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Modular Life Cycle Assessment of Municipal Solid Waste Management

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Abstract

Life cycle assessment (LCA) is commonly applied to examine the environmental performance of waste management systems. The system boundaries are, however, often limited to either one tonne of material or to specific waste treatments and are, therefore, lacking a systems perspective. Here, a framework is proposed to assess complete waste management systems based on actual waste flows, assessed with a detailed material flow analysis (MFA) in a modular MFA/LCA approach. The transformation of the MFA into a product-process-matrix facilitates a direct link between MFA and LCA, therefore allowing for the assessment of variations in flows. To allow for an up-to-date and geographically specific assessment, 190 LCA modules were set up based on primary industrial data and the ecoinvent database. The LCA modules show where there have been improvements in different recycling processes over the past years (e.g. for paper recycling) and highlight that, from an environmental perspective, closed-loop recycling is not always preferable to open-loop recycling. In a case study, the Swiss municipal solid waste management system, of which there is already a detailed MFA, was modeled using the new LCA modules and applying the modular MFA/LCA approach. Five different mass flow distribution scenarios for the Swiss municipal solid waste management system were assessed to show the environmental impact of political measures and to test the sensitivity of the results to key parameters. The results of the case study highlight the importance of the dominant fractions in the overall environmental impacts assessment; while the metal fraction has the highest impact on a per kilogram basis, paper, cardboard, glass and mixed municipal solid waste were found to dominate the environmental impacts of the Swiss waste management systems due to their mass. The scenarios also highlight the importance of the energy efficiency of municipal solid waste incineration plants and the credits from material substitution as key variables. In countries with advanced waste management systems such as Switzerland, there is limited improvement potential with further increases in recycling rates. In these cases, the focus of political measures should be laid on (i) the utilization of secondary materials in applications where they replace high-impact primary production, and (ii) an increased recovery of energy in waste-to-energy plants.

Key words (min. 6):

Life cycle assessment (LCA), material flow analysis (MFA), recycling, energy recovery, indirect energy, policy scenario

1. Introduction

Waste recycling and disposal is an important part of the life cycle of a product and is associated with environmental burdens like any other life cycle stage. Legislation often refers to the so-called waste hierarchy (prevention, re-use, recycling, other recovery, disposal) but the hierarchy alone is in-sufficient in providing guidance when considering a combination of recycling and waste treatment technologies in integrated waste management systems (WMS). A comprehensive environmental assessment such as life cycle assessment (LCA) (Finnveden et al., 2005; Gheewala, 2009), as is recommended by the European legislation (EC, 2008), is necessary to provide decision support to minimize the environmental burdens associated with waste. Generally, the first priority of the waste hierarchy (waste reduction) is well accepted as the preferred solution. The remaining waste hierarchy priorities, however, have been subject to debate. Exceptions to this hierarchy, particularly with regard to material recycling and energy recovery (see e.g. Finnveden et al. 2005; Pires et al. 2011; Laurent et al. 2014a), have been shown to exist. The scope of LCA studies on WMS is, however, often limited; several authors have analyzed either limited geographies (e.g. Rigamonti et al. 2013) or single material streams (e.g. Humbert et al. 2009; Damgaard et al. 2009; Paraskevas et al. 2013). Most studies focus on the treatment of a defined amount of waste, e.g. 1 tonne, and do not assess the overall impact of regional WMS (Andreasi Bassi et al., 2017).

LCA allows for expanding the perspective beyond the core WMS, which is important since the consequences of waste management often depend more on the impacts to surrounding systems than on the WMS specific emissions (Ekvall et al., 2007). The energy systems model, for example, is of great importance when assessing thermal waste treatments, as it defines the credits for recovered energy, and for recycling processes, for which energy consumption is often responsible for the largest share of the environmental impacts (Laurent et al., 2014a, 2014b; Münster et al., 2013). In addition, the displacement of primary material production through secondary materials from recycling, as well as the allocation of burdens and benefits, has substantial influence on the result of waste management oriented LCAs and has been extensively discussed (Gala et al., 2015; Geyer et al., 2015; Vadenbo et al., 2016; Zink et al., 2015). In order to stimulate more critical reflection and scrutiny of the underlying assumptions used for assigning avoided burdens in LCA, Vadenbo et al. (2016) proposed a reporting framework for the systematic estimation of substitution potentials from resource recovery. The framework, however, has yet to be tested on a large scale system.

Besides safe disposal and emission abatement, waste management aims to conserve resources through material and energy recovery. Hereby, energetic and material utilization of waste are often competing. Detailed and comprehensive accounts of waste generation and treatment are increasingly seen as a quantitative basis for designing and assessing measures to move towards a circular economy (Tisserant et al., 2017), thus focusing on material resource efficiency while neglecting the waste's potential energetic use (Haupt and Zschokke, 2017). In parallel, the energetic recovery from waste is an important contribution to the energy system, and maximum recovery potentials have been quantified as a benchmark in Liechti (2009) and Münster and Meibom (2011). The indirect energy savings through substitution of primary material production (and associated energy demand) with recycled material, however, often exceeds the lower heating values (LHV) of the materials. Assessments of the WMS should, therefore, include an analysis of the direct energy recovered from thermal treatment coupled with an assessment of the indirect energy flows for material production.

MFAs help to understand the stocks and flows of a WMS and are a natural starting point for an environmental assessment. MFA and LCA have been applied in parallel for waste management decision support, providing information on the environmental performance of different mass flow scenarios (Boesch et al., 2014; Turner et al., 2016; Vadenbo et al., 2013). The combination of regional MFA and LCA allows for assessing environmental impacts while ensuring consistency between variables such as MFA and LCA process model transfer coefficients, capacity restrictions of waste-treatment infrastructure, and waste resource availability. Furthermore, it enables one to capture the input-dependency of process performance and the resulting environmental implications, both for dedicated waste treatments such as municipal solid waste incineration (MSWI; Boesch et al., (2014)) and for alternative resources used as feedstock in industries such as cement or iron production (Boesch et al., 2009; Boesch and Hellweg, 2010; Vadenbo et al., 2013).

Laurent and colleagues (2014) analyzed 222 LCA studies on waste management systems (WMS) and revealed that waste composition and the surrounding energy system highly influence the outcome of the LCA. The strong dependence on these local conditions justifies the need for regional WMS assessments. The use of recent and geographically specific data in life cycle inventories (LCIs) is important for many of the outlined research gaps. First, process models of geographically varying industrial practices allow one to model the recycling output quality more appropriately and, therefore, to credit material substitution more accurately. Second, coupling MFA and LCA requires an inventory for all processes identified within the case study region. Third, if site-specific process models are used, knowledge of the waste composition, which allows for input-dependent modelling of emissions from waste management facilities (e.g. incinerators), is more coherent (Boesch et al., 2014; Gheewala, 2009; Laurent et al., 2014a). The need for regionally specific assessments has led to the development of several tools for WMS LCAs (e.g. Clavreul et al. (2014)).

This study aims at building a modular LCA model coupled with a national MFA study, while incorporating up-to-date waste flows and LCIs for thermal treatments and recycling processes. The new inventories account for the quality of both the recyclables (e.g. amount of residues) and of the resulting secondary materials. Furthermore, closed-loop and open-loop recycling is differentiated and is included to evaluate the environmental impact of moving towards a circular economy. The modular MFA/LCA design allows for a detailed assessment of recycling and treatment pathways as well as national waste management strategies. The application is illustrated by quantifying the environmental impacts of the current Swiss WMS as well as five alternative waste management strategies. The results of this case study are intended to be used by local, regional, and national decision-makers, related associations and industries as a basis for waste management policies, communication strategies and future waste management planning and investing.

