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EXERGY-BASED EVALUATION OF RESOURCE RECOVERY FROM MUNICIPAL SOLID WASTE

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SUMMARY: Exergy is based on the Second Law of thermodynamics and can be used to express physical and chemical potential and usefulness of resources. The present study reports results from the application of two different approaches of exergy analysis to evaluate the resource efficiency of four waste treatment scenarios involving increasing levels of source-segregation and recycling alternative to waste-to-energy. The scenarios achieved efficiencies between 17 and 27% based on the exergy flow analysis, where higher levels of material recycling resulted in higher efficiencies. In the exergetic life cycle assessment the scenarios were associated with efficiencies of 14-15%, with metal recovery being particularly beneficial due to savings from replacing primary metals production. Overall, the two approaches offered different quantitative results and conclusions regarding material recovery. Because the system definition is critical in both approaches and because resource quality cannot be expressed by exergy content alone, exergy-based resource consumption measures should be complimented by other impact categories for the comprehensive assessment of waste-resource systems.

1. INTRODUCTION

Exergy is based on the Second Law of thermodynamics and can be used to express physical and chemical potential and usefulness of resources (Dewulf et al. 2008). Exergy provides a unified measure for resource accounting and a basis for assessing resource efficiency of large-scale waste systems as well as individual technologies (Szargut 2005). In life cycle impact assessment (LCIA), cumulative exergy consumption indicators such as the Cumulative Exergy Demand (CExD, Bösch et al. 2007) or the Cumulative Extraction of Exergy from the Natural Environment (CEENE, Dewulf et al. 2007) have been developed to account for resource depletion. In general, the loss of exergy in a system can be used to account for resource consumption and to evaluate resource efficiency (cf. Gößling-Reisemann 2008), with applications for entire economic sectors (e.g. Ayres et al. 2011) as well as for specific recycling processes (e.g. Castro et al. 2007).

In the present work, two exergy analysis approaches using different system definitions are compared with respect to the evaluation of resource efficiency of specific waste treatment scenarios: on the hand, the quantification of all exergy flows and losses within the investigated system is

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designated as exergy flow analysis, and on the other hand, the application of life cycle assessment (LCA) principles using the CEENE indicator is designated as exergetic LCA.

For the exergy flow analysis, a step-wise procedure for quantification of exergy efficiencies is applied: first material and energy flow analysis is performed for each scenario, then the exergy contents of each flow in the scenarios are determined, and finally the resulting exergy values for all flows (input, internal, and output) are used for the calculation of recovery efficiency by dividing the exergy contents of the useful outputs by the exergy contents of the scenario inputs. The exergetic LCA extends the waste system to include all processes from natural resource extraction to final disposal or utilization of all outputs. The resource recovery efficiency is derived by dividing the CEENE of the useful outputs by the CEENE of the inputs into the waste system.

