Linking energy scenarios and waste storylines for prospective environmental assessment of waste management systems

Grégoire Meylan[a,*], Melanie Haupt[c], Mert Duygan[b], Stefanie Hellweg[c] and Michael Stauffacher[b]

[a]Center for Business in the Americas, School of Management and Law, ZHAW Zurich University of Applied Sciences, 8401 Winterthur, Switzerland

[b]Transdisciplinarity Lab, Department of Environmental Systems Science, ETH Zurich, 8092 Zurich, Switzerland

[c]Chair of Ecological Systems Design, Institute for Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

To be submitted to: Waste Management

8/3/2018

---

[*] Corresponding author: Tel.: +41 44 632 32 98. Email address: g.meylan@usys.ethz.ch; Full postal address: Grégoire Meylan, ETH Zurich, CHN K 76.2, Universitaetstrasse 22, 8092 Zurich, Switzerland

Abstract

Multiple international and supranational organizations call upon changes in current waste management practices to play a key role in developing more sustainable economies. Life cycle assessment (LCA) is a popular method used to assess the sustainability of future waste management options. The uncertainties about future energy systems and waste compositions, however, may lead to ambiguous LCA results. One way to deal with this challenge is the development of joint energy and waste scenarios to investigate the robustness of waste management options. To date, joint energy and waste scenarios rely on the integration of large economic and engineering models. Complex models can hamper the transparency required for decision-makers to understand and implement LCA recommendations. Here we present the alternative of combining diverse energy scenarios and stakeholder-based waste storylines. This is a more qualitative approach than previous sustainable energy/waste evaluations and has a double aim: to address upfront the energy and waste composition sensitivity and enhance transparency by both relying on well-documented energy scenarios and involving stakeholders in the waste storyline formulation. We apply the approach to the Swiss municipal solid waste (MSW) management system in the context of the energy transition away from nuclear power. Three energy scenarios capture how radical the transition might be, while the storylines reflect societal developments and waste policies leading to low, high, and average MSW amounts. The approach delivers feasibility spaces of energy systems and waste compositions as input to the LCAs. It ensures a high level of transparency,

which, in conjunction with the participation of decision-makers, has the potential to increase the chances of implementation of the recommendations based on LCA results.

Keywords: energy scenarios, life cycle assessment, maximally diverse scenarios, municipal solid waste, Storyline and Simulation Approach (SAS)

1 Introduction

Any decision affecting the far future, such as an investment in long-term infrastructure or the enactment of a new regulation, requires (i) scrutinizing various options and (ii) assessing these options against various criteria, which may include environmental impacts, economic benefits and costs, and social acceptance (Füssel, 2007; Lempert, 2003; Trutnevyte et al., 2012). Waste management is a typical case in which decisions are made with implications reaching far into the future. Waste treatment infrastructure, such as incineration plants with a lifetime of some 25 years (DEFRA, 2014) and longer, are key components of waste management. Different levels of authorities enact waste management regulations that are intended to last for several decades for the sake of legal certainty. Revision of these regulations comes from the need to adapt to changing circumstances such as the emergence of new technologies or due to pressure exerted by developments in other sectors like the energy transition, climate change, etc. (Allen et al., 2011; Geels and Schot, 2007).

In the years to come, many countries should see a stark increase of long-term decisions in the field of waste management, as this sector will play an important role in the initiated and upcoming transitions to low-carbon and sustainable economies. The Intergovernmental Panel on Climate Change (IPCC) indicated in its Fourth Assessment report that the contribution of waste management to reducing global greenhouse gas (GHG) emissions so far had been underestimated due to poor data (Bogner et al., 2008). The IPCC named waste prevention, material recovery (i.e., reuse or recycling) and energy recovery (e.g., incineration and industrial co-combustion) as important mitigation measures in terms of indirect reduction of GHG emissions (e.g., through improved energy efficiency), energy benefits, and fossil fuel use offsets. More recently, the United Nations Environment Programme (UNEP) heralded the potential contribution of waste management towards meeting the Sustainable Development Goals (SDGs) (Wilson, 2015). Waste management is present in more than half of the 17 SDGs, making it a key aspect for sustainable development. To support its case for improving waste management, UNEP claims that 10-15% of global GHG emissions could be avoided through improved solid waste management. Waste prevention could cause this figure rise to 20% (Wilson, 2015).

Life cycle thinking allows one to assess the long-term impacts of different options in various fields, including waste management. Such studies focus on different assessment criteria depending on their goal and scope. In a prospective life cycle assessment (LCA), the analyst models future changes of environmental flows in all life cycle stages of a product or service arising from a decision (or no decision) and assesses the resulting environmental impacts (Frischknecht et al., 2005; Guinée et al., 2011; Hellweg and Milà i Canals, 2014; Pennington et al., 2004; Rebitzer et al., 2004). Complementing the environmental perspective of LCA, prospective life cycle costing (LCC) and social or societal life cycle assessment (sLCA) focus on future economic costs and social impacts, respectively (Hunkeler, 2006; Hunkeler et al., 2008). Prospective LCA has become a popular method amongst decision-makers to assess future waste management options. In the UNEP report cited above, LCA was used to estimate the GHG savings. Likewise, the IPCC recommends the use of LCA to quantify the contributions of waste management to GHG emissions reductions. The EU uses LCA as a key decision-support tool in waste management, as its Waste Directive (European Parliament and Council, 2008) allows member-states to depart from the long-established waste hierarchy (prevention, reuse, recycling, energy recovery, landfilling) if clear-cut LCA results support doing so in a given context. Ongoing debates make it clear that LCA will continue to play an important role in the EU's revised Waste Directive, which integrates the concept of Circular Economy (Haupt and Zschokke, 2017).

The current practice of LCA in waste management, however, suffers from a number of deficits that need to be tackled if the method is to adequately inform long-term decisions. Laurent and colleagues reviewed 222 LCAs of solid waste management systems. They compared these studies and their results (Laurent et al., 2014a), identified common inconsistencies and malpractices, and provided corresponding guidance (Laurent et al., 2014b). The comparison showed that waste management LCA findings strongly depend on the energy system (see also Boesch et al. (2014)) and on the waste composition. In their review (Laurent et al., 2014b), Laurent and colleagues noted a lack of transparency in modeling energy credits. Energy credits are the benefits that arise from recovering heat and electricity created by waste incineration and replacement of the corresponding amounts of energy converted from primary fuels. Heat and electricity credits used in the reviewed studies reflected either the national electricity and heat supply mixes or a marginal energy supply. In the latter case, heat from waste incineration displaces the specific heat system that is expected to be reduced. Most of the 222 LCAs did not justify the choice of national electricity and heat supply mixes or marginal energy supply, with 25% not even indicating the data types used for energy credit modeling. It appears that LCA practitioners often resort to average or marginal data without justifying their choice, although the results of waste management LCAs are highly sensitive to energy systems. Laurent et al. (2014b) further highlighted the poor description of waste composition in LCAs of solid waste management systems and the lack of transparency with respect to waste composition data sources. Yet different waste stream parameters such as nutrient contents, material quality, and heating values are of paramount importance for the proper modeling of energy and material credits.

Given the importance of LCA for decisions in future infrastructure investment like waste management, it is urgent to tackle the fundamental challenge of adequately addressing the sensitivity to future energy mixes and waste composition. Münster et al. (2013) demonstrate how the construction of joint scenarios of energy and waste sectors constitutes a viable approach to deal with this challenge. They recommend that such scenarios reflect those dimensions most important to the LCA results. Arushanyan et al. (2017) implemented this approach for the case of all wastes in Sweden in the project Towards Sustainable Waste Management (TOSUWAMA). In TOSUWAMA, qualitative scenarios of societal development with researcher and stakeholder inputs served as input to a model of the Swedish economy (Tyskeng and Dreborg, 2008). This Computable General Equilibrium (CGE) model was in turn soft-linked with a systems engineering model of Swedish waste management (Ljunggren

Söderman et al., 2016). The output of the systems engineering model was assessed by means of LCA. Also, TOSUWAMA evaluates the impact of various policy measures on waste management performance. The study authors name complexity and uncertainty of the models as the main limitations to TOSUWAMA. Pfenninger et al. (2014) argue that model complexity is an obstacle to transparency. The economic and engineering models entail many implicit assumptions hardly accessible to decision-makers. Yet, such assumptions lead to the energy credits and waste compositions used in ensuing prospective LCAs.

The goal of this paper is to present a methodological approach for developing energy and waste scenarios that enable both a robust and transparent modeling of energy credits and waste composition in prospective waste management LCAs. A robust approach is defined as having the primary aim of the explicit use of diverse future energy credits and waste compositions. Transparency is realized through the use of well-documented, existing energy scenarios to derive energy credits as well as the involvement of stakeholders in the process of developing assumptions for future waste compositions. We illustrate the approach with a demonstrative case study of municipal solid waste (MSW) management in Switzerland. We close the paper with a systematic comparison of our approach and that used by Arushanyan et al. (2017).

2 Methodological approach: Combining existing energy scenarios and storylines of waste composition

2.1 Rationales

2.1.1 Existing energy scenarios: Transparency, robustness, consistency

Scenarios of energy systems on the global, continental, national, and regional scales are numerous and the practice of energy system scenario construction goes back several decades. The International Energy Agency (IEA, 2016) and Greenpeace, with its country scenarios “energy [r]evolution” (Teske and Klingler Heiligtag, 2013), are just some of the multilateral and non-governmental organizations developing such scenarios, while governmental agencies develop scenarios for national energy policies. Today, decision-makers mainly rely on energy system scenarios for climate policy. Scenarios inform decision-makers of the implications of potentially conflicting goals on the energy system, including energy supply security and mitigation of nuclear power risks. Energy scenarios are of predictive, explorative or normative types (Börjeson et al., 2006; Münster et al., 2013). Once the scenario type is defined, scenario analysts rely on different frameworks, mainly optimization or simulation, to model supply and demand of electricity and heat. Providing a broad review of existing scenarios, their type, or their modeling frameworks, goes beyond the scope of this paper. Instead, we refer the interested reader to existing reviews (Craig et al., 2002; Hughes and Strachan, 2010; Trutnevyte et al., 2016).

In order to fulfill the criterion of transparency sought after by Laurent and colleagues (Laurent et al., 2014a; Laurent et al., 2014b), energy scenarios used in prospective LCAs must fulfill the following conditions: disclosure of scenario types, modeling frameworks, and assumptions regarding socio-economic drivers of energy systems (e.g., population growth) as well as availability of detailed modeling results. Full disaggregation of fuels, heat, and electricity supply by energy carrier and energy conversion technology allows justifying the choice of marginal data for energy credit modeling. For instance, in Greenpeace's energy [r]evolution scenarios, countries no longer rely on fossil fuels by the end of the scenario period, so that natural gas no longer competes as a marginal heat supplier with waste management. Existing energy scenarios may provide the required transparency thanks to extensive reporting.

The range of possible, future energy states – feasibility space – eventually also allows LCA practitioners to test the robustness of waste management options to potentially very different energy credits (Münster et al., 2013). In other words, the use of different energy studies allows one to address the sensitivity of LCA results to future energy systems. For a given geographical unit and time horizon, scenarios of different studies define a range of possible future states, reflecting different modeling types and frameworks as well as assumptions, goals, and constraints. Worldviews and personal judgment of scenario analysts strongly influence scenario characteristics (Metzger et al., 2010).

