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**INTEGRATING STAKEHOLDER PERSPECTIVES INTO POLICY SUPPORT OF
MUNICIPAL SOLID WASTE MANAGEMENT**

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SUMMARY

This thesis deals with policy support in the field of Swiss municipal solid waste (MSW) management. The thesis is the result of a cooperative project between policy-makers, scientists, and stakeholders with the overarching goal of delivering strategic orientations for sustainable waste management in Switzerland. In the thesis, I start by acknowledging that current policy support focuses on technical aspects of MSW management and less on its societal implications. However, the sustainability of MSW management policies depends notably on stakeholder acceptance of these policies. The goal of the thesis is to propose a methodological procedure allowing integrating stakeholder perspectives into policy support of Swiss MSW management and to apply this procedure to two MSW fractions whose policy is contested. The main outcome of the methodological procedure is (i) a small set of stakeholder-based scenarios of MSW disposal, (ii) their environmental, economic, and social impacts as well as (iii) stakeholders' views on these scenarios. The first three thesis papers correspond to the application of these three methodological steps (i, ii, iii) to glass-packaging. The fourth paper addresses the issue of residues of MSW incineration plants, the available technologies for their treatment, and the rationale for applying the methodological procedure to this MSW fraction.

The first paper, "Transitions of municipal solid waste management. Part I: Scenarios of Swiss waste glass-packaging disposal," addresses the construction of a small set of scenarios for the year 2020. Today, consumers pay an anticipated disposal fee (ADF) on glass-packaging for beverages. The ADF amount is disbursed to municipalities responsible for glass collection depending on how source separation is done (mixed or color separated cullet) and how it is further processed (recycling, downcycling to insulation material). A certain number of stakeholders contest the ADF compensation rates, which are designed to enhance the system's ecological soundness by promoting the recycling of color-separated cullet. A historical analysis and interviews of key stakeholders of Swiss waste glass-packaging disposal allow the system variables, their possible, future development, and mutual impacts to be identified. The variables are the compensation rates, disposal schemes (i.e., combination of disposal options), and various socio-economic factors. Cross-impact balance analysis (CIB analysis) is used to synthesize this information into scenarios. The compensation rates have a limited effect on the disposal of waste glass-packaging compared to socio-economic factors such as energy prices and the relationship between supply and demand of waste glass-packaging.

The aim of the second paper, "Transitions of municipal solid waste management. Part II: Hybrid life cycle assessment of Swiss glass-packaging disposal," is to evaluate the eco-efficiency of disposal scenarios resulting from the CIB analysis (Part I). The environmental impacts of waste glass-packaging disposal and the gross value added it generates in Switzerland are evaluated. In addition to impacts generated directly by this activity, those coming from the purchase of goods and services, in Switzerland or abroad, are taken into consideration as indirect impacts. The method used for this purpose is hybrid life cycle assessment (HLCA). Preserving Swiss glass-packaging production relying on one third of waste glass-packaging combined with the growth of downcycling in Switzerland to insulation

material allows the environmental impacts to be reduced and the gross value added to be increased in comparison to the current state. Key parameters of eco-efficiency are the alternatives to glass-packaging and insulation materials as products of downcycling. Replacing them is necessary in scenarios where they are no longer produced in Switzerland. Yet European glass-packaging production pollutes more than Swiss production, while Swiss downcycling relies on a cleaner electricity mix than its European counterpart. The paper closes on the recommendation to base the compensation rates on the alternatives to waste glass-packaging disposal products.

The third paper, "Identifying stakeholders' views on the eco-efficiency assessment of a municipal solid waste management system," presents the results of an online survey of 85 stakeholders on the scenarios of the first two papers. The stakeholders were divided into three groups: supply (municipalities), demand (scrap traders, recyclers, downcyclers), and institutions (Swiss and regional environmental protection agencies). They were asked to assess the scenarios with respect to desirability and probability that they will occur in 2020. Preserving Swiss glass-packaging combined with the growth of downcycling in Switzerland is the scenario considered most desirable by stakeholders, which also consider it the most probable. Moreover, there is no substantial dissent between stakeholder groups in rating this scenario. In contrast, a scenario in which Swiss glass-packaging production expands and downcycling in Switzerland ends leads to dissent, although such a scenario would also allow the environmental impacts to be reduced and the gross value added to be increased in comparison to the current state. Institutions rate this scenario as more desirable and more probable than supply and demand. The paper discusses the motivations of stakeholder ratings.

The fourth paper, "Eco-efficiency assessment of options for metal recovery from incineration residues: A conceptual framework," deals with a particular MSW fraction, that resulting from MSW incineration. The landfilling of incineration residues has been a subject of debate in MSW management due to the dissipation of natural resources it entails (e.g., metals) and the long-term environmental risks it poses. Policy-makers and stakeholders now agree that existing MSW incineration plants should be retrofitted by implementing dry discharge of bottom ash and acid washing of filter ash. While large-scale trials are taking place in several Swiss MSW incineration plants, an assessment of scenarios of Swiss MSW incineration implementing these technologies is still lacking. The paper shows how the methodological procedure would allow for such an assessment, while highlighting challenges with respect to necessary data and stakeholder participation

The main outcome of applying the methodological procedure to waste glass-packaging disposal is the identification of a scenario that is highly eco-efficient and accepted by stakeholders. The thesis thus provides policy support for more sustainable MSW management policies. The procedure also leads to mutual learning between policy-makers, scientists, and stakeholders with respect to the investigated cases and research methods used. The thesis concludes with future research avenues on waste glass-packaging disposal and the methodological procedure itself, e.g., the participation of the broader public.

RESUME

La présente thèse de doctorat traite de l'aide à la décision en matière de politique suisse des déchets solides urbains (DSU). La thèse est le fruit d'une coopération étroite entre décideurs, chercheurs et parties intéressées, ayant pour objectif principal l'élaboration d'orientations stratégiques en vue d'une gestion soutenable des déchets en Suisse. La thèse part du constat que l'aide à la décision actuelle se concentre sur les aspects techniques de la gestion des DSU et moins sur ses implications sociétales. Or, la durabilité des politiques de gestion des DSU dépend notamment de l'adhésion des parties intéressées à ces politiques. Le but de la thèse est de proposer une procédure méthodologique permettant d'intégrer les perspectives de ces parties à l'aide à la décision en matière de politique suisse des DSU et d'appliquer cette procédure à deux types de DSU dont les politiques sont contestées. Le résultat principal de la procédure est (i) un petit ensemble de scénarios de traitement des DSU dérivé d'interviews d'acteurs clés, (ii) leurs impacts environnementaux, économiques et sociaux ainsi que (iii) les opinions de parties intéressées sur ces scénarios. Les trois premiers articles de la thèse correspondent à l'application de chacune de ces étapes méthodologiques (i, ii, iii) au verre d'emballage. Le quatrième article présente la problématique des résidus d'usines d'incinération des ordures ménagères (UIOM), les technologies disponibles pour leur traitement et l'intérêt d'appliquer la procédure à ce type de DSU.

Le premier article « Transitions de la gestion des déchets solides urbains. Première partie: Scénarios de la gestion du verre d'emballage usagé en Suisse » présente l'élaboration d'un petit ensemble de scénarios à l'horizon 2020. Aujourd'hui, le consommateur paie une taxe d'élimination anticipée (TEA) sur les emballages en verre pour boisson. Le montant de la TEA est reversé aux communes chargées de la collecte du verre en fonction du type de collecte séparée (verre mixte ou trié par couleurs) et de l'option de traitement (recyclage, décyclage en matériel d'isolation). La clé actuelle de répartition de la TEA, qui vise à rendre le système plus écologique en favorisant le recyclage du verre trié par couleurs, est contestée par quelques acteurs. L'analyse historique et les interviews d'acteurs clés de la gestion du verre d'emballage usagé permettent d'identifier les variables de ce système, leur possible développement à venir et impacts mutuels. Les variables sont la clé de répartition, l'importance relative des options de traitement et divers facteurs socio-économiques. L'analyse des bilans d'impacts croisés (analyse BIC) sert à synthétiser ces informations en scénarios de traitement. La clé de répartition n'a qu'un effet limité sur le traitement du verre usagé par rapport aux facteurs socio-économiques, tels les prix de l'énergie ou la relation entre offre et demande de verre usagé.

Le second article « Transitions de la gestion des déchets solides urbains. Deuxième partie: Evaluation hybride du cycle de vie de la gestion du verre d'emballage en Suisse » avait pour but d'évaluer l'éco-efficacité des scénarios de traitement issus de l'analyse BIC (première partie). Sont évalués les impacts qu'ont la gestion du verre usagé sur l'environnement et la valeur ajoutée brute qu'elle génère en Suisse. En plus des impacts que cette activité génère de manière directe, ceux qui proviennent de ses acquisitions de biens et services, en Suisse ou via des importations, sont pris en compte en tant qu'impacts indirects. La méthode adoptée à cet effet est l'évaluation hybride du cycle de vie (EHCV). Le maintien d'une

production suisse de verre d'emballage absorbant un tiers du verre usagé combiné à l'expansion du décyclage en Suisse permet de réduire les impacts environnementaux et de générer davantage de valeur ajoutée brute qu'à l'état actuel. Les paramètres clés de l'éco-efficacité sont les alternatives au verre d'emballage et au matériel d'isolation issu du décyclage. Leur remplacement est nécessaire lorsqu'ils ne sont plus produits en Suisse. Or la production européenne de verre d'emballage pollue davantage que la production suisse, tandis que le décyclage suisse repose sur un mix électrique plus propre que son équivalent européen. L'article clos sur la recommandation de baser la clé de répartition sur les alternatives aux produits issus du verre usagé.

Le troisième article « Identification d'opinions de parties intéressées sur l'évaluation de l'éco-efficacité d'un système de gestion des déchets solides urbains » présente les résultats d'un sondage en ligne de parties intéressées sur les scénarios des deux premiers articles. Les N=85 parties intéressées sont réparties en trois groupes : offre (communes), demande (ferrailleurs, recycleurs, décycleurs) et institutions (offices fédéral et cantonaux de la protection environnementale). Elles ont exprimé leurs préférences et estimé la probabilité que les scénarios se réalisent en 2020. Le maintien d'une production suisse de verre d'emballage combiné à l'expansion du décyclage en Suisse est le scénario préféré des parties intéressées. Ils le considèrent également comme étant le plus probable. De plus, il n'y a aucun signe de dissension entre les trois groupes dans leurs opinions sur ce scénario. Tel n'est pas le cas d'un scénario voyant l'expansion de la production suisse de verre et la fin du décyclage, bien que ce scénario permette aussi de réduire les impacts environnementaux et de générer davantage de valeur ajoutée brute qu'à l'état actuel. Les institutions jugent ce scénario plus préférable et probable que l'offre et la demande. L'article discute les motivations des opinions de parties intéressées.

Le quatrième article « Evaluation de l'éco-efficacité des options pour le traitement des résidus d'UIOM en vue de la récupération de métaux : Cadre conceptuel » se penche sur un type particulier de DSU, ceux issus de l'incinération des ordures ménagères. Les résidus d'UIOM ont fait débat dans la politique suisse de gestion des DSU à cause de leur mise en décharge doublement problématique du point de vue de la dissipation de ressources naturelles telles les métaux et des risques à long terme encourus par l'environnement. Les décideurs et parties intéressées sont maintenant d'accord que les UIOM existantes devraient être optimisées en y installant le traitement à sec des mâchefers et le lavage acide des cendres de filtres pour l'épuration des fumées. Tandis que des essais en grandeur réelle ont lieu dans plusieurs UIOM suisses, il manque une évaluation de scénarios de la gestion suisse des ordures ménagères intégrant ces technologies. L'article montre comment la procédure méthodologique permettrait une telle évaluation, tout en mettant en lumière les défis au niveau des données nécessaires et de la participation de parties intéressées.

Le résultat principal de l'application de la procédure méthodologique à la gestion du verre d'emballage usagé est l'identification d'un scénario à haute éco-efficacité et faisant l'unanimité parmi les parties intéressées. La thèse fournit donc une aide à la décision pour des politiques de gestion des DSU plus durables. La procédure a en outre débouché sur un apprentissage mutuel entre décideurs, chercheurs et parties intéressées en ce qui est des cas étudiés et des méthodes de recherche utilisées. La thèse conclut par des pistes de recherche pour le futur, tant au niveau du verre d'emballage usagé que de la procédure méthodologique en soi, telle la participation du grand public.

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1 INTRODUCTION

1.1 OF CITIES AND WASTE

Waste is certainly not a modern concept nor is it bound to a single civilization. Human settlements around the world have been coping with waste for thousands of years. In the first small and nomadic societies, such as that of the hunter-gatherer, waste was never an issue nor did it become one when first agricultural societies appeared around 10,000 BC in Mesopotamia. In hunter-gatherer societies, waste could be left behind and even constitute a valuable source of research for archeologists, while in agricultural societies, waste had value as fertilizer (Melosi, 2005). Waste-related problems appeared when human settlements became larger and more densely populated. Such cities emerged from the power they exerted over their hinterlands, which in turn supplied them with agricultural goods. Ironically, it is the same Greece that the European Union (EU) nowadays sues for poor waste management (European Commission to take Greece back to court over dumps, 2013, February 21) that in ancient times invented techniques to cope with solid waste. Near the city of Knossos, capital of the ancient realm of Crete (1,500 BC), land was reserved for the disposal of organic waste into covered pits. Later, in the city-state of Athens and because of threats to public health (400 BC), this technological solution was flanked by legal enforcements, i.e., a littering ban and the obligation to locate landfills at least one mile away from human settlements. In China (ca. 200 BC), the first police forces patrolled streets to remove waste (Melosi, 2005). In short, antiquity witnessed the birth of municipal solid waste (MSW) management. But can we find a definition of MSW management going beyond historical facts?

In their seminal Handbook of Solid Waste Management, Tchobanoglous and Keith (2002) refer to the definition of MSW by the United States' Environmental Protection Agency (US EPA): "wastes from residential, commercial, institutional, and some industrial sources" (Tchobanoglous & Keith, 2002, p. 5.1). The last provenience obviously leaves some space for interpretation. In the EU, the European Environment Agency (EEA) acknowledges a multitude of definitions, each reflecting different approaches of EU member states (EEA, 2013). However, for reporting purposes, it has its own definition which, in contrast to the definition of the US EPA, refers not only to the provenience of wastes, but also to organizations responsible for its collection, i.e., municipalities. It includes wastes similar to those whose collection municipalities are responsible for, but collected directly by the private sector. A similar definition was adopted by the United Nations Human Settlements Program, UN-HABITAT (UN-HABITAT, 2010). Probably coming from a development and cooperation perspective, the definition of MSW in emerging and developing countries tends to focus on the differences in composition between wastes from urban areas in industrial and developing countries, e.g., organic contents (UNEP, 2005).

With the responsibility of MSW management falling to municipalities comes a number of imperatives. Municipalities should provide cost-efficient and convenient solutions to their taxpayers and citizens. MSW management should not entail public health risks nor cause environmental damages. More recently, a new imperative, that of sustainable MSW

management, has gained ground. It refers to the broader concept of sustainable development (SD). A difficulty in applying SD to MSW management lies in the sheer number of its definitions and their rather generic nature. Since the first definition of the Brundtland report stating that SD is about “meeting the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987, p. 8), SD has been operationalized into the so-called triple bottom line, i.e., that any human intervention should be economically viable, socially responsible, and environmentally sound (Elkington, 1994, 1998). Such move allowed practical metrics of SD to be developed, yet these were not exempt from criticism (Norman & MacDonald, 2004). Later, SD took into consideration more systemic principles such as the context, function, and structure of systems in which humans interact with their environment (Laws et al., 2004).

1.2 MUNICIPAL SOLID WASTE MANAGEMENT IN SWITZERLAND

1.2.1 A HISTORICAL OVERVIEW

Swiss MSW management emerged in densely populated urban areas when industrialization caught up with Switzerland toward the end of the 19th century (Veyrassat, 2007). Municipal services began removing waste discarded by households onto streets and disposing of them without further control onto landfills or dumping them into streams and rivers. Waste pickers searching for metal and other valuable materials and local depot systems, the most famous of which is certainly the milk glass bottle, also marked the beginnings of Swiss MSW management. Also, the city of Zurich resorted as early as 1888 to incineration and outsourced the sales of fertilizer and compost from household waste to private companies. In just over a century, Swiss MSW management transitioned to a “dual” nationwide system of the separate collection of high-grade secondary raw materials and the incineration of residual waste including the recovery of energy and, increasingly, metals and minerals (Illi, 2002; Spoerri, 2009; Suter, 2008).

Looking at the drivers of this evolution helps in understanding the present stakeholder networks and ongoing societal debates of Swiss MSW management, which will very much influence the transitions to come.

The first, and a major, trigger of change in Swiss MSW management was the shift from an industrial to a consumption society in the 1950s (Pfister et al., 1996). Labor costs rose relative to energy and transport costs. Most depot systems disappeared because of the high labor costs involved in these systems and/or due to alternative, single-use packaging materials (e.g., brik-pak instead of glass bottles for milk). New materials made their way from niche applications (most of them with a military purpose) to consumer goods (Risch, 2009), the amount of which rapidly soared (ASS, 1971). In time, all three aspects would compel municipalities to dramatically change their approach to waste management. Materials previously managed in closed loops by private entities entered the sphere of responsibility of municipalities. Complex waste compositions made conventional disposal technologies inefficient for reducing waste volumes and producing usable outputs when not posing threats to the environment and human health (e.g., uncontrolled landfilling, composting) (Lods, 1983). Municipalities had to deal with increasing waste quantities.

It would soon become clear that municipalities were not able to independently deal with these challenges. Two major actors entered the scene of MSW management at the beginning of the

1970s. On the one hand, following the subsidiarity principle organizing the Swiss multi-level state (i.e., federal state, cantons, municipalities) (Kley, 2012), legislation affecting waste management was passed by the Swiss parliament, and institutions were established at the national and cantonal levels to enforce it. The Water Protection Act against Pollution (Swiss Confederation, 1971) and the Environmental Protection Act (USG, Swiss Confederation, 1983) paved the way for the substitution of landfilling of residual MSW by incineration and the reduction of local environmental impacts of waste treatment facilities (e.g., air emissions) (Fahrni, 2010; Spoerri, 2009). On the other hand, the private sector engaged with municipalities to set up separate collection schemes for waste paper and later glass-packaging, which allowed the former to save energy and primary raw materials and the latter to cut waste disposal costs (Lods, 1983). If not profitable at first for the private sector, as in the case of aluminum and polyethylene terephthalate (PET) bottles, environmental NGOs would push for legally enforced minimum collection rates per MSW fractions mainly to fight littering (e.g., Swiss Government, 2000b). Concerned industries (e.g., supply chains of packaged beverages and food, electric and electronic equipment, batteries) founded producer responsibility organizations (PROs) to set up tailor-made separate collection schemes (Duygan, 2013). In such schemes, municipalities would have very limited responsibilities. Recurring information campaigns were instrumental in bringing rates of separate collection to satisfactory levels (Frischknecht & Frey, 1989).

As a supplier of secondary raw materials to industry, municipalities indirectly became exposed to the competition and volatility of markets that increasingly became international as Swiss cartels for industrial and consumer goods were dismantled (Stoffel, 1999). Forced to cut production costs to stay competitive, Swiss industries gradually shifted the burden of waste disposal costs onto municipalities at first and eventually onto consumers. Depending on the MSW fraction, the Confederation enforced anticipated disposal fees (ADF) and the PROs introduced anticipated recycling contributions (ARC) on consumer goods to finance separate collection schemes. In effect, municipalities are now entirely dependent on foreign industries for the processing of some waste fractions (e.g., aluminum).

Meanwhile, MSW incineration plants, owned by private entities in the hands of municipalities, underwent constant optimization from the reduction of toxic flue gas emissions to higher yields of energy production and the recovery of secondary raw materials on-site (i.e., integrated to MSW incineration plants) or ex-situ (e.g., on landfills for incineration residues). Main drivers were the introduction of stringent air pollution regulations (Swiss Government, 1985) and market incentives for energy and material recovery. Not only are MSW incinerators legally bound to recover energy (Swiss Government, 1990), but energy from MSW incineration plants is also acknowledged as 50% renewable (Swiss Government, 1998). Optimization steps of MSW incineration plants generated small quantities of recoverable materials or residues with specific compositions for which predominantly foreign markets exist.

Besides changing waste quantities and qualities, new institutional arrangements, and trade liberalization, technical-environmental analyses and assessments were instrumental in driving MSW flows. Emerging from the need to compare the environmental impact of packaging materials from a holistic perspective, life cycle assessment (LCA) was and still is widely used to inform the government or PROs about the meaningfulness of recycling with alternatives being reuse, incineration, or a ban on materials. Such information is in turn translated into legal obligations, for instance the legally enforced minimum collection rates

mentioned above (e.g., FOEN, 1984; Habersatter, 1991; Habersatter et al., 1996a, b), or arguments for source separation used in information campaigns by PROs (Dinkel & Hauser, 2008; Gilgen, Dinkel, & Grether, 2003). Increasingly, institutions rely on LCA to design policies aiming at the optimization of MSW incineration plants (Adam et al., 2007). Material flow analysis (MFA) has been widely used to determine the fate of chemical elements of MSW in treatment plants and to identify hot spots requiring optimization (Morf, 2006; Morf & Brunner, 1998; Morf, Brunner, & Spaun, 2000; Morf et al., 2012; Morf et al., 2005). Research that has been instrumental in developing methods for technical-environmental assessment shows an impressive body of knowledge in MSW management (e.g., Ludwig, Hellweg, & Stucki, 2003).

Figure 1 shows the evolution of Swiss MSW management in terms of the yearly amounts of MSW collected separately or landfilled/incinerated per inhabitant in the last 40 years, i.e., since institutions of environmental protection were established and data were collected. Today, approximately half of MSW is collected separately and supplies national and foreign markets of secondary raw materials, while the rest is incinerated in Switzerland. Compost, waste paper and cardboard, and glass constitute the bulk of MSW collected separately.

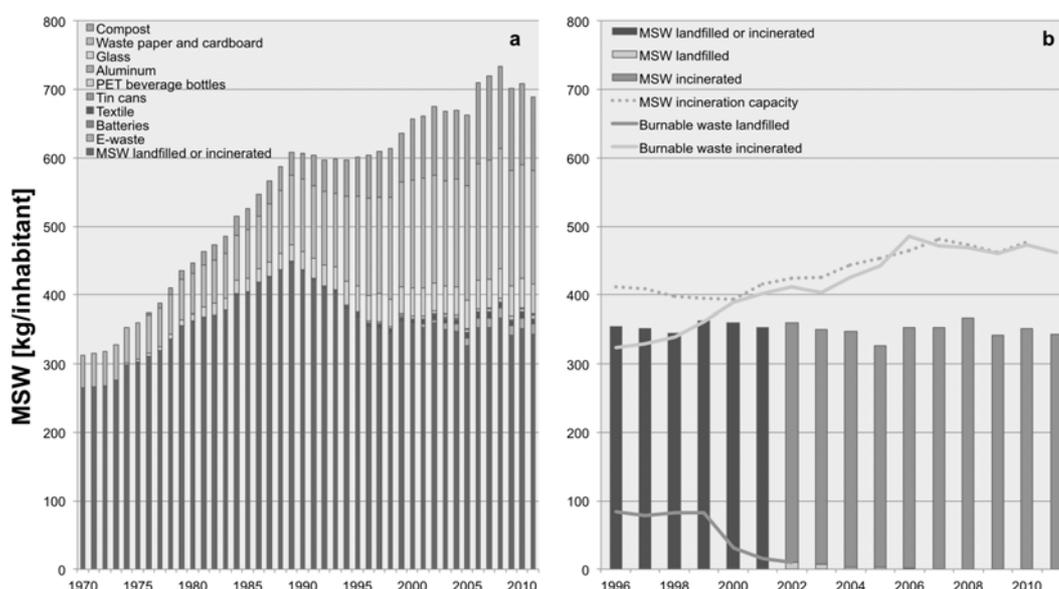


FIGURE 1 FLOWS OF MSW FRACTIONS FROM 1970 TO 2011 (a) WITH A FOCUS ON INCINERATION AND LANDFILLING SINCE 1996 (b).

1.2.2 STILL A HIGHLY CONTESTED ISSUE IN SWISS SOCIETY...

MSW management is a controversial topic regularly reported by Swiss mainstream media. Three different debates co-evolve and at times relate to the same or different MSW fractions or fraction groups: (i) the allocation of MSW management costs, (ii) effective ways to tackle littering, and (iii) the contribution of MSW management in closing material loops. I exemplify each of these debates with three recent or ongoing cases.