2. MATERIAL AND METHODS

2.1 Scenario analysis

2.2.1 Scenario layouts

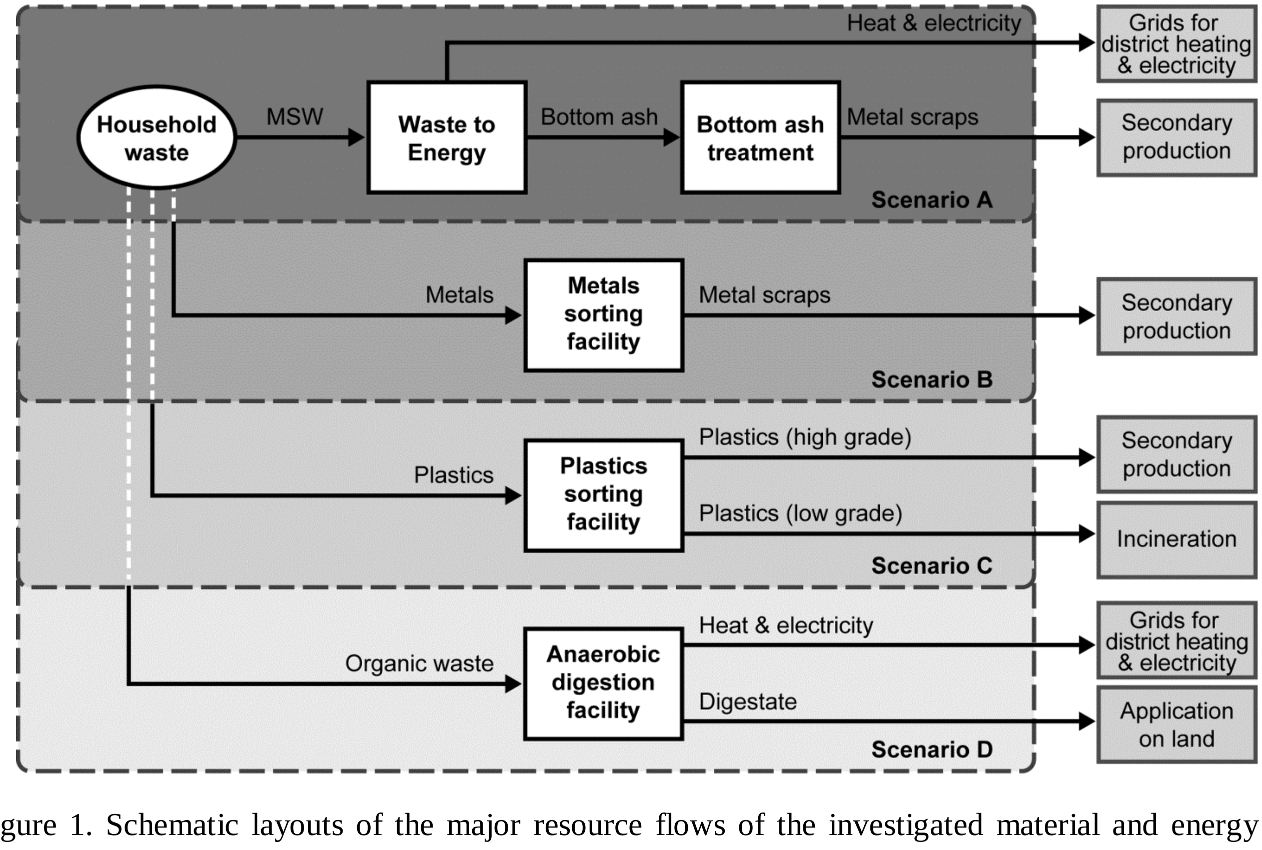

Figure 1. Schematic layouts of the major resource flows of the investigated material and energy recovery scenarios, where dashed lines indicate source-segregated waste fractions only present in some of the scenarios. The grey boxes on the right are included only in the exergetic LCA to represent savings due to secondary products substituting products from traditional production systems.

Four scenarios are defined for the management of municipal solid waste from private households. The scenarios range from direct incineration of all the residual waste in a waste-to-energy (WtE) plant in the base case (Scenario A) to source-segregation and recovery of metals, hard plastics, and organic waste in the most elaborate treatment system (Scenario D). In every further scenario from A towards D, an additional fraction of the produced household waste is subject source-segregation, subsequent separate collection, and treatment using specific technologies (see Figure 1). The scenarios are defined from a Danish perspective based on literature data. The waste composition data used for the waste input to all the scenarios is derived from waste sorting analyses of Danish single-family household waste (cf. Table 1) and waste-to-energy is used as the basic waste treatment technology, as most of the Danish residual household waste is incinerated. However, it is important to note that the scenarios are not defined to identify the best waste treatment system, but as a basis to investigate the potentials and challenges of using exergy analysis to optimize resource recovery from waste. Detailed descriptions of the scenarios, the data used, and the underlying assumptions can be found in Laner et al. (submitted).

2.2.2 Material and energy balances

Material flow analysis is performed on the level of 17 waste fractions based on the mass balance principle (cf. Brunner and Rechberger 2004) using the STAN software (free download from: http://www.stan2web.net/). Mass and energy balances are established for each process of the waste treatment system. The functional unit of the analysis is 1000 kg of household waste, which is treated according to the respective resource recovery scenario (cf. Figure 1). Uncertainties are considered in the model with respect to key parameters related to resource recovery (e.g. material and energy recovery efficiencies) using Monte Carlo Simulation, but scenario assumptions such as the composition of the waste input (cf. Table 1), source-segregation efficiencies, and material transfer coefficients related to non-resource flows (e.g. effluent from anaerobic digestion) are not addressed in the uncertainty analysis.

Table 1. Composition of the residual household waste input considered in the scenarios based on Petersen et al. (2012). The 17 waste fractions in the table can be further disaggregated into 123 characteristic material fractions for which the concentrations of 46 chemical elements were determined.