Finally, in addition to transparency and robustness, the use of existing energy scenarios in waste management LCAs increases the internal consistency of the LCA model, i.e., the consistency between future levels of different variables of the LCA model (Scholz and Tietje, 2002). Many assumptions or model results of existing energy system scenarios concern variables that are relevant to waste management LCAs. For instance, the future population growth of the investigated spatial unit is a key assumption in both energy and waste modeling. With regard to the latter, future population is one driver for the total waste amounts generated within a spatial unit. Moreover, energy scenario analysts typically model transportation in great detail and in doing so provide the information required to model waste logistics in LCA. By using the assumptions or model results from energy scenarios in the LCA model, LCA practitioners achieve consistency across economic sectors concerned by, or influencing, waste management decisions. Ultimately, ensuring consistency between the energy and waste sectors answers the call by Harrison et al. (2016) to capture cross-sector interactions and thereby appropriately model environmental impacts of individual sectors.

2.1.2 Waste storylines: Combination of qualitative and quantitative elements, involvement of experts and stakeholders, appraisal of robustness

The Story and Simulation (SAS) approach is a method for constructing possible, future scenarios (Alcamo, 2001, 2008). It consists of an iterative process of knowledge integration to produce storylines describing the future system, feed the storylines into models to assess, for example, the performance of the future system, and refine the storylines based on the model results. Knowledge integration for storyline development relies on a close, structured exchange between stakeholders and experts of the investigated system as well as scenario analysts.

The SAS approach well suits the purpose of developing waste composition scenarios. Waste composition is driven by various developments, such as waste prevention policies (e.g., a ban on polyvinyl chloride bottles), societal megatrends (e.g., soaring consumption of convenience food leading to more plastic waste, changes of consumer awareness or environmental sentiments), technological change (change in nature of packaging) or national traditions (Worrell, 2014). In other words, waste composition reflects complex societal developments (Hoornweg et al., 2013; JICA, 2005). The SAS approach enables one to link societal developments to quantitative estimations of waste stream amounts and their contents that then feed into a prospective waste management LCA. Moreover, the SAS approach allows further qualitative and quantitative elements to be integrated into storylines besides waste amounts and composition (Wiek et al., 2006a). In particular, elements of existing energy scenarios such as total population can be integrated into the waste storylines.

The involvement of experts and stakeholders in the formulation of storylines is a key aspect of the SAS approach and has several functions (Alcamo, 2008). Storylines represent the complex views of individual experts and stakeholders who are able to identify societal megatrends that significantly affect waste production and composition. In addition, involving stakeholders and opening up scenarios to these individuals can enhance the legitimacy of scenarios and acceptance in the circles the involved stakeholders represent (Wiek et al., 2006a) such as authorities, industry, consultancy, and non-governmental organizations.

Finally, the SAS approach, through its inherent openness to views of different stakeholders and experts, allows for building fundamentally different waste scenarios. Just as in the case of energy scenarios, we are looking for diverse waste amounts and compositions in order to cover a range of possible developments and test the robustness of waste management options against waste composition.

2.2 The approach: Energy Scenarios and Waste Storylines (ESWS)

Here we present the approach to link energy scenarios and waste storylines into umbrella scenarios. The approach consists of three stages: (1) a selection of three existing energy system scenarios for the investigated spatial unit and time horizon, (2) the development of three waste storylines according to the SAS procedure and (3) the combination of existing energy scenarios and waste storylines into umbrella scenarios (Figure **1**). The three scenarios and storylines are meant to cover the feasibility space (JRC, 2007) and include both a business-as-usual scenario as well as a base case storyline (Münster et al., 2013). The umbrella scenarios, with future levels for input variables (e.g., energy credits, waste composition, population, available technologies for recycling and thermal treatments), provide the information required for a prospective LCA. Within the developed umbrella scenarios, sensitivity analyses with regard to, for example, material distributions to the available treatment technologies can then be performed. Table 1 details each step to derive the energy scenarios (1) and waste storylines (2) with respect to rationale, applied method, and involved researchers and/or stakeholders.

Insert Figure 1 here

Figure 1 **The Energy Scenarios and Waste Storylines (ESWS) approach yielding umbrella scenarios to be used in prospective life cycle assessment of waste management (box with dashed border).**

Table 1 Details of steps for selecting three energy scenarios and constructing three waste storylines

Insert Table 1 here

In the third stage, the energy scenarios and waste storylines are combined pairwise. The resulting umbrella scenarios form a feasibility space feeding into the prospective waste management LCA. The LCA is performed for each combination of energy scenarios and waste storylines. In each combination, the variables shared by energy scenarios and waste storylines, e.g., population, transport modal split (i.e., shares of rail, road, and waterway transport), or energy prices, are set to the levels of the energy scenario. In the case at hand, this combination approach implies no further influence of the energy sector on the waste sector. For instance, the influence of energy pricing on waste management infrastructure is disregarded in the case study (see explanation in Section 4). Such an influence could be easily implemented by analyzing the consistency between future levels of energy scenarios and waste storylines (Brand et al., 2013). Taking into account the variables defined within each umbrella scenario, sensitivity analyses can be calculated to compare the materials distribution to the waste treatment processes under all umbrella scenarios. For example, the influence of the recycling rate on the environmental performance in different energy systems can be calculated. Ultimately, we look for the waste management options yielding environmental benefits in all umbrella scenarios according to the prospective LCA.

3 Case study results

3.1 Goal and scope of the prospective waste management LCA

Switzerland's debate on its future energy system took a dramatic turn in 2011 with the Fukushima reactor disaster, resulting in the formulation of the Energy Strategy 2050 by the Swiss government[1]: withdrawal from nuclear energy and promotion of energy efficiency and renewable energy technologies. The government also launched national research programs (NRPs) to generate the knowledge required for implementation of the Energy Strategy 2050. The "wastEturn" project, within the NRP 70 on the energy transition, investigates the potential contribution of Swiss waste management to the Energy Strategy 2050[2,3]. One of the main research questions posed in wastEturn was how to optimize Swiss MSW management to support the energy transition. The case study presented here is embedded in wastEturn and closely related to this research question, as it describes the formulation of umbrella scenarios used in a prospective LCA of Swiss MSW management options for the time horizons 2020, 2035, and 2050 (Haupt et al., in prep.).

Switzerland has a well-functioning MSW management with one of the highest per capita and per year generation rates of MSW in Europe (EEA, 2013). In 2012, each inhabitant of Switzerland generated some 700 kg MSW/cap/a (Haupt et al., 2016).

---

[1] https://www.uvek.admin.ch/uvek/en/home/energy/energy-strategy-2050.html?_organization=801&_pageIndex=0

[2] http://www.nfp70.ch/en

[3] http://www.nfp70.ch/en/projects/industrial-processes/waste-management-for-energy-turnaround

About 52% of that mass, composed mainly of paper and cardboard, glass, polyethylene terephthalate (PET) bottles and metals, was separated at the source and further processed for material recovery (Haupt et al., 2016). The rest was thermally treated in 29 MSW incinerators with energy recovery in the form of electricity and heat. Ferrous and non-ferrous metals were recovered from bottom ash and partly also from filter ash resulting from incineration. MSW is relevant to the Swiss energy transition for two main reasons: First, the 2012 average net energy efficiency (NEE) of Swiss MSW incinerators, i.e., the ratio of energy contained in waste fed to incinerators to energy produced by incinerators and used as electricity or heat elsewhere, was 57% (Rytec, 2016), and therefore lower than NEE averages found in other European countries with well-developed MSW incinerator infrastructure (Fruergaard and Astrup, 2011). The reader can find a detailed an explanation of NEE in the Appendix. A second reason is related to the notion of grey energy. Some of the incinerated waste could be separated at the source for material recycling and serve as substitute for primary raw materials. Depending on the waste stream, replacing primary through secondary raw materials can achieve substantial energy savings (Haupt et al., 2018).

3.2 Maximally diverse energy scenarios

Eight scenarios recently reviewed by the Paul Scherrer Institute (PSI) (Densing et al., 2016) fulfilled the criteria required for inclusion in the energy scenario selection by providing detailed results for the entire energy system in 2020, 2035, 2050, and were therefore preselected (Step 1.1 in Section 2.2). Figure 2 shows the final energy consumption mixes of the three maximally diverse scenarios (Step 1.2): Greenpeace's energy revolution (e[r]) (Teske and Klingler Heiligtag, 2013), the Business-as-usual (BAU C) and New Energy Policy (NEP C) of the Swiss Federal Office of Energy (SFOE) (Prognos, 2012). In BAU C and NEP C, C stands for centralized natural gas turbine combined cycle (GTCC) power plants. The three scenarios present rather similar end energy consumptions in 2020, both in terms of total amounts and mix. The year 2035 presents a different picture with a drop of 20% in final energy consumption compared to 2020 in e[r] as demand for fossil fuels drops. Still in e[r], renewable electricity is deployed to cover the phase-out of nuclear power plants. In NEP C, the final energy consumption decreases to similar levels as e[r] and GTCCs power plants compensate for the loss of nuclear power. BAU C sees its total final energy consumption decrease only slightly. Its mix remains similar except for the phase-out of nuclear power. In 2050, the final energy consumption of e[r] is only 65% of what it was in 2020. By then, fossil fuels will have almost disappeared from the mix, which is not the case for NEP C, although similar levels of total consumption are again reached. BAU C continues on the same trend observed between 2020 and 2035.

One should note that all preselected energy scenarios rely on the same population and gross domestic products (GDP) forecasts. The population forecast is the average scenario (A-00-2010) by the Swiss Federal Statistical Office (BFS, 2010). The GDP scenario is the base scenario (A00) produced in a study commissioned by the Swiss Federal Statistical Office (Ecoplan, 2011). Such identical assumptions pose a serious limitation to the diversity of waste storylines that is desired, as population influences total waste amounts. Also, Berntsen and Trutnevyte (2017) demonstrated that the

SFOE's scenarios did not cover the entire feasibility space, limiting the diversity in terms of energy credits applied in a prospective LCA.

Insert Figure 2 here

Figure 2 Final energy consumption of the maximally diverse Swiss energy scenarios in 2020, 2035, and 2050 (E: electricity, e[r] = energy revolution by Greenpeace, BAU C = Business as usual by SFOE, NEP C = New energy policy by SFOE) (Source: Teske and Klingler Heiligtag (2013) and Prognos (2012)).

3.3 Waste storylines

The Scenario Team is composed of five researchers from wastEturn from the fields of environmental engineering and science with experience in the fields of scenario analysis and LCA (see Step 2.1 in Section 2.2). The Scenario Panel is made up of members of the wastEturn Advisory Board. The Advisory Board is composed of representatives of national and local environmental protection agencies, waste management organizations, and the private sector, e.g., the cement industry.

Once established, the Scenario Team met on several occasions to define and refine the required input variables of the prospective LCA (Step 2.2):

- MSW composition and amounts per capita
- total Swiss population (figures provided by selected energy scenarios)
- future capacity of MSW incinerators
- energy recovery efficiencies in MSW incinerators (heat and electricity)
- material recovery efficiencies in MSW incinerators (bottom ash and filter ash)

- capacity of the domestic cement industry to utilize plastics as alternative fuels and raw materials

Different options for processing separately collected waste (e.g., plastics and biogenic waste) will be investigated in the ensuing LCA itself. The future levels of the input variables identified in Step 2.2 were defined jointly with members of the Scenario Panel according to their expertise and by reviewing relevant literature (Step 2.3). The Scenario Team quantified the future levels of input variables in the three time horizons in Step 2.4 by relying on an extensive analysis of official MSW statistics and other information. Below, we present the 2020, 2035, and 2050levels for waste composition and the 2035 levels for all other input variables for the sake of conciseness. All results are available in the Appendix.