2. Methodology

Life cycle assessment (LCA) is a comprehensive framework for systematically evaluating the potential environmental impacts of product systems throughout their entire life cycles (ISO 14040:2006). This is achieved by modeling the cause-effect relationships in the environment induced by resource extraction or emissions (Hellweg and Milà i Canals, 2014). In comparison, material flow analysis (MFA) maps the existing waste flows and the treatment processes in place (Brunner and Rechberger, 2004). MFA provides, for example, the transfer coefficients of all treatment processes as well as data on residues in separate collection systems that can be used in the LCA calculations. MFA is also the basis for an input dependent modeling of waste management LCAs, e.g. for the thermal treatment of waste in MSWI and the recycling processes. The knowledge of the transfer coefficients for all treatments allows for modeling the sorting and recycling process inventories in accordance with the MFA and assures mass balance conservation in the system. In addition, the modular study set-up enables the simulation of material flow variations. As the modules are defined based on system decision nodes that result from the direct coupling of regional MFA and LCA, environmental consequences of political decisions, e.g. a change in a process model or on the mass-flow distribution, can be efficiently assessed and visualized.

Figure 1 exemplifies the combination of MFA and LCA. First, the MFA is completed, including the systems input (e.g. 1 tonne of waste material or all wastes occurring in a region), the distribution to the processes (flows a to d) and the secondary products (flow s to substitution process 1 including only the credits for the substitution). Second, LCA modules for all processes and substitutions are modeled and the impacts calculated for as many indicators as preferred (climate change and cumulative energy demand (CED) in Figure 1). The MFA is then translated into a technology matrix with a product-process-structure showing all transfer coefficients of the processes (positive numbers) and the processes absorbing the flows ("-1“ in the matrix). Multiplying the input of each process with the respective transfer coefficients then yields the activity levels of all processes. By further multiplying the activity levels with the LCA modules, the environmental impacts for both individual flows and the overall system can be calculated. The substitution achieved through recycling is also integrated in the product-process-structure and modeled using the avoided burden approach.

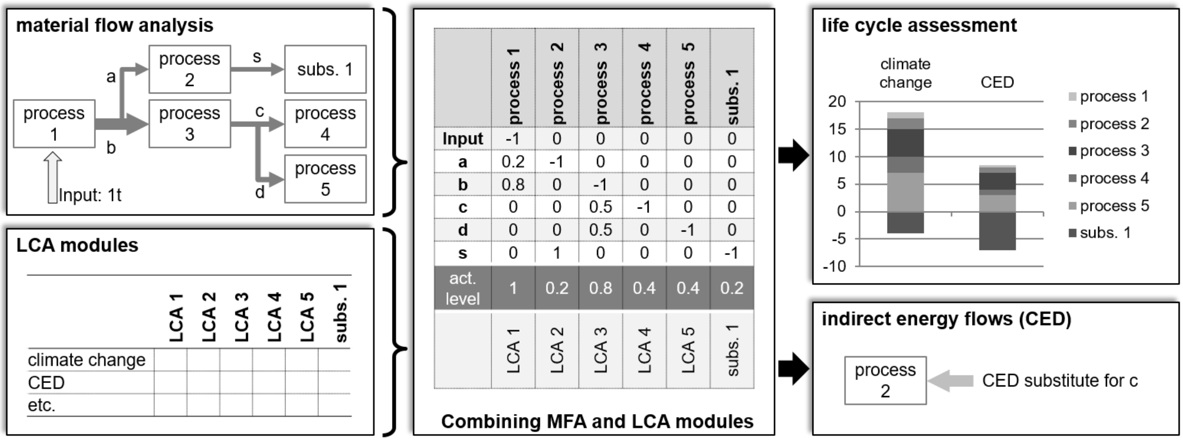


Figure 1: *Schematic representation of combination of material flow analysis with life cycle assessment using a modular LCA structure. LCA modules describe process LCAs (collection, sorting, recycling, thermal treatment, etc.) as well as the substitution of materials and energy (as individual modules), as indicated for process 1 to 5 and the substitution “subs. 1”. CED = cumulative energy demand.*

The present model aims at an analysis of the status quo of the system and therefore follows an attributional approach. The system boundary includes the collection, sorting, preparation for recycling,

recycling, thermal treatment, thermal treatments of residues and the final disposal of residual fractions. Background processes, such as energy inputs and capital equipment are also considered. In general, the framework allows for assessing a wide range of indicators. The focus was placed on climate change due to its importance for policy makers (using the Global Warming Potentials 100 years of IPCC (2013) as characterization factors) and the CED (Frischknecht et al., 1998) for assessing the indirect energy implications of the WMS. Biogenic CO_2 emissions are assumed to be climate neutral. Both climate change impacts and CED have been shown to correlate with many other impact indicators (Huijbregts et al., 2006). An important exception is toxicity, which may show diverging results for waste treatment systems. Therefore, the USEtox methodology was added to assess any toxic impact on humans and the ecosystem (Rosenbaum et al., 2008). Besides these specific indicators, the ILCD indicators (EU-JRC 24708 EN, 2010) were assessed on a midpoint level and are presented in the Supporting Information (Section 2.2). Long-term emissions have been modelled in the life cycle inventories for all processes.

The framework of Vadenbo et al. (2016) was followed to report the assumptions for material substitution. The resulting substitution factors were integrated when coupling the activity level with the respective LCA module (Figure 1). The main components of the framework are the waste-specific resource potential, the recovery efficiency, and the displacement rate. The latter is determined by technical limitations, user-perceived equivalence and institutionally prescribed functionalities. The physical resource potential, i.e. the amount of secondary resources in the waste stream, and the recovery efficiency are modeled in the MFA. The point of substitution of all fractions is defined to be after all recycling processes at the level of secondary raw materials, i.e. materials substituting other, often primary, streams, without undergoing further treatments.

The LCA, based on the product-process-matrix from the MFA, was calculated using Brightway2 (Mutel, 2017), an open source framework for LCA in Python (version 3.6). This allows for coupling a large number of inventories from different sources and allows for the inclusion of additional modelling steps such as the substitution modelling.

2.1. Analysis of direct and indirect energy flows

In parallel to the environmental impact assessment, an analysis of the direct and indirect energy flows was performed. Direct energy flows denote the waste materials' energetic content, i.e. the lower heating value, and represent the maximum energy potential that can be exploited by thermal utilization. Indirect energy savings stem from avoided energy consumption due to the substitution of a material's primary production route with recycling. Indirect energy gains were taken from the full LCA as described above. The indirect energy gains are given as net CED total (Frischknecht et al., 1998), i.e. as the difference between the CED of primary and secondary production. As the study focuses on the net savings from the production of secondary materials and the respective substituted production routes, alternative waste treatment of substituted materials, e.g. XPS insulation versus foam glass, were not taken into account.

2.2. LCA modules

Because the study aims for a modular design, the waste treatments were split into several small processes describing individual treatment steps. The treatment of recyclables is divided into collection (curbside, centralized, etc.), sorting, pre-treatment and recycling phases. Between these phases, material can be shifted from one process chain to another. Transport, therefore, often marks the beginning and end of these modules giving the opportunity to choose the further treatment options. Thermal treatments are modeled as six modules, namely the collection, the incineration (process-specific and input-specific emissions), the bottom and fly ash treatment processes, and the electricity and heat recovery. The individual modules for fly ash and bottom ash treatments allow for modeling the ash processing independently of the incineration process, e.g. at different locations and with different technological specifications.

The foreground system of the study includes the set of processes directly affected by the decision of the study (Clift et al., 2000). While some inventories exist from database providers such as ecoinvent (Wernet et al., 2016) and literature (e.g. Arena et al. (2003), Merrild et al. (2009), Chilton et al. (2010), European aluminium association (2013)), many are outdated or geographically not applicable to Switzerland. Therefore, most inventories have been revised in collaboration with industrial partners and experts in a large primary data collection effort (Haupt et al., submitted). The data for the LCIs has been collected in 2015 and 2016. The LCA modules described are modeled primarily for Switzerland but can also be used for, or adapted to, similar WMS. All processes, methodological and technical assumptions, and inventories are described and provided in Haupt et al. (submitted). Data for the background system, i.e. data on processes that interact with the foreground system supplying or receiving material or energy, was taken from ecoinvent (system model cut-off, version 3.3 (Wernet et al., 2016)).

