants with a capacity over 50 kt/y where extraction turbines are common. In both cases, the WTE plants produce as much heat as it is possible for each capacity. Figure 2a presents an example of the GWP dependency on the capacity. This can be used as an input into NERUDA tool. Similar input in terms of economy, which is used by NERUDA today, is a gate fee curve that is listed in the Figure 2b. From the results, it is clear that with increasing capacity the avoided CO_2 emissions per tonne of waste are lower, which is an undesired trend. For comparison, we provide treatment cost profile. Gate fee declines with increasing capacity, which is a positive trend. This shows that the environmental benefits are opposite to the economic ones.



a) *b)*

Figure 2 The dependence between GWP and capacity (a) and between gate fee and capacity (b)

3. GWP of disposal processes for residual waste

GWP-burdens and credits of other residual waste treatment processes and transport were compared in Figure 3. Displayed intervals are highly dependent on local conditions. WTE plants (1 in Figure 3) have been discussed separately in the previous section.

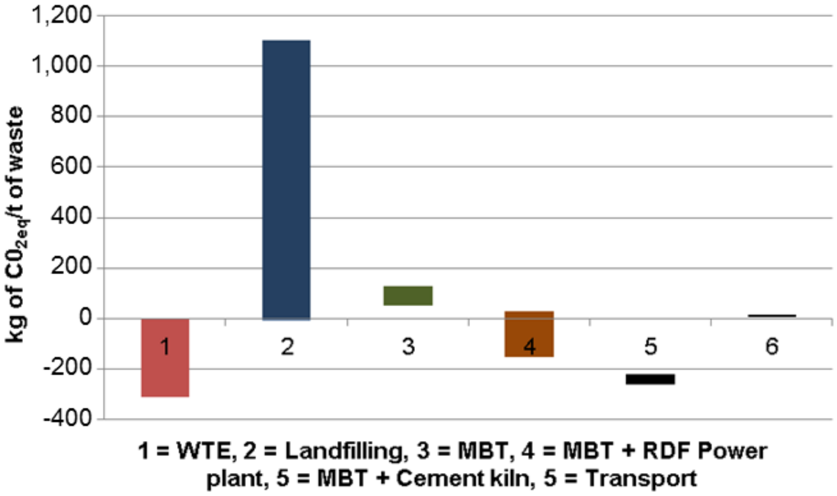


Figure 3: GWP intervals for a set waste composition

Number 2 in Figure 3 is landfilling. The landfilling of residual waste produces landfill gas and leachate. Environmental burdens are almost exclusively due to the landfilling process itself and the emissions of landfill gas. Landfill gas collection efficiencies vary between 50 % and near 100 %, dependent on the cover type and the coverage of the LFG collection system (Barlaz et al., 2009). Small environmental benefits are due to the electricity production in a gas motor if installed. Due to this, the environmental impact lays in the interval from about -5 kg CO_{2eq}/t of waste for complete gas collection to 1,100 kg CO_{2eq}/t of waste for the gas collection efficiency at 50 %.

Numbers 3, 4 and 5 in Figure 3 relate to MBT. Number 3 shows the interval of net GWP-burdens associated with the inner MBT processes without RDF utilisation. The main burdens are from energy and supplies demands for MBT treatment. The numbers 4 and 5 shows the MBT process together with RDF utilisation in RDF power plant and in a cement kiln. The wider interval in for RDF power plant is due to the possibility of utilising the energy for either power or heat production (similar to Figure 1). The narrower interval for cement kiln is caused by utilising energy for heat production and mainly by substitution of coal as an energy source.

The last bar (5) in Figure 3 represents GWP interval for transportation of residual waste. Two independent phases should be distinguished. First, the waste is gathered, for example in kerbside collection system, with garbage collection vehicles. Second reloading of the waste and an onward shipment in high-volume transport vehicles is common in the case of long distances to the disposal plant. Most of the environmental burdens about 80 % are due to the kerbside collection. CO_2 equivalents resulting from the transport to treatment (15 %) and from reloading (5 %) play a minor role. Thanks to this and to the comparison to the GWP-impact of the disposal processes the GWP-impact of collection and transportation is of minor relevance. However, it plays an important role in the case of cost as was shown in Gregor et al. (2017).

4. Conclusions

The residual waste treatment involves the generation and avoiding of climate-relevant emissions. The emphasis of this paper is on WTE plants and consequences to allocation planning considering reduced GHG emissions. The main parameters that influence GHG emissions from a WTE are the incineration of waste and energy utilisation. The fossil carbon content is the main factor from the waste composition that determines the GWP-burdens from waste incineration. The GWP-credits from energy utilisation are mainly dependent on the operating mode. This means, whether is the plant heat- or power-operated. The dependence between the GWP values and the heat utilisation or capacity is set in Figure 1 and 2a. This capacity dependent function is then the main input into NERUDA tool as an environmental criterion. The avoided emissions from electricity and heat production are dependent on the emission data from the substituted energy sources, i.e., national fuel mixes for generic country-level evaluation or specific emissions from energy source actually being replaced by a precise local-level assessment. GHG emissions from landfilling are mainly affected by the collected or escaped landfill gas. The MBT is characterised by the refuse derived fuel (RDF) utilisation (incineration and heat and power production) and the important parameters are similar to WTE process. In comparison to the disposal processes themselves, the transportation plays a minor role due to it being the same for each waste-handling process. These issues related to GHG emissions will be implemented into the existing tool NERUDA and afterwards, the competitive environment in the field of waste management can be simulated with both economic and ecological aspects being taken into account. The allocation performed by NERUDA will be based on the trade-off between the curves in Figure 2 for many localities simultaneously.

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