MSW amounts and composition

Past trends of waste streams most important in terms of mass and possible policies serve to quantify the future levels corresponding to low, high and base case MSW amounts (Figure 3). In the storyline with low MSW amounts, the reduction of biogenic waste achieved by 2035 corresponds to reductions both in kitchen waste and garden waste. Kitchen waste was assumed to decrease by 60% based on the reduction targets set by in the EU action plan for Circular Economy for 2030 (-50%) (EC, 2015) and the high amount of avoidable food waste found in Switzerland (Beretta et al., 2013). The continuation of current government action in the form of fostering stakeholder dialogue and supporting research (Projektgruppe Food Waste des Bundes, 2015) and the up-scaling of grass-root initiatives make this reduction possible. A reduction of

20% is assumed in garden waste, as the densification of human habitat leads to a decrease of private and public green areas (Haaland and van den Bosch, 2015; Lin et al., 2015). Trends of paper and cardboard consumption observed between 2003 and 2015 endure until 2035. The cardboard consumption statistics do not include imported cardboard through online shopping, which was assumed to be negligible in this scenario. The quantification leads to a total amount of 481 kg MSW/a/cap.

In the storyline with high amounts, the trend of biogenic waste observed between 2000 and 2013 is applied to household food waste, while garden waste is kept at the 2012 level. Paper waste amounts remain constant as well, while cardboard waste amounts are assumed to drastically increase due to an increase in imported cardboard, possibly related to an increase of online shopping. To derive corresponding future amounts, we extrapolate the trend of cardboard waste amounts observed between 2003 and 2015, which include imported cardboard through online shopping. The quantification leads to a total amount of 869 kg MSW/a/cap.

The MSW amount in the base case is 716 kg MSW/cap/a as in 2012 (Haupt et al., 2016).

Insert Figure 3 here

Figure 3 Waste amounts and composition of the three waste storylines in 2020, 2035, and 2050.

Future capacity of MSW incinerators

The Scenario Team grouped the current 29 MSW incinerators into five clusters reflecting different energy production characteristics and designed future levels depending on MSW amounts. Each of these five clusters has a different treatment capacity. Details of each of the clusters are described below.

- Five MSW incinerators are optimized to supply mainly steam to industrial processes all year around. Heat for district heating networks and electricity are regarded as “by-products”.
- Four MSW incinerators provide the base load of district heating networks for residential areas and office spaces. The highest efficiencies of these plants are reached in winter. Seasonal variation of heat recovery efficiency can be large if heat is mostly used for heating. Electricity production remains low in all seasons.
- Eight MSW incinerators are optimized for heat recovery and power generation (CHP plants) with low energy recovery efficiencies. These MSW incinerators focus on heat in winter and electricity in summer resulting in seasonal variations for heat and electricity (opposed).
- Three MSW incinerators are optimized for heat recovery and power generation (CHP plants) with high energy recovery efficiencies. These MSW incinerators focus on heat in winter and electricity in summer resulting in seasonal variations for heat and electricity (opposed).

- Nine MSW incinerators are optimized for the production of electricity from the recovered energy. From the leftover energy, heat or steam is produced and delivered to the neighborhood.

In a highly centralized storyline with low waste amounts, only 10 plants, having a total capacity of 2 million tons of MSW, are in operation. Decommissioning incinerators with low energy recovery efficiency achieves the necessary decrease in treatment capacity. A second storyline includes more moderate centralization and operates under similar waste amounts as today. This storyline reflects foreseeable or planned infrastructure change. One incinerator is planned to close, while two others are examining the possibility of a common site from 2030. In the case with higher waste amounts, 29 plants are operated and located at the same sites as in 2012.

The third storyline includes foreseeable or planned infrastructure change to 27 incinerators. One incinerator will close, while two others are examining the possibility of a common site as from 2030.

Energy recovery efficiencies of MSW incinerators

For a storyline with low energy recovery efficiencies, quantification of small increases in energy recovery efficiency occurs through new waste legislation. The Ordinance on Waste Prevention and Treatment (Schweizerischer Bundesrat, 2016) prescribes a minimum NEE of 55%, however there is not yet a binding implementation deadline. In this storyline, all MSW incinerators reach a NEE of 55% by 2035. Some MSW incinerators already reach or surpass 55% in 2012, so that the overall NEE in this storyline is 57%.

In the storyline with optimization of energy recovery, the new NEE is the result of the centralization of MSW incinerators and a focus on district heating. Also, the electricity and heat recovery efficiencies of district heating plants increase according to the highest improvements observed in the past years in Switzerland and abroad. Such developments lead to an overall NEE of 83%. In the base case, the NEE is 62%, which reflects average improvements observed in the past years in Switzerland.

Material recovery efficiencies at MSW incineration plants

In the base case of material recovery efficiencies, small increases of material recovery efficiencies correspond to the continuation of current trends of increasing material recovery. By 2035, all MSW incinerators will be connected to a bottom ash treatment system or recover the valuables from bottom ash at the incinerator site. Ferrous metals and a non-ferrous metal concentrate will be recovered. In a storyline with high material recovery efficiencies, the implementation of current technological developments (e.g., Supersort (DHZ, 2016), ZAV Recycling AG (Morf et al., 2013)) in bottom ash treatment at several MSW incinerators enables the optimization of material recovery at the national scale. Beside ferrous metals, aluminium, copper, and other heavy non-ferrous metals, glass is recovered as well from most bottom ashes.

As for the filter ash, a new waste regulation will make the recovery of metals from fly ash mandatory (Schweizerischer Bundesrat, 2016). Therefore, all fly ash from the MSW incinerators (ZAR, 2014, 2016) will be washed with acids to retrieve a metal containing hydroxide sludge. The metal recovery will take place either in a centralized recycling plant in Switzerland or in a Waelz process with subsequent processing of the zinc concentrate in a zinc smelting plant elsewhere in Europe.

Alternative fuels and raw materials (AFR) capacity of Swiss cement industry

The energy scenarios provided part of the information necessary to define the future levels of AFR capacity in the Swiss cement industry. As stated in Section 3.2, all selected energy scenarios rely on the same GDP forecast, the base scenario (A00) produced in a study commissioned by the Swiss Federal Statistical Office (Ecoplan, 2011). In this scenario, the mineral sector, including the cement industry, is forecasted to shrink. A cement industry representative on the Scenario Panel believes such a decline would lead to a -20% decrease of AFR capacity in comparison to the 2012 level.

With regard to the recycling processes, no future levels were defined in the umbrella scenarios, as the distribution of recyclables to recycling or other dedicated waste treatments is not directly linked to the energy system and can be assessed in separate sensitivity analyses. Compared to thermal processes, the treatment capacity in the recycling sectors can vary faster due to a shorter life time of the equipment and is not defined on a national level, as recyclables are treated internationally. We therefore assume that the necessary treatment capacity for 2035 can be constructed or found abroad, if such a capacity is found to be environmentally beneficial in the prospective LCA.

Table 2 summarizes the input variables of the prospective LCA and their 2035 levels. Box 1 provides the storyline “low MSW amount” as an example. The two other storylines, “high MSW amounts” and “base case” can be found in the Appendix.

Table 2 **Future levels of waste storylines**[4]

Insert Table 2 here

---

[4] To be used in prospective LCA of Swiss MSW management

Box 1 Storyline “low MSW amounts”, future levels of input variables are highlighted in bold.

Municipal solid waste (MSW) amounts decrease from 716 kg per capita per year in 2012 to **481** kg per capita per year in 2035. Efforts by the Confederation in the form of fostering stakeholder dialogue and promoting research to reduce food waste and various grass-root initiatives pay off with a 60% reduction in **food waste**, an amount corresponding to avoidable food waste. Additionally, there is a **strong reduction in paper and cardboard** consumption as digitalization reduces paper use and shipping packaging use is avoided because of the trend to buy local.

The reduced MSW amounts lead to a reorganisation of MSW incineration infrastructure. From the existing 29 MSW incinerators in 2012, only **10** plants continue to operate with a treatment capacity of some 2.1 million tons in 2035. These 10 plants have high NEE mainly thanks to district heating and thus allow for a **strong increase in energy recovery efficiency**. The reorganisation of MSW incineration also enables a **strong increase in material recovery efficiency**. The current technological developments (SuperSort, ZAV Recycling AG) lead to a **substantial increase in material recovery** from bottom ash on a national scale. Beside ferrous metals, aluminium, copper and other heavy non-ferrous metals, glass as well is recovered from most bottom ashes. Ferrous metals are sent to a Swiss steel company that recovers steel scrap by relying on an electric-arc furnace or foreign plants. Non-ferrous metals are sent to a metals recycling plant abroad. Due to quality issues, glass recovered from bottom ash is used to produce the insulation material in building foundations. A **centralized recycling plant** in Switzerland or **Waelz kilns** with subsequent processing of the zinc concentrate in a zinc smelting plant elsewhere in Europe recover zinc metal from sludge produced by acid washing of fly ash in the MSW incinerators.

MSW incinerators compete with cement plants for specific MSW fractions, for instance for residues from plastics recycling. However, clinker production will decrease by 2035 leading to a **drop in capacity for processing alternative fuels and raw materials by 20%**. The drop in clinker production reflects decreasing population growth and structural change in the Swiss economy, in which energy intensive economic sectors are replaced by sectors with lower energy demand.

Validation of waste storylines

The Scenario Team presented the quantified waste storylines at a meeting of the wastEturn Advisory Board (validation Step 2.5 in Section 2.2). The Scenario Panel intensively discussed the plausibility of centralizing MSW incinerators. Swiss waste management is organized in a decentralized fashion and it is difficult to close down MSW incinerators supplying energy to local users. Also, in the eyes of some members of the Scenario Panel, the demand for district heating from MSW incinerator should decrease in the future in contrast to some of the energy scenarios. They argue that heat demand for office space and residential heating should decrease due to better insulation of buildings and increasingly be met by heat pumps, solar thermal, etc. Members of the Scenario Panel advised to carefully scrutinize these issues in the ensuing LCA.

3.4 Combination of energy scenarios and waste storylines

The three selected energy scenarios are combined with the three storylines developed for waste composition and related waste input variables. The resulting umbrella scenarios provide, in a transparent way, future values of variables required to conduct the prospective LCA, such as population, the split between different modes of transportation, or the NEE of MSW incinerators. Transport activities in waste management are modeled consistently with coupled energy scenarios. All combinations represent a feasibility space allowing the appraisal of robustness of waste management options against future energy systems and waste compositions.

3.5 Integration of umbrella scenarios in LCA

The umbrella scenarios will be operationalized within a consequential LCA framework based on Haupt et al. (2018). The modular LCA structure facilitates adapting waste treatment technologies, and their related life cycle inventories, and integrating new treatment technologies. Furthermore, the knowledge on the energy scenarios allow for defining the marginal energy technologies and analyzing the interactions between the incineration sector and the background energy sector.

4 Discussion

Prospective LCA requires addressing the sensitivity of results to future energy credits and waste composition in order to identify robust waste management options in long-term decision-making. Constructing joint scenarios of energy and waste scenarios is a promising path forward. At the same time, such an approach should be understandable and accessible to those using the LCA results so as to ensure full transparency. In warranting transparency, decision-makers are given the possibility to bring in their knowledge and expertise as well as to challenge assumptions and other characteristics of scenarios. We believe the approach presented in this paper (ESWS) is overall better than the one applied in the TOSUWAMA project presented in the Introduction (Arushanyan et al., 2017), because it addresses upfront the important sensitivities and maximizes transparency. The discussion starts with a review of differences between the ESWS approach and the approach of the TOSUWAMA project, which relied on integrated, large economic and engineering models (Ljunggren Söderman et al., 2016). The comparison enables for a discussion of the advantages and disadvantages of both approaches. We close by providing the limitations of the presented approach and indicating avenues for further research.