2.3. Case study

The case study serves to both illustrate the application of the modular LCA and to draw policy conclusions from it. It encompasses the region of Switzerland for the reference year 2012, and is based on a detailed assessment of both municipal solid waste (MSW) flows from Swiss households and industrial waste with a similar composition (Haupt et al., 2017a). This MFA served as the basis for the process-product matrix for Switzerland. The functional unit of the case study is the treatment of all MSW fractions occurring in Switzerland in 2012. A zero burden assumption was chosen (Finnveden, 1999), therefore the environmental burden of the production of the materials which reach the WMS was neglected. A total of 67% of the MSW was specified on the level of material fractions, i.e. paper, cardboard, glass, PET bottles and other plastics, ferrous metals incl. tinplate, aluminum incl. used beverage cans, and biogenic waste. As data regarding the exact composition of the total MSW was lacking, 9% were as assumed to be mixed MSW (consisting of composites, minerals, textiles, and natural products such as leather). Of the national MSW, 21% are direct deliveries to MSWI plants (from small business or private persons). These direct deliveries were assumed to have the same composition as regular mixed MSW. The remaining 3% of the MSW, i.e. electronic waste, batteries and other hazardous wastes, were not taken into account due to missing data regarding both their mass flows and treatment process LCAs of their treatment processes. The material substitution was modeled by taking the material quality into account (e.g. open-loop and closed-loop systems as defined in Haupt et al. (2017a)). The substitution modeling for Switzerland is described based on Vadenbo et al. (2016) and can be found in the Supporting Information S2.

The direct energy flows in the waste fractions are calculated by quantifying the LHV to each individual flow of the Swiss MFA (Table S1.1 in the Supporting Information). The same LHV are used in the LCA of thermal waste treatments. It was assumed that residual fractions, e.g. from the sorting process of separate collected fractions, have the same composition as mixed MSW. The energy recovery in MSWI was calculated by categorizing the MSWI plants in Switzerland into 5 archetypes as described in Meylan et al. (submitted) and as presented in the Supporting Information (Section 1.4).

2.4. Scenario Analysis for Case study

Five scenarios were developed and assessed to highlight the improvement potential of political measures in the Swiss MSW management system. In all scenarios, the functional unit was kept constant (treating all MSW occurring in Switzerland in 2012). If mass flows into a specific treatment process are changed, this is balanced with a reduction in the amount of the same material in the previous treatment pathways. These scenarios, therefore, present what-if scenarios of waste management actions. All assumptions are described in the following sections. It is important to keep in mind that the scenarios vary in the level of changes necessary for their implementation. Some are rather extreme scenarios that assume drastic changes in WMS, while others reflect changes that have already taken place.

2.4.1. Scenario 1: Increase recycling rates

The collection rates of paper, cardboard, glass, PET, aluminum, tinplate and organic waste were increased by 5%, as this value corresponds to a realistic improvement potential as identified in Steiger (2014). Plastics were kept constant, as an increase in collection rate was tested in scenario 4. The distribution in closed-loop and open-loop recycling pathways was kept consistent with 2012 data. It was assumed that the additional paper and cardboard would be collected together, as this facilitates higher recycling rates. In contrast to paper, 30% of the glass was assumed to be collected as mixed color cullet and 70% as color separated fractions, as found in 2012.

2.4.2. Scenario 2: Increase closed-loop recycling

The recycling rates of 2012 were kept at the same level as identified in Haupt et al. (2017a), however, all materials (exceptions being PET bottles and mixed aluminum) entered the closed-loop recycling pathways. For PET, only blue and transparent bottles are currently used in bottle production and therefore qualify for closed-loop recycling. For aluminum, only source separated used beverage cans are allowed in the closed-loop recycling. In addition, the amount of glass reused was kept constant while substantially increasing the use of cullet in packaging glass production and decreasing the production of foam glass. The recycling of plastic and the utilization of organic waste remain unchanged.

2.4.3. Scenario 3: Increase open-loop recycling

Scenario 3 shows the environmental impact of moving towards more open-loop recycling under the assumption that all material is treated in open-loop processes as defined in (Haupt et al., 2017a). The recycling rates were kept constant. Similar to scenario 2, the recycling of plastic and utilization of organic waste was kept constant.

2.4.4. Scenario 4: Increase plastic recycling

In 2012, only PET bottles and a minor share of the polyethylene bottles were collected separately. Since 2012, however, the amount of separately collected plastic has increased and has reached 11,000 tonnes in 2016. Of this plastic, 48% was collected at retailers (mostly bottles), 10% at communities and public collection points and 42% in a mixed plastic collections bag (Dinkel et al., 2017). This scenario therefore evaluates the effects of the increase in plastic recycling in Switzerland between 2012 and 2016. To enable for comparison with other scenarios, it assumes that overall plastic consumption has not changed. It also assumes that the plastic would be recycled and sorted in Switzerland and residues would be treated in Swiss cement kilns.

2.4.5. Scenario 5: Increase efficiencies in the MSWI

The environmental impact of waste incineration is largely dependent on the energy recovery from the waste (Boesch et al., 2014; Cherubini et al., 2009; Christensen et al., 2009; Harrison et al., 2000; Jeswani et al., 2012). An increase in the energy recovery efficiency is therefore modeled in scenario 5. The efficiencies for the MSWI archetypes are taken from Meylan et al. (submitted) (scenario for 2035, “low MSW amount”) and provided in the Supporting Information (Section 1.4).

3. Results

In total, 190 LCA modules for MSW management were either newly developed or adapted from ecoinvent processes (Table 1). The data for 51 recycling process LCI has been collected to either update existing processes or create new process models. Two modules for biogenic processes were taken from literature and 10 processes were based on the existing ecoinvent processes with minor adjustments. The substitution of 36 materials from recycling processes was modeled. In addition, the thermal treatment of 12 waste fractions was modeled within 84 modules comprising the thermal waste treatment and the recovery and recycling of recovered fractions from fly and bottom ash. The inventories and a description of all modules are provided in (Haupt et al., submitted). These modules can be combined flexibly to model a WMS.

In the Swiss MSW management system case study, the LCA modules are used to model the more than 500 processes of the Swiss MSW management system. The number of processes exceeds the number of modules, as some modules were used to approximate several processes. For example, the same LCA module was used for sorting used beverage cans, sorting aluminum from tinplate and sorting tinplate. The new LCA modules, their contribution to the overall system and the overall environmental impact of the Swiss MSW management system are described in the following sections.

Table 1: *List of process life cycle inventories developed and applied in this paper, ordered according to the material waste fractions. A detailed description of the models as well as the resulting inventories can be found in* (Haupt et al., submitted)*.*