Who should pay for MSW management? A revision of the USG in 1997 seemed to have definitely answered this question by prescribing the application by cantons of the polluter-payer principle in the field of waste management. In particular, the law states that costs for MSW disposal should be borne by waste producers through fees or other taxes (Swiss

Confederation, 1983, Art. 32a). While some cantons introduced a garbage bag fee on all of their territory, others delegated this responsibility to municipalities. As a result, a minority of cantons saw a limited application of the polluter-payer principle with one prominent argument being the socio-economic implications of a garbage bag fee on low-income classes and large families. Among them are most cantons of Latin-speaking Switzerland known to have rather different views from the rest of the country on socio-economic policies (see e.g., Dardanelli, 2008). The debate seemed settled 14 years after the USG revision with the ruling of the Federal (Supreme) Court of Switzerland 137 I 257 of July 4, 2011 in favor of the nationwide introduction of the garbage bag fee. The decision received both immediately and in the following months a large echo in the national media (Prodoliet, 2013, May 6; Sackgebühr in der ganzen Schweiz Pflicht [Garbage bag fee becomes mandatory in all of Switzerland], 2011, August 4; TF a favore della tassa sul sacco [Federal court rules in favor of the garbage bag fee], 2011, August 4). While most recalcitrant cantons implemented the law by January 1, 2013 with already clear results in terms of reduction of waste quantities in the following months, others still show opposition through e.g., municipal referenda. Lorenzo Quadri, a Swiss MP from one of the latter cantons, Ticino, even submitted on September 29, 2011 a motion to abrogate taxes for the disposal of MSW according to the polluter-payer principle.

Littering and possible ways to reduce it played an important role in the recent history of Swiss MSW management, as described in Section 1.2.1. A new round of public debate on this issue was triggered when Swiss MP Alois Gmür submitted a parliamentary initiative on September 27, 2012 demanding the introduction of a depot on beverage cans and bottles. Its goal was to fight littering and so to reduce the absolute impact of waste onto the environment by increasing collection rates (Häne, 2013, April 8). The debate is also fueled by cleaning costs estimated to reach some 200 Million Swiss Francs yearly (ca. 160 Million Euros), borne by municipalities (75%) and public transportation companies (25%) (Berger & Sommerhalder, 2011). Opponents of the mandatory depot—the recycling industry and lobbies at their forefront—emphasized the already high collection rates of cans and bottles and argued that the depot would not affect other, more problematic, MSW fractions (e.g., free newspapers) (Nationalrat lehnt obligatorisches Pfand auf Dosen und Flaschen ab [Parliament rejects mandatory depot on cans and bottles], 2013, April 17). They further advanced permanent information campaigns as a more effective means to increase collection rates. The parliamentary initiative was eventually rejected by Parliament on April 17, 2013.

The Green Party of Switzerland initiated a new debate in the broader context of its popular initiative¹, “For a sustainable and resource-efficient economy (Green Economy).” It addresses the issue of whether the reparation of electric and electronic appliances and devices should be favored over material recycling, which entails dismantling, sorting into recoverable and non-recoverable materials (later landfilled or incinerated), and recovery in possibly distant facilities not meeting state-of-the-art environmental and social standards (Reparieren statt wegwerfen dank Gerätegebühr [Reparing instead of discarding thanks to an appliance fee], 2013, May 6). The government is preparing a counterproposal to the popular initiative in the form of a revision of the USG and related federal ordinances, including the Ordinance on the Return, Tack-back, and Recovery of Electric and Electronic Equipment (VREG) (Swiss Government, 2000a). A major change considered in the latter is the shift from an end-of-pipe

¹ Popular initiatives are constitutional amendments proposed by civil society and requiring at least 100,000 signatures of citizens before they can be submitted to popular vote.

focus to a life cycle approach (Duygan, 2013). Sorting facilities should not only minimize onsite emissions and ensure the state-of-the-art disposal of hazardous components, but also maximize the output of recoverable resources. Until now, this was to a large extent left up to market prices for secondary raw materials and prices of disposal as an alternative to recovery. Interestingly, this particular discussion goes beyond the dyad of separate collection versus disposal through incineration and landfilling and delves into what happens to waste beyond the consumer act of source separation.

Figure 2 shows the search volume index in Switzerland for four keywords of MSW management on Google since its launch. Littering is used in all three official languages, while disposal does not exist in French. Such a metric gives an idea of the interest of all sectors of Swiss society for a specific topic. One can see that search volumes appear and then remain rather constant over time.

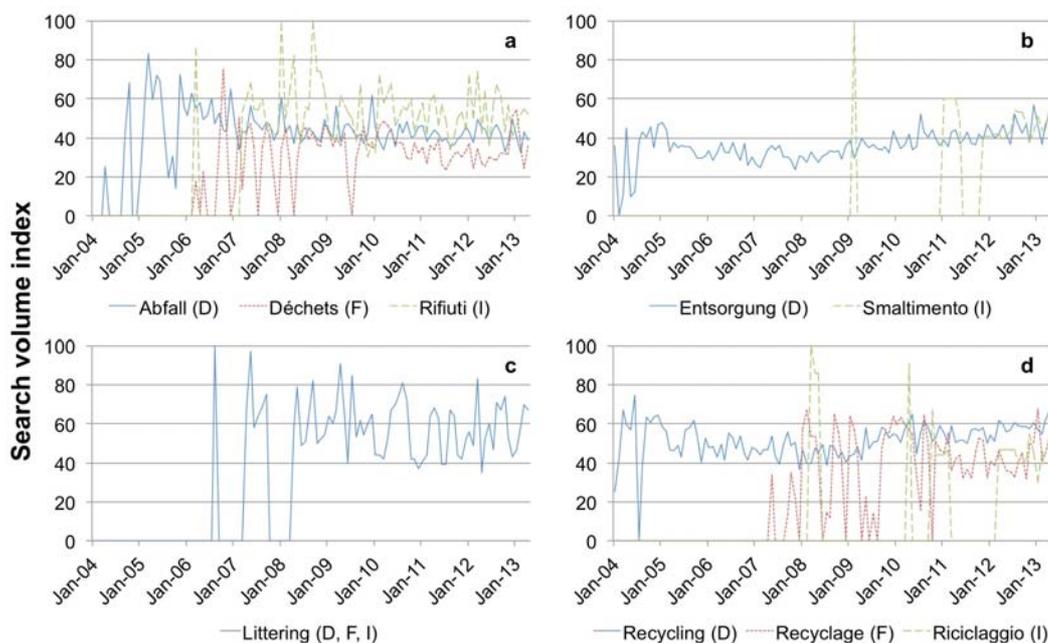


FIGURE 2 SEARCH VOLUME INDEXES IN SWITZERLAND FOR FOUR KEYWORDS OF MSW MANAGEMENT (a: WASTE, b: DISPOSAL, c: LITTERING, d: RECYCLING). INDEXES OF INTENSIVELY SEARCHED WORDS ARE DEFINED ON A WEEKLY BASIS, WHILE OTHERS ON A MONTHLY. HENCE THE PEAKS (I.E., 100) ARE SHOWN ONLY FOR THE LATTER (D: GERMAN, F: FRENCH, I: ITALIAN; SOURCE: GOOGLE TRENDS).

1.3 SUPPORTING POLICIES FOR MUNICIPAL SOLID WASTE MANAGEMENT

1.3.1 STAKEHOLDER PARTICIPATION, CONSULTANCY, AND TRANSDISCIPLINARY PROCESSES

Stakeholder participatory processes are understood as decision-making processes integrating any form of stakeholder knowledge (e.g., views) (Holmes & Scoones, 2001; Renn, 2006; Scholz, 2011; Van den Hove, 2000). Switzerland has a long tradition of stakeholder participation when it comes to designing laws, plans, and policies. According to the Consultative Procedure Act (VLG, Swiss Confederation, 2005), drafts of constitutional amendments, provisions of federal acts, and projects with major political, financial,

economic, ecological, social, or cultural implications for stakeholders must undergo a consultative procedure with cantons, political parties, and interested parties. The goal of a consultative procedure is to “provide information on material accuracy, feasibility of implementation and public acceptance of a federal project” (VLG, art. 2, para. 2). An example of a consultative procedure touching the field of MSW management is the current revision of the USG already mentioned in Section 1.2.2. The ongoing consultative procedure for the revision of the USG includes cantons; political parties; Swiss associations of municipalities, cities, and mountain regions; Swiss economic associations; and interested parties. They have three months to express their position based on the revised sections of the USG and an explanatory report.

A part from the legal obligations of the VLG, the federal administration is keen on integrating expert and stakeholder knowledge to elaborate other forms of projects. This is the case of the elaboration of new Guidelines on Swiss Waste Management that should soon replace the first edition (FOEN, 1986). After a critical evaluation of some 20 years of waste policy (Hanser, Kuster, Gessler, Ehrler, et al., 2006), the Swiss EPA relied on representatives from academia, cantonal EPAs, operators of waste treatment facilities, the private sector, and other federal authorities to set new goals and priorities as the basis for the revision of the guidelines (Hanser, Kuster, Gessler, & Ehrler, 2006).

The Swiss EPA also relies on consultancy to form environmental policies. In consultancy, scientists provide new forms of knowledge in a decision-making process under the control of policy-makers (Scholz, 2011). The USG gives the confederation the possibility to mandate or support research and technological studies in the field of environmental protection (USG, art. 49, para. 2). Federal environmental research is an “essential basis for efficient and effective environmental and resource policy.”² On a five-year basis, the Swiss EPA defines a research concept in the form of research foci subdivided into relevant research areas. The latest research concept covers the period of 2013-2016 (Miranda, Jacquat, & Zürcher, 2012). In the cited document, the focus Sustainable Use of Resources and its research area Waste Management allow for consultancy in the field of MSW management. The latter is also more implicitly the object of research areas Green Economy and Environmental Technology in the focus Act for the Protection and Promotion of a Sound Environment. Of the 32 Swiss research groups listed by the Swiss EPA³ with waste as a key research topic, 13 are engineering- and natural science-oriented and have resource efficiency or resource management as another key research topic (debate iii of Section 1.2.2), and only one conducts research in public law susceptible to address all three debates. Of course, the confederation is not the only entity interested in research in the field of Swiss MSW management. For instance, the Swiss EPA together with the EPA of Canton Zurich, the cities of Winterthur and Zurich, and the PRO for battery collection mandated research on the psychological determinants of waste behavior and littering (Hansmann, Bernasconi, Smieszek, Loukopoulos, & Scholz, 2006; Hansmann, Loukopoulos, & Scholz, 2009; Hansmann & Scholz, 2003). Besides academia, private firms also conduct consultancy.

² <http://www.bafu.admin.ch/innovation/06631/06641/index.html?lang=en>

³ <http://www.bafu.admin.ch/innovation/06631/10646/index.html?lang=en>

An ongoing initiative of the Swiss EPA aiming at increasing plastics recycling, the Round Table on Plastics Recycling,⁴ is a unique form of consultancy, as it is the first policy support process to adopt an approach inclusive of stakeholders defining stepwise the need for further knowledge on, e.g., feasibility of plastic recycling technologies in the Swiss context. The initiative was launched in the spring of 2010.

The ongoing project "Options Management for Sustainable Waste Management Options (Options-Management Nachhaltige Abfallwirtschaft, OMNA)" aims at providing strategic orientations for sustainable waste management in a cooperative framework between science (Natural and Social Sciences Interface at ETH Zurich) and practice (EPAs of Switzerland and Canton Zurich). It is transdisciplinary, as policy-makers, scientists, and stakeholders control a process at the interface of decision-making, research, and public discourse (Scholz, 2011; Thompson Klein et al., 2001). In the first doctoral thesis of the OMNA project (later referred to as OMNA 1), the focus was on developing methods of expert knowledge integration in the field of waste management, while providing insights into specific cases (Spoerri, 2009), e.g., identifying drivers and barriers of technologies for the treatment of waste incineration residues (Spoerri, Lang, Staeubli, & Scholz, 2010). The present work constitutes the second thesis of the OMNA project (OMNA 2).

1.3.2 LIMITATIONS OF THE CURRENT APPROACH TO POLICY SUPPORT

Stakeholder participatory approaches are broadly applied when it comes to defining goals and priorities of Swiss MSW management, i.e., its normative framework. As expected, these significantly impact the design of concrete policy tools, e.g., amounts of taxes fostering source separation of households or economic incentives targeting municipalities and aiming at driving a specific waste flow to a desired treatment technology. For these concrete policies, the Swiss EPA seems to rely on consultancy provided by private or public research entities with little involvement of stakeholders. These entities develop technologies or evaluate the feasibility, efficiency, etc. of technological or management options against the normative framework of Swiss MSW management. Less attention is given to the societal implications of developed technologies or alternative technological or management options, e.g., their acceptance by stakeholders. In other words, natural and technical science perspectives dominate consultancy. The Round Table on Plastics Recycling and the OMNA project mentioned in Section 1.3.1 remain exceptions in the policy-making landscape of Swiss MSW management.

I see three limitations to such an approach. First, while goals and strategies do flow into concrete policy tools, there is little learning from the experiences gained with policy tools. Such learning could in turn serve to adapt the normative framework. Instead, the new Guidelines of Swiss Waste Management will probably be adopted some 30 years after their first edition as a result of a broad evaluation (Hanser, Kuster, Gessler, & Ehrler, 2006; Hanser, Kuster, Gessler, Ehrler, et al., 2006). Second, consultancy relying on technical-environmental assessments (e.g., LCAs) for policy support does not include an analysis of the acceptance of such policies among stakeholders. In turn, this gap could lead to a blocked or delayed policy implementation. Third, the lack of participatory processes under the umbrella of the Swiss EPA can lead to the formation of stakeholder coalitions pushing for policy change

⁴ <http://www.bafu.admin.ch/abfall/01472/01483/index.html?lang=en>

based on shared interests. While this has nothing reprehensible, other stakeholders might be better off if a more inclusive process were to take place.

1.4 PROPOSED APPROACH FOR SOCIETALLY ROBUST POLICY SUPPORT OF MUNICIPAL SOLID WASTE MANAGEMENT

The goal of this thesis is the development of an alternative approach to policy support of MSW management addressing the limitations described under Section 1.3.2 and its application to specific case studies in an explorative way.

1.4.1 THEORETICAL FOUNDATIONS

Before presenting the theoretical foundations of the proposed approach for societally robust policy support of Swiss MSW management, I discuss a fundamental assumption of these theories: the inextricably coupled nature of human and environmental systems. Liu and colleagues (Liu, Dietz, Carpenter, Alberti, et al., 2007; Liu, Dietz, Carpenter, Folke, et al., 2007) investigate the nature of couplings between human and natural systems (e.g., ecosystems). Coming from the resilience paradigm (Folke et al., 2002), Liu and colleagues focus on natural systems on which human systems rely for livelihood or income, while industrial systems are not in their scope of research. In contrast, technologies and their embedding in society lay at the heart of the research interests of Geels and colleagues (Geels, 2002; Geels & Schot, 2007). Such embedding is conceived of as sociotechnical systems. The latter are further decomposed into three interacting levels: (i) a landscape of societal developments (e.g., increasing environmental awareness), (ii) a sociotechnical regime of stakeholders, rules, and built infrastructure framing the dominant regime technology and its use, and (iii) a technological niche, in which research and development are carried out on alternative technologies with the aim of substituting the regime technology. This decomposition is known as the multilevel perspective (MLP). Finally—although I do not strive for an exhaustive review—the concept of human-environment systems (HES) seeks to cover a broader scope (Scholz, 2011). It investigates human systems on different hierarchical levels (from individuals up to groups, organizations, societies, supranational entities, and the human species) interacting with their environments (from ecosystems to industrial systems as well as other human systems on the same or different hierarchical levels).

Building on this coupled system understanding, the same research communities developed process designs or blueprints of processes involving policy-makers, stakeholders, and scientists to different extents and with the common aim of achieving sustainable transitions.

Coming from sociotechnical transition theory, Loorbach and colleagues propose an iterative cycle of transition management (TM) (Kemp & Rotmans, 2009; Loorbach, 2007). The goal of TM is to steer and accelerate sustainable transitions. In the first stage, stakeholders (constituting a so-called transition arena) are asked to provide their visions of a sustainable sociotechnical system with a time horizon of a generation at least (i.e., 20 years) and reach a consensus on a collection of shared visions (e.g., “Swiss MSW management is carbon neutral”). In the second stage, an agenda of measures is defined to achieve these visions (e.g., “Introduction of nationwide source separation of household organic waste and anaerobic digestion”). The third stage consists of short-term (i.e., five to ten years) experiments with technologies of the transition agenda in a real-world setting (e.g., implementing source separation and anaerobic digestion in a Swiss municipality). The fourth

and final stage foresees the monitoring and evaluation of transition experiments in the light of the collection of shared visions (e.g., “Does anaerobic digestion of household organic waste efficiently contribute to carbon neutrality of Swiss MSW management?”). Visions are then subject to possible adaptation (e.g., “Given the results of the transition experiments, is carbon neutrality a feasible vision?”).

Scholz and colleagues developed HES-based transdisciplinary (TD) processes based on the assessment that science must acknowledge the role of norms and values in contested societal decision processes if it aims to contribute meaningfully (Scholz, 2011; Seidl et al., 2013). In other words, orientations from science must address uncertainties of technical-environmental analyses and assessments (see Section 1.2.1) as well as uncertainties arising from views and interests of stakeholders if they are to be societally robust (Nowotny, 2003; Seidl et al., 2013). A coupled systems (i.e., HES-based) understanding is necessary to systematically capture all aspects of a problem, while transdisciplinarity consists in integrating stakeholder perspectives in an appropriate way (see Section 1.3.1). For instance, different stakeholders might be needed at different times for problem definition and structuring, data collection, validation, etc. (Krütli, Stauffacher, Flüeler, & Scholz, 2010; Stauffacher, Krutli, Flueeler, & Scholz, 2012). Decision-makers, scientists, and stakeholders control the HES-based TD process by jointly defining research questions, methods, and case studies (Scholz, 2011).

It is worth mentioning that both TM and HES-based TD processes still suffer from a lack of case study research. Loorbach and Rotmans (2010) report on four TM case studies that took place in the Benelux region. In Belgium, TM was applied first to the Flemish waste agency (OVAM) as a means to shift its paradigm from the “management of waste” to the “management of production to prevent waste” (Loorbach & Rotmans, 2010, p. 242) and implement such shift in its internal processes and structures. OVAM then set up a transition arena including relevant societal actors, which developed a new vision of consumption habits. At the time of publishing, a transition agenda had been defined and experiments were under way and being evaluated. The main conclusion of the case study review is that TM should explicitly tackle the present structures and interests of regime actors obstructing sustainable transitions.

1.4.2 METHODOLOGICAL PROCEDURE FOR SOCIETALLY ROBUST POLICY SUPPORT

The overarching goal of the procedure is to deliver societally robust orientations to policy-makers in contested decision processes of Swiss MSW management (see debates described under Section 1.2.2). The procedure can be assimilated to the first stage of TM applied to specific MSW management systems, i.e., generating a consensus among stakeholders on futures of specific MSW management systems. However, the proposed procedure differs from TM in that it seeks to collect views of stakeholders on concrete scenarios instead of visions. Recent research has shown that stakeholders’ views might differ when they are confronted with concrete scenarios including attributes instead of generic visions (Trutnevyte, Stauffacher, & Scholz, 2012).

The proposed procedure for societally robust policy support of Swiss MSW management consists of the successive application of three methods of knowledge integration (Scholz & Tietje, 2002). The first methodological step is a scenario analysis of a MSW management system (Scholz & Tietje, 2002; Spoerri, Lang, Binder, & Scholz, 2009). A prerequisite is the

definition of appropriate system boundaries, i.e., a MSW fraction (e.g., paper and cardboard) or a MSW treatment technology or infrastructure (e.g., MSW incineration). Possible, future policy alternatives and developments exogenous to the investigated system serve to define a small set of consistent scenarios of the MSW management system. The necessary knowledge is acquired through literature review and interviews with key stakeholders. The second methodological step consists of an assessment of direct and indirect environmental, economic, and/or social impacts of scenarios. A life cycle approach is adopted for this purpose (Hellweg, Doka, Finnveden, & Hungerbühler, 2005; Pennington et al., 2004; Rebitzer et al., 2004). In the third and final methodological step, views of stakeholders on scenarios and their impacts, i.e., preferences and estimations of the probability that scenarios will occur, are identified to assess the acceptance and feasibility of scenarios (Bügl, Stauffacher, Kriese, Lehmann Pollheimer, & Scholz, 2012). Differences between stakeholder groups (e.g., municipalities and institutions) are investigated as well. The collection of stakeholder views is done via online survey to reach a large number of stakeholders nationwide. Such a setting also serves to identify consent and dissent areas independent of any group dynamics that might take place in workshops as foreseen in the cycle of TM.

The main outcome of the methodological procedure is a small set of scenarios including information on their impacts and views of stakeholders.

1.4.3 CASE STUDIES

The selection of case studies to apply the proposed methodological procedure was done by the body responsible for steering and advising TD processes within the OMNA project: the OMNA Consulting Committee (see Figure 3). Three organizations are represented and meet twice a year: the Natural and Social Science Interface at ETH Zurich from academia and the Waste Management Sections of the EPAs of Switzerland and Canton Zurich from practice.

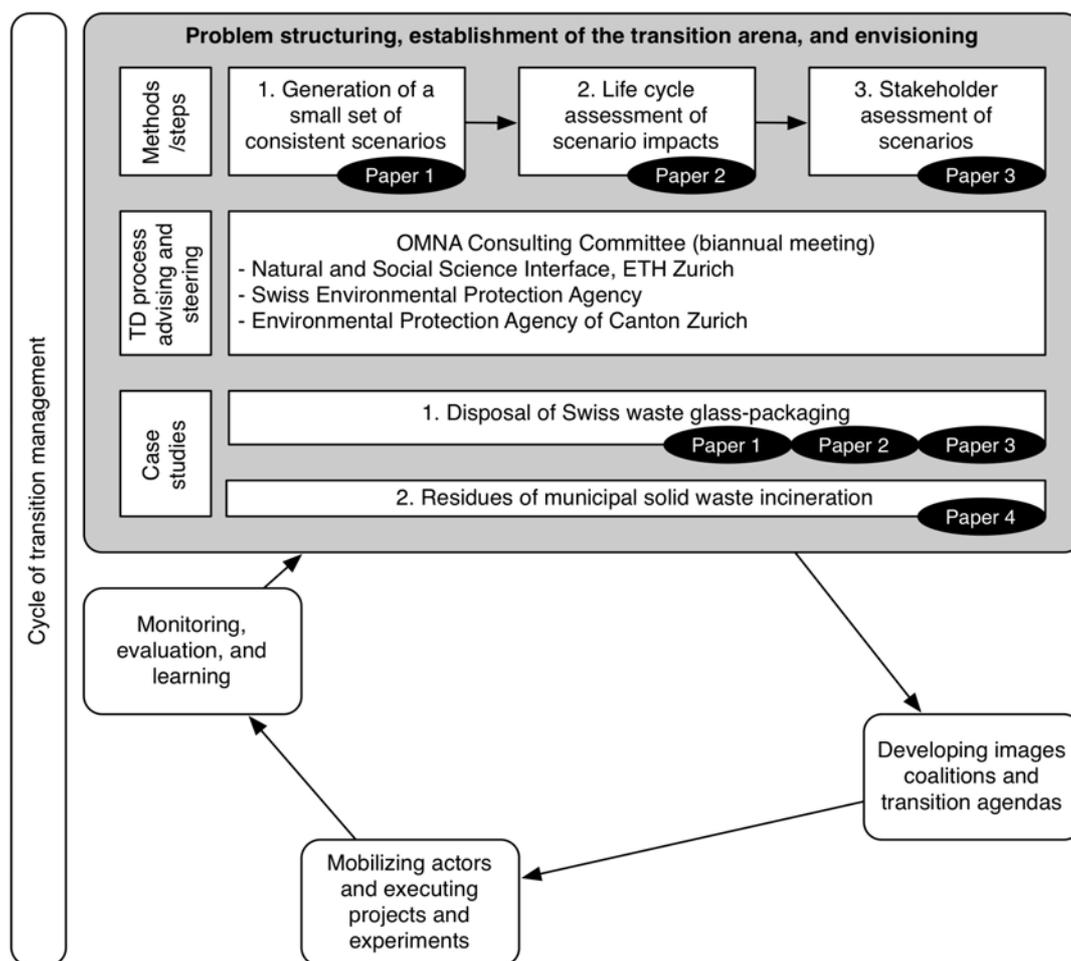


FIGURE 3 MAPPING OF THE CASE STUDIES, METHODOLOGICAL STEPS, AND PAPERS FROM OMNA 2 WITHIN THE CYCLE OF TRANSITION MANAGEMENT, ADAPTED FROM LOORBACH AND ROTMANS (2010).

In its initial meetings, the OMNA Consulting Committee was interested in two cases. The main conclusion of the last module of OMNA 1 was that Swiss MSW incineration is in a technological lock-in, i.e., retrofitting of existing incinerators is largely favored over technological alternatives, e.g., gasification and downstream ash melting (Spoerri et al., 2010). Although initially interested in an “objective” technical-environmental assessment of the different thermal treatment options to complement these insights, the OMNA Consulting Committee eventually came to the conclusion that such an assessment would come too late. At the time (i.e., 2012), the nationwide introduction of retrofitting was already highly probable, as full-scale tests yielded promising results both in terms of the quality of incineration residues to be landfilled and resource recovery (Buechi, Boeni, & Di Lorenzo, 2012; Buehler & Schlumberger, 2010; Fierz & Bunge, 2007; Morf et al., 2012; Schlumberger, 2010).