ESWS considers the energy scenarios and waste storylines with the largest differences for the purpose of robust decision-making. The energy scenarios are selected from a pool of scenario studies representing different worldviews (Hamarat et al., 2013). The waste storylines have diverging MSW amounts and compositions as a starting point. In TOSUWAMA, societal developments such as increased globalization or regionalization are the qualitative input to models yielding, among others, future energy systems and waste compositions. Different societal developments might lead to similar energy systems or waste compositions. In other words, ESWS tackles sensitivity of LCA results upfront in contrast to TOSUWAMA.

TOSUWAMA has the advantage of always ensuring consistency of joint energy and waste scenarios as both sectors are integrated in the same models (Harrison et al., 2016). In contrast, ESWS would require a consistency analysis (Brand et al., 2013) on the existing energy scenarios and waste storylines. Such a consistency analysis was not conducted in the present case application for two reasons. Firstly, in the case application of ESWS (MSW in Switzerland) and in contrast to TOSUWAMA (waste in Sweden), the energy system seems to have no or little influence on waste flows through oil prices, the carbon permit price, and the energy system performance. Price influences would in practice mean that one cannot develop waste storylines independently from existing energy scenarios and require a consistency analysis. Yet, the composition of packaging, one of the components of MSW, seems to depend mainly on national traditions in packaging, policies, technology, and economic developments (Worrell, 2014). Secondly, one could ask whether energy recovery efficiencies of MSW incinerators depend on energy prices. In Switzerland, in the context of a CO_2 emissions market, Liechti (2012) argues that such an influence does not exist, because MSW incinerators, having a monopoly of waste incineration in a catchment area, could simply pass any additional costs arising from CO_2 emissions onto customers. However, one could imagine MSW incinerators upgrading for energy efficiency to secure a comparative advantage against more CO_2 intensive heat sources. An end to the so-called disposal monopoly for municipal solid waste in Switzerland – a situation prevailing in the EU (European Parliament and Council, 2000) – could trigger new dynamics, including but not limited to an increase in energy efficiency stimulated by CO2 taxation. Indeed, another consequence could be the drastic reduction of the number of MSW incinerators in favor of those offering the most attractive prices for waste treatment.

Both societal developments (e.g., the dramatic increase in online shopping reflecting increased globalization) and policy (e.g. the government action on food waste), explain the differences in waste composition in ESWS. TOSUWAMA investigates the effect of a single policy measure on waste management and its environmental impacts at the time horizon of interest. ESWS allows for narrating a dynamic interplay between waste flows and policy measures, better reflecting the sociotechnical nature of waste management and the co-evolution of society and technology (Meylan et al., 2013; Raven, 2007; Spoerri et al., 2010).

ESWS and TOSUWAMA are similar in their lack of scenarios of material substitution. TOSUWAMA used the same avoided production in all scenarios. In ESWS, the waste storylines did not include future levels of material substitution. The substitution benefits, for instance the environmental benefits of substituting mineral fertilizers through products of biogenic waste treatment, however, should be included in the prospective LCA because of their relevance for the LCA results (Bjorklund and Finnveden, 2005; Blengini et al., 2012; Knoeri et al., 2013; Vadenbo et al., 2016). The question here is whether energy and material credits should be defined at the same stage of a scenario analysis. The energy system, including the direct energy recovery from waste, is characterized by long-term infrastructure in a very much national context of energy supply security (Turton and Barreto, 2006). In contrast, secondary resources from MSW and competing primary resources are found on international markets that, if not global, are at least continental in scale (Meylan et al., 2013; Nakatani et al., 2010). Also, in contrast to heat and electricity, institutional and consumer-related factors play an important role in material substitution (Vadenbo et al., 2016). As a consequence, within the same energy scenario, different material substitution sub-scenarios (Münster et al., 2013) are conceivable.

Finally, waste storylines in ESWS heavily depend on input from experts and stakeholders, an important difference to TOSUWAMA, which relied on such input only for constructing the scenarios of societal developments. The stakeholder process leads to mutual learning (Wiek et al., 2006b) as researchers learn more from the case and stakeholders and experts have the possibility to reflect on the(ir) case(s) in new ways. For instance, stakeholders have the opportunity to think in terms of scenarios instead of forecasts (Kahane, 1992; Meristö, 1989) in such complex instances as long-term developments of waste management. Participation in ESWS increases the uptake chances of recommendations of waste management LCAs by decision-makers (Joos et al., 1999; Krütli et al., 2010).

Participation allows for moving the discussion to the limitations of ESWS, besides those inherent to the use of existing energy scenarios (Section 3.2). The reverse side of the benefits of participation is the lack of reproducibility of waste storylines (Kok et al., 2006). Each stakeholder process is unique in its participants, dynamics, and context of events. Reproducing the same waste storylines is highly unlikely, which is why great care must be given to the selection of Scenario Panel and Scenario Team members and to the management of the ensuing process to reach a high level of process credibility and of results validity. Another limitation consists in the arbitrary limitation to three energy scenarios and three waste storylines. While the idea is to capture a base case and two extremes, an energy scenario presenting particular characteristics might be overseen, or the Scenario Panel might be interested in developing a fourth storyline reflecting a newly emerging societal trend. An implementation of the ESWS approach as online tool could help reduce the time required to construct these additional scenarios.

5 Conclusions

The current practice of waste management LCA suffers from a lack of transparency, ultimately threatening implementation of recommendations by decision-makers. We presented a methodological approach tackling this challenge. It allows constructing energy and waste scenarios for prospective LCAs of waste management and was applied to the case of Swiss MSW management. The approach aims at supporting long-term decisions in the context of the strong sensitivity of waste management LCAs to energy credits and waste composition. The approach relies on existing energy scenarios and a participatory process for constructing waste storylines in order to ensure transparency. Likewise, decision-makers are as well part of the process and thus implementation is secured.

Acknowledgements

This research project is part of the National Research Programme "Energy Turnaround" (NRP 70) of the Swiss National Science Foundation (SNSF). Further information on the National Research Programme can be found at www.nrp70.ch. We would like to thank Carl Vadenbo for helpful comments on an earlier version of the manuscript and Christie Walker for English proofreading of the manuscript.

References

Alcamo, J., 2001. Scenarios as tools for international environmental assessments. European Environment Agency (EEA), Copenhagen.

Alcamo, J., 2008. The SAS Approach: Combining Qualitative and Quantitative Knowledge in Environmental Scenarios, in: Alcamo, J. (Ed.), Developments in Integrated Environmental Assessment. Elsevier, Amsterdam, pp. 123-150.

Allen, C.R., Fontaine, J.J., Pope, K.L., Garmestani, A.S., 2011. Adaptive management for a turbulent future. J. Environ. Manage. 92, 1339-1345.

Arushanyan, Y., Björklund, A., Eriksson, O., Finnveden, G., Ljunggren Söderman, M., Sundqvist, J.-O., Stenmarck, Å., 2017. Environmental Assessment of Possible Future Waste Management Scenarios. Energies 10, 247.

Beretta, C., Stoessel, F., Baier, U., Hellweg, S., 2013. Quantifying food losses and the potential for reduction in Switzerland. Waste Manage. 33, 764-773.

Berntsen, P.B., Trutnevyte, E., 2017. Ensuring diversity of national energy scenarios: Bottom-up energy system model with Modeling to Generate Alternatives. Energy 126, 886-898.

BFS, 2010. Szenarien zur Bevölkerungsentwicklung der Schweiz 2010–2060. Bundesamt für Statistik (BFS), Neuchâtel.

Bjorklund, A., Finnveden, G., 2005. Recycling revisited - life cycle comparisons of global warming impact and total energy use of waste management strategies. Resour. Conserv. Recycl. 44, 309-317.

Blengini, G.A., Busto, M., Fantoni, M., Fino, D., 2012. Eco-efficient waste glass recycling: Integrated waste management and green product development through LCA. Waste Manage. 32, 1000-1008.

Boesch, M.E., Vadenbo, C., Saner, D., Huter, C., Hellweg, S., 2014. An LCA model for waste incineration enhanced with new technologies for metal recovery and application to the case of Switzerland. Waste Manage. 34, 378-389.

Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A., Gao, Q., Zhang, T., Ahmed, M.A., Sutamihardja, R.T.M., Gregory, R., 2008.

Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report. Working Group III (Mitigation).

Börjeson, L., Höjer, M., Dreborg, K.-H., Ekvall, T., Finnveden, G., 2006. Scenario types and techniques: Towards a user's guide. Futures 38, 723-739.

Brand, F.S., Seidl, R., Le, Q.B., Brändle, J.M., Scholz, R.W., 2013. Constructing Consistent Multiscale Scenarios by Transdisciplinary Processes: the Case of Mountain Regions Facing Global Change. Ecol. Soc. 18.

Craig, P.P., Gadgil, A., Koomey, J.G., 2002. What can history teach us? A retrospective examination of long-term energy forecasts for the United States. Annu. Rev. Energy Env. 27, 83-118.

DEFRA, 2014. Energy from waste. A guide to the debate Department for Environment, Food and Rural Affairs (DEFRA), London.

Densing, M., Panos, E., Hirschberg, S., 2016. Meta-analysis of energy scenario studies: Example of electricity scenarios for Switzerland. Energy 109, 998-1015.

DHZ, 2016. Supersort-Technologie: Gewinnung von Kupfer, Silber, Gold und Aluminium aus Siedlungsabfällen. DHZ AG, Lufingen, Switzerland.

EC, 2015. Closing the loop - An EU action plan for the circular economy. European Commission (EC), Brussels.

Ecoplan, 2011. Branchenszenarien 2008 - 2030. Bundeskanzlei, Bundesamt für Statistik (BFS), Bern.

EEA, 2013. Managing municipal solid waste - a review of achievements in 32 European countries. EEA Report No 2/2013. European Environment Agency (EEA), Copenhagen.

European Parliament and Council, 2000. Directive 2000/76/EC on the incineration of waste. Official Journal of the European Union. L332.

European Parliament and Council, 2008. Directive 2008/98/EC on waste. Official Journal of the European Union. L312/3.

Frischknecht, R., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Jungbluth, N., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. Selected modelling principles applied in the ecoinvent database. J. Life Cycle Assess. Japan 1, 112-122.

Fruergaard, T., Astrup, T., 2011. Optimal utilization of waste-to-energy in an LCA perspective. Waste Manage. 31, 572-582.

Füssel, H.-M., 2007. Adaptation planning for climate change: concepts, assessment approaches, and key lessons. Sustainability Sci. 2, 265-275.

Geels, F.W., Schot, J., 2007. Typology of sociotechnical transition pathways. Res. Pol. 36, 399-417.

Guinée, J.B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., Rydberg, T., 2011. Life Cycle Assessment: Past, Present, and Future. Environ. Sci. Technol. 45, 90-96.

Haaland, C., van den Bosch, C.K., 2015. Challenges and strategies for urban green-space planning in cities undergoing densification: A review. Urban For. Urban Greening 14, 760-771.

Hamarat, C., Kwakkel, J.H., Pruyt, E., 2013. Adaptive Robust Design under deep uncertainty. Technol. Forecast. Soc. Change 80, 408-418.

Harrison, P.A., Dunford, R.W., Holman, I.P., Rounsevell, M.D.A., 2016. Climate change impact modelling needs to include cross-sectoral interactions. Nature Clim. Change advance online publication.