material	process	process description	LCI
paper	collection	collection of waste paper	new LCI
	sorting	sorting of waste paper CH	new LCI (same as for cardboard)
	recycling	paper recycling to secondary fibers for newsprint production CH	new LCI
	recycling	reuse of waste paper in the production of insulation material CH	new LCI
	recycling	paper recycling to secondary fibers for newsprint production RER	LCI adapted from ecoinvent
	substitution	substitution of newsprint from virgin fibers	S, LCI from ecoinvent
	substitution	substitution of insulation made from cellulose	LCI adapted from ecoinvent
cardboard	collection	collection of waste cardboard CH	new LCI
	sorting	sorting of waste cardboard CH	new LCI
	recycling	cardboard recycling to secondary fibers for linerboard production CH	new LCI
	recycling	cardboard recycling to secondary fibers for fluting medium production CH	new LCI
	recycling	reuse of waste cardboard in the production of insulation material CH	new LCI (same as for paper)
	recycling	cardboard recycling to secondary fibers for cardboard production RER	LCI adapted from ecoinvent
	substitution	substitution of corrugated board from virgin fibers	S, LCI from ecoinvent
	substitution	substitution of insulation made from cellulose	LCI adapted from ecoinvent
biogenic waste	collection	collection of biogenic waste CH	new LCI
	composting	composting of biogenic waste from household	Zschokke and Schleiss (2016)
	anaerobic digestion	anaerobic digestion of biogenic waste form household	Zschokke and Schleiss (2016)
	substitution	N fertilizer replaced by compost	S, LCI from ecoinvent
	substitution	P fertilizer replaced by compost	S, LCI from ecoinvent
	substitution	K fertilizer replaced by compost	S, LCI from ecoinvent
	substitution	N fertilizer replaced by liquid digestate	S, LCI from ecoinvent
	substitution	P fertilizer replaced by liquid digestate	S, LCI from ecoinvent
	substitution	K fertilizer replaced by liquid digestate	S, LCI from ecoinvent
	substitution	N fertilizer replaced by solid digestate	S, LCI from ecoinvent
	substitution	P fertilizer replaced by solid digestate	S, LCI from ecoinvent
	substitution	K fertilizer replaced by solid digestate	S, LCI from ecoinvent
	substitution	substitution of natural gas through biogas	S, LCI from ecoinvent
	substitution	substitution of peat from compost and digestate	S, LCI from ecoinvent
	substitution	substitution of straw from compost and digestate	S, LCI from ecoinvent
plastics	collection	collection of post-consumer plastic bottles or mixed plastics at curbside CH	new LCI
	collection	collection of post-consumer plastic bottles or mixed plastics at collection points CH	new LCI
	collection	collection of post-consumer plastic bottles or mixed plastics at retailers CH	new LCI
	sorting	sorting of mixed plastics or plastic bottles CH	new LCI
	sorting	sorting of mixed plastics or plastic bottles DE	new LCI
	sorting	sorting of mixed plastics or plastic bottles AT	new LCI
	recycling	recycling of polyethylene to polyethylene granulate, non-food-grade CH	new LCI
	recycling	recycling of polyethylene to polyethylene granulate, non-food-grade RER	new LCI
	substitution	substitution of primary, high impact polystyrene granulates	S, LCI from ecoinvent
	substitution	substitution of primary high-density polyethylene granulates	S, LCI from ecoinvent
	substitution	substitution of primary low-density polyethylene granulates	S, LCI from ecoinvent
	substitution	substitution of primary polypropylene	S, LCI from ecoinvent
	substitution	substitution of wood	S, LCI from ecoinvent
	substitution	substitution of concrete	S, LCI from ecoinvent

Table 1: *continued*

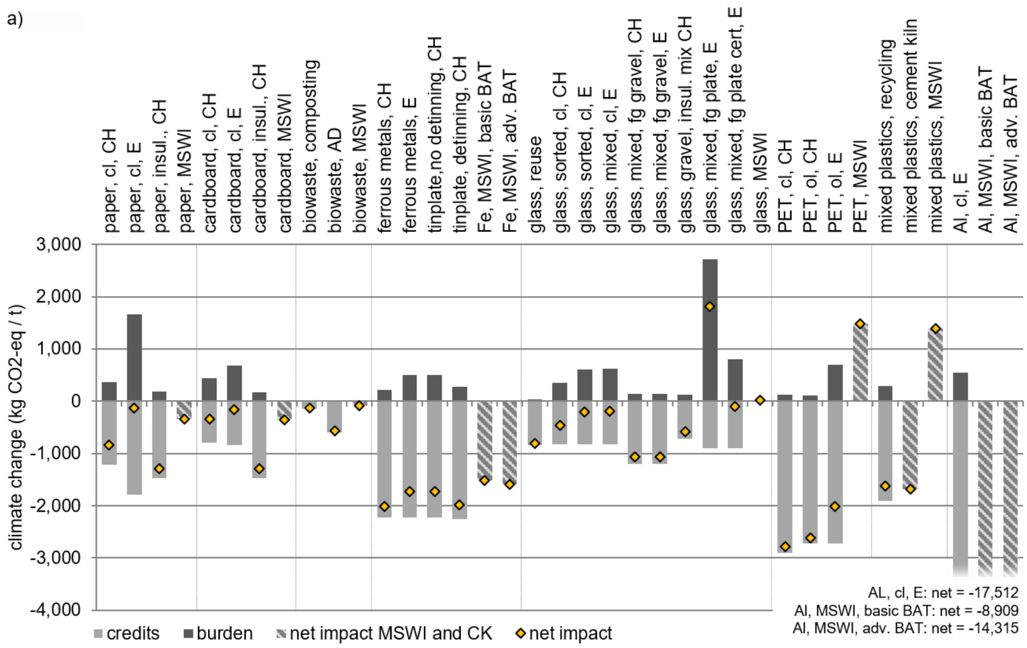
material	process	process description	LCI
PET bottles	collection	collection of waste PET bottles	new LCI
	sorting	sorting of waste PET bottles (from residues and according to color) CH	new LCI
	sorting	sorting of waste PET bottles (from residues) and transport for export CH	new LCI
	recycling	recycling of PET bottles to PET, bottle-grade CH	new LCI
	recycling	recycling of PET bottles to PET, amorphous CH	new LCI
	recycling	recycling of PET bottles to PET, bottle-grade RER	new LCI
	recycling	recycling of PET bottles to PET, amorphous RER	LCI adapted from ecoinvent
	substitution	substitution of primary bottle-grade PET granulates	S, LCI from ecoinvent
	substitution	substitution of primary amorphous PET granulates	S, LCI from ecoinvent
beverage cartons	collection	collection of post-consumer beverage cartons at curbside CH	new LCI
	collection	collection of post-consumer beverage cartons at collection points CH	new LCI
	collection	collection of post-consumer beverage cartons at retailers CH	new LCI
	sorting	sorting of beverage cartons from mixed plastics or plastic bottles CH	new LCI
	sorting	sorting of beverage cartons from mixed plastics or plastic bottles DE	new LCI
	sorting	sorting of beverage cartons from mixed plastics or plastic bottles AT	new LCI
	recycling	recycling of fibers in beverage cartons to linerboard CH	new LCI
	recycling	recycling of fibers in beverage cartons to linerboard DE	new LCI
	recycling	recycling of fibers in beverage cartons to linerboard AT	new LCI
	substitution	substitution of linerboard from primary production	S, LCI from ecoinvent
ferrous metals	collection	collection of waste tinplate and aluminum CH	new LCI (same as for tinplate)
	sorting	sorting of waste tinplate and aluminum CH	new LCI (same as for tinplate)
	transport	transport of ferrous metals from CH to RER	new LCI
	recycling	recycling of ferrous scrap to low-alloyed steel in EAF CH	new LCI
	recycling	recycling of ferrous scrap to low-alloyed steel in EAF RER	LCI from ecoinvent
	substitution	substitution of primary steel from converter	S, LCI from ecoinvent
tinplate	collection	collection of waste tinplate and aluminum CH	new LCI
	collection	collection of waste tinplate and aluminum and export CH	new LCI
	sorting	sorting of waste tinplate and aluminum CH	new LCI
	sorting	sorting of waste tinplate and aluminum RER	new LCI
	recycling	detinning of waste tinplate CH	new LCI
	recycling	tin production from concentrate RER	new LCI
	recycling	recycling of black plate to low-alloyed steel in EAF CH	new LCI (same as steel scrap)
	substitution	substitution of primary tin	S, LCI from ecoinvent
	substitution	substitution of primary steel from converter	S, LCI from ecoinvent
aluminum, UBC	collection	collection of waste tinplate and aluminum (mixed) CH	new LCI (same as for tinplate)
	sorting	sorting of waste tinplate and aluminum CH	new LCI (same as for tinplate)
	sorting	sorting of waste tinplate and aluminum RER	new LCI (same as for tinplate)
	recycling	remelting of sorted aluminum to cast aluminum RER	LCI from ecoinvent
	recycling	remelting of sorted used beverage cans to wrought aluminum RER	LCI from ecoinvent
	substitution	substitution of primary wrought aluminum from UBC	S, LCI from ecoinvent
	substitution	substitution of cast aluminum from mixed post-consumer aluminum	S, LCI from ecoinvent