Waste fraction	**g/100 g**
Vegetable & food waste	47.0
Aluminium foil & containers	0.5
Aluminium cans	0.4
Diapers & hygiene products	5.6
Glass	2.4
Paper and cardboard	18.8
Paper-plastic-composites	1.7
Plastics rest	2.2
Plastic (hard)	4.5
Cat litter	1.4
Stones and other non-combustibles	2.8
Fe metals	0.9
Other metals	0.9
Textiles, shoes, rubber	2.3
Garden waste & wood	4.9
Other combustibles	3.4
Hazardous waste (batteries)	0.1
Total	100.0

The major processes defined as part of the scenarios are collection and transport (based on data from EASETECH, cf. Clavreul et al. (2014)), waste-to-energy (material transfer coefficients based on Koehler et al. (2011) and energy efficiencies based on Reimann (2013)), bottom ash treatment (based on Allegrini et al. (2015)), sorting of source-segregated metals and plastics (based on Møller et al. (2013)), and anaerobic digestion (based on Banks et al. (2011)). For details about the process models see Laner et al. (submitted).

2.2 Exergy analysis

Exergy analysis measures the loss of available work due to the transformation of matter and energy. Exergy does not satisfy a law of conservation, because every irreversible process causes exergy destruction.

2.2.1 Exergy flow analysis approach

$$Ex_{ch} = \sum_i n_i e_{ch,i} + RT_0 n \sum_i x_i \ln(x_i) \qquad (1)$$

The chemical exergy of a material flow is calculated according to equation (1), where Ex_{ch} is the total chemical exergy of the material flow [J], n_i is the number of moles of component i in the material flow, n is the total number of moles in the mixture, $e_{ch,i}$ is the specific chemical exergy of component i [J/mol], R is the gas constant (8.31 J/mol K), T_0 is the standard temperature [K], and x_i is the molar fraction of the component i in the mixture of the material flow. The most common components of the natural environment are chosen as reference species, to calculate the specific chemical exergy of a compound (Szargut 2005). In addition to the chemical exergies, the physical exergies (due to differences in temperature and/or pressure) as well as electricity are included in the exergy flow calculations.

Due to the fact that waste materials are complex mixtures of multiple compounds, simplifications and assumptions are necessary to perform the analysis. The composition of each flow is approximated by a mixture of several representative compounds, reflecting the major constituents of the materials. For details and a discussion of the effect of compound resolution on the resulting exergy flow values see Laner et al. (submitted).

2.2.2 Exergetic life cycle assessment (Exergetic LCA)

The functional unit of the assessment is the treatment of 1000 kg of household waste. In addition to the material and energy flows of the waste treatment scenarios, life-cycle inventory (LCI) data are retrieved from the ecoinvent v3.1 database. CEENE is used as an LCIA method to evaluate the impact on natural resources, because it includes an evaluation of energy carriers, non-energetic resources, and land occupation (Alvarenga et al. 2013). Savings for resource recovery and recycling are credited to the scenarios based on the substitution of products by the waste-derived products. The zero burden assumption is abandoned in the analysis, to be consistent with the exergy efficiencies for the exergy flow analysis. Hence, the upstream burden of the input waste streams (i.e. CEENE rucksack of the materials in the waste) is included in the assessment and compared to the recovery of materials from the waste for secondary production. In general, the products constituting the waste input are chosen on the level of primary production (e.g. low-alloyed steel for ferrous metals in the waste) with exceptions for example for waste batteries (e.g. NiMH batteries were used to calculate the input burden).