Haupt, M., Kägi, T., Hellweg, S., 2018. Modular life cycle assessment of municipal solid waste management. Waste Manage.

Haupt, M., Vadenbo, C., Hellweg, S., 2016. Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System. J. Ind. Ecol., n/a-n/a.

Haupt, M., Vadenbo, C.O., Hellweg, S., in prep. Where should future waste go? Environmental optimization of Swiss municipal solid waste management.

Haupt, M., Zschokke, M., 2017. How can LCA support the circular economy?—63rd discussion forum on life cycle assessment, Zurich, Switzerland, November 30, 2016. Int. J. Life Cycle Assess., 1-6.

Hellweg, S., Milà i Canals, L., 2014. Emerging approaches, challenges and opportunities in life cycle assessment. Science 344, 1109-1113.

Hoornweg, D., Bhada-Tata, P., Kennedy, C., 2013. Environment: Waste production must peak this century. Nature 502, 615-617.

Hughes, N., Strachan, N., 2010. Methodological review of UK and international low carbon scenarios. Energy Pol. 38, 6056-6065.

Hunkeler, D., 2006. Societal LCA Methodology and Case Study. Int. J. Life Cycle Assess. 11, 371-382.

Hunkeler, D., Lichtenvort, K., Rebitzer, G., 2008. Environmental Life Cycle Costing CRC Press.

IEA, 2016. World Energy Outlook 2016. International Energy Agency (IEA), Paris.

JICA, 2005. Supporting Capacity Development in Solid Waste Management in Developing Countries Japan International Cooperation Agency (JICA), Tokyo.

Joos, W., Carabias, V., Winistoerfer, H., Stuecheli, A., 1999. Social aspects of public waste management in Switzerland. Waste Manage. 19, 417-425.

JRC, 2007. Online Foresight Guide. European Commission, Joint Research Center (JRC), http://forlearn.jrc.ec.europa.eu/guide/4_methodology/meth_scenario.htm.

Kahane, A., 1992. Scenarios for energy: Sustainable world vs global mercantilism. Long Range Plan. 25, 38-46.

Knoeri, C., Sanyé-Mengual, E., Althaus, H.-J., 2013. Comparative LCA of recycled and conventional concrete for structural applications. Int. J. Life Cycle Assess. 18, 909-918.

Kok, K., Patel, M., Rothman, D.S., Quaranta, G., 2006. Multi-scale narratives from an IA perspective: Part II. Participatory local scenario development. Futures 38, 285-311.

Krütli, P., Stauffacher, M., Flüeler, T., Scholz, R.W., 2010. Functional ‐ dynamic public participation in technological decision ‐ making: site selection processes of nuclear waste repositories. J. Risk Res. 13, 861-875.

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H., 2014a. Review of LCA studies of solid waste management systems – Part I: Lessons learned and perspectives. Waste Manage. 34, 573-588.

Laurent, A., Clavreul, J., Bernstad, A., Bakas, I., Niero, M., Gentil, E., Christensen, T.H., Hauschild, M.Z., 2014b. Review of LCA studies of solid waste management systems – Part II: Methodological guidance for a better practice. Waste Manage. 34, 589-606.

Lempert, R.J., 2003. Shaping the next one hundred years: new methods for quantitative, long-term policy analysis. Rand Corporation, Santa Monica, CA.

Liechti, J., 2012. Energieoptimierung der KVA Basispapier zur Energie- und Ressourcenpolitik der Schweizer KVA. Verband der Betreiber Schweizerischer Abfallverwertrungsanlagen (VBSA), Bern.

Lin, B., Meyers, J., Barnett, G., 2015. Understanding the potential loss and inequities of green space distribution with urban densification. Urban For. Urban Greening 14, 952-958.

Ljunggren Söderman, M., Eriksson, O., Björklund, A., Östblom, G., Ekvall, T., Finnveden, G., Arushanyan, Y., Sundqvist, J.-O., 2016. Integrated Economic and Environmental Assessment of Waste Policy Instruments. Sustainability 8, 411.

Meristö, T., 1989. Not forecasts but multiple scenarios when coping with uncertainties in the competitive environment. Eur. J. Oper. Res. 38, 350-357.

Metzger, M., Rounsevell, M., Van den Heiligenberg, H., Pérez-Soba, M., Soto Hardiman, P., 2010. How personal judgment influences scenario development: an example for future rural development in Europe. Ecol. Soc. 15.

Meylan, G., Seidl, R., Spoerri, A., 2013. Transitions of municipal solid waste management. Part I: Scenarios of Swiss waste glass-packaging disposal. Resour. Conserv. Recy. 74, 8-19.

Morf, L.S., Gloor, R., Haag, O., Haupt, M., Skutan, S., Di Lorenzo, F., Boeni, D., 2013. Precious metals and rare earth elements in municipal solid waste - Sources and fate in a Swiss incineration plant. Waste Manage. 33, 634-644.

Münster, M., Finnveden, G., Wenzel, H., 2013. Future waste treatment and energy systems – examples of joint scenarios. Waste Manage. 33, 2457-2464.

Nakatani, J., Fujii, M., Moriguchi, Y., Hirao, M., 2010. Life-cycle assessment of domestic and transboundary recycling of post-consumer PET bottles. Int. J. Life Cycle Assess. 15, 590-597.

Pennington, D.W., Potting, J., Finnveden, G., Lindeijer, E., Jolliet, O., Rydberg, T., Rebitzer, G., 2004. Life cycle assessment Part 2: Current impact assessment practice. Environ. Int. 30, 721-739.

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. Renew. Sustainable Energy Rev. 33, 74-86.

Prognos, 2012. Die Energieperspektiven für die Schweiz bis 2050. Bundesamt für Energie (BfE), Bern.

Projektgruppe Food Waste des Bundes, 2015. Food Waste. Bilanz Stakeholderdialog 2013 - 2014 und weitere Arbeiten der Projektgruppe Food Waste des Bundes. Bundesamt für Landwirtschaft (BLW), Bundesamt für Umwelt (BAFU), Bundesamt für Lebensmittelsicherheit und Veterinärwesen (BLV), Direktion für Entwicklung und Zusammenarbeit (DEZA), Bern.

Raven, R., 2007. Co-evolution of waste and electricity regimes: Multi-regime dynamics in the Netherlands (1969-2003). Energy Pol. 35, 2197-2208.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.P., Suh, S., Weidema, B.P., Pennington, D.W., 2004. Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environ. Int. 30, 701-720.

Rytec, 2016. Einheitliche Heizwert- und Energiekennzahlenberechnung der Schweizer KVA nach europäischem Standardverfahren. Bundesamt für Energe (BFE), Bundesamt für Umwelt, Bern.

Scholz, R.W., Tietje, O., 2002. Embedded case study methods: Integrating quantitative and qualitative knowledge. Sage, Thousand Oaks, London.

Schweizerischer Bundesrat, 2016. Verordnung über die Vermeidung und die Entsorgung von Abfällen (VVEA). SR 814.600.

Spoerri, A., Lang, D.J., Staeubli, B., Scholz, R.W., 2010. Technological change in Swiss thermal waste treatment: An expert-based socio-technical analysis. Waste Manage. 30, 1382-1394.

Teske, S., Klingler Heiligtag, G., 2013. energy [r]evolution - Eine nachhaltige Energieversorgung für die Schweiz. Greenpeace Switzerland, Zurich.

Trutnevyte, E., McDowall, W., Tomei, J., Keppo, I., 2016. Energy scenario choices: Insights from a retrospective review of UK energy futures. Renew. Sustainable Energy Rev. 55, 326-337.

Trutnevyte, E., Stauffacher, M., Schlegel, M., Scholz, R.W., 2012. Context-Specific Energy Strategies: Coupling Energy System Visions with Feasible Implementation Scenarios. Environ. Sci. Technol. 46, 9240-9248.

Turton, H., Barreto, L., 2006. Long-term security of energy supply and climate change. Energy Pol. 34, 2232-2250.

Tyskeng, S., Dreborg, K.H., 2008. Framtida förutsättningar för en hållbar avfallshantering: Övergripande omvärldsscenarier samt referensscenario. Kungliga Tekniska Högskolan, Stockholm.

Vadenbo, C., Hellweg, S., Astrup, T.F., 2016. Let's Be Clear(er) about Substitution: A Reporting Framework to Account for Product Displacement in Life Cycle Assessment. J. Ind. Ecol., n/a-n/a.

Wiek, A., Binder, C.R., Scholz, R.W., 2006a. Functions of scenarios in transition processes. Futures 38, 740-766.

Wiek, A., Binder, C.R., Scholz, R.W., 2006b. Functions of scenarios in transition processes. Futures 38, 740-766.

Wilson, D.C., 2015. Global waste management outlook. United Nations Environment Programme (UNEP), Nairobi.

Worrell, E., 2014. Chapter 21 - Recycling of Packaging, in: Worrell, E., Reuter, M.A. (Eds.), Handbook of Recycling. Elsevier, Boston, pp. 297-306.

ZAR, 2014. SwissZink - zentrale KVA-Hydroxidschlammverwertung. Projektblatt 1. Zentrum für nachhaltige Abfall- und Ressourcennutzung, Hinwil.

ZAR, 2016. SwissZink - zentrale KVA-Hydroxidschlammverwertung. Projektblatt 2. Zentrum für nachhaltige Abfall- und Ressourcennutzung, Hinwil.

Graphical Abstract

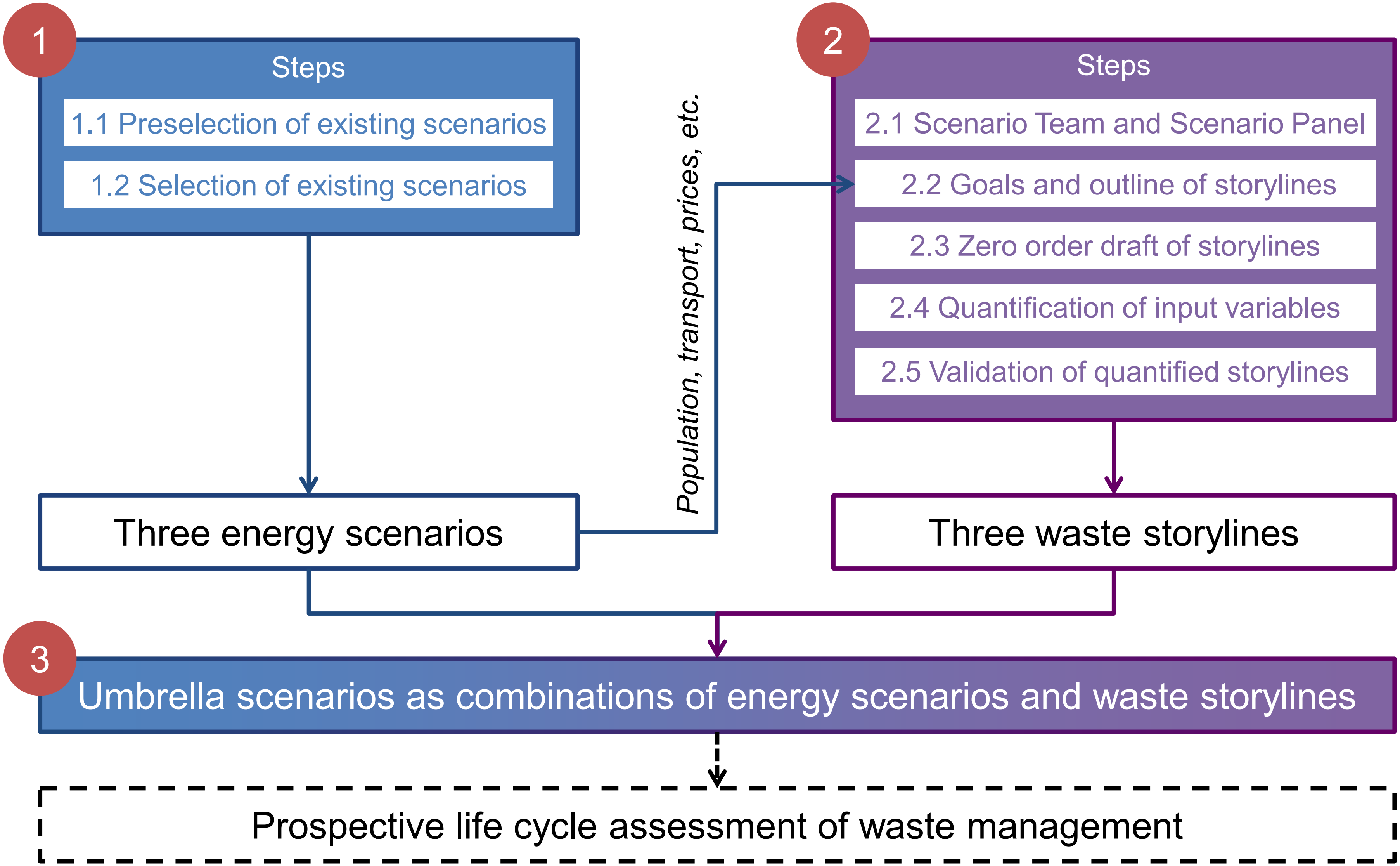


Table 1 Details of steps for selecting three energy scenarios and constructing three waste storylines