Table 1: *continued*

material	process	process description	LCI
glass	collection	collection of waste packaging glass	new LCI
	sorting	sorting of waste packaging glass CH	new LCI
	sorting	sorting of waste packaging glass RER	new LCI
	recycling	washing of packaging glass for reuse CH	new LCI
	recycling	recycling of glass to green packaging glass CH	new LCI
	recycling	recycling of glass to green packaging glass DE	LCI from ecoinvent
	recycling	production of green packaging glass from primary raw materials CH	new LCI
	recycling	production of green packaging glass from primary and secondary raw materials CH	new LCI
	recycling	recycling of glass to foam glass gravel CH	new LCI
	recycling	recycling of glass to foam glass plates RER	LCI from ecoinvent
	recycling	recycling of glass to foam glass gravel RER	LCI from ecoinvent
	recycling	recycling of glass to glass sand CH	new LCI
	substitution	substitution of average Swiss insulation mix	S, LCI from ecoinvent
	substitution	substitution of XPS	S, LCI from ecoinvent
	substitution	substitution of green packaging glass made from primary materials	S, LCI from ecoinvent
	substitution	substitution of primary foam glass plates RER	S, LCI from ecoinvent
	substitution	substitution of foam glass plates from primary and secondary materials	S, LCI from ecoinvent
	substitution	substitution of sand by glass sand from cullet	S, LCI from ecoinvent
mixed MSW	collection	collection of mixed municipal solid waste from curbside CH	LCI from ecoinvent
	collection	transport of sorting residues to municipal solid waste incineration CH	LCI from ecoinvent
	incineration	incineration of various fractions CH	12 LCIs from Boesch et al. (2014)
	incineration	incineration of MSW (incl. ash treatments and energy recovery) DE	LCI from ecoinvent
	bottom ash treatment	advanced bottom ash treatment for various fractions CH	12 LCIs from Boesch et al. (2014)
	bottom ash treatment	basic bottom ash treatment for various fractions CH	12 LCIs from Boesch et al. (2014)
	fly ash treatment	fly ash in underground deposit	12 LCIs from Boesch et al. (2014)
	fly ash treatment	fly ash in residual material landfill (after stabilization with cement)	12 LCIs from Boesch et al. (2014)
	fly ash treatment	acid fly ash washing and treatment of hydroxide sludge in Waelz kiln (FLUWA process)	12 LCIs from Boesch et al. (2014)
	fly ash treatment	acid fly ash washing and direct zinc electrolysis (FLUREC process)	12 LCIs from Boesch et al. (2014)
	heat recovery	flows of recovered heat were integrated in product-process matrix (60 flows)	-
	electricity recovery	flows of electricity produced were integrated in product-process matrix (60 flows)	-
	substitution	material substitution according to Boesch et al. (2014)	S, LCI from ecoinvent
	substitution	substitution of alternative energy carriers in district heating networks	new LCI
	substitution	substitution of alternative heating systems	new LCI
	substitution	substitution of Swiss electricity mix	S, LCI from ecoinvent
cement kiln	treatment	use of PE as alternative fuel in cement kiln (clinker production) CH	LCI adapted from ecoinvent
	substitution	substitution of clinker produced from coal as energy carrier CH	LCI adapted from ecoinvent
all fractions	building	waste preparation facility	new LCI

3.1. LCA of individual modules

Figure 2 shows the environmental impacts for the treatment of one tonne of various materials in the given valorization pathway, including its collection, preparation for recycling, recycling and the resulting material substitution. The results describe the collection of 1 tonne of the recyclable material as well as the respective residues in their collection (e.g. the collection of 1 t of PET also includes 0.3 t of mixed MSW, which is sent for treatment in a MSWI during the sorting or recycling process).



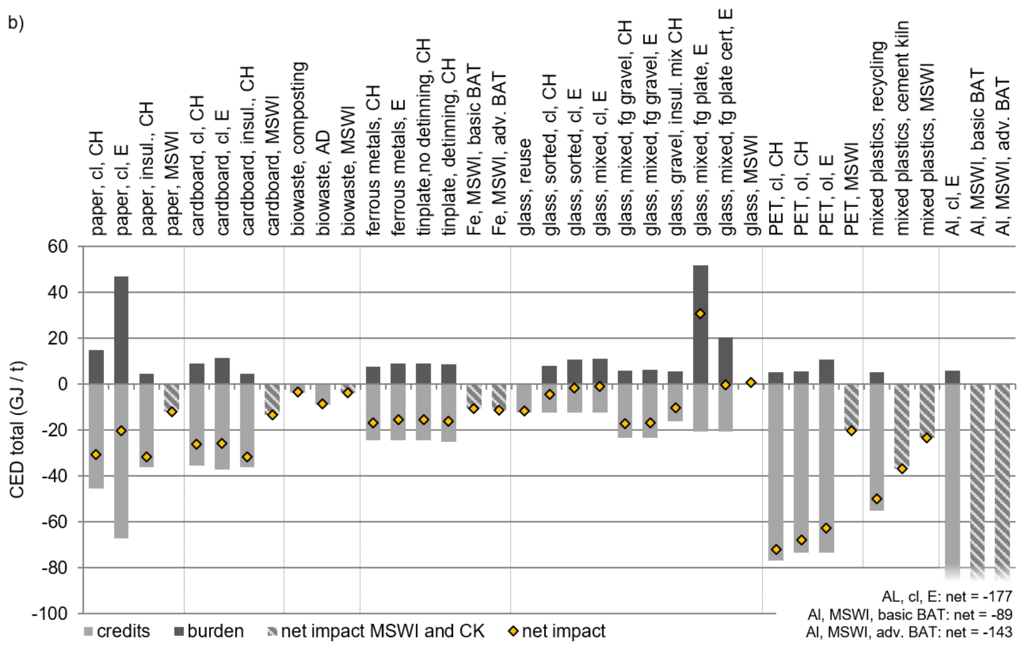


Figure 2: *Climate change impacts (a) and CED (b) per tonne of material recycled including the treatment of the residues arising in the separate collection system. cl = closed-loop, ol = open-loop, insul = to cellulose insulation production, for glass: mixed = mixed color collection and sorted = color sorted collection, fg = foam glass, cert = produced with certified electricity, MSWI = municipal solid waste incineration, CK = cement kiln, BAT = bottom ash treatment, adv = advanced, CH = recycling in Switzerland, E = exported material which is recycled in Europe.*

3.1.1. Paper and cardboard recycling

For paper and cardboard, both the recycling and the treatment in MSWI with energy recovery is environmentally beneficial. Because of industry wide environmental improvement initiatives, the new LCI for paper recycling in Switzerland has reduced impacts by half due to 25% lower electricity use and reduced water consumption. These changes have led to a substantial increase in the environmental benefits associated with paper recycling when recycling compared to previous studies in which paper recycling was not necessarily beneficial (depending on the indicator, for example in Merrild et al. (2009) and Dinkel and Kägi (2014)). Overall life cycle impacts from recycling amount to -350 kg CO_2-eq/t of cardboard and -840 kg CO_2-eq/t of paper. If paper and cardboard wastes were used to produce insulation material, the highest credits (-1290 kg CO_2-eq/t of paper, see Figure 2) were yielded if XPS is substituted. For impacts measured as CED, the insulation production from waste paper and the closed-loop recycling reveal similar credits (-32 GJ-eq/t and -31 GJ-eq/t, respectively). If waste paper is recycled abroad or treated in MSWI, credits were -20 GJ-eq/t and -12 GJ-eq/t, respectively.

3.1.2. Metal recycling

On a per tonne basis, metals are, from an environmental perspective, the most significant fraction being studied. Environmental benefits of aluminum recycling are as high as -17.5 t CO_2-eq/t or -177 GJ-eq/t of recycled aluminum assuming a global aluminum market. There is a large range of possible credits, as Damgaard et al. (2009) identified credits ranging between -3.8 to -19 t CO_2-eq/t for recycled aluminum. For tinplate and ferrous scrap, the recycling resulted in -2 t CO_2-eq/t of ferrous metals recycled (-17 GJ-eq/t) within Switzerland and -1.7 t CO_2-eq/t (-15 GJ-eq/t) for material recycled elsewhere in Europe. While not evident from the chosen main impact indicators, the toxicity of slag disposal resulting from steel recycling can dominate other, toxicity based, impact categories. While the burdens of recycling differ geographically based on the electricity sources, the credits given (converter steel from Europe) were assumed to be the same everywhere. This assumes a European market for primary steel, and hides the differences regarding the environmental burdens (primary production creates tenfold the environmental impact compared to recycling).