The second case is the disposal of waste glass-packaging. The rationale here is a federal policy strongly impacting waste glass-packaging disposal, namely the anticipated disposal fee (ADF) on glass-packaging, which is contested by a certain number of stakeholders. The ADF, introduced in 2001, consists of financially compensating municipalities for collecting waste glass-packaging and fostering environmental efficacy by applying different compensation rates whether municipalities reuse (i.e., as entire bottles), recycle (i.e., as cullet), or downcycle their glass to different construction materials. Figure 4 provides national figures

on the collection of waste glass-packaging. The Swiss EPA wished to acquire a thorough decision-base prior to any policy review (including a possibility of going beyond ADF adjustment). All members of the OMNA Consulting Committee viewed the case as an opportunity to contribute to a real-world problem just as transdisciplinarity is meant to do. Another interesting aspect of the case is that some stakeholders of Swiss waste glass-packaging meet on a regular basis to discuss the situation. These meetings do not take place under the umbrella of the Swiss EPA nor with its participation (Vetroswiss, 2012, 2013) [see Section 1.3.2].

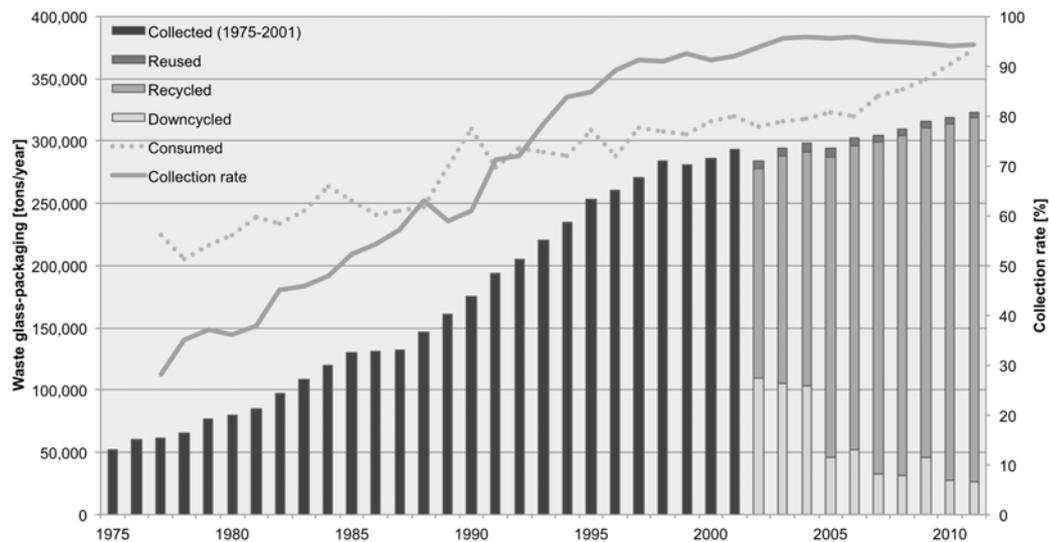


FIGURE 4 GLASS-PACKAGING CONSUMED, COLLECTED BY SWISS MUNICIPALITIES, AND PROCESSED (SOURCE: VETROPACK AND VETROSWISS).

Papers 1, 2, and 3 each address one step of the methodological procedure applied to Swiss waste glass-packaging disposal. Paper 4 is the result of initial work on residues of MSW incineration; it presents the retrofitting technologies and discusses why the approach should still be applied to that case. Paper 4 was submitted before the stakeholders' views on scenarios of waste glass-packaging disposal were surveyed (methodological step 3, Paper 3). There are slight differences between the methodological step 3 presented in Paper 4 and the way this step was implemented for waste glass-packaging disposal.

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2 PAPER 1 – TRANSITIONS OF MUNICIPAL SOLID WASTE MANAGEMENT. PART I: SCENARIOS OF SWISS WASTE GLASS-PACKAGING DISPOSAL

Meylan, G., Seidl, R., & Spoerri, A. (2013). *Resources, Conservation and Recycling*, 74, 8-19.

ABSTRACT

All municipal solid waste (MSW) management systems—even “high quality systems” or those employing “best practices”—face multiple challenges, e.g., decreasing prices of secondary raw materials recovered by municipalities, increasing complexity of waste composition, technological lock-ins. Policy-making involves translating these challenges into goals that are generic in nature and implementing them on MSW fractions thanks to tailor-made policy tools, e.g., anticipated disposal fees. Anticipating the impacts of policies can provide valuable insights into the adequacy of policy tools with respect to economic, political, and social contexts of MSW. The goal of this paper is to construct consistent, future scenarios of Swiss waste glass-packaging disposal based on literature and stakeholder knowledge, including the allocation of waste to different disposal routes. These scenarios are future states to which the current system could transit to due to alternative policies in line with waste policy goals and varying societal constraints (e.g., commodity prices). Results of scenario construction show that policy has a limited effect on waste glass-packaging disposal because of economic constraints, preventing goals from consistently being achieved. For instance, increases in energy prices can impede a policy favoring recycling over downcycling to foam glass, an energy-saving product. The procedure applied to construct possible scenarios suits well the ambition of considering uncertain future developments affecting MSW management as it integrates qualitative and quantitative knowledge of various sources and disciplines.

2.1 INTRODUCTION

The management of municipal solid waste (MSW) distinguishes itself through the sheer diversity of schemes that are used in various regions around the world (Davies, 2008; UN-HABITAT, 2010). While some regions still struggle with the containment of environmental and health risks, e.g., groundwater pollution from uncontrolled landfills, others have achieved both risk prevention and enhanced source separation through integrated solid waste management (ISWM) (Ludwig, Hellweg, & Stucki, 2003; Tchobanoglous & Keith, 2002). Switzerland exemplifies a variant of a well-functioning ISWM system with high collection rates for recyclable wastes (e.g., 80% for PET bottles, 91% for aluminum-packaging, and 94% for glass-packaging in 2010), state-of-the-art grate incineration of the non-recyclable fraction with recovery of energy and metals, and marginal MSW directly sent to sanitary landfills (FOEN & FSO, 2011).

However, even under current conditions, well-functioning ISWM systems (e.g., Switzerland, the Netherlands, and Sweden) continuously face challenges. First, MSW quantities are steadily increasing due to population and economic growth as well as increased per capita

consumption (Adhikari, Barrington, & Martinez, 2006; Beede & Bloom, 1995). Second, MSW composition is continuously becoming more complex. This trend is related to the new materials being applied in consumption goods (e.g., nanomaterials) (Roes, Patel, Worrell, & Ludwig, 2012; Walser, Demou, Lang, & Hellweg, 2011) to meet consumers' sophisticated functionality requests. MSW recycling requires a sufficient demand for recyclables (i.e., recovered materials and energy) (Diamadopoulos, Koutsantonakis, & Zaglara, 1995; Hervani, 2005). A third challenge can be identified by the fact that such demands are not stable but driven by manifold changes in domestic and foreign market structures and economic development. Moreover, on a different conceptual level, it can be difficult to implement innovative waste treatment technologies that mitigate remaining deficiencies and thus improve the ISWM system's performance. This phenomenon is known as technological lock-in, i.e., a situation in which an existing sociotechnical system configuration blocks promising innovative technologies from entering the market (see Spoerri et al., 2010, who analyzed patterns of technological change in Swiss thermal waste treatment). Accounting for these challenges in supporting policy-makers in the field of MSW management is considered a prerequisite for deriving societally robust orientations for future MSW management systems.

Policy support in the field of MSW management relies on a portfolio of analysis and assessment methods. Those most popular are certainly material flow analysis (MFA), system dynamics, and life cycle assessment (LCA) (Scholz, 2011). The latter has been and still is dominated by the comparison of different MSW management systems relying on a single technology and at a unit level, e.g. incineration vs. recycling of 1 kilogram of a particular waste stream (Carlsson Reich, 2005; Dinkel & Hauser, 2008; Gilgen, Dinkel, & Grether, 2003; Hellweg, Doka, Finnveden, & Hungerbühler, 2005; Hong, Hong, Otaki, & Jolliet, 2009; Konecny & Pennington, 2007; Waeger, Hirschier, & Eugster, 2011; Welz, Hirschier, & Hilty, 2011). The goal of these LCAs is determining which technology, i.e., MSW management system based on this technology, should be implemented by policy, as it achieves higher life cycle environmental performance than the other technological options. However, from the perspective of policy support, these approaches commonly fail to consider up-scaling issues (Frischknecht & Stucki, 2010) and future developments (Zamagni, Guinee, Heijungs, Masoni, & Raggi, 2012). Indeed, political decisions (e.g., landfill bans, waste incineration taxes) target waste amounts in their entirety (and not specific units such as 1 kg) and have a strong future impact on waste disposal due to the longevity of waste policy outcomes. According to the authors, it is crucial to consider MSW's societal embedding to end up with societally robust orientations for MSW policy-making.

This also applies to the field of waste glass-packaging disposal in Switzerland (cf. Doka, 2006), which, on one hand, is an illustrative example for a currently well-functioning recycling and downcycling system (cf. above) but, on the other hand, requires continual adaptation to maintain or improve its performance under changed future conditions related to the challenges mentioned above. The policy instrument at hand to enable this adaptation is the disbursement of an anticipated disposal fee (ADF) on glass-packaging. The compensation rates for the different disposal paths (e.g., bottle-to-bottle recycling, downcycling to insulation materials or sand substitute) depend on their environmental benefits; therefore, the ADF acts as a financial scheme to foster environmentally sound waste glass-packaging management.

Given the shortcomings of current assessments, we argue for approaches that consider the future disposal of total waste glass-packaging flows as a result of the interaction between the broader economic, political, and social contexts of MSW (i.e., societal embedding of MSW). In line with this claim, this paper introduces a novel approach based on scenario analysis. Its overarching aim is to derive future scenarios for glass-packaging disposal as a basis for informing societally robust decisions, i.e., that acknowledge the interplay between waste policy goals, ADF settings, external societal constraints, and resulting glass-packaging disposal schemes. The specific research questions are the following:

- 1) What drivers and interrelations among them crucially affect the upcoming transformation of the Swiss glass-packaging disposal system?
- 2) Given alternative ADF settings and uncertain external constraints, what are possible, consistent future patterns of waste glass-packaging flows in Switzerland?

Following the development of the future scenarios, the second part of the paper series goes a step further by illustrating an integrative eco-efficiency assessment of the scenarios based on a hybrid life cycle assessment.

2.2 METHODOLOGICAL APPROACH

As one example of coupled human-environment systems (HES) (Liu, Dietz, Carpenter, Alberti, et al., 2007; Liu, Dietz, Carpenter, Folke, et al., 2007; Scholz, 2011) MSW management systems can be conceptualized as sociotechnical systems (Newton, 2012; Raven, 2007; Scholz, Spoerri, & Lang, 2009; Spoerri, Lang, Staeubli, & Scholz, 2010). On one hand, human systems on different levels—from national policy-makers to private sector and MSW-generating individual consumers—act upon their respective environment according to a system of goals and available strategies, e.g., ADF rates in the case of national policy-makers. On the other hand, environmental changes, from national waste flows to installed waste treatment capacity and collection centers, lead human systems to modify their goal systems or to adapt their policies. In other words, MSW management systems are the result of a co-evolution of human and environmental systems.

Figure 1 depicts the methodological approach to provide policy-support in the field of waste management systems. We acknowledge the co-evolutionary nature of waste management systems in both methodological steps of Part I leading to a set of consistent, future scenarios with associated disposal schemes for waste glass-packaging. In Step 1, we analyze the past co-evolution of the MSW management system and its resulting present structure to identify drivers that crucially affect upcoming transitions. In Step 2, we construct scenarios of the waste management system based on the drivers identified in Step 1. The target year of the scenario construction is 2020, which in Switzerland corresponds to two planning periods in MSW policy. In Part II, the associated disposal schemes are the objects of an eco-efficiency assessment that is carried out with a hybrid life cycle assessment; insights are provided into the economic and environmental performances of the disposal schemes. This integrative performance assessment will be presented in a follow-up article. In the next subsections, we go more into detail about the methods and data/knowledgebase used in the two steps of Part I.

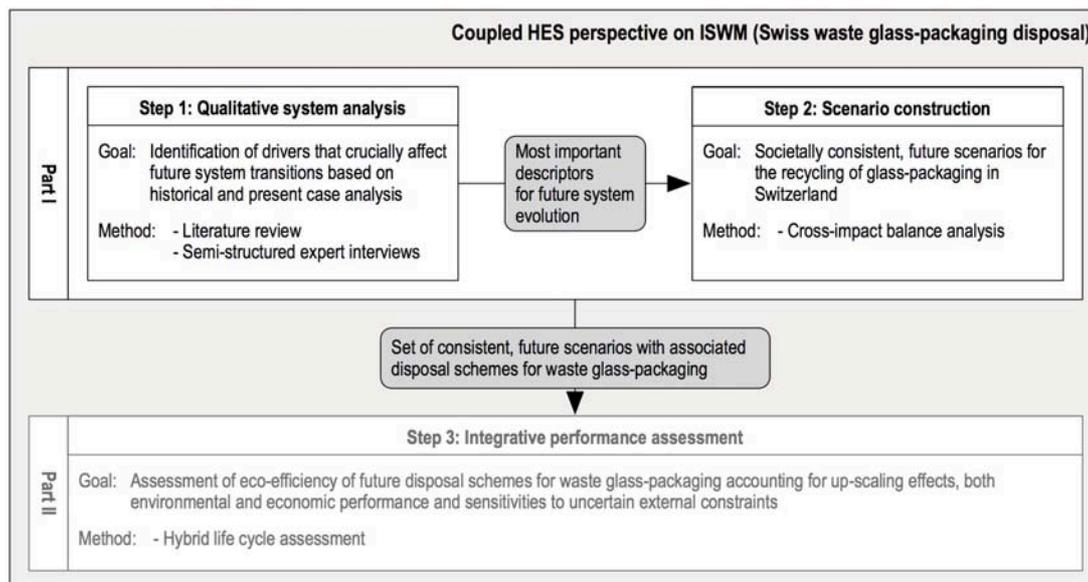


FIGURE 1 METHODOLOGICAL APPROACH TO THE CONSTRUCTION AND ASSESSMENT OF CONSISTENT, FUTURE SCENARIOS OF SWISS WASTE GLASS-PACKAGING DISPOSAL.

2.2.1 QUALITATIVE SYSTEM ANALYSIS

The goal of the qualitative system analysis is to identify the drivers that crucially affect upcoming transitions of Swiss waste glass-packaging disposal and thus provide the foundation to construct the scenarios. We selected 2009 as the reference point for the present waste management system, as extensive data on waste glass-packaging flows are available for that year. Due to the fact that upcoming transitions are co-shaped and constrained by past developments, a historical analysis of drivers of Swiss waste glass-packaging disposal was performed to reconstruct the co-evolution of the waste management system from its emergence until 2009. The system is understood as an ensemble of drivers (e.g., energy prices, separate collection of waste glass-packaging). Drivers interact through promoting or restricting influences, e.g., rising energy prices promote the source separation of waste glass-packaging. If strong enough, an influence or a combination of influences can eventually lead to a transition in which new drivers appear in a system while others disappear. Literature from various sources, e.g., annual reports from industry, technical surveys, and the historical dictionary of Switzerland, was used to carve out the essential drivers and their dynamic interplay. The drivers crucially affecting upcoming transitions of the waste management system were then validated in semi-structured interviews of 13 stakeholders who are experts in the field of glass packaging in Switzerland (Bogner, 2005; Mieg & Näf, 2006; Spoerri et al., 2010). The stakeholders/experts interviewed are key actors in all of the fields related to Swiss waste-glass packaging disposal, including: municipalities responsible for collection; waste glass-packaging transport, trade, and processing (i.e., recycling or downcycling); regional and national policy-makers; consultants providing policy-support. If the stakeholders/experts disagreed on a driver, the majority opinion was selected.

2.2.2 SCENARIO CONSTRUCTION

The goal of this second step is to construct consistent scenarios for the future disposal of waste glass-packaging in Switzerland, including disposal schemes, which the present waste management system could transit to, given alternative policies (e.g., ADF rates) and/or

uncertain external constraints (e.g., commodity prices). We derived n descriptors⁵ of scenarios, denoted as d_i ($i=1, \dots, n$), from the drivers identified in the qualitative analysis. The first descriptor is derived from the goal system of waste management, which policy-makers are supposed to pursue when designing new policies. A goal system has several goals, e.g., the sustainable use of raw materials or the reduction of local environmental impacts of MSW processing facilities. In the scenario construction, we successively prioritize one goal and translate it into an alternative policy through policy descriptors, e.g., an economic incentive promoting or hindering a disposal route. Material flow descriptors are the waste flows to the different disposal routes as of 2009, e.g., waste glass-packaging recycled in Switzerland in 2009. The allocation of waste flows to disposal routes results from the combined influence of policy descriptors and of other socio-economic factors that are either endogenous to Swiss waste glass-packaging disposal, e.g., costs of waste glass-packaging collection, or exogenous, e.g., commodity prices. Exogenous and endogenous constraints can also exert influence on one another⁶. The future co-evolution perspective is concretized through the interplay of goal prioritizations, corresponding policies, material flow descriptors, and constraints.

Scenario construction is based on cross-impact balance analysis (CIB analysis) (Weimer-Jehle, 2006). The first step of this analysis is defining m_i possible, future states⁷ (denoted as d_i^j ($j=1, \dots, m_i$)) for each descriptor d_i . Second, the mutual influences between the states of two different descriptors are systematically quantified in a cross-impact matrix, applying a 7-point ordinal scale from strongly restricting (-6) to strongly promoting (+6)⁸. For instance, state d_1^1 has a weakly promoting influence (denoted by +2) on d_2^2 .

In the case at hand, the states of the goal descriptor, their influences on policy descriptors, and the future states of the latter were derived from the applicable waste management goal system. The influences of the policy descriptors on the material flow descriptors correspond to the economic incentives of the ADF itself. Future states and mutual influences of material flow descriptors and constraints were derived from the expert interviews and the reviewed literature. Experts did not fill the cross-impact matrix themselves.

Third, consistent scenarios are constructed by analyzing the cross-impact matrix. A scenario is defined as a unique combination of specific states for all descriptors. To sort out consistent scenarios, the influences exerted on a specific state of a descriptor (e.g., d_1^1) by all states of

⁵ In the scenario analysis community (see, e.g., Saner et al., 2011; Scholz and Tietje, 2002; Spoerri et al., 2009), descriptors are also known as impact variables or impact factors.

⁶ The use of the terms "endogenous and exogenous constraints" differs from that of the economic-modeling community. By endogenous and exogenous, we mean factors specific to the investigated waste management system respectively common to various systems. By constraints, we mean factors that constrain material flows of the waste management system.

⁷ In the scenario analysis community, states, a term used by Weimer-Jehle, are also known as (future) levels.

⁸ The rationale of the 7-point ordinal scale with -6 and +6 indicating the most extreme ratings is the alignment of all influences to the incentive set by the ADF rates, the maximum being 60% with a 20% interval.

the other descriptors (i.e., d_2^1 and d_2^2 , if the second descriptor has only two states) are added up as a single figure known as the impact balance. If d_1^1 undergoes a higher total influence than the other states of the first descriptor (i.e., d_1^2) and is the scenario state, the scenario is considered consistent for this descriptor.

The final selection of consistent scenarios was performed by means of succession analysis. This procedure permits the selection of those consistent scenarios that the present system can transit to given its current structure (i.e., specific states of the descriptors) and the mutual influences among descriptor states (i.e., transition dynamics). Thereby, a start scenario is defined, exhibiting inconsistencies in one or more descriptors (e.g., d_1^1 is the scenario state and has a lower impact balance than d_1^2). In a first succession, a new scenario—the *successor*—is defined by correcting inconsistencies. Concretely, states with the highest impact balance replace the inconsistent ones (i.e., d_1^2 becomes the state of the successor). As the first correction can lead to new inconsistencies in other descriptors, this iterative procedure is repeated until a consistent scenario is reached—the *attractor*. We conducted the succession analysis for waste glass-packaging disposal in Switzerland with a dedicated software (Weimer-Jehle, 2011).

Following is an example of CIB analysis derived from the case at hand to illustrate the method. The states of three descriptors interrelate: the ADF rate setting an incentive for recycling cullet to new glass-packaging (descriptor A, a policy descriptor); the possible, future processing of green cullet exported to glass-packaging factories in 2009 (descriptor B, a material flow descriptor); and the prices of exporting cullet to such factories (descriptor C, an exogenous constraint). Table 1 is the cross-impact matrix, in which mutual influences of states are rated. When all states of the three descriptors are combined, it results in a total of $1 \times 3 \times 3 = 9$ scenarios. In Table 1, the example scenario has the following states (rows highlighted in grey): a specific ADF rate (60% corresponding to some 60 Swiss Francs per ton of waste glass-packaging collected), the export of green cullet as in 2009, and higher export prices than in 2009. While the impact balances for the export prices are all nil because they are not influenced by any other descriptor and thus no state is more consistent than the other, we obtain +8, -2, and -2 for the descriptor “processing of green cullet exported in 2009.” As the continuation of the export exhibits the highest balance and corresponds to the scenario state, the scenario as a whole is consistent. In an example of succession analysis, the combined influence of higher export prices and the ADF rate would lead to the replacement of high-grade downcycling (i.e., start scenario) by exporting to glass-packaging factories abroad (i.e., attractor).

TABLE 1 EXAMPLE OF SCENARIO CONSTRUCTION WITH CIB ANALYSIS (ADF: ANTICIPATED DISPOSAL FEE, CH: SWITZERLAND; DC: DOWNCYCLING; EUR: EUROPE; EXP: EXPORT; REC: RECYCLING). THE INFLUENCE IS RATED FROM ROW TO COLUMN, E.G., STATE C3 OF DESCRIPTOR C HAS A WEAKLY PROMOTING INFLUENCE (+2) ON STATE B1 OF DESCRIPTOR B.

	A	B			C		
	A1	B1	B2	B3	C1	C2	C3
A. ADF rate REC separated A1: 60%		6	0	0	0	0	0
B. Processing green for EXP B1: REC separated EUR B2: High-grade DC green CH B3: Low-grade DC green CH	0 0 0				0 0 0	0 0 0	0 0 0
C. Export prices separated C1: 2009 C2: Lower level C3: Higher level	0 0 0	0 -2 2	0 2 -2	0 2 -2			
	v	v			v		
Balance:	0	8	-2	-2	0	0	0

2.3 RESULTS OF THE QUALITATIVE SYSTEM ANALYSIS

The following subsections describe the historical transitions of the waste glass-packaging disposal system of Switzerland from 1950 up to 2009, resulting in a set of crucial drivers for the upcoming transition⁹. Figure 2 depicts the dynamics of the four transitions that have taken place since 1950 by showing the involved drivers and the interactions among them. Figure 3 illustrates the waste glass-packaging disposal systems that resulted from the respective transitions in the form of material flow analyses.