Steps	Rationale	Method	Involved researcher or stakeholder
1.1 Preselect existing energy scenarios	Identify scenarios with sufficient and transparent reporting	Review based on conditions provided in Section 2.1.1	Scenario analyst
1.2 Selection of existing energy scenarios	Select scenarios showing large differences	Maximally diverse scenarios (Trutnevyte et al., 2012) based on split of final energy amounts produced with various energy carriers	Scenario analyst
2.1 Scenario Team and Scenario Panel	Establish a Scenario Team of scenario analysts and LCA researchers and a Scenario Panel including representatives of society knowledgeable on waste management (can be extended depending on ensuing steps, e.g., for storyline validation, 2.5)	Storyline and Simulation (SAS) approach (Alcamo, 2008)	Scenario analyst
2.2 Goals and outline of storylines	Define which input variables must be included into the storyline development besides waste amounts and composition (i.e., functional unit of the prospective LCA)	SAS approach (Alcamo, 2008) (step conducted in parallel to the conceptual development of the LCA model to facilitate identification of input variables)	Scenario Team
2.3 Zero order draft of storylines	- The Scenario Panel revises goals and outline of scenarios - Team and Panel define future levels of the input variables - Team and Panel discuss how future levels of input variables could influence one another to inform the elaboration of waste storylines.	SAS approach (Alcamo, 2008) (bearing in mind business-as-usual, maxima, and minima of input variables to appraise robustness)	Scenario Team and Scenario Panel in joint meeting and/or interviews
2.4 Quantification of input variables	Quantification of future levels based on official statistics, legislation, scientific literature, or business, industry, market reports, for example	SAS approach (Alcamo, 2008) (in SAS terminology, input variables are called driving forces)	Scenario Team
2.5 Validation of quantified storylines	Discuss possible inconsistencies in storylines prior to running LCA	Additional step compared to SAS approach in order to check validity of storylines prior to performing the prospective LCA	Scenario Tam and Scenario Panel in joint meeting

Table 2 Future levels of waste storylines[1]

Input variables	**Unit**	**Explanation**	**2035 levels**
MSW amount and composition	kg/cap/a	Amount of MSW generated by households and other entities producing similar types of waste. Composition refers to the materials (e.g., glass, metal, plastic) used in packaging.	- 481 (low MSW amounts) - 716 (base case) - 869 (high MSW amounts) For composition, see **Error! Reference source not found.**
Energy recovery efficiency at MSW incinerators	%	Refers to the net energetic yield (electricity and heat) of MSW incinerators (Morf, 2011).	- 83 (low MSW amounts) - 62 (base case) - 57 (high MSW amounts)
Centralization of MSW incinerators	Number of MSW incinerators in Switzerland	Today, there are 29 MSW incinerators treating Swiss MSW. The future might see a lower amount of MSW incinerators due to lower total MSW amounts.	- 10 (low MSW amounts) - 27 (base case) - 29 (high MSW amounts)
Material recovery efficiency at MSW incinerators	Technology used	Refers to the recovery of metals and inert materials in incineration residues.	- Nationwide adoption of new technologies (e.g., Supersort, ZAV Recycling AG) (low MSW amounts) - Business-as-usual technologies (base case, high MSW amounts)
AFR capacity of Swiss cement industry	% change in absolute capacity	Refers to the absolute capacity of Swiss cement plants to use alternative fuels and raw materials (AFR) in 2035, incl. MSW.	- 20 (all storylines)

---

[1] To be used in prospective LCA of Swiss MSW management

Figure 1

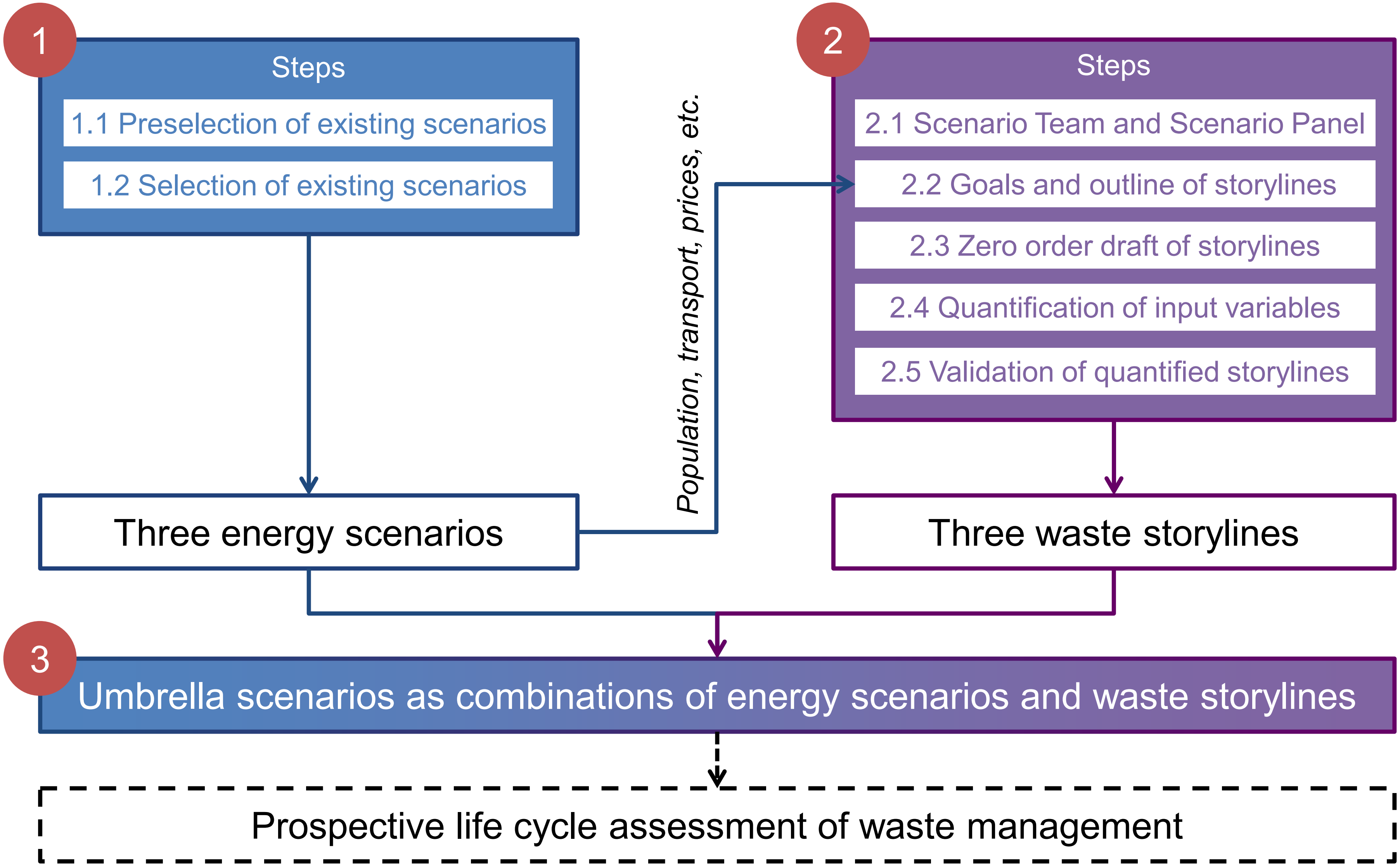

1
Steps
1.1 Preselection of existing scenarios
1.2 Selection of existing scenarios
2
Steps
2.1 Scenario Team and Scenario Panel
2.2 Goals and outline of storylines
2.3 Zero order draft of storylines
2.4 Quantification of input variables
2.5 Validation of quantified storylines
Population, transport, prices, etc.
Three energy scenarios
Three waste storylines
3
Umbrella scenarios as combinations of energy scenarios and waste storylines
Prospective life cycle assessment of waste management