Impacts from tinplate recycling differ depending on the pre-treatment of the recyclables. Separately collected tinplate that undergoes a detinning procedure (electro-chemical process to separate tin from steel) reveals an environmental benefit of -2 t CO_2-eq/t (-16 GJ-eq/t). Tinplate that is recycled without prior detinning (where tin is lost in the steel product) has lower (12%) environmental benefits than detinned tinplate. As the tin content of collected tinplate is lower than Swiss and European scrap specification tin limits (Eurofer, 2008; Haupt et al., 2017b; Stahl Gerlafingen AG and Swiss Steel AG, 2010), it was assumed that tin would not restrict the future utilization of the steel in its first recycling cycle. The accumulation of tin, however, was not modeled, as this would require a global model for the accumulation of impurities (similar to Daehn et al. (2017) for copper) for the alloying element tin (similar to Nakamura et al. (2017)). The net benefits for both metals are within the range outlined in Brogaard et al. (2014).

For comparison, metals recovered from the bottom ash of thermally treated aluminum or ferrous scrap treatment and later recovery of metals was modeled. The differences between the basic and advanced bottom ash treatment are described using different recovery efficiencies for metals (Haupt et al., submitted). Relative to the credits from separately collected metals (see Figure 2), the credits that can be realized through metal recovery in bottom ash treatment plants are between 75% and 80% for ferrous metals and between 50% and 81% for aluminum.

3.1.3. Glass recycling

The impacts of glass recycling vary depending on the secondary product and the substitution of primary material. The new inventories lead to benefits of -805 kg CO_2-eq/t of waste for glass reuse, -466 kg CO_2-eq/t of waste cullet used in domestic packaging glass production and -211 kg CO_2-eq/t if the glass is exported for recycling to packaging glass (Figure 2). The production of foam glass gravel is highly beneficial if XPS insulation material and foam glass plates are substituted, and results in -1066 kg CO_2-eq/t. The results in terms of CED also highlight the benefit of foam glass gravel and bottle reuse (Figure 2).

Foam glass gravel was assumed to replace a mixture of XPS and primary foam glass plates based on

Stettler et al. (2016), but the sensitivity of the results to this assumption was tested by substituting a common Swiss insulation mix (EPS, XPS, PUR, mineral wool, and glass wool (Kasser et al., 2016)), which lead to a reduced foam glass gravel credit by 45% (Figure 2). The production of foam glass plates is highly energy intensive and the related substitution of XPS only results in credits if certified electricity is used for the recycling (as currently done in Belgium (IBU, 2015)). Also, the energy inputs required for the production of packaging glass are responsible for a large share of the burdens and, therefore, the overall impacts are largely dependent on the location (-1320 kg CO_2-eq/t in Switzerland and -800 kg CO_2-eq/t in Europe).

3.1.4. Plastic recycling

The Swiss collection rates of PET are high (85%) compared to international rates. The PET recycling system is regularly assessed (Dinkel and Hauser, 2008; FOEN, 2013), and was updated for this study. The potential net savings arising from substitution of virgin plastic were estimated to be between -2,567 and -1,766 kg CO_2-eq/t (at collection rates of 1% and 99%, respectively, assuming the 2012 shares between open- and closed-loop recycling) of plastic waste, depending on the collection rate, the related purity and the transport distance (Haupt et al., submitted).

The recycling of polyethylene and other plastics is less environmentally beneficial than the recycling of PET (-1,600 kg CO_2-eq and -50 GJ-eq/t compared to -2,800 kg CO_2-eq and -72 GJ-eq/t, respectively) because their primary production is less energy intensive. The use of plastic as auxiliary fuel in cement kilns reveals credits in the same order of magnitude as the recycling of polypropylene, polyethylene and polystyrene for climate change impacts. By contrast, co-processing of PET in clinker kilns results in lower credits than material recycling (-50% for climate change impacts). In this study, only packaging material was considered, which means pollutant content was relatively low compared to waste electric and electronic equipment. The inclusion of polluted fractions could substantially increase toxicity impacts of plastic utilization, e.g. in cement kilns. Direct landfilling of plastic was not considered based on Swiss regulations (VVEA, 2016).

3.2. LCA of the Swiss MSW management system

Taking a zero burden assumption (burden free reception of waste by the WMS), the environmental assessment results in credits of -0.6 million tonnes of CO_2-eq/a and -60 PJ-eq/a, therefore compensating for 1% of the total climate change impacts and 4% of the CED of total Swiss consumption reported by Frischknecht et al. (2014) and shown in Figure 3. Paper, cardboard and mixed MSW represent 22%, 9% and 33%, respectively, of the 700 kg MSW per person per year in 2012. Because of the relatively high collection rates for cardboard and paper (89% and 74%, respectively; Haupt et al. (2017a)), the result in terms of CED is dominated by paper (23%), cardboard (23%) and the MSWI contribution (38%). Compared to CED, where air emissions are burden-free, air emissions of the MSWI lead to its dominating role in terms of climate change impacts; MSWI is responsible for the vast majority of burdens, with paper and cardboard contributing 36% to the credits, aluminum 27% and biogenic waste 18%.

Figure 3 shows the distribution of burdens and benefits for CED, cumulative exergy demand (CExD), climate change, human toxicity and ecotoxicity, and highlights the shares of the different materials contributing to the different impact indicators. From these results and the assessment of the ILCD categories (see details in Supporting Information, section 2.2), four groups of indicators can be identified. For the first group, consisting of climate change, eutrophication, and photochemical ozone creation, the burdens related to the MSWI (mainly CO_2 and NO_x emissions) are dominating the LCA outcome. Large credits from aluminum recycling occur, as primary production of aluminum releases substantial amounts of process-dependent CO_2 in the de-oxidization of alumina to aluminum metal. The eutrophication is substantially influenced by the utilization of biogenic waste from households and the related substitutions. The second group consists of the CED, CExD and the ozone layer depletion and is characterized through large credits from MSWI occurring based on the substitution of primary energy carriers. CED and CExD only account for energy inputs, which leads to lower burdens from the thermal process. Due to the lower energy demand in paper recycling compared to primary production, paper and cardboard together make up two thirds of the credits in terms of CED and CExD. The third group includes impacts related to the ionizing radiation, which are dominated by large credits from electricity substitution from MSWI plants (due to the high share of nuclear power in Switzerland). The toxicity related impact categories, ecotoxicity, human toxicity, and carcinogenic and non-carcinogenic effects, form the fourth group. The results of these impact categories are dominated by recycling processes, while the thermal treatment of waste plays an insignificant role. From the materially recycled fractions, metals and fibrous materials are important for both ecotoxicity and human toxicity. While paper and cardboard production mainly lead to non-carcinogenic emissions, primary metal production causes heavy metal emissions from the disposal of tailings and ore processing wastewater.