⁹ A more detailed historical analysis can be downloaded at <http://www.uns.ethz.ch/pub/wp> (NSSI Working Paper #48)

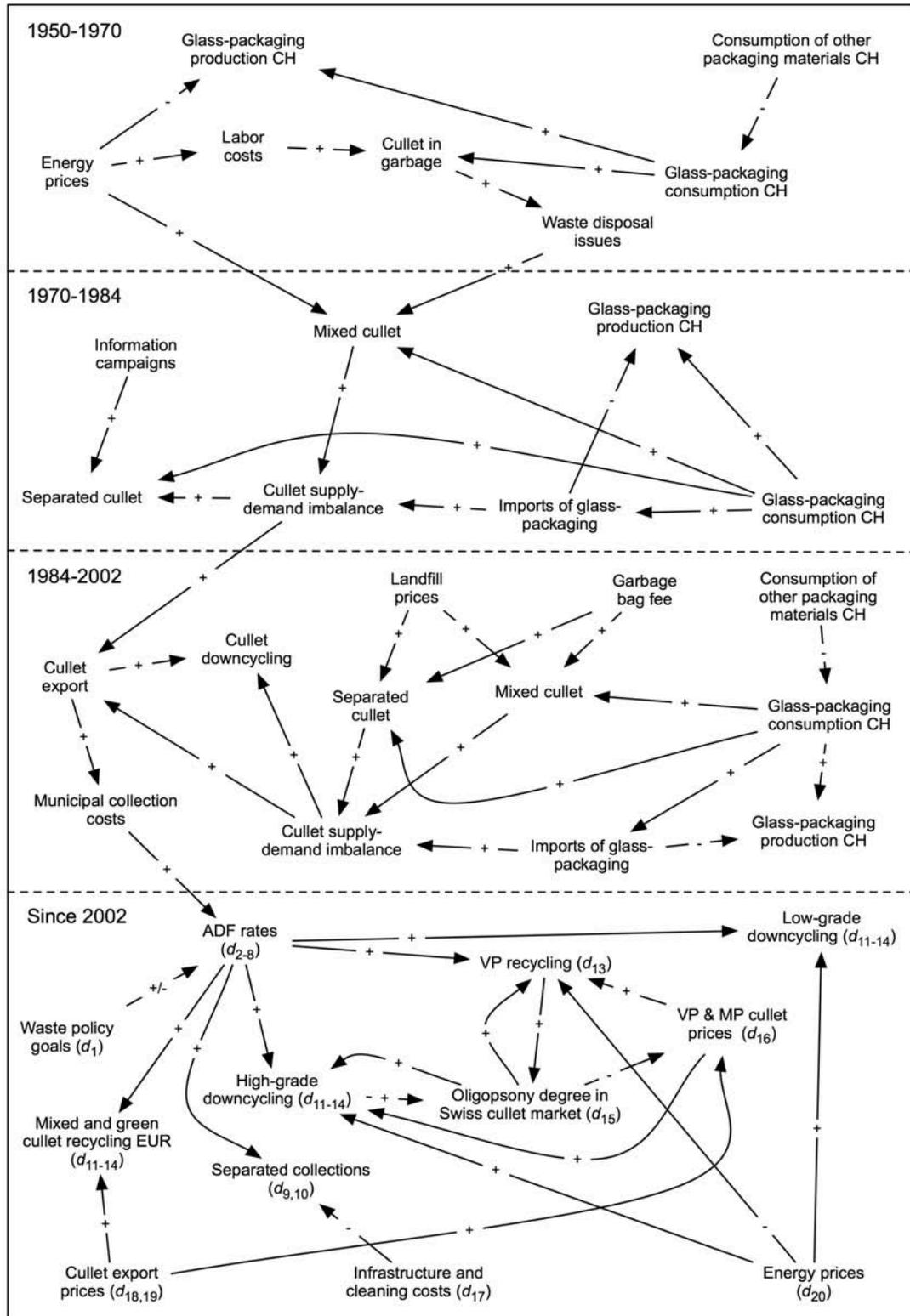


FIGURE 2 DRIVERS OF WASTE GLASS-PACKAGING DISPOSAL IN SWITZERLAND FROM 1950 UNTIL 2009 AND THEIR INFLUENCES (ADF: ANTICIPATED DISPOSAL FEE; CH: SWITZERLAND; EUR: EUROPE; MP: MISAPOR; VP: VETROPACK). POSITIVE INFLUENCE (I.E., PROMOTING) IS DENOTED BY "+"; NEGATIVE (I.E., RESTRICTING) IS DENOTED BY "-." IN THE PRESENT SYSTEM (I.E., SINCE 2002), WE INDICATE WHICH DESCRIPTORS (USED THEREAFTER IN SCENARIO CONSTRUCTION) CORRESPOND TO THE DRIVERS.

Transitions of municipal solid waste management
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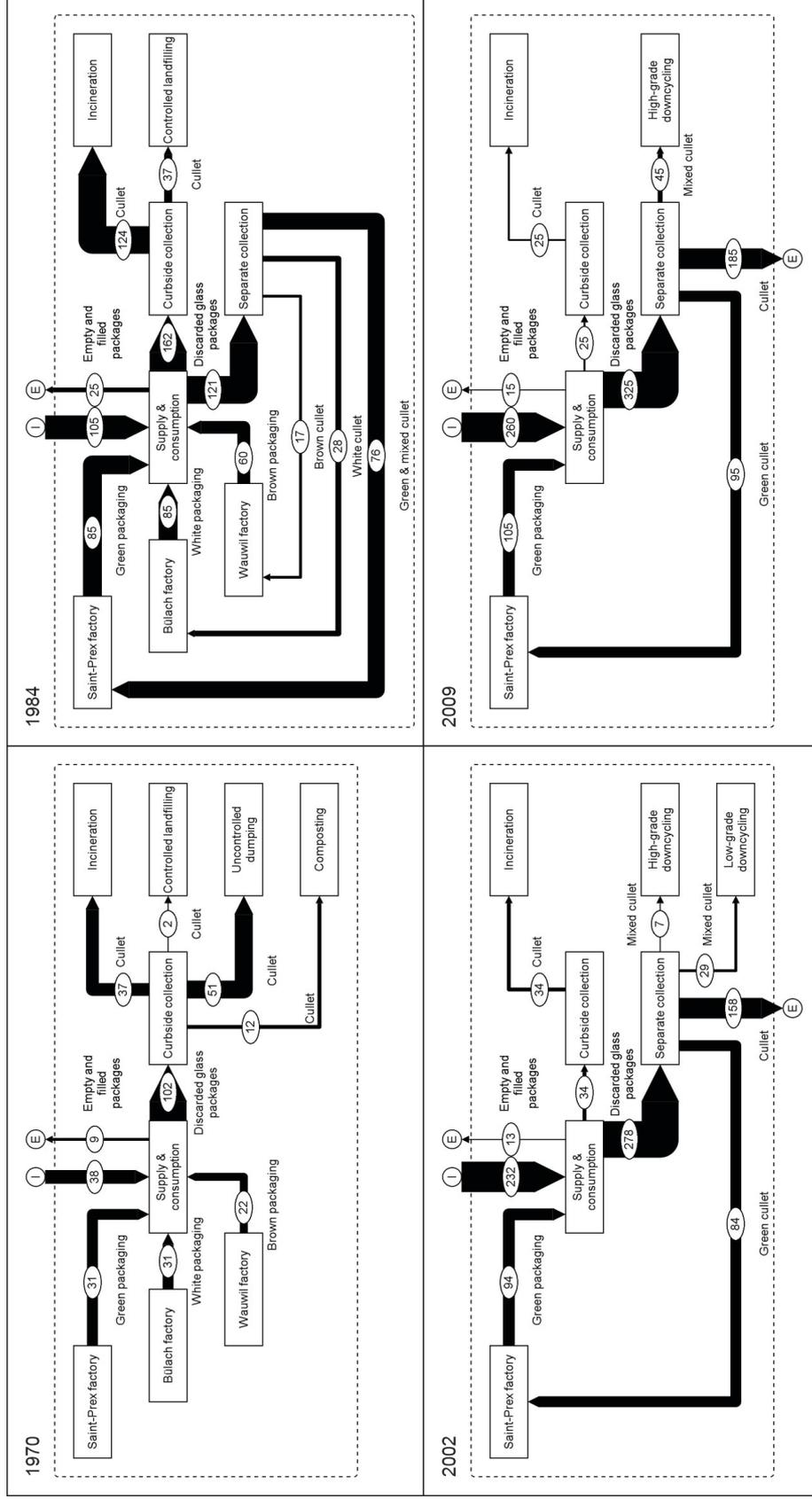


FIGURE 3 SWISS GLASS-PACKAGING FLOWS (IN 1,000 TONS). THE SYSTEM BOUNDARIES ARE INDICATED BY DOTTED LINES AND CORRESPOND TO THE NATIONAL BORDERS [E: EXPORT; I: IMPORT]. "BÜLACH," "SAINT-PREX," AND "WAUWIL" ARE SWISS MUNICIPALITIES WITH GLASS FACTORIES (FIGURES PROVIDED BY OR ESTIMATED BASED ON SURVEYS AND ASSESSMENTS BY ASS (1971), FOEN (1984, 2010), FRISCHKNECHT AND FREY (1989), VETROPACK (1985), AND VETROSSWISS (2003, 2011)).

2.3.1 1950-1970: THE ROUTE TO RECYCLING

In the middle of the 20th century, Switzerland was producing 25,000 tons of glass-packaging and importing 5,000 tons per year (Keller, 2006). The energy transition (i.e., from coal to oil) along with a drastic energy price decline in the 1950s resulted in a switch from energy to labor as the primary cost factor (Pfister et al., 1996). This seems to explain why single-use glass-packaging became more attractive than labor-intensive, multi-trip systems (e.g., for beer, milk, and wine bottles) and glass production volumes consequently increased. Single-use glass-packaging was meant to be disposed of together with other wastes through curbside collection and not recovered. In addition, at that time, new packaging materials (e.g., plastics, brik-pak, and aluminum) started to compete with glass. These packaging materials were more convenient, as they were lighter, easier to dispose of (i.e., less volume), and more solid (Berger, 2005). However, consumption growth overcompensated for substitution effects, and the demand for glass rose from an annual total of 10 to 16 kg per capita between 1960 and 1970 (ASS, 1971).

2.3.2 1970-1984: INTRODUCTION OF POST-CONSUMER CULLET RECYCLING

In 1972, in order to save energy and resources, Vetropack, the only active glass-packaging company in Switzerland, adopted a new raw-material practice. It used post-consumer cullet in addition to that already collected from bottlers for its production process, because cullet melts at lower temperatures than primary raw materials (Lods, 1983). The energy crisis of 1973 strongly reinforced this strategy (Marek, 2005). Energy prices, together with waste disposal issues related to single-use glass-packaging (e.g., amounts landfilled) and publicized by environmental NGOs (e.g., ASS, 1971), were responsible for the introduction of separate collection of cullet by municipalities.

With the curbside collection of waste glass-packaging, municipal collection costs were high and cullet was mixed with respect to color; as a result, only green glass-packaging could be produced. Hence, in 1975 Vetropack introduced the bring-system for the color-separated (i.e., brown, green, white) collection of waste glass-packaging and founded a new company, Vetro-Recycling. Its task was to prepare cullet and to ensure its continuous supply to the three glass-packaging factories of Switzerland. Vetro-Recycling bore a large share of the logistics costs (i.e., transportation of cullet from regional storage to the preparation facility) and compensated municipalities for the collected cullet based on the raw materials' corresponding price (Vetropack, 1976).

As early as the 1970s, Vetropack needed less green and mixed cullet than what was being supplied by Vetro-Recycling. The reason for this imbalance was due to the increased imports of cheap glass-packaging due to overcapacities in the European glass-packaging industry (Vetropack, 1976).

2.3.3 1984-2002: SEARCHING FOR ALTERNATIVES TO CULLET RECYCLING

Environmental legislation in Switzerland contributed, both directly and indirectly, to ever-increasing collection rates, mainly through water protection legislation banning uncontrolled dumping (Water Protection Act of 1971), a mandatory permit for the construction and operation of controlled landfills (Environmental Protection Act, Swiss Confederation, 1983), and a fee on garbage bags giving households a direct incentive to recycle. The latter was introduced by a revision of the Environmental Protection Act in 1997. Waste management

legislation combined with information campaigns led to a collection rate of 60% in 1990, rising to about 95% by the end of the century (Vetropack, 1991, 2001). Moreover, the need for larger, economically more efficient glass-packaging factories all over Europe led to the closure of two of the three Swiss glass-packaging factories in 1993 and 2001. Lost domestic production capacities were substituted by increases in the imports of glass-packaging and alternative packaging materials. Yet lost production capacity, along with higher collection rates, also exacerbated the cullet supply-demand imbalance.

Since the mid-1980s, Vetropack countered the cullet supply-demand imbalance by exporting cullet to glass-packaging factories in neighboring countries. Because of the high costs associated with the latter option, in 1988, Vetro-Recycling investigated the possibility of downcycling cullet to construction materials, e.g., foam glass as insulation material (Vetropack, 1989). Overall, the business of collecting and recycling cullet became increasingly costly, and when no agreement could be reached among stakeholders about introducing an anticipated disposal fee, Vetro-Recycling shifted the burden of cullet transport costs onto municipalities (Vetropack, 1999), and the Swiss government introduced an anticipated disposal fee (ADF) (Swiss Government, 2000). The ADF was first levied in 2002.

2.3.4 SINCE 2002: FOSTERING THE ECOLOGICAL DISPOSAL OF WASTE GLASS-PACKAGING

The Swiss EPA commissioned a private organization, Vetroswiss, to collect and disburse the ADF income to municipalities. The EPA also established compensation rates following earlier policy papers such as the Guidelines for Swiss Waste Management of 1986 and the Waste Concept for Switzerland of 1992 (FOEN, 1986, 1992). Cullet recycling (some 60 Swiss francs per ton of collected cullet) was fostered over downcycling (ca. 20 Swiss francs per ton), while separated collection (40 Swiss francs per ton) was promoted over mixed collection (no compensation). The EPA introduced a high rate for downcycling to foam glass (ca. 60 Swiss francs per ton for mixed glass and ca. 100 for separated glass) to allow municipalities located far from glass-packaging factories, for instance in mountainous areas, to process their cullet in an environmentally sound way (Vetroswiss, 2003).

Between 2002 and 2009, downcycling to sand substitute (i.e., low-grade downcycling) by local construction firms ended and was replaced by downcycling to foam glass (i.e., high-grade downcycling) by a single company, Misapor. Today, the demand side of the Swiss cullet market is an oligopsony with two dominant firms, Vetropack and Misapor. Vetropack needs green cullet with a specific grain size to produce high-quality green glass-packaging, and Misapor is content with mixed or green cullet of any grain size. Hence, the two entities work in partnership and acquire cullet from municipalities to allocate it optimally to either recycling or high-grade downcycling. The oligopsony, reinforced by this partnership, gives Vetropack and Misapor the possibility to dictate lower cullet prices to municipalities.

Besides ADF rates and the oligopsony structure of the Swiss cullet market, the experts considered that three drivers play a key role in the allocation of waste glass-packaging flows to the different disposal routes: energy prices, prices for exporting cullet, and the cleaning and infrastructure costs of cullet collection. For instance, increases in energy prices promote high-grade downcycling, while cleaning and infrastructure costs favor color-mixed over color-separated collection (see also Jaeger et al., 2005). Indeed, a higher demand for insulation materials such as foam glass induced by an energy price increase has a stronger

effect (i.e., promoting effect) on Misapor output than higher transport and process energy costs (i.e., restricting effect).

Based on the reference year of 2009, the next section outlines possible, future states for the identified key descriptors (summarized in Figure 4) and the scenarios resulting from different sets of initial states (cf. Figure 5).

2.4 RESULTS OF THE SCENARIO CONSTRUCTION

2.4.1 DESCRIPTORS, STATES, AND INFLUENCES

Figure 4 provides an overview of the groups of descriptors, their states, and their types of influences. All state-to-state influences are disclosed in Table SM 1 in Appendix A. Additionally, we provide various examples to illustrate and explain specific states and influences.

Transitions of municipal solid waste management
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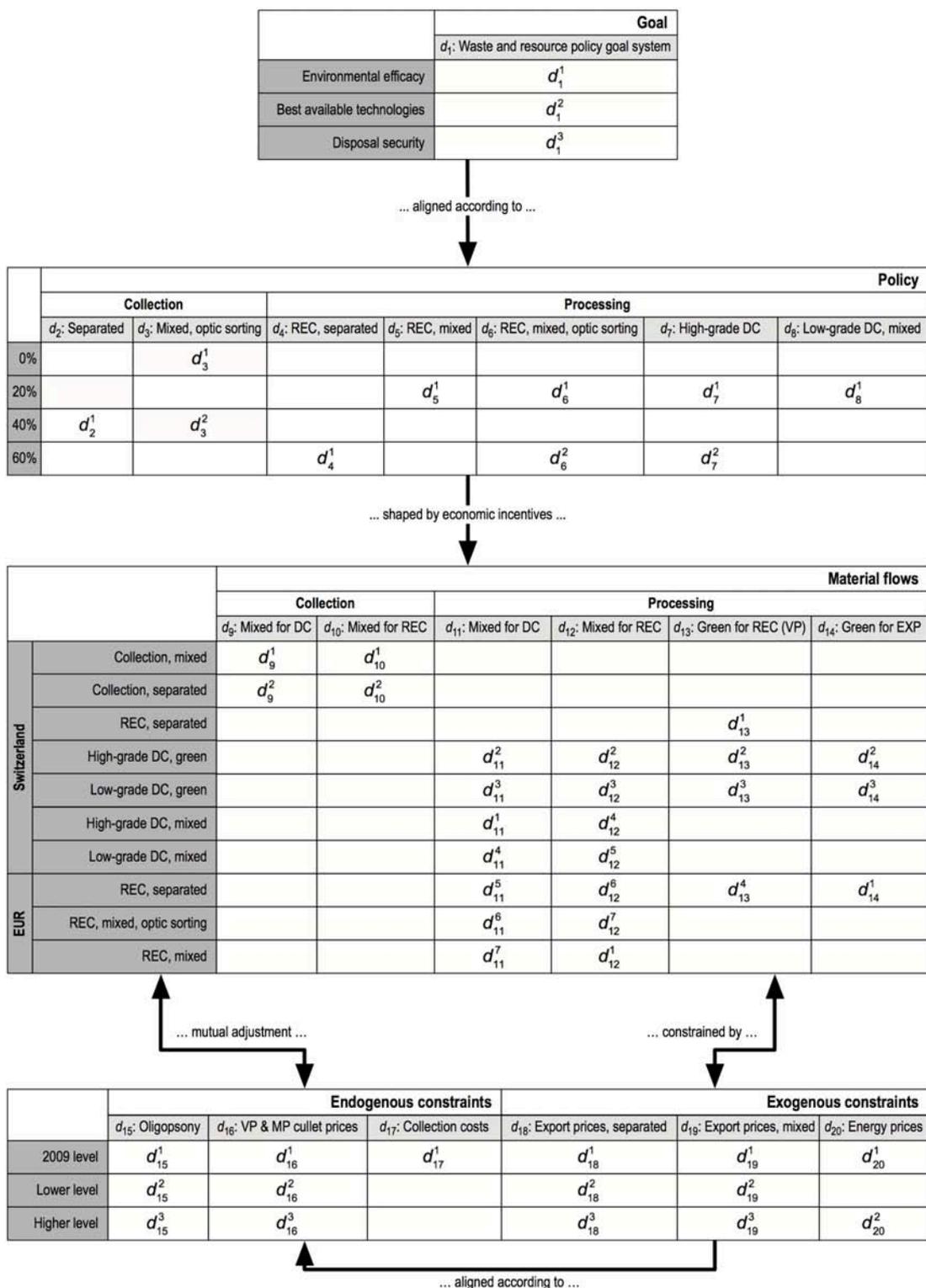


FIGURE 4 DESCRIPTORS, STATES, AND INFLUENCES OF WASTE GLASS-PACKAGING DISPOSAL (DC: DOWNCYCLING; EXP: EXPORT; MP: MISAPOR; REC: RECYCLING; VP: VETROPACK).

The qualitative system analysis resulted in a total of 20 descriptors with corresponding future states characterizing the five clusters of descriptors: one goal descriptor, seven policy descriptors (two for the way cullet is collected, five for the way it is processed), six material flow descriptors, and three endogenous and three exogenous constraints. The states of the

goal descriptor depict different prioritizations of specific goals outlined by Swiss policy guidelines (Hanser, Kuster, Gessler, & Ehrler, 2006). Environmental efficacy (d_1^1) means recycling is favored over downcycling, hence promoting the collection of separated cullet or the optic sorting of mixed cullet. Best available technologies (d_1^2) refer to the minimization of local process emissions, and hence to the maximization of cullet processing within Switzerland, as it is known to be among the countries having the highest environmental standards (FOEN & FSO, 2011). Finally, disposal security (d_1^3) stands for a diversification of disposal routes (i.e., competition on the demand side of the cullet market to ensure acceptable cullet prices for collecting municipalities).

The states of the goal descriptor are translated into states of the policy descriptors, i.e., the levels of ADF rates for collection (d_2^1, d_3^{1-2}) and processing ($d_4^1, d_5^1, d_6^{1-2}, d_7^{1-2}, d_8^1$). For instance, the state “environmental efficacy” of the goal descriptor goes hand in hand with states of policy descriptors that provide economic incentives for the recycling of separated cullet and of mixed cullet with upstream optic sorting. Hence, the ADF rates of collecting cullet in a mixed way prior to optic sorting and of recycling are set at the highest level, whereas mixed collection and subsequent downcycling are disfavored.

In addition to the states of the policy descriptors as economic incentives, the way waste glass-packaging is collected and processed also depends on the state of the endogenous ($d_{15}^{1-3}, d_{16}^{1-3}, d_{17}^1$) and exogenous constraints ($d_{18}^{1-3}, d_{19}^{1-3}, d_{20}^{1,3}$), which are not under the control of waste policy-makers. For instance, higher energy prices foster high-grade downcycling and hinder recycling in Switzerland ($d_{20}^2 \rightarrow d_{11-14}^2, d_{11}^1, d_{12}^4, d_{13}^1$). Indeed, Vetropack cannot increase the share of cullet in its raw-material mix without risking losses in product quality and loosing its market shares. A higher degree of oligopsony in the Swiss cullet market facilitates Vetropack and Misapor’s access to cullet, while additional cullet market shares for the two companies reinforce the oligopsony ($d_{15}^3 \leftrightarrow d_{13}^1, d_{11-14}^2, d_{11}^1, d_{12}^4$). In addition to waste flow allocations, states of endogenous constraints are also influenced by exogenous constraints. For example, Vetropack and Misapor adapt their cullet prices to export prices to ensure that domestic processing does not become too unattractive for collecting municipalities ($d_{18-19}^{1-3} \rightarrow d_{16}^{1-3}$).

Material flow descriptors depict the waste management scheme itself, i.e., the types of collection (d_9^{12}, d_{10}^{12}) and processing ($d_{11}^{1-7}, d_{12}^{1-7}, d_{13}^{1-4}, d_{14}^{1-3}$), yet they only cover those waste flows of 2009 whose allocation can potentially undergo change in the future, given the influence of policy descriptors and constraints. The possible range of reallocations is covered by the states of these descriptors. For instance, green cullet currently recycled by Vetropack (d_{13}^1) could be reallocated to high-grade downcycling (d_{13}^2), low-grade downcycling (d_{13}^3), or recycling abroad (d_{13}^4), if the energy prices were higher. In this case, a reallocation would also mean a proportional reduction in production, i.e., a closure of the Vetropack glass-packaging factory. A reallocation of cullet currently downcycled to foam glass would lead to the relocation of Misapor production capacities abroad. In contrast, cullet newly exported to

foreign glass-packaging factories would substitute primary raw materials (i.e., quartz sand), while production levels there would not be affected.

In 2009, four important waste flows were susceptible to change with respect to the type of collection and/or processing: mixed cullet downcycled to foam glass (45,000 tons), mixed cullet recycled in neighboring countries (45,000 tons), separated cullet recycled by Vetropack (95,000 tons, composed of some 80% green cullet), and green cullet recycled in neighboring countries (70,000 tons). A smaller quantity of green cullet was downcycled to Misapor (8,800 tons). Such practice had no influence on other descriptors and was entirely dependent on Misapor's presence in the Swiss cullet market. Should Misapor disappear, the 8,800 tons of green cullet would either be downcycled to sand substitute or exported depending on the relative importance of these disposal routes. Hence, green cullet that was downcycled in 2009 is not a descriptor in the cross-impact matrix. The five waste flows amount to 85% of total cullet collected in 2009 (311,000 tons), the rest being exported brown and white cullet from separated collections. The quantities are disclosed in or derived from the Vetroswiss annual report of 2009 (Vetroswiss, 2010).

Besides these influences, two constraints were fed into the cross-impact matrix. First, cullet collected in a separated way cannot be processed as mixed, and vice versa. The second constraint represents the irreversibility of switching from color-mixed to color-separated cullet collection. Both influences are rated with -99.

2.4.2 SUCCESSION ANALYSIS

The succession analysis was performed for the three goal prioritizations, the corresponding ADF rates, and the 2009 states of environmental descriptors. Additionally, we investigated the impact of varying exogenous environmental descriptors, i.e., energy prices and prices for the export of cullet, on the evolution of waste glass-packaging disposal. Concretely, export prices with states equal to, higher, and lower than those of 2009 were combined with energy prices with states equal to and higher than those of 2009. We thereby assume, as can be checked in the cross-impact matrix (cf. Table SM 1), that no correlation exists between the two prices' categories.

The scenarios resulting from the succession analysis are shown in Figure 5. While goal prioritization, policies, and exogenous environmental descriptors remain constant during the whole succession analysis, the way waste glass-packaging is collected and its allocation to disposal routes and endogenous constraints are subject to change. The allocation of 2009 is illustrated in Figure 5 as well to allow for comparison with the scenario allocations. For endogenous and exogenous constraints, 2009 levels and levels lower and higher than 2009 levels are abbreviated 09, L, and H respectively. There are two aspects common to all scenarios. First, there is no switch from mixed to separated collections, as collection costs interfere with the ADF rate of separated collection. Second, low-grade downcycling never takes place. There are other disposal routes available with higher ADF rates.