3. RESULTS AND DISCUSSION

3.1 Exergy efficiency of recovery scenarios

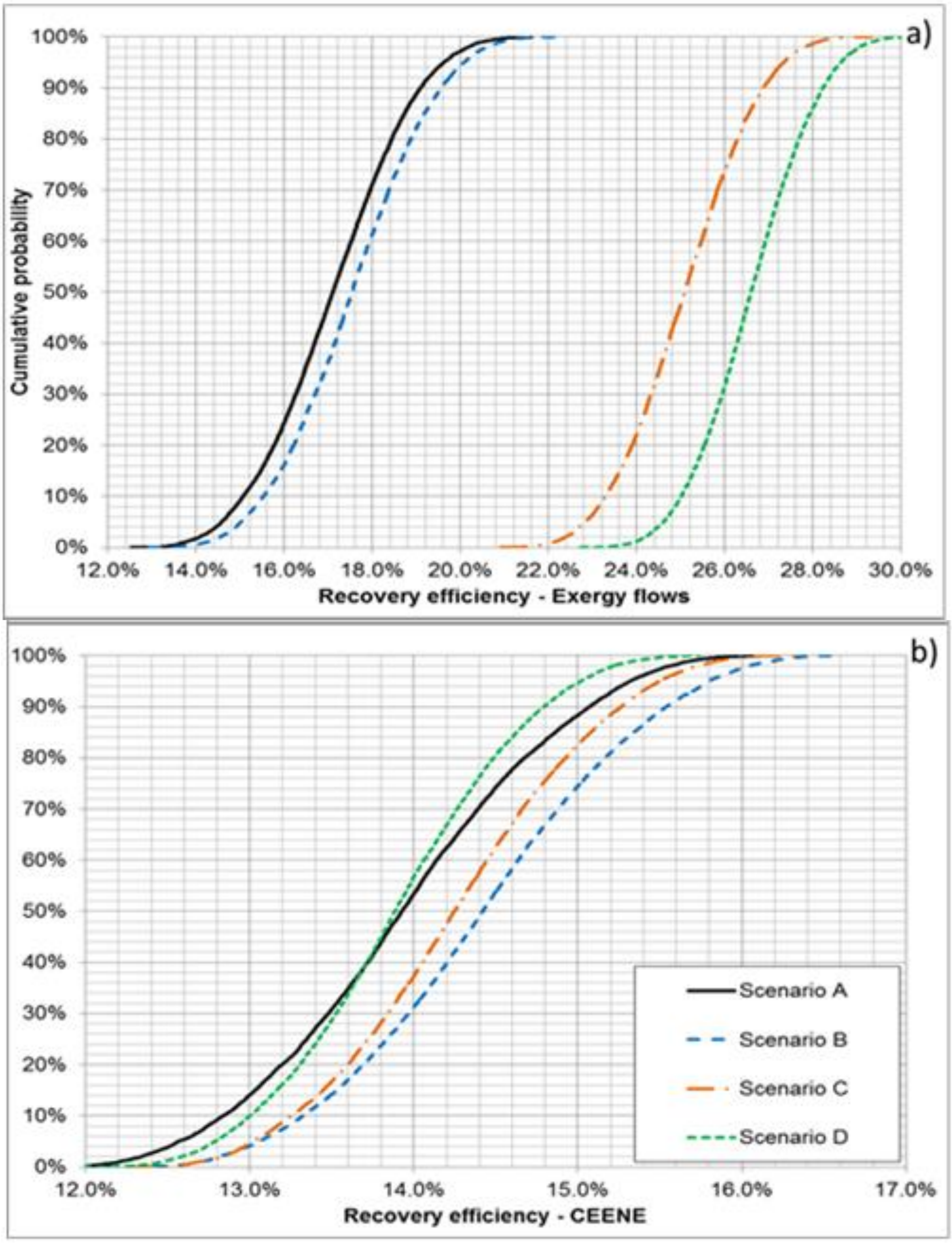

Figure 2. Cumulative probability functions of the scenario efficiency results for the exergy flow analysis (top, a) and the exergetic LCA (bottom, b).

The exergy efficiency is calculated by dividing the total product output (representing potential savings) by the total input (representing burdens in the system) of a specific resource recovery scenario. The recovery efficiencies of the four scenarios resulting from the exergy flow analysis (top) and the exergetic LCA (bottom) are shown in Figure 2. In case of the exergy flow analysis, the recovery efficiency increases from Scenario A towards Scenario D. From the cumulative probability curves it is apparent, that the recovery efficiencies of Scenario C and D (mean values around 25 – 27%) are significantly higher than those of Scenario A and B (mean values around 17.5%). The primary reasons for the substantial difference between the two pairs are a) the high losses of exergy during combustion processes, which is the case for all the plastic during the residual waste incineration in the WtE plant in A and B, and b) the comparatively low exergy value of metals relative to combustibles, which results in a very limited effect of source-segregation and improved recovery for metals on the overall efficiencies. Whereas the recovery efficiency increased together with increasing material recycling in case of the exergy flow analysis-based evaluation (Figure 2, top), this is not the case for scenario efficiencies derived from the exergetic LCA (cf. Figure 2, bottom). In the latter case, Scenario A has the lowest recovery efficiency (more or less together with Scenario D) and Scenario B achieves the highest resource recovery efficiencies. However, the large overlaps of the CDF curves in Figure 2 (bottom) highlight that the differences between the scenarios are rather small. Overall, the achieved recovery efficiencies are low compared to the exergy flow analysis results, because of accounting for the CEENE burdens associated with the products contained in the waste input. In particular, the burden of bio-based products in the waste can be compensated by savings from resource recovery only to a small degree, because of the substitution of production chains with lower CEENE scores than the orginial CEENE burdens of the bio-based production systems.