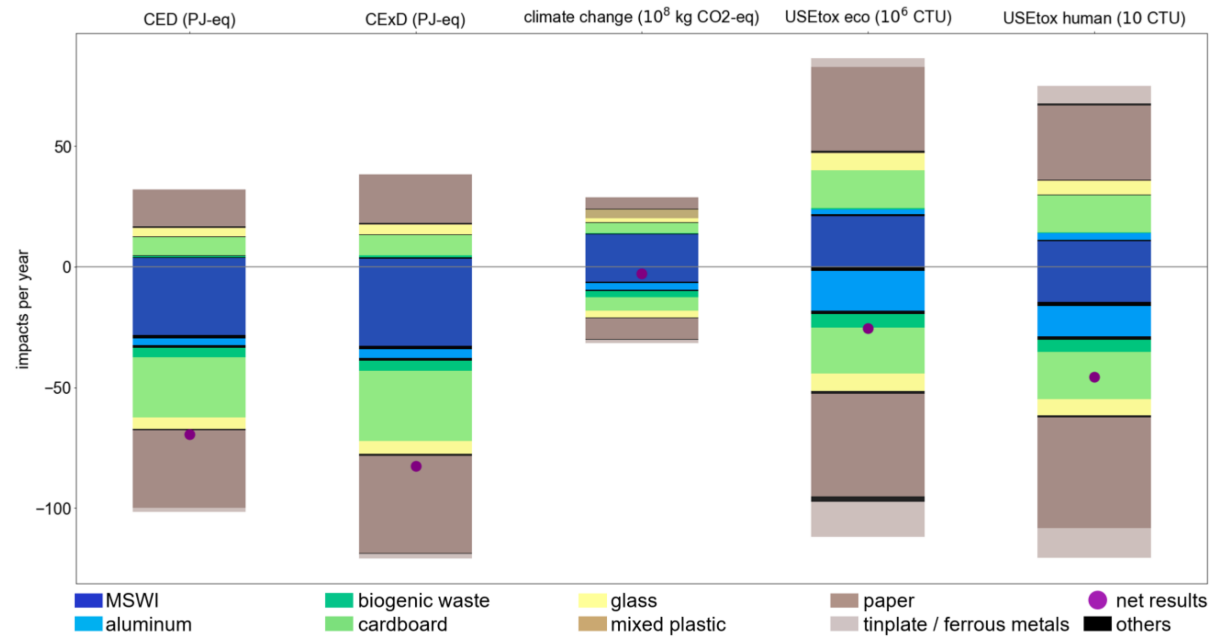


Figure 3: *Positive, negative and net environmental impacts for all recycling fractions in Switzerland in 2012. The results for the MSW include the treatment of residues from recycling processes. The units for the different impact categories are given on the x-axis. The numeric results of the impact categories are not comparable with each other but should be interpreted individually.*

For all categories, the results per tonne of material stream highlighted the large difference in environmental impacts between primary and secondary metal resource use. Nevertheless, metal's contribution to the overall impacts of the WMS is limited because of the small fraction of metal waste in MSW. By contrast, paper, cardboard and glass cause a larger share of overall impact due to their sheer mass.

3.3. Scenario analysis

Using the linked MFA and modular LCA model, various scenarios evaluating different waste related political measures were calculated for Switzerland. Scenario 5, increasing energy recovery in MSWI, shows a large overall environmental benefit (climate change benefit +44%) compared to the current Swiss WMS. This is due to the rather low average electricity and heat recovery efficiencies from Swiss MSWI (25% for heat and 15% for electricity (Rytec, 2013)) compared to other countries (65% for heat and 29% for electricity in Denmark (Fruergaard and Astrup, 2011)). These low efficiencies are due to the decentralized structure of the Swiss WMS and the small plant size. Furthermore, the plants are often not optimized for energy recovery because of their size and age. Scenario 2 (promotion of closed-loop recycling) also shows an improvement to the current system with a climate change benefit of +22%. The increased savings are mostly related to additional paper recycling, which yields larger credits than the use of paper fibers in cardboard production. Surprisingly, an increase of open-loop recycling for all fractions (scenario 3) also results in an increase of the overall environmental benefit (climate change impact +18%) compared to the reference scenario. The main reason is the large credit for glass recycling related to the substitution of the insulation materials XPS and primary foam glass plates. It is, therefore, not possible to deduce general recommendations for or against open- or closed-loop recycling system. Instead, a mix of both, optimized for minimizing environmental impacts, would provide the largest benefit. While for paper closed-loop recycling to paper fibers is favorable compared to open-loop recycling to cardboard, the production of insulation material from glass cullet results in higher credits than recycling to packaging glass. A 5% increase in the recycling rates leads to a 7% net increase of climate change credits, highlighting that mere quantitative recycling rate increases have a limited improvement potential in countries with already high recycling rates such as Switzerland.

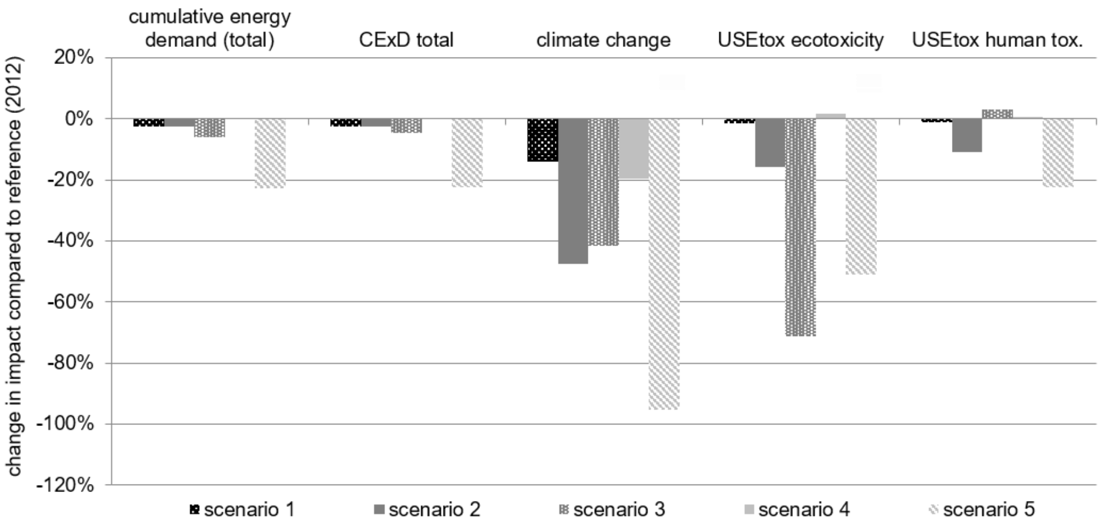


Figure 4: *Results of the scenario assessment for the case study on the Swiss MSW management system. The reference system (ref) is used to normalize the impacts for each impact category. The following scenarios are shown: (1) increased collection rates by 5% for all source separated fractions except plastic, (2) increased closed-loop recycling, (3) increased open-loop recycling, (4) increased plastic recycling, and (5) higher energy recovery efficiency in the MSWI.*

Scenario 4 represents a moderate increase of plastic recycling compared to the reference year 2012.

The recycling rates were set to Switzerland's 2016 rates (Dinkel et al., 2017). Although the amount of plastic recycled was doubled, only 6% of the plastic consumed was recycled in 2016. The increase in recycling rates leads to a 20% improvement in climate change impacts compared to the overall environmental performance of the Swiss MSW management system in 2012. This is due to the reduced CO_2 emissions, as less plastic is found in the thermally treated MSW. There was a small reduction of the CED credits, as the increased plastic recycling rate only reveals marginal credits and less energy is produced in the MSWI (-1%). With regard to toxicity, no significant improvement could be found when increasing plastic recycling. Note that if more ambitious increase in recycling rates had been assumed, the benefits would have been much larger.

3.4. Direct and indirect contribution to energy system

The lower heating value (LHV) of all MSW streams of the Swiss WMS summed to 71,000 TJ (Figure 5, based on Haupt et al. (2017a)). Approximately 40% of MSW, by calorific value, is currently collected in a source separated manner, and the remaining 60% was treated in waste-to-energy plants. Of the 37,000 TJ contained in thermally treated waste, 10,000 TJ of heat and 6,300 TJ of electricity were recovered. Taking the substitution of primary heat and electricity into account, the resulting net cumulative energy benefits, i.e. indirect energy benefits, amount to 30,000 TJ-eq. The indirect savings from materially recycled fractions from households or utilized biogenic waste from gardens and kitchens were found to substantially surpass the LHV fractions (LHV: 30,000 TJ, net CED savings through substitution: 45,000 TJ (neglecting credits from WEEE, battery and textile recycling)). Relative to its primary production, aluminum shows the highest savings per tonne. Waste paper and cardboard, however, are the largest waste streams by mass and therefore offer the largest total indirect energy gain (34,000 TJ, 72% of all indirect net CED gains).