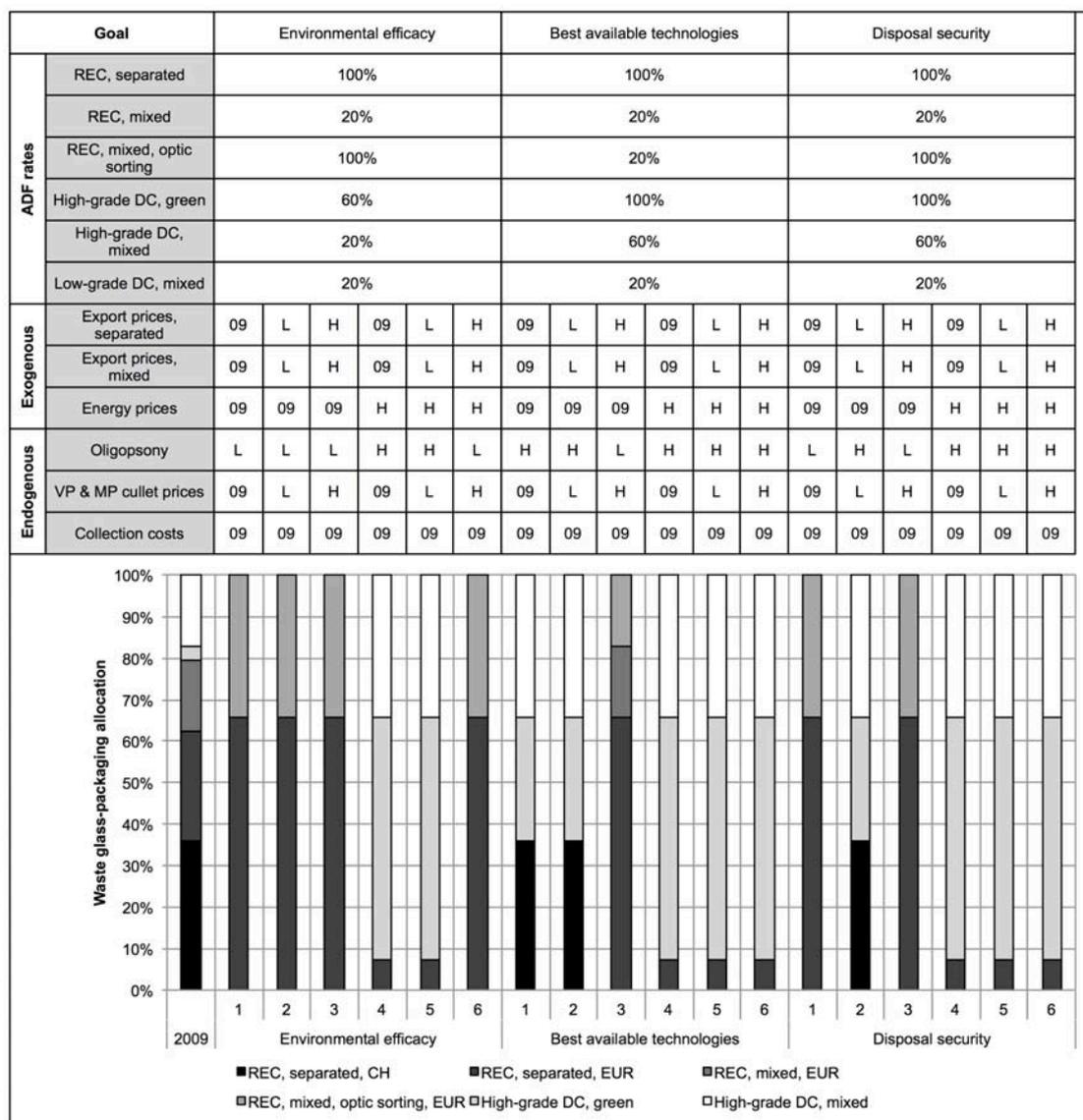


FIGURE 5 SCENARIOS OF WASTE GLASS-PACKAGING DISPOSAL (ADF: ANTICIPATED DISPOSAL FEE; CH: SWITZERLAND; DC: DOWNCYCLING; EUR: EUROPE; MP: MISAPOR; REC: RECYCLING; VP: VETROPACK).

Goal prioritization of environmental efficacy (EE) leads to the same allocations of waste glass-packaging with the exception of two sets of exogenous environmental descriptors. In allocations EE1, EE2, EE3, and EE6, all mixed cullet is recycled following optic sorting as a result of the dedicated ADF rate of 100%. Recycling no longer takes place in Switzerland, as the end of downcycling leads to a weakening of the oligopsony and the closure of the Vetropack glass-packaging factory. In allocations EE4 and EE5, 2009 or lower export prices and higher energy prices bring about the switch from recycling to the downcycling of green and mixed cullet. Brown and white cullet originally recycled by Vetropack is exported.

Goal prioritization of best available technologies (BAT) generates three different allocations. In allocations BAT1 and BAT2, all mixed and green cullet not needed by Vetropack is downcycled. In allocation BAT3, higher export prices bring about the closure of the Vetropack glass-packaging factory and the export of all its cullet. As a result of a weakened oligopsony

and higher export prices, the recycling of mixed cullet with or without optic sorting equally (i.e., same impact balance) prevails over high-grade downcycling. In allocations BAT4, BAT5, and BAT6, higher energy prices lead to the closure of the Vetropack glass-packaging factory and the reallocation of its green cullet to high-grade downcycling, as the demand for energy-saving products stimulates this disposal route. For this reason, green cullet exported and mixed cullet recycled in 2009 is downcycled as well.

Goal prioritization of disposal security (DS) leads to four different allocations of waste glass-packaging. In allocations DS1 and DS3, all waste glass-packaging is exported and recycled, either directly or following optic sorting. All mixed fractions are optically sorted prior to recycling because of the difference between rates for color optic sorting prior to recycling and high-grade downcycling (100% and 60%). The oligopsony becomes weaker; as a result, the Vetropack glass-packaging factory closes and its cullet is exported instead of downcycled. Higher export prices (DS3) only reinforce the dominance of export. In allocation DS2, high-grade downcycling expands as a result of lower export prices. A higher degree of oligopsony and lower export prices allow Vetropack to pursue its activities in Switzerland. In allocations DS4, DS5, and DS6, all mixed and separated fractions are downcycled, with the exception of the brown and white cullet originally recycled by Vetropack, because higher energy prices cause it to close and stimulate the demand for energy-saving products (from high-grade downcycling). Higher export prices (DS6) are not influential enough to foster their export to foreign glass-packaging factories.

2.5 DISCUSSION

The key result of Part I of this paper series is a set of scenarios, including allocations of waste glass-packaging to disposal routes, to which initial states differing with respect to policy and/or exogenous constraints could transit due to the dynamics found in this MSW management system. We first interpret the scenario results by discussing them and then reflect on the method applied to generate them.

2.5.1 DISCUSSION OF SCENARIO RESULTS

The analysis revealed that current dynamics and potentially resulting upcoming transitions of the Swiss glass-packaging disposal system are primarily influenced by a set of intertwined economic variables. Economic incentives, set by waste policy-makers in the form of ADF rates for the various disposal routes (i.e., collection and processing), interfere with and are constrained by endogenous (e.g., the degree of oligopsony and the cullet prices paid by domestic processors) and exogenous economic constraints (i.e., energy and export prices), respectively. As the scenarios were examined in greater detail, the impact of these incentives on waste glass-packaging flows is twofold. First, they determine which collection and subsequent processing options pay out the most, i.e., increasing energy prices foster the demand of energy-saving insulation materials, foam glass among others. More indirectly, they can induce more fundamental—*structural*—changes in waste flows through their negative effect on the economic viability of specific cullet processing industries, which potentially alter the processing capacities in the future. For instance, the domestic recycling company Vetropack produces high-end glass-packaging. Higher energy prices could lead to its closure, as it could not increase its share of cullet in its raw-material mix without losing its market shares.

Bearing in mind the evidence gained from the historical analysis, it is clear how the types of transition drivers changed throughout the evolution of the glass-packaging disposal system. Whereas possible, upcoming transitions (i.e., foreseen by stakeholders/experts and through literature review) are exclusively driven by economic incentives and by the way actors react to such incentives, drivers of all societal systems played a role in past waste glass-packaging disposal. For instance, societal pressure to solve serious environmental problems (waste disposal issues), consumer preferences, the competition of glass with newly developed, alternative packaging materials, and the implementation of financing schemes for waste management have all had a decisive impact on the development of waste management schemes since 1950. In short, the current system is one of highly optimized nature, so that stakeholders/experts have no reason to expect fundamental change in the foreseeable future.

The 18 selected scenarios indicate the spectrum of possible, future disposal schemes that can emerge from different constellations of economic incentive variables (i.e., ADF rates being aligned to the pursued policy goal in combination with endogenous and exogenous constraints). The scenarios outline only four different types of future allocations of waste glass-packaging flows to the available disposal routes. Two types represent complete bottle-to-bottle recycling in foreign countries either with (cf. EE1-3,6; DS1,3) or without (cf. BAT3) the optic sorting of mixed cullet prior to recycling. In contrast, a third type corresponds to the high-grade downcycling of all green and mixed cullet and the recycling abroad of brown and white cullet processed by Vetropack in the current state (EE4,5; BAT4-6; DS4-6). The last type depicts a combination of domestic bottle-to-bottle recycling and high-grade downcycling (BAT1,2; DS2).

It is striking that for specific policy goals, being pursued by corresponding policy incentives, different disposal schemes turn out to be consistent (cf. EE1-3,6 vs. EE4-5; BAT1,2 vs. BAT3 vs. BAT 4-6; DS1,3 vs. DS2 vs. DS4-6) and, moreover, that the same future disposal schemes can emerge independently from the pursued policy goals (cf. EE4,5 and DS4-6; EE1-3,6 and DS1,3; BAT1,2 and DS2). This highlights that policy goals are not necessarily achieved with the alternative ADF rates and under current and future states of endogenous and exogenous constraints. Higher energy prices, which foster high-grade downcycling and put domestic recycling at risk, can hinder environmental efficacy (EE4,5) while possibly promoting inland processing and thus the best environmental technologies (BAT4-6). It seems that if energy prices are to remain at 2009 levels, higher export prices compromise both domestic processing options (BAT3). As for disposal security, no scenario allocation can be considered as a successful implementation of market diversification due to ADF rates and/or endogenous and exogenous constraints. Ideally, recyclers and high-grade downcyclers should compete for green and mixed cullet in a balanced supply-demand relationship. In other words, the oligopsony should be dismantled. Now in scenario allocations DS1 and 3-6, green and mixed cullet is either entirely exported or downcycled. In scenario allocation DS2, recyclers and downcyclers which constitute the oligopsony (i.e., Vetropack and Misapor) process exclusively green and mixed cullet.

The scenario results indicate that financial incentives set by political regulations can, to a considerable extent, be counteracted by other endogenous and exogenous financial constraints (cf. energy prices), which are out of policy-makers' control. They either depend on the strategies of other key actors in the Swiss disposal system (e.g., domestic processing

industries) or prices emerging from international market dynamics (e.g., energy prices). However, what the future scenarios mean in terms of environmental and economic system performance, two crucial evaluation dimensions for policy-making, is not clear. The integrated performance assessment of the selected scenarios, including the definition of adequate assessment criteria, is addressed in the second part of the paper series.

Finally, performing a succession analysis on other waste fractions in Switzerland or on waste glass-packaging in other countries would allow putting the scenario results in contrast. Such studies would permit a validation of the results and an evaluation of the impacts of different policies when considering context-specific endogenous and exogenous constraints (Oosterhuis, Bartelings, Linderhof, & van Beukering, 2009). In this respect, the prospective approach adopted in this paper complements historical analyses that have demonstrated the limited effects of waste policy in specific contexts (Mazzanti, Montini, & Nicolli, 2009; Mazzanti & Zoboli, 2008). In turn, it could contribute to meaningful transfer of policies from one waste fraction to another, respectively from one country to another. Indeed, LCA-based policy support acknowledges already the importance of context in assessing future environmental benefits arising from the supply of energy or secondary raw materials by MSW management systems (Eriksson et al., 2005; Höjer et al., 2008).

2.5.2 METHODOLOGICAL CONSIDERATIONS

The procedure applied to construct consistent, future scenarios of waste glass-packaging disposal systems is based on a variant of scenario analysis: succession analysis (Weimer-Jehle, 2006). We further refined it by bringing in more decision-theoretic principles concretized by the distinction of goals, policies, material flow descriptors, and endogenous and exogenous constraints. Succession analysis suits well the ambition of taking into consideration the societal embedding of waste disposal processes as (i) it relies on system-theoretic and not disciplinary principles—we go beyond economic and technological scenarios (Munster & Meibom, 2011)—and (ii) it permits the integration of both qualitative and quantitative knowledge in describing the relationships between drivers of different natures.

A potential alternative to the proposed scenario approach is system dynamics models, offering as well the possibility of constructing futures of waste glass-packaging disposal based on qualitative and quantitative knowledge. For instance, Karavezyris, Timpe, and Marzi (2002) integrated fuzzy logic into system dynamics in order to account for the influence of qualitative variables, e.g., environmental behavior, on future MSW quantities. However, the aim of system dynamics is to forecast future MSW quantities or other variables relevant for MSW management based on selected factors. In other words, it emphasizes the most likely developments. In contrast, the goal of succession analysis is to gain insight into the spectrum of possible scenarios that can result from the interplay of variables whose future development is highly uncertain.

The resolution of the allocation of future waste flows to disposal routes is highly dependent on the scope of the study and constrained by the current allocation itself. In the case of Swiss glass-packaging disposal, the total cullet quantity of 2009 was broken down into material flow descriptors according to policy descriptors and endogenous and exogenous constraints. In other words, the allocation reflected the type of processing, its location, and the economic actors involved in domestic recycling and downcycling. In turn, such approach allowed capturing the impacts of ADF rates, cullet export prices, and the degree of oligopsony and

Vetropack and Misapor cullet prices, respectively, on waste flows. The current allocation shows the highest resolution of waste flows. The resolution of future allocations can only be equal or lower to this allocation.

While the current allocation as a constraint for resolution is a limitation of the proposed approach, the dependency of material descriptors on scope calls for an explicit consideration of spatial scale. For waste glass-packaging, looking at flows on a national level made sense because of the small number of processors and their nationwide presence as cullet purchasers. What about the MSW that is currently being incinerated in the 29 incinerators around the country? The heat and electricity that are recovered from this process are strongly subject to different local societal constraints. Some incinerators provide residential neighborhoods with district heating while others supply industries such as paper fabrics. Likewise, electricity distribution is managed by hundreds of firms exhibiting different characteristics (e.g., size, economic structure). Here, a higher spatial resolution translated into regional descriptors would seem appropriate. The present approach could thus be extended to include regional scenarios besides national scenarios, where national descriptors act upon regional descriptors and vice-versa. Ideas of how such an extension could be operationalized have already been proposed (Biggs et al., 2007; Ozkaynak & Rodriguez-Labajos, 2010).

2.6 CONCLUSION

As stated in the introduction, policies in the field of waste management are too often based on decontextualized, isolated environmental or economic assessments of waste management processes (e.g., assessing the environmental benefits of recycling 1 kg of cullet in comparison to downcycling it to foam glass). However, these processes are inextricably embedded in society; therefore, policies relying on incentives are only one of many possible drivers promoting or hindering their implementation. Consequently, policies may fail to achieve their desired outcome (i.e., a goal of waste policy) on the scale at which they are supposed to operate (e.g., at a national scale for waste glass-packaging disposal), if incentives are designed based on comparative assessments of processes.

The presented combination of qualitative system analysis and subsequent scenario construction turned out to be a promising methodological approach to bridge this gap. It permits MSW management systems to be analyzed from a comprehensive perspective and therefore enables MSW management schemes to be embedded in their societal context. Concretely, goals serve to define policies, whose effects on disposal schemes were investigated by means of succession analysis. This requires, in turn, the integration of knowledge of various types (i.e., literature, stakeholders/experts) and disciplines, for which the proposed approach is highly suitable.

Finally, because of its generic and interdisciplinary nature, we believe the procedure can be applied to entire ISWM systems and even other sociotechnical systems, e.g., energy systems. It could become the first step in supporting local, regional, and national authorities when confronted with the question of which of two technologies should be fostered, when both assume the same function (e.g., the disposal of waste or electricity production). After all, the only requirements for such a step would be background literature and a panel of stakeholders/experts of the sociotechnical system of interest to provide an understanding of

its societal embedding as well as a policy goal system and its corresponding tool (e.g., economic incentive).

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APPENDIX A. SUPPLEMENTARY MATERIALS

Table SM 1 is the cross-impact matrix of waste glass-packaging disposal in Switzerland. It reveals the influence that a particular state of one descriptor has on that of another descriptor on a 7-point ordinal scale with -6 and +6 indicating the most extreme ratings. Following is a set of examples of such influences highlighted in red in Table SM 1 and their rationales.

- Environmental efficacy (A1) of **A. Waste and resource policy goal system** on **C. ADF rate collection mixed optic sorting**. Mixed collection followed by optic sorting permits the glass-packaging industry to be supplied with color-separated cullet and thus serves the goal of environmental efficacy. C2 is thus rated as +2.
- 40% (B1) of **B. ADF rate collection separated** on **I. Collection mixed for DC** and **K. Processing mixed for DC**. This rate provides an incentive to switch from mixed collection to separated collection. A 40% rate corresponds to the strength of influence of +4. For K2 and K3, cullet is collected in a separated way and green cullet is downcycled, while brown and white cullet is exported and recycled in neighboring countries.
- 60% (D1) of **D. ADF rate REC separated** on **K. Processing mixed for DC**. It gives collecting municipalities an incentive to proceed to recycling (+6) following separated collection.
- 60% (G2) of **G. ADF rate high-grade DC** on **K. Processing mixed for DC**. This rate provides a strong incentive (+6) for downcycling independently of how cullet is collected.
- Collection separated (I2) of **I. Collection mixed for DC** on **K. Processing mixed for DC**. Collecting cullet in a separate way and processing it as mixed cullet is impossible. A rating of -99 ensures that no scenario will exhibit such a profile.
- REC separated EUR (K5) of **K. Processing mixed for DC** on Collection separated (I2) of **I. Collection mixed for DC**. Switching from separated to mixed collections is viewed as highly improbable by stakeholders; hence, disposal routes implying separated collection (e.g., K5) exert an influence of -99 on mixed collection.
- REC separated EUR (K5) of **K. Processing mixed for DC** on **O. Oligopsony degree**. Processing of cullet by a company other than Vetropack or Misapor contributes to bringing the oligopsony to a lower level (+4).

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- Higher level (O3) of **O. Oligopsony degree** on **K. Processing mixed for DC**. A higher degree of oligopsony provides Vetropack and Misapor with preferential access to cullet (+4).
- Lower level (O2) of **O. Oligopsony degree** on **P. VP & MP cullet prices**. The higher the oligopsony, the lower the prices offered by Vetropack and Misapor. The influence is rated as +4.
- **R. Export prices separated** on REC separated EUR (K5) of **K. Processing mixed for DC**. Depending on their levels, export prices of separated cullet apply no influence (0), a weakly promoting (+2), or a weakly restricting influence (-2) on disposal routes involving exports (e.g., K5). A similar approach is adopted for export prices of mixed cullet and prices proposed by Vetropack (i.e., domestic recycling) and Misapor (i.e., high-grade downcycling).
- Lower level (P2) of **R. Export prices separated** on **P. VP & MP cullet prices**. Vetropack and Misapor tend to lower (+2) their prices when export prices are lower.
- Higher level (R2) of **T. Energy prices** on **K. Processing mixed for DC**. Higher energy prices foster both forms of downcycling (+4), as high-grade downcycling serves energy-saving purposes and low-grade downcycling is done locally, i.e., allowing for short transport distances. Hence, exports are penalized for such a development (-4).
- 2009 level (T1) of **Q. Collection costs** on **I. Collection mixed for DC** and **K. Processing mixed for DC**. Separated collection implies higher cleaning and infrastructure costs than its mixed counterpart and thus exerts a moderately promoting influence on the latter (+4) and on those disposal routes involving mixed collection.

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3 PAPER 2 – TRANSITIONS OF MUNICIPAL SOLID WASTE MANAGEMENT. PART II: HYBRID LIFE CYCLE ASSESSMENT OF SWISS GLASS-PACKAGING DISPOSAL

Meylan, G., Ami, H., & Spoerri, A. (resubmitted). *Resources, Conservation and Recycling*.

ABSTRACT

In policy support of municipal solid waste (MSW) management, life cycle assessment (LCA) can serve to compare the environmental or economic impacts of two or more options for waste processing. The scope of waste management LCAs generally focuses less attention on future developments, e.g., where will recycling take place, and more on the environmental performance of prototypes, e.g., the incineration of all waste compared to recycling. In an attempt to provide more robust support for Swiss waste glass-packaging disposal, scenarios of Swiss waste glass-packaging disposal are assessed from a life cycle perspective. The scenarios consist in schemes for the disposal of the total amount of Swiss waste glass-packaging, i.e., different combinations of recycling and downcycling in Switzerland or abroad (cf. Part I, Meylan, Seidl, & Spoerri, 2013). In Part II, the disposal schemes are assessed with respect to eco-efficiency, an indicator that combines total environmental impacts and gross value added in Switzerland. Results show that no policy alternative guarantees environmental impact reductions and gross value added gains under all developments of exogenous constraints. Moreover, downcycling to foam glass in Switzerland is not only an environmentally sound disposal option, but it also buffers gross value added losses in case domestic recycling (and thus glass-packaging production in Switzerland) ceases in the future. Since the substitution of products based on raw materials other than Swiss cullet is the main responsible for change in environmental and economic impacts, a policy maximizing eco-efficiency of Swiss waste glass-packaging disposal should consider the resulting products of disposal schemes. The combination of scenario analysis and eco-efficiency assessment as presented in this paper can be applied to other contexts (i.e., countries, waste fractions).

3.1 INTRODUCTION

When evaluating and comparing options for municipal solid waste (MSW) management, policy-makers must take into consideration various environmental, economic, and social criteria. Multi-criteria evaluations serve various purposes: e.g., avoiding environmental problem-shifting when implementing an alternative option (e.g., replacing landfilling and waterborne emissions by incineration and airborne emissions) (Laurent, Olsen, & Hauschild, 2012; Raadschelders, Hettelingh, van der Voet, & Udo de Haes, 2003; Saner, Walser, & Vadenbo, 2012; Venkatesh & Brattebo, 2009), identifying win-win and trade-off situations (e.g., an alternative option allows reducing environmental impacts but involves higher costs than the status-quo), acknowledging all stakeholders of MSW management (e.g., municipalities collecting MSW, industry valorizing it). Life cycle assessment (LCA), an analytical tool to assess human activities from an integrative perspective (Pennington et al., 2004; Rebitzer et al., 2004), is a powerful method for multi-criteria evaluation. LCA allows

highlighting problem-shifting as well as win-win and trade-off situations. It even goes a step further by proposing standardized procedures to aggregate indicators into single scores and thus overcome trade-off situations. These features certainly explain LCA popularity among academia, consulting, and MSW practitioners (e.g., Bjorklund & Finnveden, 2005; den Boer, den Boer, & Jager, 2007; Dinkel & Hauser, 2008; Doka, 2006; Finnveden & Ekvall, 1998; Finnveden et al., 2009; Gilgen, Dinkel, & Grether, 2003; Hellweg, Doka, Finnveden, & Hungerbühler, 2005; Hong, Hong, Otaki, & Jolliet, 2009; Liamsanguan & Gheewala, 2008; Pasqualino, Meneses, Abella, & Castells, 2009).

Despite numerous applications, there are persisting challenges of LCA in supporting MSW management planning and decision-making, mainly related to their scope (i.e., system boundaries and time horizons, e.g., Hellweg, Hofstetter, & Hungerbuhler, 2005) and inconsistency between waste LCA models (Gentil et al., 2010). First, there has been a focus on environmental concerns, although policy decisions are strongly based on economic grounds (i.e., financial feasibility, see Jeswani, Azapagic, Schepelmann, & Ritthoff, 2010). This holds particularly true for MSW management with few exceptions (e.g., Carlsson Reich, 2005). Second, the goal and scope of MSW LCAs involve a comparison of prototypes, whose occurrence in the foreseeable future might be highly improbable or even impossible due to a multiplicity of exogenous factors. Upscaling, i.e., scaling the functional unit (e.g., disposal of 1 kg of waste) up to the real amount upon which a function is applied (e.g., disposal of the total amount of MSW in a city, region, or country), is necessary to assess possible systems from a life cycle perspective (Caduff, Huijbregts, Althaus, & Hendriks, 2010; Caduff, Huijbregts, Althaus, Koehler, & Hellweg, 2012; Frischknecht & Stucki, 2010; Lundin, Bengtsson, & Molander, 2000). Third, and building on the latter point, most decisions of MSW management are intended to have long-lasting impacts. There is a need to take future developments properly into account with regard to e.g., technology development, treatment capacities, economic incentives of the system of interest (also known as the foreground system in LCA) and those linked to it (i.e., background systems). These developments significantly drive the performance of MSW management systems.