3.2 Critical aspects of the scenario evaluations

The resource recovery efficiencies of the scenarios are associated with substantial uncertainty due to uncertain model parameters, i.e. a specific plant could have recovery efficiencies quite different from the applied literature data. It should also be noted, that multiple other scenarios would be possible and that the scenarios in this study are not intended to be all-embracing with respect to resource recovery options from waste, but rather serve as a basis to compare exergy analysis approaches for evaluating the resource efficiency of waste systems.

Exergy appears to be problematic as a proxy for resource quality due to several reasons: A) There is no (obvious) direct correspondence between a material’s exergy content and the functionality of this material for non-energetic use (cf. Gaudreau et al. 2009). In this way, fuels turn out to be more important in the exergy flow analysis than material resource flows. B) The exergy content of a flow is a result of all the compounds contained and it does not distinguish between contaminants and valuables. Thereby, highly contaminated flows can have very similar exergy values than clean secondary raw materials. This is also because the exergy of mixing typically has a very small effect on the exergy content of a material flow (cf. Laner et al. submitted). C) The waste system definition is critical, because the utilization of waste-derived products and their effects on the alternative production systems are often not part of the waste system, due to the limited knowledge and data about recycling processes.

The evaluation of resource efficiency within the exergetic LCA is done based on the CEENE method, which accounts for all the exergy extracted from the natural environment in order to provide a certain product or service. Using this method, bio-based production systems obtain greater importance relative to systems dominantly relying on fossil energy sources because of the explicit accounting for land occupation. Therefore, the exergetic resource depletion assessment should be complemented with emission-oriented impact categories, such as climate change, in a full waste LCA study. Another challenge related to waste LCA is the quantification of substitution ratios and substitution pathways. Because choices on substitution are often not unambiguous, it is important to carefully evaluate the effect of assumptions about substitution on the recovery efficiencies. Finally, with respect to the consideration of the waste’s upstream burden, it is important to point out, that it does not change the relative performance of the scenarios among each other, but it allows for identifying resource losses in the system due to the quantification of the resource potential of the waste input. From this perspective, further refinement of this upstream burden approach could be attractive for prioritizing resources to be recovered based on the environmental rucksack of the materials in the waste. In the present study, the choices related to the products constituting the waste primarily affect the absolute efficiency levels, but not the relative performance of the scenarios.

4. CONCLUSIONS

In this study, two different approaches of exergy analysis were applied to evaluate the resource efficiency of four scenarios involving increasing levels of source-segregation and recycling of selected resources as alternatives to the base case of all the waste input going to waste-to-energy (with subsequent bottom ash treatment). The average recovery efficiencies of the different scenarios were 17-27% based on the exergy flow analysis (higher efficiencies were associated with high levels of material recycling), while the scenario efficiencies based on the exergetic LCA were 14-15%. Metal recovery was beneficial in both types of analyses, but had more influence on the recovery efficiency in the exergetic LCA, because the avoided burdens from primary metal production were much more important than the exergy content of the recovered metals. On the other hand, plastic recovery was highly beneficial in the exergy flow analysis, but rather insignificant in exergetic LCA.

With respect to the evaluation of resource quality, the main challenge for the exergy flow analysis is the use of exergy content as a proxy for resource quality, because exergy content is not per se correlated with the functionality of a material. In addition, appropriate system boundary definitions are critical for the exergy efficiencies derived from the flow analysis, but often confronted with limited information about the composition of flows in the system and about the effect of waste-derived materials on secondary production processes. In the exergetic LCA, resource quality was reflected by the savings achieved by product substitution. In addition, the consideration of the waste's upstream burden allowed for a quantification of the waste's resource potential. Because of the significant influence of choices concerning product substitution pathways (i.e., what is actually replaced by the waste-derived products) on the resource efficiency assessment in the exergetic LCA, the sensitivity of accounting for product substitution needs to be critically analysed in LCA of waste systems. Overall, cumulative exergy consumption measures should be complimented by other impact categories in comprehensive assessments of resource recovery from waste.

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