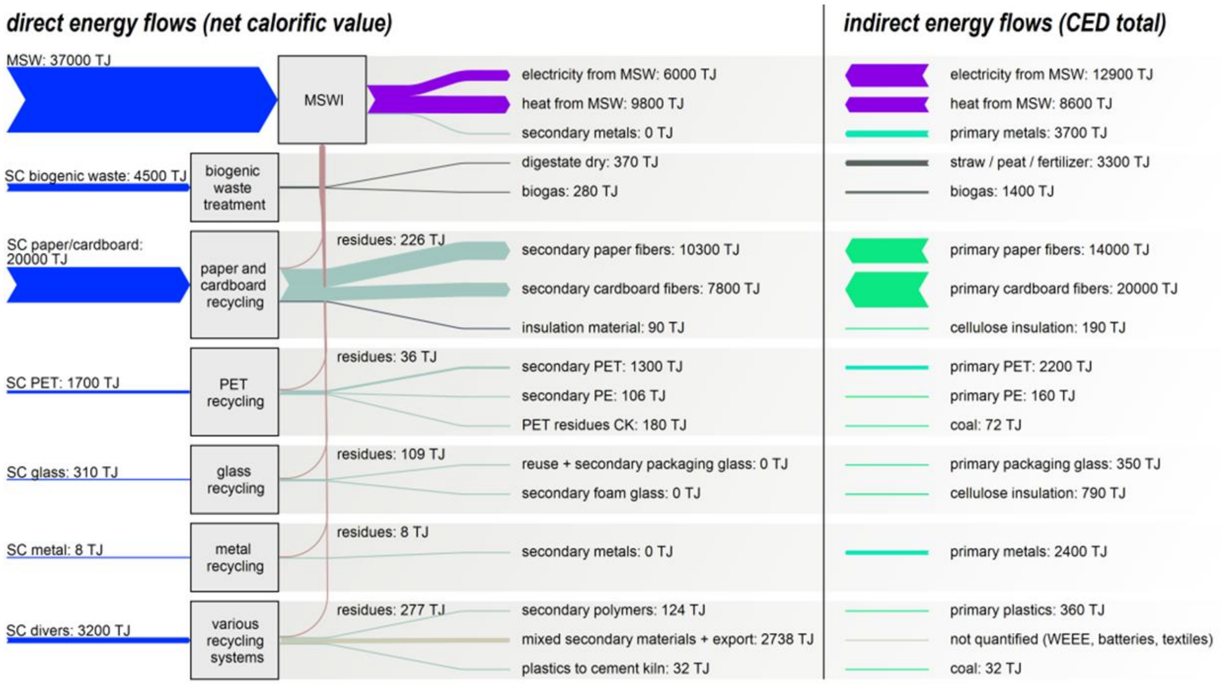


Figure 5: *Direct energy flows in the Swiss MSW management system (left) compared to indirect energy flows measured as total net cumulative energy demand savings (difference in CED of the recycling processes and the related credits for material substitutions (right)). SC = material from separate collection.*

The results are particularly sensitive to the electricity and heat substituted by the recovered energy. In the base case (shown in Figure 5) it was assumed that today's mix of energy carriers feeding into district heating network was substituted. The assumption that heat production would take place at a household level, if no district heating network would exist (resulting in a higher share of oil and gas substituted), increased the CED gain of the heat recovery by 50%.

4. Discussion and Conclusions

The use of MFA as a basis of the LCA has enabled for evaluation of the input-dependent assessment of emissions and impacts of all recycling processes, the thermal treatment of MSW, and the overall impacts of the Swiss WMS. The LCA results are dominated by the impacts from paper and cardboard recycling and the thermal treatment of residual waste. Although the environmental benefit per tonne of paper and cardboard recycling is relatively low, this fraction dominates the total impact score due to their high share of the overall waste produced (30%) and high collection rates (74% and 89%, respectively (Haupt et al., 2017a)). The results of the Swiss WMS highlight the need to investigate

WMS with reference to the actual material flows in order to prioritize impact-reduction efforts on the waste flows that will provide the most impactful results.

Taking a zero burden assumption, the overall impact results are negative and, therefore, quantify the environmental benefit of the MSW management system. The results should not lead to the erroneous conclusion that waste production should be increased.

Overall, the WMS was found to compensate for 1% (CO_2-emissions) and 4% (CED) of the impact of Swiss consumption. This is a significant contribution that highlights the need to optimally manage waste as a material and energetic resource.

Substitution benefits are much more uncertain than the direct impacts of the recycling and disposal processes. Therefore, the uncertainty on the net environmental impact is rather high. As argued by Zink and Geyer (2017), substitution benefits require a market where the recycled material can substitute primary material . A sensitivity analysis showed that a 20% demand reduction for all fractions results in a 66% environmental benefit reduction. The uncertainty with regard to substitution benefits is difficult to quantify due to the large dependence on the global market, consumer patterns and product development, and this uncertainty should be kept in mind when drawing conclusions from the LCA. Furthermore, the results are particularly sensitive to the Swiss electricity mix, which contributed between 13% (USEtox) to 61% (climate change) to the overall environmental impacts, taking all direct and upstream electricity consumptions into account.

While the concept of Circular Economy assumes that closed material cycles are preferred, several open-loop recycling pathways have been found to be environmentally superior. The substitution of insulation material with foam glass and recycled paper and cardboard, for example, leads to higher environmental credits than the production of packaging glass, linerboard or newsprint from recycled material. For glass, open-loop systems yield higher credits if the polystyrene material XPS is replaced. If paper and cardboard are used in insulation, fewer fibers are lost in the production of insulation material compared to the pulping required for closed-loop recycling, leading to higher environmental benefits. The share of paper and cardboard used as cellulose insulation material has increased in Switzerland over the last years and might also increase further as paper consumption and, therewith, the need for waste paper shrinks. The results highlight the need to integrate LCA in the Circular Economy concept in order to avoid environmentally adverse circles.

While the direct energy production from the Swiss WMS can be increased, the findings highlight that the indirect energy benefits are substantial. Although the indirect energy savings are much higher, most of the benefits are not local due to the high import share of goods. Therefore, they do not influence the national energy system as much as the direct energy recovered from incineration plants or fuel substitutions. Policy makers are therefore advised to take these indirect effects into account, as reaching the overall optimum requires thinking beyond national boundaries and taking a consumption footprint perspective (Frischknecht et al., 2014).

Several recommendations can be drawn from the scenario analysis. On the one hand, increasing the energy recovery efficiency of the MSWI is essential to improving system performance. This can be realized through a relocation of MSWI plants to industrial or urban areas with a high heat demand. On the other hand, recycling pathways should be optimized with a systems perspective which would allow for an optimal distribution of recyclables into open- and closed-loop recycling systems.

The modular approach chosen in this study allows for flexible evaluation of different mass flow distributions in the Swiss WMS and, therefore, assessing future waste management strategies. It also facilitates the integration of new modules (e.g. new technologies, treatments, collection routes, or WEEE recycling systems), the assessment of the influence of the new modules and their environmental contribution to the overall system. Also, changes in the waste composition, the respective treatment options and capacities as described in Meylan et al. (submitted) can be environmentally assessed. The presented model can, furthermore, be used in a mathematical optimization by providing the inputs for a linear programming extended matrix based LCA (Heijungs and Suh, 2002; Saner et al., 2014; Vadenbo et al., 2014a, 2014b). While the chosen attributional system model allows for modeling the current waste management, the application in optimization and, ultimately, in decision making requires a consequential perspective taking imposed system changes into account. The chosen modular structure enables for the formulation of a consequential LCA, therefore providing a framework for future decision making based on up-to-date LCIs.

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Melanie Haupt and Stefanie Hellweg have designed the study. Melanie Haupt was responsible for the main modelling work and the preparation of the manuscript and has, together with Thomas Kägi, collected the industrial data for the life cycle inventories presented. Both, Stefanie Hellweg and Thomas Kägi, also have contributed to the manuscript and the related Supporting Information.

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