Overcoming these challenges has also been a requirement of Swiss waste practice for several decades. The Guidelines for Swiss Waste Management prescribe principles for methods to evaluate systems of integrated solid waste management (ISWM) (FOEN, 1986). First, methods should capture detailed characteristics of waste management processes, while embedding them into the entire national economy, i.e., linking them with other economic sectors and considering total flows of waste and secondary raw materials. Second, methods must account for transboundary waste exports, treatments abroad, and imports of corresponding products. Third, different evaluation dimensions are to be considered, i.e., the total environmental impacts of recycling or alternatives and the economic feasibility.

This paper is the second part of a paper series on Swiss waste glass-packaging disposal having the overarching aim of providing societally robust orientations to relevant policy-makers. Part I yielded possible, future scenarios of Swiss waste glass-packaging disposal, including disposal schemes as combinations of disposal options (e.g., recycling abroad, downcycling in Switzerland). The goal of Part II of this paper series is the life cycle-based eco-efficiency assessment of these scenarios. The assessment properly accounts for upscaling effects, uncertain future developments of waste technologies, and related policies and economic incentives, i.e., for the societal embedding of MSW management systems. Part

II builds on the development of future scenarios of waste glass-packaging disposal under the explicit consideration of the societal context (i.e., economic, political, and social contexts) by means of a systematic literature review coupled by knowledge integration from stakeholders/experts (cf. Part I, Meylan et al., 2013). The economic dimension complements the traditional environmental indicators. The following, specific research questions are addressed in this paper:

- 1) What is the overall eco-efficiency of scenarios?
- 2) How well do the scenarios of Part I perform compared to waste disposals schemes which were not identified as scenarios and involve a single disposal option (thereafter referred to as prototypes)?
- 3) Are there trade-offs between scenarios and prototypes, e.g., does scenario A perform better than B in one environmental indicator, but worse in another?
- 4) To which parameters is the eco-efficiency of scenarios and prototypes sensitive?

Section 3.2 details the procedure applied to assess the eco-efficiency of Swiss waste glass-packaging disposal. Section 0 presents the results of the assessment, which are discussed in Section 3.4 from both policy and methodological perspectives. A brief conclusion is provided in Section 3.5.

3.2 METHODOLOGICAL APPROACH

Figure 1 shows the methodological approach adopted to provide policy support in the field of ISWM. In Part II, the disposal schemes of Part I are the objects of an integrative performance assessment (for similar combinations of scenario analysis and assessment, see Saner, Blumer, Lang, & Koehler, 2011; Trutnevyte, Stauffacher, & Scholz, 2012; Walser, Demou, Lang, & Hellweg, 2011). A coupled human-environment systems (HES) perspective (Liu, Dietz, Carpenter, Alberti, et al., 2007; Liu, Dietz, Carpenter, Folke, et al., 2007; Scholz, 2011) underlies both parts: transitions of Swiss waste glass-packaging disposal are conceptualized as a human system's (i.e., policy-makers) co-evolution with its environment, and the integrative performance assessment is based on the relevant model and evaluation dimensions for this particular human system. The section starts with an illustration of the assessment method and its application to Swiss waste glass-packaging disposal (cf. Section 3.2.1) and closes with a synopsis of the different scenarios and prototypes to be assessed (cf. Section 3.2.2). For a detailed illustration of the scenarios, see Meylan et al. (2013).

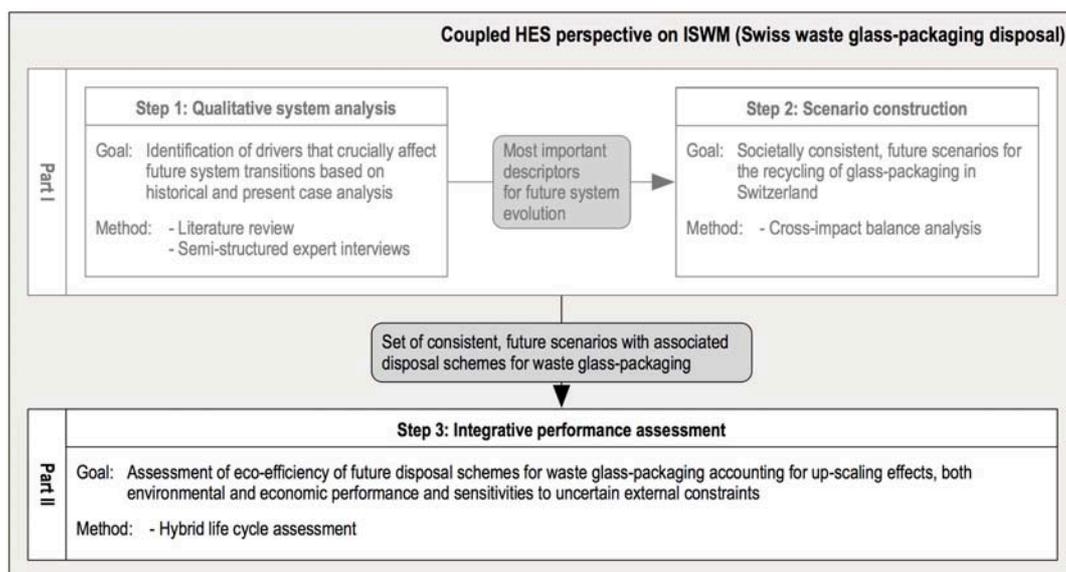


FIGURE 1 METHODOLOGICAL APPROACH FOR THE CONSTRUCTION AND ASSESSMENT OF CONSISTENT, FUTURE SWISS WASTE GLASS-PACKAGING DISPOSAL SCENARIOS (CF. MEYLAN ET AL., 2013).

3.2.1 INTEGRATIVE PERFORMANCE ASSESSMENT

Hybrid life cycle assessment (HLCA) (Nakamura & Kondo, 2002, 2009; Suh & Nakamura, 2007) is a promising method to tackle some of the challenges mentioned in Section 1 (Introduction) and is thus applied to the case of Swiss waste glass-packaging disposal. As any LCA, HLCA allows capturing the direct and indirect impacts of MSW management processes (Hawkins, Hendrickson, Higgins, Matthews, & Suh, 2006). It combines the economy-wide view of an environmentally-extended input-output assessment (EE-IOA) or input-output life cycle assessment (IO-LCA) with the detailed perspective of a process-based LCA. Thus, the focus can be equally placed on economic developments in all sectors of the economy (e.g., the changing origin of imports, CO₂ emission reductions within a sector) and technological developments within the realm of waste management (e.g., a recycling process's energy efficiency gains). Also, EE-IOAs, and so HLCAs, rely on economic and environmental data, making an eco-efficiency assessment possible that takes into account ripple effects throughout the entire economy. We now detail its application to the case of Swiss waste glass-packaging disposal according to an LCA's four stages defined by the International Standardization Organization (ISO, 2006a, b).

3.2.1.1 GOAL AND SCOPE DEFINITION

The goal is to assess the eco-efficiency of waste glass-packaging disposal schemes. To allow for comparison, not only the economic and environmental impacts of these schemes should be considered, but also product substitution effects that result from changed quantities of waste disposal products under the different scenarios. Indeed, waste disposal products compete with functionally equivalent product alternatives exhibiting different economic and environmental impact characteristics. Figure 2 shows the options within scenarios¹⁰ to

¹⁰ Other options exist in Switzerland and abroad to manage waste glass-packaging (Chen et al., 2002), from collecting entire glass-packaging and washing it prior to reuse, all the way to recovering glass from MSW incineration residues prior to downcycling, as foreseen in Switzerland.

manage Swiss cullet (e.g., foam glass production), their products (e.g., standard foam glass)¹¹, and the competing alternatives in Switzerland and abroad (e.g., a perimeter insulation system based on extruded polystyrene (XPS) produced in Switzerland) that exhibit their own supply chain (e.g., supply of XPS-based system). To acknowledge these product substitutions, the functional unit is defined as the disposal of the annual waste glass-packaging volume and the supply of corresponding functions in the reference year 2009. In short, we perform system expansion to compare different waste disposal schemes (ISO, 2006a, b).

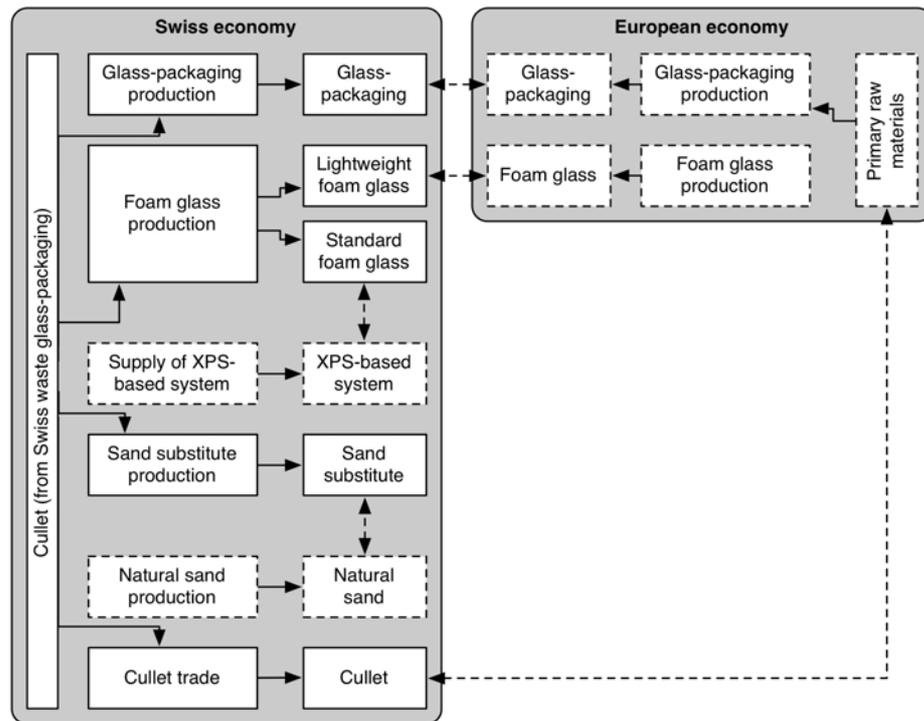


FIGURE 2 OPTIONS FOR THE MANAGEMENT OF SWISS CULLET, PRODUCTS, AND COMPETING ALTERNATIVES INDICATED BY DASHED ARROWS AND BOXES (XPS: EXTRUDED POLYSTYRENE).

3.2.1.2 LIFE CYCLE INVENTORY

The modeling principle of HLCA (i.e., the hybridization of LCA) is the combination of one or more technical-environmental models of agricultural and industrial processes, among others, with an environmentally-extended input-output table (EE-IOT). The technical-environmental model of a process consists of inventories of inputs from the technosphere and the environment (i.e., natural resources) and outputs to the technosphere (i.e., products or services provided by the process) and the environment (i.e., emissions to air, soil, and water). EE-IOTs reflect the economic activity of a region, nation, or larger entity and its impact on the environment (Huppel et al., 2006; Mazzanti, Montini, & Zoboli, 2008). They account for the exchange of goods and services between the economic sectors and the final economic demand and for direct environmental inputs and outputs of sectors and demand (Finnveden et al., 2009; Nakamura & Kondo, 2002; Suh & Nakamura, 2007). EE-IOTs are also known as national accounting matrices with environmental accounts (NAMEAs). The models

¹¹ Natural sand (usually SiO₂) can be substituted by cullet only in some applications (e.g., fill material in construction works).

are combined by disaggregation of economic sectors of an EE-IOT or integration of process databases into an EE-IOT (Acquaye et al., 2011; Wiedmann et al., 2011). We first elaborate on the EE-IOT used and then explain how Swiss waste glass-packaging disposal processes were combined with it.

The EE-IOT used is that of Jungbluth et al. (2011) reflecting the Swiss economy in 2005. In addition to inter-sector flows in monetary units, the EE-IOT provides sector-specific gross value added, direct environmental impacts, and goods and services imports. These imports are responsible for environmental impacts abroad. The resolution of the Swiss NAMEA is $n=43$ sectors. It considers the imports of 65 categories of goods and 15 categories of services by integrating associated process databases.

The technical-environmental process models of Swiss waste glass-packaging disposal were combined with the Swiss NAMEA by means of disaggregation. A process originally located within an economic sector of the NAMEA becomes a new economic sector (in terms of the model), while the sector of origin loses this particular activity (Lenzen, 2011). In the Swiss NAMEA, waste management processes belong to different sectors depending on the main product or service they provide. For instance, MSW incineration primarily provides the service of eliminating waste and is found in the “Disposal” sector. However, recycling cullet to new glass-packaging corresponds to producing new glass-packaging. This activity belongs to the “Mineral products” sector. The processes of recycling cullet to new packaging glass and downcycling cullet to foam glass and sand substitute are disaggregated from the relevant sectors and modeled explicitly within a new NAMEA with $n'=43+3$ (cf. Table 1). Mathematically, disaggregation entails characterizing waste management processes according to their yearly inputs from other economic sectors, imports, gross value added, outputs to other economic sectors, and direct environmental impacts. The sectors losing waste management processes lose equivalent amounts and become smaller sectors. The economic information needed (e.g., which sector glass-packaging production belongs to in the Swiss NAMEA) as well as the direct inputs and data sources for the disaggregated processes' direct environmental impacts can be found in the Supplementary Materials (cf. Appendix A).

Cullet export generates trade, modeled through a demand in the sector “Wholesale and retailing trade” of the disaggregated Swiss NAMEA. The cullet trade process is thus not disaggregated. In Germany mainly, mixed cullet can be sorted with respect to color prior to recycling. The price of exported cullet and the amount of electricity required to sort cullet optically are available in the Supplementary Materials. The environmental impacts of electricity consumption for optic sorting are those arising from German electricity production and distribution.

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TABLE 1 SWISS NAMEA WITH DISAGGREGATED PROCESSES OF GLASS-PACKAGING, FOAM GLASS, AND SAND SUBSTITUTE PRODUCTION. INTER-SECTOR FLOWS Z' , VECTORS OF FINAL DEMAND Y' , AND TOTAL OUTPUT/OUTLAY X' ARE EXPRESSED IN MONETARY FLOWS PER YEAR. PRIMARY INPUTS CONSIST IN GROSS VALUE ADDED gva' , IMPORTS OF GOODS AND SERVICES imp' . SECTORS GENERATE DIRECT ENVIRONMENTAL IMPACTS r' . PRIMARY INPUTS AND DIRECT ENVIRONMENTAL IMPACTS ARE EXPRESSED IN UNITS PER SECTOR OUTPUT (E.G., KILOGRAMS OF IMPORTED MEAT PER SECTOR OUTPUT). $a'_{ij} = \frac{Z'_{ij}}{X'_j}$ FOR $i, j=1, \dots, n'$ IS THE RATIO OF INPUT FROM SECTOR i PER OUTPUT OF SECTOR j , ALSO KNOWN AS INPUT OR TECHNOLOGICAL COEFFICIENT.

	Economic sectors 1, ..., 43	Glass- packaging	Foam glass	Sand substitute	Final demand	Total output
Economic sectors 1, ..., 43	$Z'_{1,1} \dots Z'_{1,43}$ $\vdots \quad \ddots \quad \vdots$ $Z'_{43,1} \dots Z'_{43,43}$	$Z'_{1,gp}$ \vdots $Z'_{43,gp}$	$Z'_{1,fg}$ \vdots $Z'_{43,fg}$	$Z'_{1,ss}$ \vdots $Z'_{43,ss}$	$Y'_{1,tot}$ \vdots $Y'_{43,tot}$	X'_1 \vdots X'_{43}
Glass- packaging	$Z'_{gp,1} \dots Z'_{gp,43}$	$Z'_{gp,gp}$	$Z'_{gp,fg}$	$Z'_{gp,ss}$	$Y'_{gp,tot}$	X'_{gp}
Foam glass	$Z'_{fg,1} \dots Z'_{fg,43}$	$Z'_{fg,gp}$	$Z'_{fg,fg}$	$Z'_{fg,ss}$	$Y'_{fg,tot}$	X'_{fg}
Sand substitute	$Z'_{ss,1} \dots Z'_{ss,43}$	$Z'_{ss,gp}$	$Z'_{ss,fg}$	$Z'_{ss,ss}$	$Y'_{ss,tot}$	X'_{ss}
Primary inputs	$imp'_1 \dots imp'_{43}$ $gva'_1 \dots gva'_{43}$	imp'_{gp} gva'_{gp}	imp'_{fg} gva'_{fg}	imp'_{ss} gva'_{ss}		
Total outlay	$X'_1 \dots X'_{43}$	X'_{gp}	X'_{fg}	X'_{ss}		
Env. impacts	$r'_1 \dots r'_{43}$	r'_{gp}	r'_{fg}	r'_{ss}		

The production of competing goods in Switzerland is modeled through a demand in the disaggregated Swiss NAMEA, which is functionally equivalent to the goods produced out of 1 kilogram of cullet. Competing goods production abroad is modeled by a demand in the ecoinvent database (ecoinvent Centre, 2010), which is functionally equivalent to the production of goods out of 1 kilogram of cullet. With regard to the product competing with Swiss glass-packaging, the assessment is done for glass-packaging reflecting average European production standards as a base case and for glass-packaging reflecting German production standards. This sensitivity analysis is meant to investigate the range of production standards in Europe and their effect on environmental impacts. Detailed information on the data used to model the production of corresponding goods is available in the Supplementary Materials.

Further, the environmental impacts arising from the transport of exported and imported Swiss waste glass-packaging disposal products and competing goods are considered (see Supplementary Materials for data used). We also assume that foreign transport firms operate this trade and that it does not generate economic value added in Switzerland.

Finally, we assume that changes in the amounts of glass-based and competing products do not lead to changes in technologies in supply chains of these products. All activities related to

Swiss waste glass-packaging are small compared to other industrial activities in Switzerland. Moreover, glass-packaging production in Switzerland is a highly optimized activity, so that an increase in production should not lead to major technological shifts. Foam glass production, a younger activity with the potential to increase energy efficiency, is the object of a sensitivity analysis in this respect. Sand substitute production, which has been taking place at a large scale since the 1980s, is based on milling technologies implemented for other, older purposes such as stone milling.

3.2.1.3 EVALUATION DIMENSIONS

Environmental impacts and economic value added are the two dimensions of eco-efficiency on the macroeconomic and mesoeconomic levels (Huppes & Ishikawa, 2005; Tukker, Eder, & Suh, 2006). Environmental flows, i.e., natural resource consumption and air, soil, and water emissions, were aggregated to a single score according to the Ecological Scarcity Method 2006 (Frischknecht, Steiner, & Jungbluth, 2009). This environmental impact assessment method evaluates environmental flows according to how distant the yearly flows caused by Switzerland are from Swiss environmental policy goals. It is the relevant method for the Swiss Environmental Protection Agency (EPA), the policy-maker in charge of waste glass-packaging disposal in Switzerland. A sensitivity analysis was conducted with the ReCiPe 2008 impact assessment method (Goedkoop et al., 2009), which evaluates environmental flows with respect to their damage to safeguard objects. As for economic value added, due to limited data, we focused on gross value added directly and indirectly by activities/processes taking place in Switzerland.

3.2.2 SCENARIOS OF SWISS WASTE GLASS-PACKAGING DISPOSAL

Figure 3 gives an overview of the scenarios of Swiss waste glass-packaging disposal in 2020 derived from the literature and stakeholders/experts in Part I of this paper series (cf. Meylan et al., 2013). Concretely, some 264,000 tons of cullet, mainly mixed and green, are reallocated to different processing options depending on the combined influences of alternative policies and external societal constraints. The anticipated disposal fee (ADF), concretizing alternative policies, is levied by the Swiss government on glass-packaging to compensate municipalities for collecting waste glass-packaging. The ADF also acts as economic incentive with respect to the way municipalities collect cullet (separated or mixed with respect to color) and which processing option they choose (e.g., bottle-to-bottle recycling). The economic incentive is concretized by the height of compensation rates (100% corresponds to ca. CHF 100 per ton of collected waste glass-packaging). In the scenarios of Swiss waste glass-packaging disposal, the rates are successively aligned to three goals of resource and waste policy defined by the Swiss government (Hanser, Kuster, Gessler, & Ehrler, 2006). Prioritizing environmental efficacy means fostering recycling over downcycling; prioritizing the best available technologies means reducing local process emissions, i.e., processing as much cullet as possible domestically; and prioritizing disposal security corresponds to diversifying the demand for Swiss cullet. Other drivers are either endogenous (e.g., cullet prices of Vetropack and Misapor) or exogenous (e.g., energy prices) to Swiss waste glass-packaging disposal. These drivers have higher (H), lower (L), or the same levels as in 2009 (09). Two prototypes were added to allow for further comparison: the domestic recycling of the total allocation quantity (i.e., 264,000 tons), abbreviated as REC CH 100%, and the downcycling of all green and mixed cullet to sand substitute in Switzerland, abbreviated as low-grade DC 100%.

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The differences in cullet allocation to processing options and resulting product changes (i.e., substitutions) are shown in comparison to the 2009 allocation in terms of the mass-percentage of cullet. For instance, in the scenario of environmental efficacy with endogenous constraints at their 2009 levels, all cullet to domestic processing (i.e., glass-packaging and foam glass, ca. 35% of total cullet) is newly exported to glass-packaging factories in neighboring countries. Glass-packaging and foam glass production no longer take place in Switzerland. More glass-packaging and lightweight foam glass must be produced abroad, and more XPS-based insulation systems must be produced domestically (i.e., substitution). There are a total of four different waste disposal schemes.

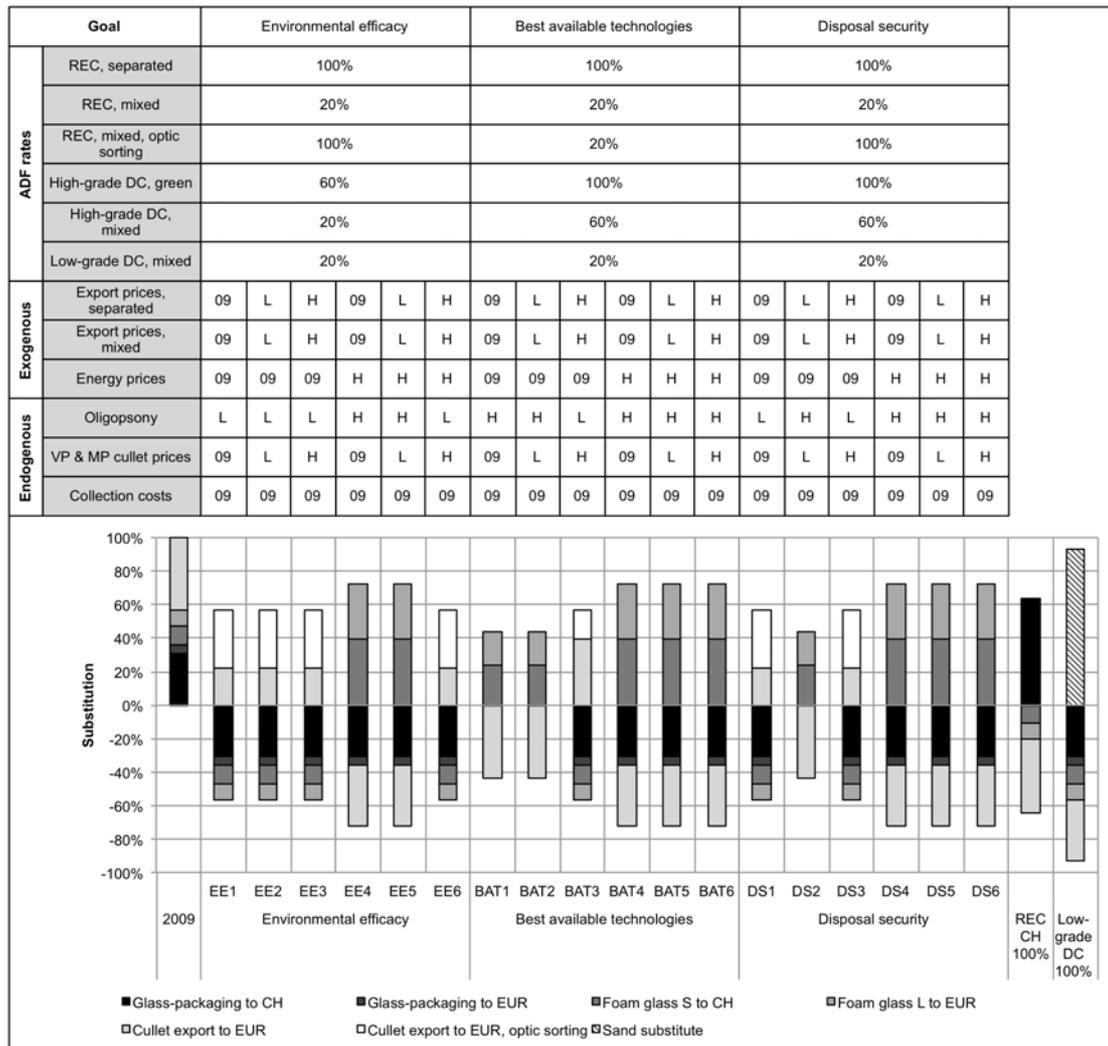


FIGURE 3 SCENARIOS AND PROTOTYPES OF WASTE GLASS-PACKAGING DISPOSAL (ADF: ANTICIPATED DISPOSAL FEE; CH: SWITZERLAND; DC: DOWNCYCLING; EUR: EUROPE; L: LIGHTWEIGHT; S: STANDARD; MP: MISAPOR, REC: RECYCLING, VP: VETROPACK).