Figure 2

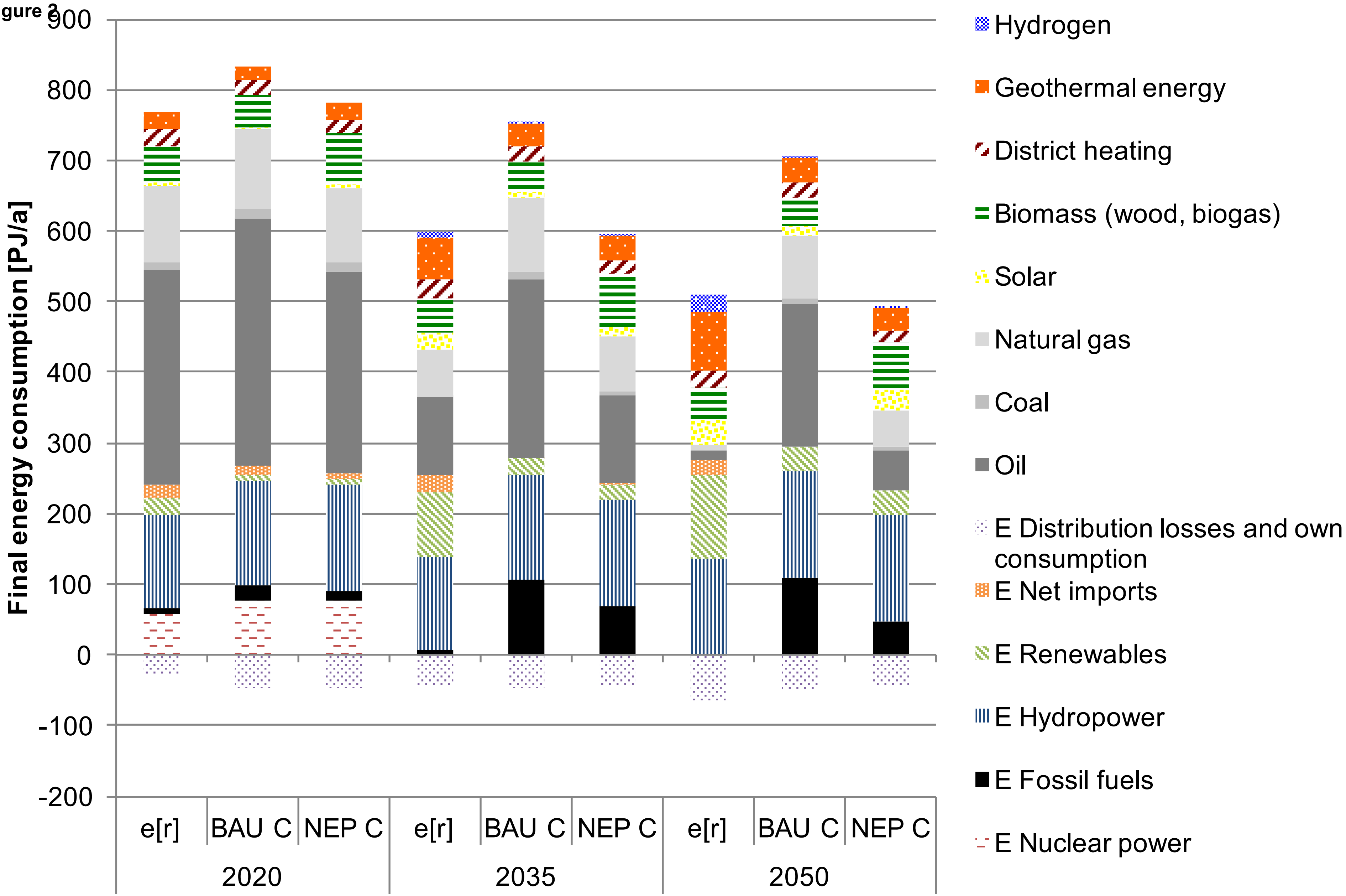
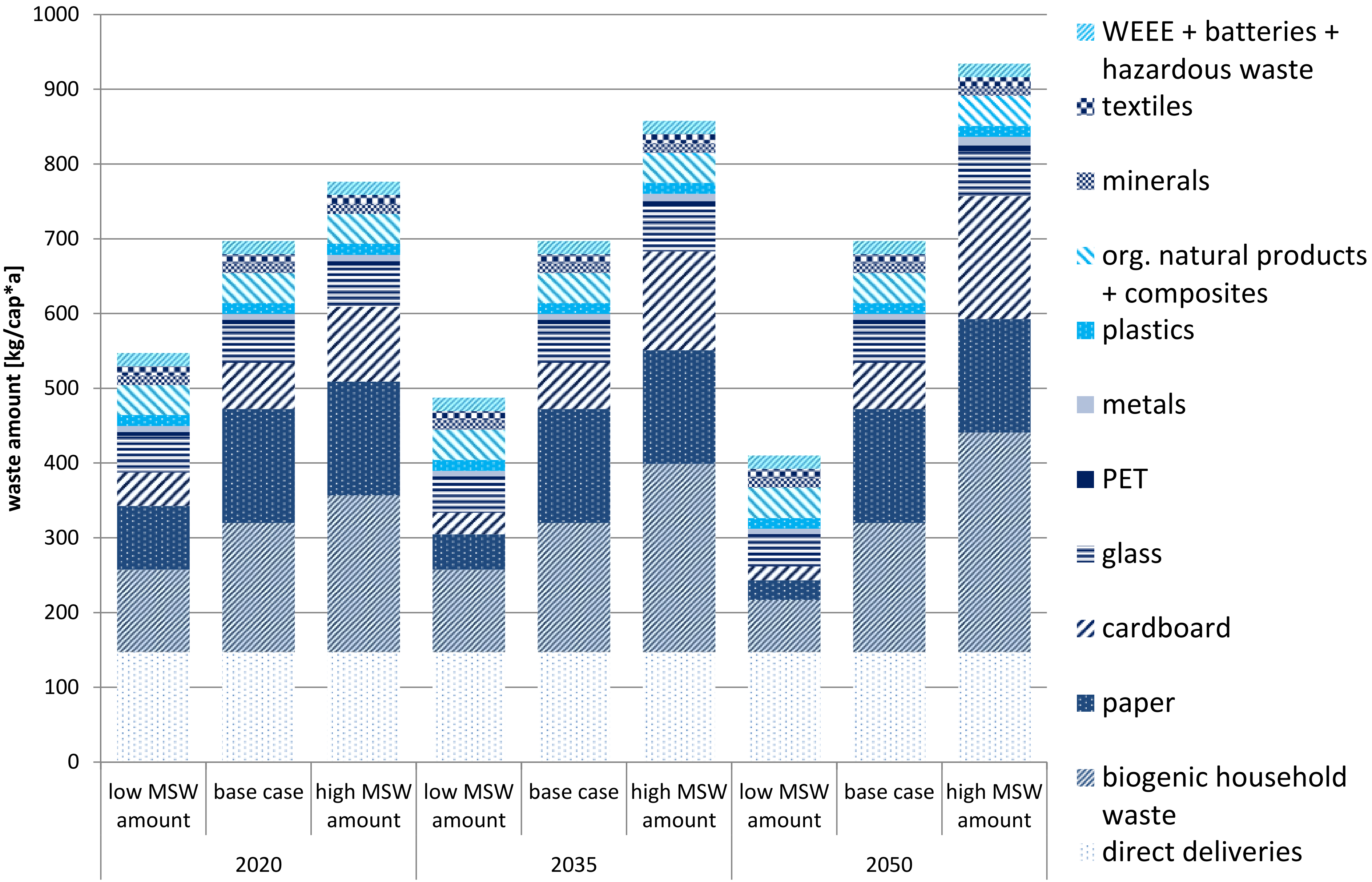

Final energy consumption [PJ/a]
900
800
700
600
500
400
300
200
100
0
-100
-200
e[r]
BAU C
NEP C
e[r]
BAU C
NEP C
e[r]
BAU C
NEP C
2020
2035
2050
Hydrogen
Geothermal energy
District heating
Biomass (wood, biogas)
Solar
Natural gas
Coal
Oil
E Distribution losses and own consumption
E Net imports
E Renewables
E Hydropower
E Fossil fuels
E Nuclear power

Figure 3


waste amount [kg/cap*a]
1000
900
800
700
600
500
400
300
200
100
0
low MSW amount
base case
high MSW amount
low MSW amount
base case
high MSW amount
low MSW amount
base case
high MSW amount
2020
2035
2050
WEEE + batteries + hazardous waste
textiles
minerals
org. natural products + composites
plastics
metals
PET
glass
cardboard
paper
biogenic household waste
direct deliveries

Linking energy scenarios and waste storylines for prospective environmental assessment of waste management systems

Grégoire Meylan[a], Melanie Haupt[b], Mert Duygan[c], Stefanie Hellweg[b] and Michael Stauffacher[c]

[a]Center for Business in the Americas, School of Management and Law, ZHAW Zurich University of Applied Sciences, 8401 Winterthur, Switzerland

[b]Chair of Ecological Systems Design, Institute for Environmental Engineering, ETH Zurich, 8093 Zurich, Switzerland

[c]Transdisciplinarity Lab, Department of Environmental Systems Science, ETH Zurich, 8092 Zurich, Switzerland

Appendix

1 Explanation of net energy efficiency

Energy recovery efficiency is measured by the net energy efficiency (NEE), which is the ratio of energy entering a MSW incinerator over energy leaving the incinerator in a useful form and is calculated as follows (Morf, 2011):

$$NEE = \frac{\left(E_{\exp} - \left(E_f + E_i\right)\right)}{0.97 \times \left(E_w + E_f\right)} \qquad \textbf{Eq. 1}$$

$$E_{\exp} = 2.6 \times E_{\exp\, e} + 1.1 \times \left(E_{\exp\, st} + E_{\exp\, h}\right) \qquad \textbf{Eq. 2}$$

$E_{\exp}$ is the net exported energy. $E_{\exp\, e}$ is the exported electrical energy. $E_{\exp\, st}$ is heat exported as process steam. $E_{\exp\, h}$ is heat exported for district heating. E_f and E_i correspond to additional fuels for steam production and other purposes, respectively. E_w is the energy contained in waste, measured as lower heating value. A factor of 0.97 is used to take into account slag and radiation losses in the boiler.

2 Future levels of MSW amounts and composition

Figure A 1 shows the waste composition of MSW in Switzerland for the three time horizons of the case study (2020, 2035, and 2050). The following subsections describe the development of the scenarios "low MSW amounts" and "high MSW amounts" for the waste fractions for which future scenarios were modelled. As "base case" scenario, the waste composition of 2012 was assumed (Haupt et al., 2017; Steiger, 2014). For all fractions not described below, it was assumed that the amounts stay constant until 2050. Furthermore, the amount of direct deliveries to the MSW incinerator (i.e., commercial waste which is not collected by the municipality) was kept at 150 kilograms per person and year until 2050.In 2012, the per capita ratio of waste over real gross domestic product was 10.4 kg MSW/kCHF2010. By 2035, the scenario “low MSW amounts” corresponds to a strong decoupling with 6.2 kg MSW/kCHF2010, while the base case represents a slight decoupling with 9.1 kg MSW/kCHF2010. The scenario “high MSW amounts” implies a slight increase in waste intensity per gross domestic product with 11.1 kg MSW/kCHF2010.

The statistical analyses described in the following paragraphs are based on the Swiss waste statistics on separate collection and the residual, mixed MSW composition (surveyed by the Swiss Federal Office of the Environment (Steiger, 2014)). While the separate collected fractions are reported for all years, the MSW composition is surveyed only every ten years and was interpolated linearly. The numbers for 2012, i.e., the base case, are taken from Haupt et al. (2017).

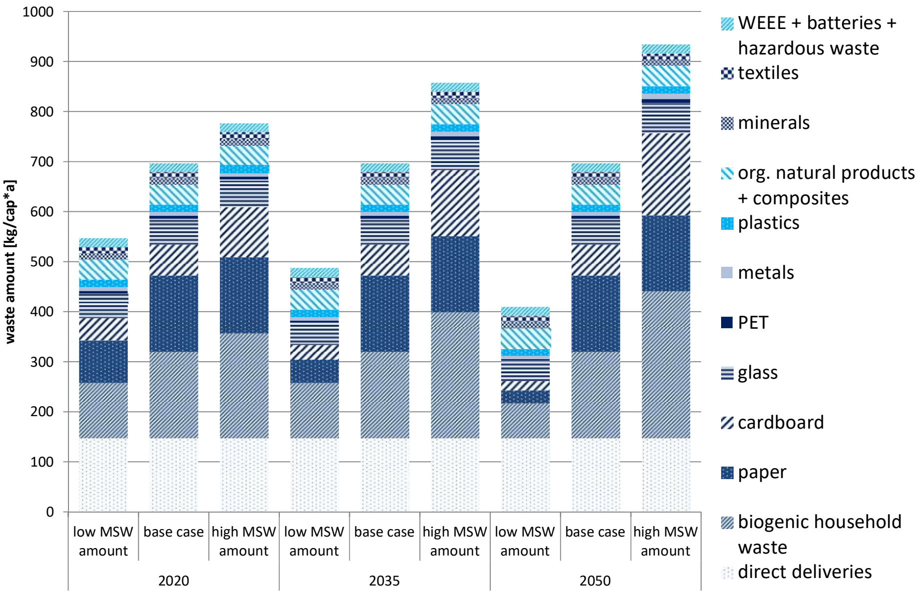


Figure A 1 Waste composition in the waste storylines “low MSW amounts”, “base case”, and “high MSW amounts” for the three time horizons 2020, 2035, and 2050.