3.3 RESULTS

3.3.1 ENVIRONMENTAL IMPACTS AND GROSS VALUE ADDED OF SCENARIOS AND PROTOTYPES

Figure 4 (a, b) shows environmental impact reductions/increases and gross value added gains/losses of scenarios in comparison to the 2009 cullet allocation as a result of the different disposal schemes and resulting product changes (i.e., substitutions). The results are normalized to the total values (i.e., total environmental impacts and gross value added) of the 2009 allocation.

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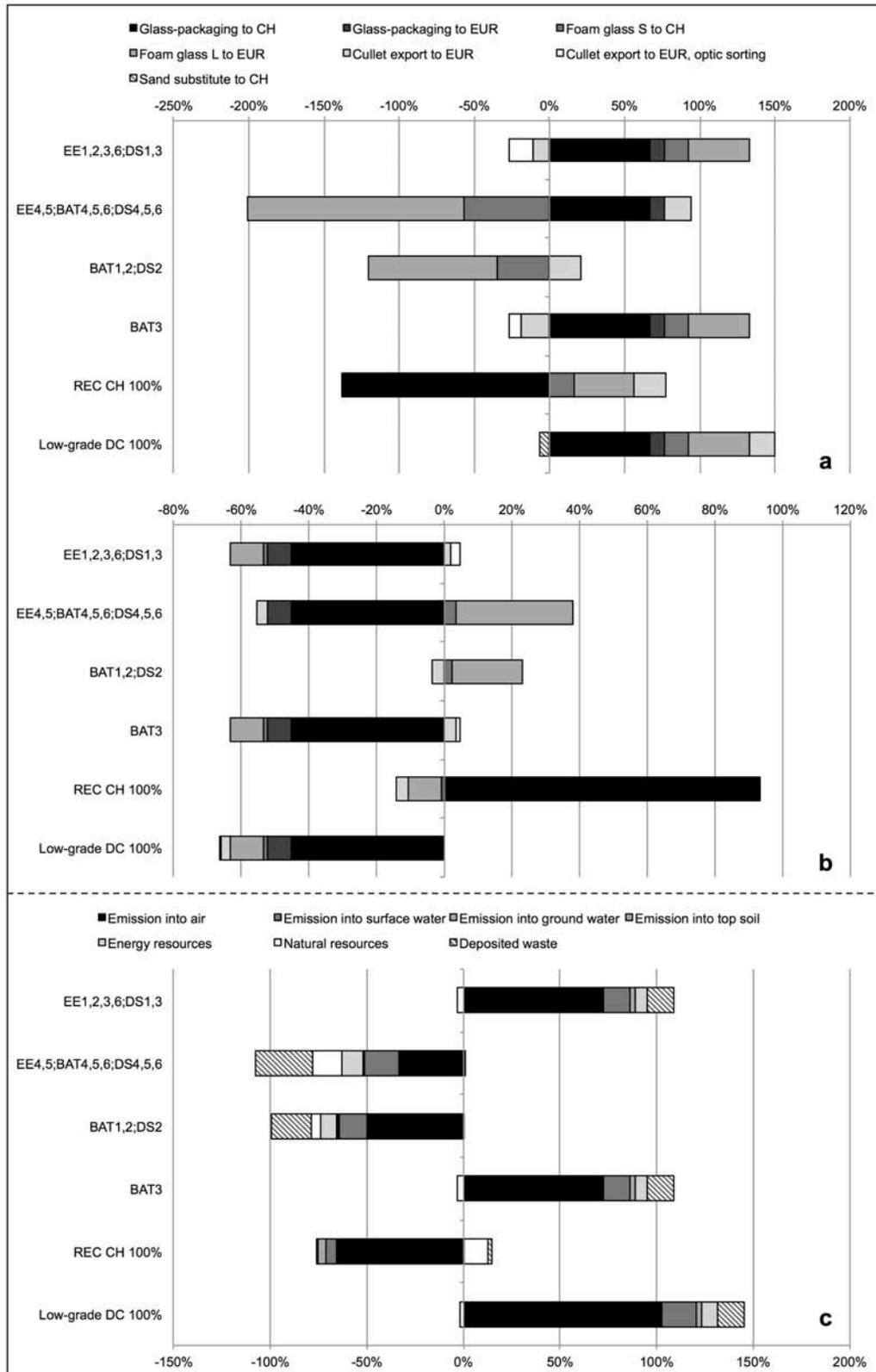


FIGURE 4 ENVIRONMENTAL IMPACT REDUCTIONS/INCREASES (a) AND GROSS VALUE ADDED GAINS/LOSSES (b) PER SUBSTITUTION; ENVIRONMENTAL IMPACT PER IMPACT CATEGORY (c) OF SCENARIOS AND PROTOTYPES. RESULTS ARE NORMALIZED TO THE ENVIRONMENTAL IMPACTS AND GROSS VALUE ADDED OF THE 2009 ALLOCATION (BAT: BEST AVAILABLE TECHNOLOGIES; CH: SWITZERLAND; DC: DOWNCYCLING; DS: DISPOSAL SECURITY; EE: ENVIRONMENTAL EFFICACY; EUR: EUROPE; L: LIGHTWEIGHT; S: STANDARD; REC: RECYCLING).

Scenarios in which all cullet is exported to foreign glass-packaging factories (EE1, 2, 3, and 6; DS1 and 3; BAT3) have greater environmental impacts than the 2009 allocation. The increased environmental impact arising from the end of domestic recycling and high-grade downcycling (and thus the end of glass-packaging and foam glass production in Switzerland) cannot come close to being offset by the reductions achieved by substituting primary raw materials (e.g., quartz sand) in the foreign glass-packaging factories. In addition, the increased use of optic sorting in EE1, 2, 3, and 6 and DS1 and 3 does not visibly affect this scenario's environmental performance. Mixed cullet that is no longer directly recycled as such is now recycled as brown, green, and white thanks to upstream optic sorting. The same amount of energy and raw materials are saved in glass-packaging production in both cases and the use of optic sorting has little impact on the environment. These scenarios would also bring about a loss in gross value added. Domestic recycling ceases and a perimeter insulation based on standard foam glass generates a higher gross value added than its XPS-based counterpart. The gross value added generated by the additional export activity (i.e., cullet trade) is very low.

The scenarios in which all green and mixed cullet is downcycled to foam glass in Switzerland (EE4 and 5; BAT4, 5, and 6; DS4, 5, and 6) have weaker environmental impacts than the 2009 allocation. Indeed, the increased environmental impact arising from the end of domestic recycling is overcompensated for by the reduction achieved by high-grade downcycling. However, gross value added is lost in this scenario, as recycling generates higher gross value added per kilogram of cullet than high-grade downcycling. Additionally, standard foam glass replaces XPS-based insulation systems, a domestic activity that also generates gross added value.

The scenarios in which all cullet is processed domestically either through recycling or high-grade downcycling (BAT1 and 2; DS2) have weaker environmental impacts than the 2009 allocation, thanks to the expansion of high-grade downcycling. These are the only scenarios achieving a higher gross value added than the 2009 allocation, as domestic recycling is preserved and Swiss foam glass replaces European foam glass and XPS-based insulation systems. The latter generates lower gross value added than standard foam glass.

The two prototypes show different results, both in terms of their environmental impacts and gross value added. While recycling all cullet would not result in even lower environmental impacts than scenarios EE4 and 5; BAT4, 5, and 6; DS4, 5, and 6, it would by far generate the highest gross value added. Downcycling all green and mixed cullet to sand substitute in Switzerland would lead to the greatest environmental impact increase. The reductions achieved by substituting local natural sand are indeed very small. The gross value added losses would be similar to those of the scenarios in which all cullet is exported.

Looking at the nature of environmental impacts (Figure 4c), we see that scenarios corresponding to the export of all cullet (EE1, 2, 3, and 6; DS1 and 3; BAT3) lead mainly to a stark increase in emissions to air, while deposited waste and emissions into surface water grow in lesser proportions. These increases indicate the European glass-packaging industry's reliance on an electricity mix characterized by higher air emission factors (e.g., higher use of fossil fuels) and nuclear waste generation (i.e., higher share of nuclear power) than Swiss electricity, as well as on less efficient flue gas filter technology. The larger transport distances as a result of increased glass-packaging imports and cullet exports also

lead to higher air emissions. The scenarios in which all green and mixed cullet is downcycled to foam glass in Switzerland (EE4 and 5; BAT4, 5, and 6; DS4, 5, and 6) permit reduced environmental impacts to a similar extent in all impact categories except in emissions into ground water and top soil. Higher air emissions and deposited waste resulting from an increased production in foreign glass-packaging factories are overcompensated for by the reduction achieved by high-grade downcycling. Scenarios in which domestic recycling persists and the remainder cullet is downcycled to foam glass in Switzerland (BAT1 and 2; DS2) allow for greater reductions in air emissions, but lower reductions in natural resources and deposited waste than the scenarios in which all green and mixed cullet is downcycled to foam glass. As for the prototypes, recycling all cullet (REC CH 100%) leads to greater air emission reductions than the four disposal schemes of scenarios. This prototype does not perform as well for natural resources, reflecting the substitution of perimeter insulation based on standard foam glass by XPS-based systems. If all green and mixed cullet were to be downcycled to sand substitute in Switzerland, air emission increases would exceed those of all other scenarios. The share in impact categories is similar to scenarios in which all cullet is exported, demonstrating that substituting Swiss glass-packaging and foam glass with alternative products/systems drive the nature of environmental impacts.

3.3.2 ECO-EFFICIENCY PROFILE

Figure 5 depicts eco-efficiency as a vector whose dimensions are environmental impact reductions/increases (x-axis) and gross value added gains/losses (y-axis) in comparison to the 2009 allocation. A positive value on the x-axis denotes more environmental impacts than in the 2009 allocation. A positive value on the y-axis denotes more gross value added than in the 2009 allocation. This graphical representation is a variant of the well-known eco-efficiency profile (Hellweg, Doka, et al., 2005; Kondo & Nakamura, 2005).

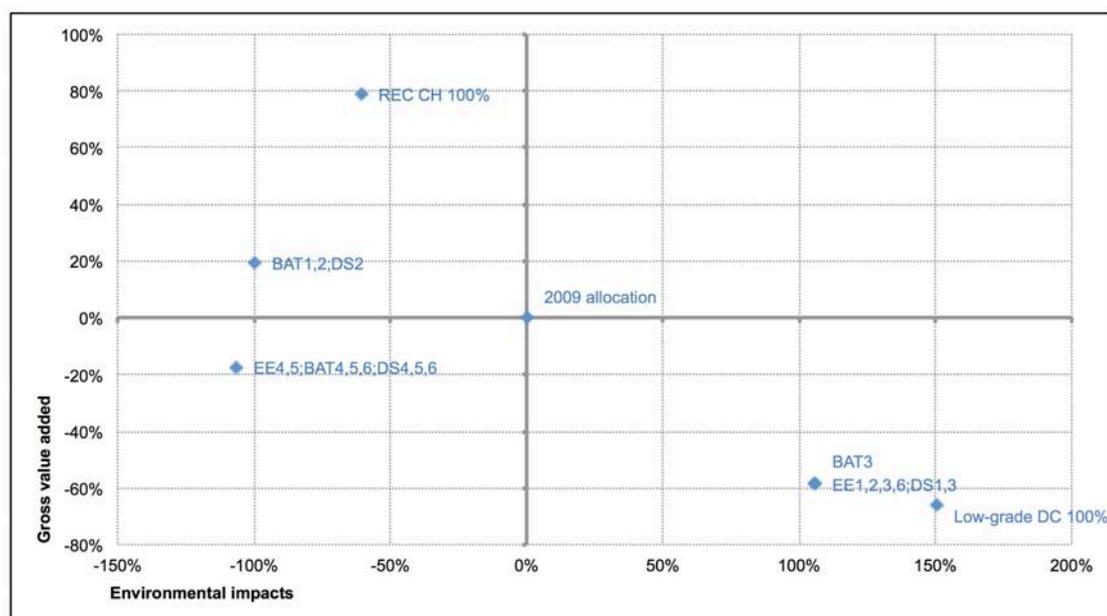


FIGURE 5 ECO-EFFICIENCY PROFILE OF SCENARIOS AND PROTOTYPES. RESULTS ARE NORMALIZED TO THE ENVIRONMENTAL IMPACTS AND GROSS VALUE ADDED OF THE 2009 ALLOCATION (BAT: BEST AVAILABLE TECHNOLOGIES; CH: SWITZERLAND; DC: DOWNCYCLING; DS: DISPOSAL SECURITY; EE: ENVIRONMENTAL EFFICACY; EUR: EUROPE; REC: RECYCLING).

No scenario or prototype leads to an environmental impact increase and a gross value added gain (upper-right quadrant of Figure 5). The scenarios having the least environmental impact are those in which all green and mixed cullet is downcycled to foam glass in Switzerland (EE4 and 5; BAT4, 5, and 6; DS4, 5, and 6) followed closely by a combination of domestic recycling and high-grade downcycling (BAT1 and 2; DS1) (-107% and -100%, respectively). The allocation achieving the highest gross value added is the domestic recycling of all cullet (REC CH 100%) with +79%. It also has a lower environmental impact than the 2009 allocation (-61%). The downcycling of all green and mixed cullet to sand substitute in Switzerland (Low-grade DC 100%) leads to the greatest environmental impact increase and gross value added loss (+150% and -66%, respectively). It generates fairly the same amount of gross value added as the export of all cullet to foreign glass-packaging factories (EE1, 2, 3, and 6; DS1 and 3; BAT3).

3.3.3 SENSITIVITY ANALYSES

Figure 6 shows the eco-efficiency profile's sensitivity to (a) substituting Swiss glass-packaging with German glass-packaging instead of average European glass-packaging and to (b) two shifts in the product mix of Swiss foam glass production, i.e., 100% of standard foam glass and 100% of lightweight foam glass. The eco-efficiency results are neither sensitive to the assessment of environmental impacts with another impact assessment method (i.e., ReCiPe 2008) nor to an increase in energy efficiency of foam glass production. The results of these two sensitivity analyses can be found in the Supplementary Materials.



FIGURE 6 ANALYSIS OF THE ECO-EFFICIENCY PROFILE'S SENSITIVITY TO (a) THE LOCATION OF FOREIGN GLASS-PACKAGING PRODUCTION AND (b) THE PRODUCT MIX OF FOAM GLASS PRODUCTION (BAT: BEST AVAILABLE TECHNOLOGIES; CH: SWITZERLAND; DC: DOWNCYCLING; DS: DISPOSAL SECURITY; EE: ENVIRONMENTAL EFFICACY; EUR: EUROPE; L: LIGHTWEIGHT; REC: RECYCLING; S: STANDARD). ARROWS INDICATE THE SHIFT FROM THE BASE CASE TO THE SENSITIVITY ANALYSIS RESULTS.

German production of glass-packaging has a lower environmental life cycle impact than average European production. Hence, scenarios in which domestic recycling no longer takes place (and thus domestic glass-packaging production) perform better in terms of their environmental impacts than in the base case (i.e., shift of ca. 60%). If all cullet were to be domestically recycled (cf. REC CH 100%), the increased environmental impact arising from the end of high-grade downcycling would no longer be overcompensated for by increased exports of Swiss glass-packaging. In fact, such a prototype would perform similarly to scenarios in which all cullet is exported for recycling (EE1, 2, 3, and 6; DS1 and 3; BAT3).

A change in the product mix of Swiss foam glass production leads to a change in the rankings of scenarios and prototypes. If Misapor were to produce only lightweight foam glass, the environmental impact of scenarios in which all green and mixed cullet is downcycled to foam glass (EE4 and 5; BAT4, 5, and 6; DS4, 5, and 6) would decrease by more than 200%, while they would achieve economic gains instead of losses in the base case. In contrast, if Misapor would only produce standard foam glass, no European lightweight foam glass would be replaced as in the base case. Unlike lightweight foam glass, producing only standard foam glass would lead to different scenario and prototype rankings in both evaluation dimensions. Domestic recycling of all cullet (REC CH 100%) would result in the greatest environmental impact reduction. Scenarios in which all green and mixed cullet is downcycled to foam glass in Switzerland (EE4 and 5; BAT4 and 5, and 6; DS4, 5, and 6) would not score better from an economic point of view than those in which all cullet is exported (EE1, 2, 3, and 6; DS1 and 3; BAT3).

3.4 DISCUSSION

The discussion of results is structured as follows. First, we interpret the scenarios with the new insights provided by the HLCA (cf. research questions 1 to 3) and provide strategic orientations with respect to the key policy instrument of Swiss waste glass-packaging disposal, i.e., the anticipated disposal fee (ADF) (cf. research question 4). Second, we reflect on the assessment method adopted, including its limitations.

3.4.1 SCENARIO INTERPRETATION

In the initial scenario analysis, 18 scenarios of Swiss waste glass-packaging disposal and four disposal schemes resulted from alternative policies and uncertain exogenous constraints (cf. Section 3.2.2). In turn, the four disposal schemes resulted in three different eco-efficiency scores. Prioritizing one of the generic goals of the Swiss resource and waste policy (Hanser et al., 2006) and implementing the corresponding ADF compensation rates as policy did not lead to a clear ranking in environmental impacts or gross value added, as waste disposal schemes depend heavily on external constraints.

In terms of environmental impacts, the three prioritized goals (i.e., environmental efficacy, best available technologies, disposal security) can lead to the greatest reductions and increases. It is striking to see that scenarios achieving the goal of environmental efficacy (EE1, 2, 3, and 6) by exporting all cullet to foreign glass-packaging factories actually perform bad in terms of their environmental impacts. This highlights the crucial role high-grade downcycling in Switzerland plays in the environmental performance of the whole waste management system. It allows the increased environmental impact arising from the end of domestic recycling to be absorbed. This is, to a certain extent, also true for gross value added. The fact that one product of high-grade downcycling—standard foam glass—substitutes other products of the Swiss economy limits this effect.

Moving to the exogenous constraints of Swiss waste glass-packaging disposal, we observe that a combination of higher cullet export prices than those of 2009 and energy prices as of 2009 leads to environmental impact increases and gross value added losses no matter what goal is prioritized (EE3, BAT3, and DS3). Such a combination leads to the end of glass-packaging and foam glass production in Switzerland, which brings about environmental impact increases. The combinations of higher energy prices and current or lower cullet

export prices all lead to environmental impact reductions. In contrast, no combination of exogenous constraints yields gross value added gains irrespective of the prioritized goal.

Testing the results with respect to parameters other than allocation of waste glass-packaging to disposal processes in Switzerland and in Europe provides considerable insights with respect to policy, i.e., with regard to ADF rates. What determines the environmental performance of the allocation is first and foremost the alternative to the product based on Swiss waste glass-packaging. Importing German instead of average European glass-packaging is enough to disrupt the ranking of scenarios, just as a change in the product mix of high-grade downcycling does. The main explanation for this sensitivity lies in the different environmental standards of production found in different European countries and the consideration of the Swiss component of gross value added by processing waste glass-packaging as economic evaluation dimension.

There is no policy (i.e., combination of ADF rates) allowing for environmental impact reductions and gross value added gains irrespective of future developments (e.g., higher cullet export prices). Like many other instruments for waste policy, e.g., landfill and incineration taxes (Nilsson, Björklund, Finnveden, & Johansson, 2005; Oosterhuis, Bartelings, Linderhof, & van Beukering, 2009; Porter, 2002), the ADF targets waste flows (i.e., their allocation to treatment processes) and fails to explicitly consider the products of waste treatment and their alternatives. Furthermore, the ADF sets an incentive to switch from mixed to separated collection. From an environmental life cycle perspective, this does not make sense, as optic sorting allows separated cullet to be supplied with negligible additional environmental impacts (cf. scenarios EE1, 2, 3, and 6; DS1 and 3; BAT3). Considering the results of the HLCA, and those of the sensitivity analysis in particular, ADF rates should target allocation to disposal processes and resulting products, not collection, in order to foster the substitution of competing products that generate high environmental impacts and low gross value added for Switzerland.

The two prototypes for the disposal of Swiss waste glass-packaging we have added to the assessment permit policies of MSW management to be discussed on a more general level. According to the scenario analysis, the prototypes are not considered possible in the foreseeable future (cf. Section 3.2.2). The ranking including the two prototypes nevertheless shows that domestic recycling of all cullet does not result in the greatest environmental impact reductions. It seems to indicate that when the scope of an assessment is the disposal of total waste flows within a specific context, i.e., that of the Swiss economy, the waste hierarchy is partially contradicted. Such findings support the general principle that, depending on the waste fraction and the context, departing from the waste hierarchy can make sense from a life cycle perspective, as revealed by other LCAs of options for regional or national waste flow treatment (e.g., Eriksson et al., 2005; Schmidt, Holm, Merrild, & Christensen, 2007). These assessments all support the recent changes in waste policy frameworks. The recently revised Waste Framework Directive of the European Union (European Parliament and Council, 2008) permits a departure from the waste hierarchy, provided such move makes sense from an environmental life cycle perspective. In Switzerland, the waste hierarchy has been supplanted by a system of goals that were used to construct the scenarios of Swiss waste glass-packaging disposal of Part I (Hanser et al., 2006).

3.4.2 METHODOLOGICAL CONSIDERATIONS

An important step is made towards achieving a more contextualized assessment of entire MSW management systems based on life cycle thinking. In comparison to conventional LCAs of MSW management (e.g., Bjorklund & Finnveden, 2005; Dinkel & Hauser, 2008; Doka, 2006; Finnveden et al., 2009; Gilgen et al., 2003; Hellweg, Doka, et al., 2005; Hong et al., 2009), the HLCA of Swiss waste glass-packaging disposal presented in this paper takes into consideration one aspect of economic sustainability (i.e., gross value added in Switzerland). It also bridges the gap between changes in markets (be them glass-packaging or cullet markets) and the performance of MSW management systems. In this respect, it is interesting to note that in his comparative LCA of recycling and downcycling to sand substitute in Switzerland, Doka (2006) did not consider where production of glass-packaging based on primary raw materials takes place if cullet is downcycled to sand substitute. The focus was indeed on the benefits of recycling versus downcycling and their dependency on transport distances to recycling facilities. We showed however that production standards do play a crucial role in overall environmental impacts of Swiss waste glass-packaging disposal. Thanks to the upscaling approach, issues linked to one nation's limited production capacities or competitive advantages over another make these considerations unavoidable in assessments. Such an approach could easily be applied to other waste fractions or in other countries or regions as more EE-IOTs are being compiled and/or being consistently integrated to form multi-regional EE-IOTs, e.g. in Europe with the EXIOPOL project (Tukker et al., 2013).

Having said that, the proposed upscaling approach and the prospective assessment add new uncertainties to those already plaguing more conventional LCAs of waste management. Without a doubt, the drivers of Swiss waste glass-packaging disposal affect other systems that may constitute an important part of the future background system of MSW management (Spielmann, Scholz, Tietje, & de Haan, 2005). For instance, higher energy prices might lead to the development of alternative energy production systems (Hang & Tu, 2007; Popp, 2004). Conversely, possible, future states of descriptors might be the consequence of technological change in the future background system, e.g., through new policies (Munksgaard & Morthorst, 2008). In turn, an altered background system might affect the environmental and economic performance of an MSW management system. For the case of Swiss waste glass-packaging disposal, the European energy system's move away from nuclear and coal-based power towards renewables such as wind and solar farms could lead to higher energy prices. With this altered background system, high-grade downcycling could become much less attractive. Hence, a refining step of the methodological approach presented in this paper series, and a feasible way to reduce this model uncertainty, would be to develop scenarios for sectors to which the performance of an MSW management system is sensitive¹². Such scenarios would be generic, as they could be used for other MSW fractions, quite in the sense of Höjer et al. (2008).

¹² Also, the software used in this work to model waste management processes, i.e., SimaPro, does not permit such sensitivity analyses. Indeed, not only the electricity mix of European foam glass production should be modified to reflect the change of European electricity production, but also the mix of all other European production processes upstream of foam glass production. SimaPro does not allow changing the process of electricity production, only copying it.