2.1 Paper and Cardboard

The annual Swiss paper and cardboard consumption from 2003 to 2015 is reported in the annual report of the association of the cellulose, paper, and cardboard industries (ZPK, 2003-2014). Previous studies show that the waste statistics are not sufficient to identify the total cardboard consumption (Haupt et al., 2017). The information about paper and cardboard consumption is therefore compared to the waste statistics regarding paper and cardboard to identify the non-reported fractions from, for example, online shopping of private consumers and the related shipping activities. Figure A 2 shows the consumption as provided by national statistics as well as the waste amounts reported and the respective trend lines.

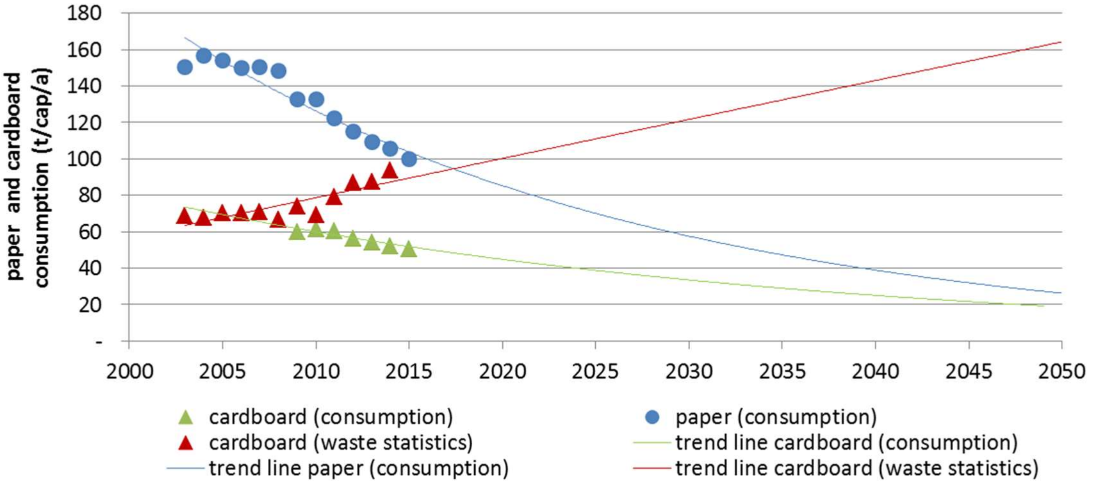


Figure A 2 Paper and cardboard consumption based on waste and consumption statistics (source of data is indicated in brackets) and respective trend lines.

Low MSW amounts: A continuous reduction of the paper and cardboard usage according to the Swiss consumption statistics was assumed.

High MSW amounts: It was assumed that the difference between consumption and waste statistics arise only due to online shopping and the related shipping activities (cardboard boxes are not included in consumption statistics). The difference between these statistics showed that since 2009, the consumed amounts were underestimated. A trend line from 2009 to 2015 was used to calculate the cardboard consumption in 2035.

2.2 Biogenic waste

Biogenic waste from households includes kitchen as well as garden waste. In Switzerland, 66% of the biogenic waste from households is assumed to be kitchen waste (assumption based on total amount of biogenic waste separately collected (Dettli, 2014) and of kitchen waste separately collected (K. Schleiss, October 2015, personal communication; Frischknecht et al., 2014; Kohler, 2015)). Kitchen waste from households is assumed to be 86% avoidable and 14% unavoidable food waste based on Beretta et al. (2013). Within the EU, a food waste reduction target of 50% has been set for 2030 (EC, 2015).

Low MSW amounts: Kitchen waste was assumed to decrease by 60% based on the reduction targets of the EU action plan for Circular Economy (-50%) (EC, 2015) and the high amount of avoidable food waste found in Switzerland (Beretta et al., 2013). Garden waste is assumed to decrease by 20% in 2035 due to a reduction in (urban) farming related to a densification within populated areas.

High MSW amounts: Increase of kitchen waste as observed between 2000 to 2012 (linear trend assumed; 2013 to 2015 were excluded due to the large increase of biogenic waste which could not be explained and might be related to altered data collection methods). Garden waste is assumed to stay at 2012 levels.

2.3 Aluminium

The consumption of aluminium has increased by 370% in the last 15 years. Possible drivers for this increase are the growing consumption in the public space (e.g. take-away) and the rise of energy drinks in the last years.

Low MSW amounts: It is assumed that the consumption continuous to grow and levels at 2 kilogram per person and year.
High MSW amounts: An increasing use of aluminium as light packaging material results in a growth corresponding to a linear trend based on the data from 2000 to 2015. This leads to a 250% increase of the aluminium consumption by 2035.

2.4 Tinplate

The consumption of tinplate has been decreasing since 1992, which can be explained by reduced stock keeping in households and an increasing use of aluminium in the packaging industry. An exponential decay fits the data ($R^2 = 0.96$).

Low MSW amounts: The trend of the last 23 years is expected to continue resulting in a further decrease of the tinplate consumption.
High MSW amounts: The decay is assumed to slow down and the consumption therefore is projected to stay at 2 kilogram of tinplate per person and year.

2.5 PET bottles and mixed plastic

The amount of mixed plastic in mixed waste fractions has decreased over the last years but numbers for separate collection systems are not available. Large consumer trends (e.g., shift towards glass/cotton containers, zero-waste shopping) as well as industry initiatives (e.g., reduction of plastic packaging) could not be modelled. Therefore, it was assumed that the amount of mixed plastic (incl. plastic bottles other than PET) would stay constant. The PET consumption reached a plateau in 2009 and has ever since stayed between 5.6 and 5.9 kilogram per person and year. However, current market developments could lead to both an increase or a decrease of the PET consumption.

Low MSW amounts: A decrease in consumption based on current "zero waste" movements is assumed and the PET consumption therefore decreases to 4 kilogram per person and year (-30% by 2035).
High MSW amounts: A current trend to substitute other plastics with PET (identified in discussion with experts from the respective industries) is assumed to increase the PET consumption to 7 kilograms per person and year in 2035 (+20%).

2.6 Glass

After a rise in glass consumption between 1992 and 1998, the amounts oscillated between 48 and 52 kilograms per person and year between 1998 and 2015. Since 2010, a decreasing tendency can be seen. However, no long-term trend can be observed based on the data.

Low MSW amounts: The trend to lighter packaging is expected to lead to lower glass consumption in the future (decrease is based on the trend line between 2010 and 2015).
High MSW amounts: The trend to reusable packaging material is assumed to lead to an increased consumption of glass until the amounts stabilize at 60 kilograms per person and year in 2035.

3 Storylines

"High MSW amounts"

MSW amounts increase from 716 kg per capita per year in 2012 to **869** kg per capita per year in 2035. Current trends in **cardboard** and **paper** consumption endure until 2035. The cardboard fraction soars due to global markets with increased shipping activities. The lack of measures and initiatives leads to an increase in **biogenic waste**. The amount of paper is assumed to stay on the level of 2012.

The MSW incineration infrastructure of 2012 is maintained to cope with these large quantities. **Twenty-nine** MSW incinerators have a treatment capacity of some four million tons in 2035. In terms of energy recovery efficiency, all MSW incinerators fulfil the minimal requirement of 55% of net energy recovery efficiency laid out by the Ordinance on waste prevention and treatment, Article 32. As some incinerators are above that threshold, the average energy recovery efficiency is **57%**. The retrofit of existing combined heat and power plants yields the energy efficiency improvement. **Current trends to increased material recovery** continue until 2035. By 2035, all MSW incinerators are connected to a bottom ash treatment system or recover the valuables from bottom ash at the incinerator site. Ferrous metals and a non-ferrous metal concentrate are recovered. Ferrous metals are sent to a Swiss steel company that recovers steel scrap by relying on an electric-arc furnace or foreign plants. Non-ferrous metals are sent to a metals recycling plant abroad. A **centralized recycling plant** in Switzerland or **Waelz kilns** with subsequent processing of the zinc concentrate in a zinc smelting plant elsewhere in Europe recover zinc metal from sludge produced by acid washing of fly ash in the MSW incinerators.

MSW incinerators compete with cement plants for specific MSW fractions, for instance for residues from plastics recycling. However, clinker production will decrease by 2035 leading to a **drop in capacity for processing alternative fuels and raw materials by 20%**. The drop in clinker production reflects decreasing population growth and structural change in the Swiss economy, in which energy intensive economic sectors are replaced by sectors with lower energy demand.

“Base case”

MSW amounts and composition **remain at levels of 2012**: **716** kg per capita per year. More than half (55%) of MSW is made of **biogenic waste** (24%), **paper** (21%), and **cardboard** (9.7%).

The MSW incineration infrastructure of 2012 is maintained with **two exceptions**. As planned, a small plant in Canton Zurich is closed and two plants in a neighbouring canton are merged. The net energy efficiency is **62%**, which reflects average improvements observed in the past years in Switzerland. **Current trends to increased material recovery** continue until 2035. By 2035, all MSW incinerators are connected to a bottom ash treatment system or recover the valuables locally. Ferrous metals and a non-ferrous metal concentrate are recovered. Ferrous metals are sent to a Swiss steel company that recovers steel scrap by relying on an electric-arc furnace or foreign plants. Non-ferrous metals are sent to a metals recycling plant abroad. A **centralized recycling plant** in Switzerland or **Waelz kilns** with subsequent processing of the zinc concentrate in a zinc smelting plant elsewhere in Europe recover zinc metal from sludge produced by acid washing of fly ash in the MSW incinerators.

MSW incinerators compete with cement plants for specific MSW fractions, for instance for residues from plastics recycling. However, clinker production will decrease by 2035 leading to a **drop in capacity for processing alternative fuels and raw materials by 20%**. The drop in clinker production reflects decreasing population growth and structural change in the Swiss economy, in which energy intensive economic sectors are replaced by sectors with lower energy demand.

4 References

Beretta, C., Stoessel, F., Baier, U., Hellweg, S., 2013. Quantifying food losses and the potential for reduction in Switzerland. Waste Manage. 33, 764-773.

Dettli, R., R. Fasko, U. Frei, and F. Habermacher, 2014. Transformation der Abfallverwertung in der Schweiz für eine hohe und zeitlich optimierte Energieausnutzung. econcept/Rytec, Zurich.

EC, 2015. Closing the loop - An EU action plan for the circular economy. European Commission (EC), Brussels.

Frischknecht, R., Nathani, C., Büsser Knöpfel, S., Itten, R., Wyss, F., Hellmüller, P., 2014. Entwicklung der weltweiten Umweltauswirkungen der Schweiz. Umweltbelastung von Konsum und Produktion von 1996 bis 2011. Umwelt-Wissen Nr. 1413. Bundesamt für Umwelt (BAFU), Bern, p. 120.

Haupt, M., Vadenbo, C., Hellweg, S., 2017. Do We Have the Right Performance Indicators for the Circular Economy?: Insight into the Swiss Waste Management System. J. Ind. Ecol. 21, 615-627.

Kohler, I., 2015. Futtermittel aus Lebensmittelabfällen für Heim- und Nutztiere: Aktuelle Verwertung und Potenzial. Bachelorarbeit. ETH Zürich, Zürich.

Morf, L.S., 2011. Feststellung und Anwendung des „Standes der Technik“ für die Energienutzung in KVA. Amt für Abfall Wasser, Energie und Luft (AWEL), Zürich.

Steiger, U., 2014. Erhebung der Kehrichtzusammensetzung 2012. Bundesamt für Umwelt (BAFU), Bern.

ZPK, 2003-2014. Annual reports 2003-2014. Swiss Pulp, Paper, and Cardboard Industry Association (ZPK), Zurich, Switzerland.