Another uncertainty not accounted for in the proposed approach is that of data, i.e., the uncertainty in the amounts of goods and services, as well as in the environmental flows of the inventory. Both ecoinvent databases and the Swiss NAMEA offer the distribution and standard deviation of these figures. The estimated standard deviation is based on the Pedigree matrix, which integrates different qualitative aspects (e.g., temporal correlation of data) into a quantitative figure (Weidema & Wesnaes, 1996). No data uncertainty analysis was conducted for the eco-efficiency of scenarios because the Pedigree approach fails to consider one component of data uncertainty highly relevant for such an HLCA. The Pedigree approach does not consider the uncertainties arising from truncating processes in LCAs based on bottom-up modeling (i.e., conventional LCAs) and those from aggregating single processes to economic sectors (i.e., EE-IOAs) (Lenzen, 2000; Majeau-Bettez, Stromman, & Hertwich, 2011; Williams, Weber, & Hawkins, 2009). With respect to truncation errors, the authors of the three cited publications recommend the hybridization of bottom-up inventories with IOTs. As for aggregation errors, the solution is to further disaggregate IOTs into subsectors. In the case of glass-packaging, further disaggregation of the Swiss NAMEA would permit uncertainties to be reduced with respect to the XPS-based insulation system. Hybridizing conventional LCAs of imported goods/services in the Swiss NAMEA and products competing with those of Swiss waste glass-packaging disposal (i.e., glass-packaging) with European IOTs is deemed to diminish truncation errors. Analyzing such an uncertainty component would have been beyond the scope of this paper, as it would require data that is simply not yet readily available.

Furthermore, we fully recognize the arbitrariness of gross value added generated in Switzerland as a sole indicator measuring the economic viability of an MSW management system. In contrast to ecological sustainability, no discourse has taken place so far in Swiss MSW management practice to come up with an aggregated score reflecting various economic criteria and indicators despite recent advances in the development of economic sustainability indicators (Finkbeiner, Schau, Lehmann, & Traverso, 2010; Heijungs, Huppes, & Guinée, 2010; Schau, Traverso, Lehmann, & Finkbeiner, 2011). This perhaps has to do with the lack of a definition for long-term economic viability of MSW management strived for by the Guidelines for Swiss Waste Management (FOEN, 1986). Considering the prominence given to MSW management costs, gross value added, as defined by Huppes and Ishikawa (2005), which is oriented at the macroeconomic level, remains one of many aspects of economic viability in the eyes of MSW stakeholders. Whether new indicators of economic and social sustainability and methods for their aggregation to single scores will be adopted by these same policy-makers in the future remains to be seen. An alternative to the three sustainability dimensions could be developing performance indicators based on the goal system of Swiss resource and waste management (cf. Hanser et al., 2006). As for ecological sustainability, adopting the evaluation dimensions of policy-makers, including the relevant environmental life cycle impact assessment method, seems a feasible way to reduce the inherent subjectivity of all LCAs, which hinders clear-cut solutions (Lazarevic, Buclet, & Brandt, 2012). As LCAs assess human activities according to value systems, it seems adequate to adopt the value system of legitimate policy-makers.

Finally, an unsettled issue both in this study and in others (Hellweg, Doka, et al., 2005; Kondo & Nakamura, 2005) is the task of defining weights for the environmental dimension and its economic counterpart in an eco-efficiency assessment. Based on which value system should

this be done? The issue is highly relevant for Swiss waste glass-packaging disposal. Indeed, while there are two disposal schemes that clearly perform worse in terms of eco-efficiency (EE1, 2, 3, and 6; DS1 and 3; BAT3), the most eco-efficient disposal scheme depends on which weights are given to the evaluation dimensions. In other words, just as the aggregation of environmental flows to a single score is value-laden (Anex & Focht, 2002; Bengtsson & Steen, 2000; Hunkeler, 2006), such a valuation step would be needed to weight environmental impact reductions/increases against gross value added gains/losses. The challenging question is, then, who provides these weights—policy-maker, stakeholders, and/or experts—in which procedure (Hofstetter, Baumgartner, & Scholz, 2000; Hofstetter, Braunschweig, Mettier, Mueller-Wenk, & Tietje, 1999; Mettier & Hofstetter, 2004; Trutnevyte et al., 2012)?

3.5 CONCLUSION

The proposed methodological approach combining scenario analysis and assessment has proven useful in identifying what policies of Swiss waste glass-packaging disposal could effectively be implemented in the foreseeable future and whether they are worth implementing from an eco-efficiency perspective. The assessment of scenarios, i.e., hybrid life cycle assessment, showed that no policy can guarantee environmental impact reductions and gross value added gains under all possible, future developments (e.g., higher energy prices). From an environmental point of view, the best disposal scheme consists of downcycling all green and mixed cullet to foam glass in Switzerland (the rest is recycled abroad), while the worst corresponds to downcycling all cullet to sand substitute. From an economic point of view, the best disposal scheme consists in recycling all cullet in Switzerland, while the worst corresponds again to downcycling all cullet to sand substitute. Downcycling all green and mixed cullet to foam glass in Switzerland makes from an environmental point of view more sense than recycling it abroad, a contradiction to the waste hierarchy. Results indicate that financial compensation of municipalities for collecting waste glass-packaging (i.e., ADF rates) should focus less on the way it is collected and more on the outputs of its processing and competing products, if the ADF rates are to provide an incentive for a more eco-efficient disposal system. Yet an open issue with respect to decision-making is the weighting of environmental and economic dimensions to a single figure in eco-efficiency assessments. Methodological limitations of the performed HLCA exist, but some can certainly be overcome to enhance the robustness of results, whereby an increased interaction with stakeholders is deemed crucial (e.g., generic scenarios of future background systems, new criteria/evaluation dimensions for the integrative performance assessment). Nevertheless, such an approach could be used elsewhere or for other waste fractions (i.e., in different contexts) for the same reasons as the Swiss case of waste glass-packaging disposal.

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APPENDIX A. SUPPLEMENTARY MATERIALS

Table SM 1 provides the general economic information used to disaggregate the processes of waste glass-packaging disposal from their respective sectors. Each activity nested in a sector of the Swiss national accounting matrix with environmental accounts (NAMEA) (Jungbluth et al., 2011) results in the production of a good that competes with an alternative product exhibiting functional equivalency.

TABLE SM 1 ECONOMIC INFORMATION FOR THE DISAGGREGATION OF PROCESSES OF SWISS WASTE GLASS-PACKAGING DISPOSAL FROM SECTORS OF THE SWISS NAMEA. A SENSITIVITY ANALYSIS IS PERFORMED FOR THE PRODUCT COMPETING WITH SWISS GLASS-PACKAGING (INDICATED IN ITALICS).

Activity/process	Sector in Swiss NAMEA (abbreviation in Jungbluth et al., 2011)	Products	Amounts in weight percent	Competing product
Recycling to new glass-packaging	Mineral products (G26)	1. Glass-packaging for Switzerland	86%	European glass-packaging
		2. Glass-packaging for export	14%	<i>(German glass-packaging)</i>
High-grade downcycling	Wholesale and retail trade (G51b52)	1. Standard foam glass for perimeter insulation	54%	Swiss XPS-based insulation system
		2. Lightweight foam glass as lightweight aggregate in construction	46%	European foam glass
Low-grade downcycling	Disposal (G90)	Sand substitute	100%	Swiss natural sand

Only two companies in Switzerland, Vetropack and Misapor, represent the sectors of glass-packaging and foam glass production in Switzerland, respectively. Both municipalities and construction firms processed waste glass-packaging to sand substitute in 2005. Yet as municipalities produced the majority of sand substitute prior to selling it to construction firms, the totality of this activity is modeled as part of the “Disposal” sector. Such simplification of the reality leads to a presumably small error, as sand substitute production generated a very small economic output compared to that of the two sectors in which this activity is embedded.

Disaggregating Vetropack, Misapor, and municipalities from their respective sectors requires knowing all inputs from the Swiss economy, primary inputs (i.e., gross value added and imports), outputs to other sectors or the final demand, and direct environmental impacts.

Inputs needed to produce glass-packaging and foam glass are energy, raw materials, ancillaries, transport, infrastructure, packaging, and waste disposal. Therefore, only the inputs from these six sectors were modeled as higher than zero. If it was not possible to obtain data on one of the six inputs, we assumed that the company has a similar input coefficient as the sector from which it was disaggregated, i.e., ratio $a'_{i,j}$ of input per output (see Table 1). This is the case of infrastructure, waste, packaging and transport for glass-packaging production and infrastructure for foam glass production. For glass-packaging

production, only physical data (e.g., kilowatt-hours of electricity, tons of minerals) and total economic output in 2010 were provided. The missing prices of inputs to glass-packaging production are estimated with average prices within the region of the production facility. If these were not available, global average prices of the world glass-packaging sector were used (Mintec, 2009). Also, the price of glass-packaging as outputs are the same for all purchasers (i.e., the “Food industry” and “Wholesale and retail trade” sectors and exports). The gross value added is the total output of the waste disposal process minus its inputs from the Swiss economy and abroad. The price of milling waste glass-packaging (i.e., input from the “Construction” sector) and the price of sand substitute as output are that of Lausanne, a large municipality in Southwestern Switzerland that downcycled all of its cullet to sand substitute in 2005.

Table SM 2 details direct inputs to disaggregated processes of Swiss waste glass-packaging disposal per sector outputs, i.e., inputs from the Swiss NAMEA and from abroad (i.e., imports) as well as gross value added.

TABLE SM 2 DIRECT INPUTS TO DISAGGREGATED PROCESSES OF SWISS WASTE GLASS-PACKAGING DISPOSAL.

Direct inputs	Glass-packaging production	Standard foam glass production	Lightweight foam glass production	Sand substitute production
<i>Inputs from Swiss NAMEA [CHF/CHF output]</i>				
Mining and quarrying (G10b14)	0.0467			
Refineries (G23)	0.0879			
Chemical industry (G24)	0.00107	0.0389	0.0396	
Plastics and rubber (G25)	0.0029	0.00518	0.00622	
Energy and water distribution (G40b41)	0.0197	0.0756	0.077	
Construction (G45)	0.0119	0.00697	0.00697	0.0746
Wholesale and retail trade (G51b52)	0.000828	0.00101	0.00102	
Transport (G60b62)	0.0572	0.118	0.0783	
Disposal (G90)	0.00195	0.00576	0.00586	
<i>Imports of goods [kg/CHF output]</i>				
Crude fertilizers and crude minerals (SITC-27)	0.242			
<i>Imports of services [CHF/CHF output]</i>				
Transport (G60b62)			0.0608	
<i>Gross value added [CHF/CHF output]</i>				
	0.677	0.749	0.724	0.925

Data from ecoinvent (ecoinvent Centre, 2010) is used to model direct environmental impacts (e.g., particulate matter emissions into the air) per the output of Swiss glass-packaging and foam glass production: green glass-packaging production in Germany (“Packaging glass, green, at plant/DE U”) and average foam glass production in Europe (“Foam glass, at plant/RER U”). Sand substitute production has no direct environmental impacts.

The price of exported cullet, which allows modeling the demand in the sector “Wholesale and retail trade” in the Swiss NAMEA, is 0.058 CHF per kg of Swiss cullet. This price was provided by a Swiss scrape trader exporting cullet of all colors, i.e., brown, green, white, and mixed. Abroad, mixed cullet can be sorted with respect to color prior to recycling. A firm in Germany

that processes Swiss cullet specified the amount of electricity needed to sort optically 1 kg of cullet: 0.0015 kWh. The environmental impacts of consumption are modeled with the ecoinvent process "Electricity, medium voltage, at grid/DE U" (ecoinvent Centre, 2010).

Figure SM 1 provides the amounts of products resulting from the processing of 1 kg of Swiss cullet through the different options and the amount of competing goods needed to meet the same function. For the insulation system based on extruded polystyrene (XPS), no amount is indicated as the equivalent demand is modeled as the difference in needed inputs compared to the Misapor-based system (see Table SM 3).

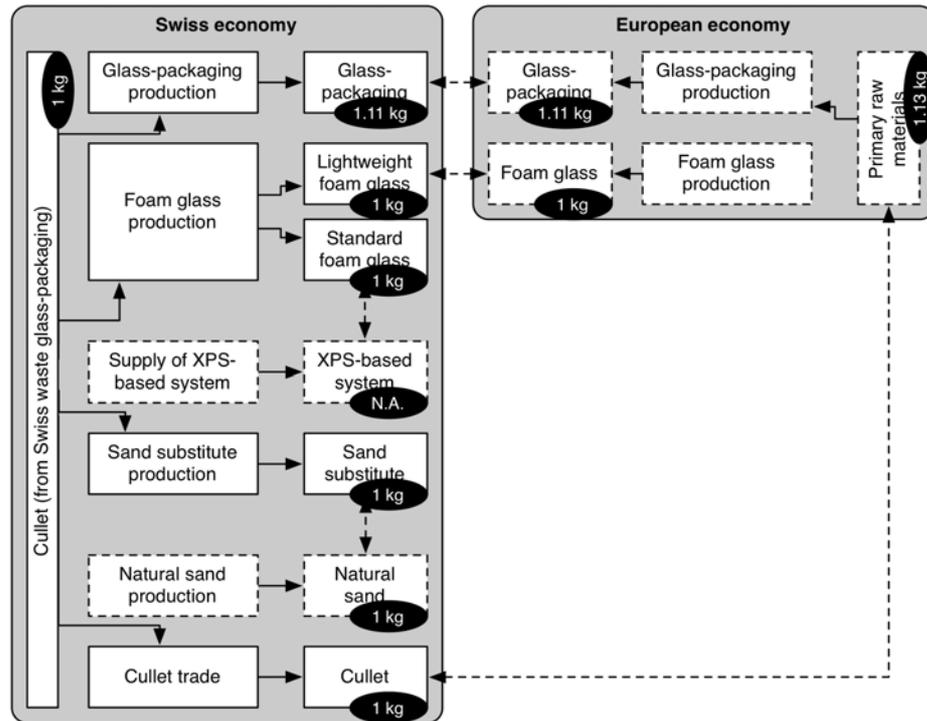


FIGURE SM 1 AMOUNTS OF PRODUCTS FROM SWISS CULLET PROCESSING OUT OF 1 KG OF CULLET AND AMOUNTS OF COMPETING GOODS ENSURING FUNCTIONAL EQUIVALENCE (XPS: EXTRUDED POLYSTYRENE).

Table SM 3 details the inputs from the Swiss NAMEA into the production of competing goods taking place in Switzerland. The figures refer to the production of an amount of competing goods functionally equivalent to 1 kg of standard foam glass and sand substitute. The inputs for the XPS-based system correspond to the additional goods and services needed to supply the insulation system compared to the Misapor-based system.

TABLE SM 3 DIRECT INPUTS TO THE PRODUCTION OF COMPETING GOODS IN SWITZERLAND (XPS: EXTRUDED POLYSTYRENE).

Direct inputs [CHF/CHF output]	Supply of XPS-based system	Natural sand production
Mining and quarrying (G10b14)	0.159	0.0312
Plastics and rubber (G25)	0.734	0
Mineral products (G26)	0.203	0
Construction (G45)	0.0494	0

For the XPS-based insulation system, i.e., the alternative system to standard foam glass, the necessary information was obtained from Misapor and could unfortunately not be crosschecked with the providers of this alternative system. Also, publicly available LCAs focus on the insulation material instead of insulation systems based on these materials¹³. Only the latter would allow for a proper validation of the Misapor data. The demand functionally equivalent to the production of sand substitute out of 1 kilogram of cullet is 1 kilogram of local natural sand from the NAMEA sector "Mining and quarrying." The price for this primary raw material is that paid by the municipality of Lausanne.

The ecoinvent processes used to model glass-packaging and foam glass production in Europe correspond to "Packaging glass, green, at plant/RER U" and "Foam glass, at plant/RER U" (ecoinvent Centre, 2010). When Swiss cullet replaces primary raw materials (e.g., silica sand) in European glass-packaging production, it also allows saving energy in this production process. Total environmental impact reductions arising from the substitution of primary raw materials are calculated on the basis of brown, white, and green glass-packaging relying each on different shares of cullet in their total raw material input. The corresponding models are "Packaging glass, brown, at plant/DE U", "Packaging glass, white, at plant/DE U", and "Packaging glass, green, at plant/DE U".

For imports and exports of cullet and glass-based products, a distance of 250 km by truck representing an average European fleet was modeled based on Doka (2006). The ecoinvent process "Transport, lorry >16t, fleet average/RER U" is used.

Figure SM 2 shows the eco-efficiency profile's sensitivity (a) to the evaluation of environmental impacts with the ReCiPe 2008 impact assessment method (Goedkoop et al., 2009), which values environmental flows with respect to their damage to safeguard objects and to (b) a 30% increase in the energy efficiency of Swiss foam glass production¹⁴.

¹³ See e.g., <http://www.daemmstoff.org>

¹⁴ Potential estimated by Misapor

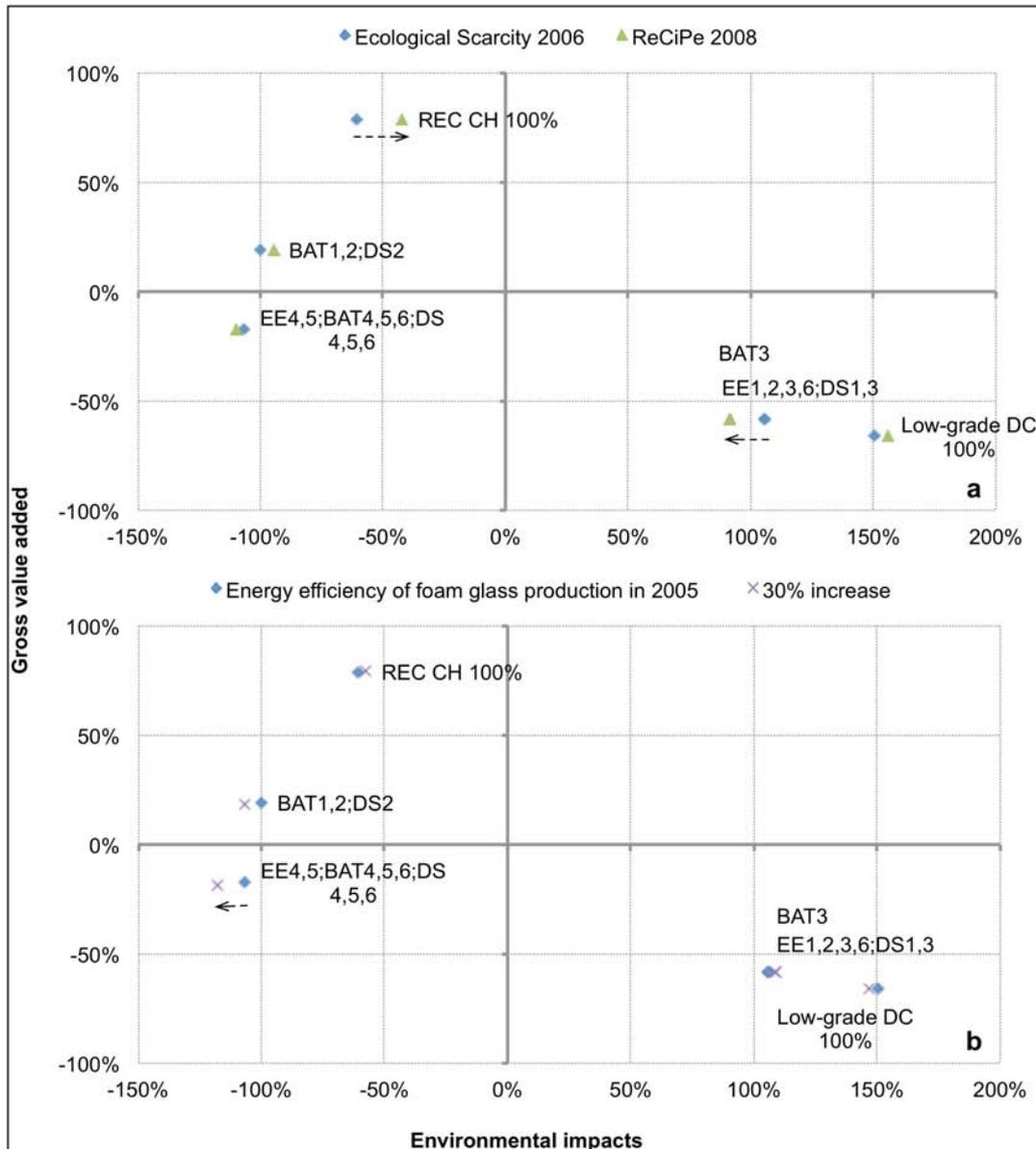


FIGURE SM 2 ANALYSIS OF THE ECO-EFFICIENCY PROFILE'S SENSITIVITY TO (a) THE IMPACT ASSESSMENT METHOD AND (b) THE EFFICIENCY GAINS OF FOAM GLASS PRODUCTION (BAT: BEST AVAILABLE TECHNOLOGIES; CH: SWITZERLAND; DC: DOWNCYCLING; DS: DISPOSAL SECURITY; EE: ENVIRONMENTAL EFFICACY; EUR: EUROPE; REC: RECYCLING). ARROWS INDICATE THE SHIFT FROM THE BASE CASE TO THE SENSITIVITY ANALYSIS RESULTS.

Looking closer at the nature of environmental impacts assessed with ReCiPe 2008 (cf. Figure SM 3) we see that the dominant environmental impacts are caused only by the burning or material use of fossil fuels. These impacts consist in resource (fossil) depletion, effects of climate change on human health and on ecosystems, and particulate matter formation. Somewhat surprisingly at a first glance, less domestic recycling brings about larger agricultural land occupation. A closer examination of the average European glass-packaging's production inputs reveals its dependence on solid unbleached board for packaging the glass. This board is fabricated with Scandinavian softwood, which explains the agricultural land use. In the Ecological Scarcity 2006 method, all land uses fall under the category "Natural resources."

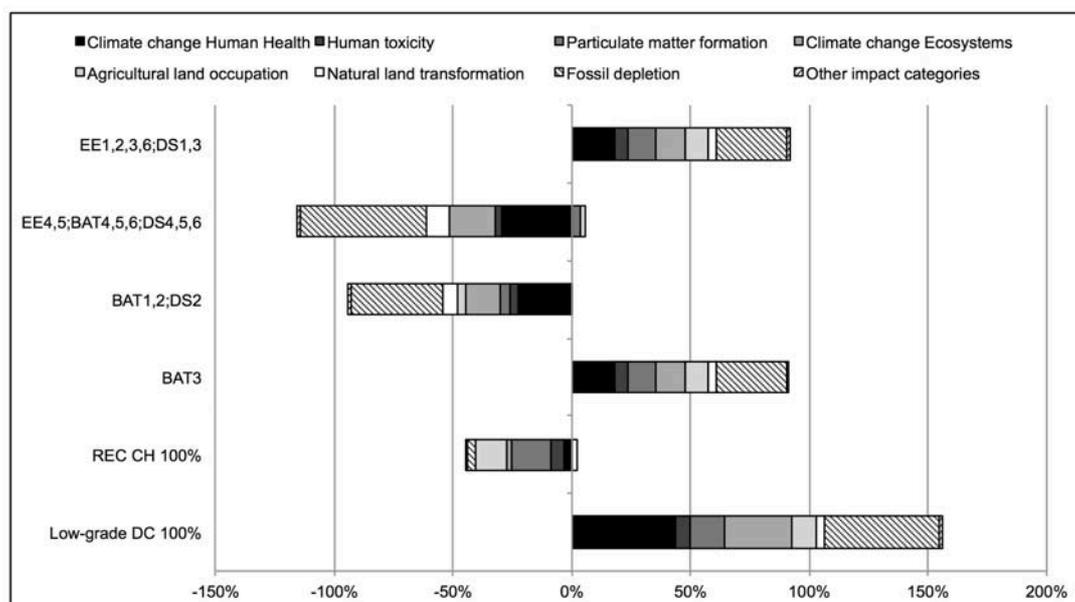


FIGURE SM 3 ENVIRONMENTAL IMPACT REDUCTIONS/INCREASES OF SCENARIOS AND PROTOTYPES PER IMPACT CATEGORY OF RECIPE 2008. RESULTS ARE NORMALIZED TO THE ENVIRONMENTAL IMPACTS AND GROSS VALUE ADDED OF THE ALLOCATION IN 2009 (BAT: BEST AVAILABLE TECHNOLOGIES; CH: SWITZERLAND; DC: DOWNCYCLING; DS: DISPOSAL SECURITY; EE: ENVIRONMENTAL EFFICACY; EUR: EUROPE; REC: RECYCLING).

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4 PAPER 3 – IDENTIFYING STAKEHOLDERS' VIEWS ON THE ECO-EFFICIENCY ASSESSMENT OF A MUNICIPAL SOLID WASTE MANAGEMENT SYSTEM

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ABSTRACT

Life cycle assessment (LCA) is one of the most popular methods of technical-environmental assessment for informing environmental policies, like for instance in municipal solid waste (MSW) management. Because MSW management involves many stakeholders with possibly conflicting interests, the implementation of an LCA-based policy can, however, be blocked or delayed. A stakeholder assessment of future scenarios helps identify conflicting interests and anticipate barriers of sustainable MSW management systems. This paper presents such an approach for Swiss waste glass-packaging disposal, currently undergoing a policy review. In an online survey, stakeholders (N=85) were asked to assess disposal scenarios showing different LCA-based eco-efficiencies (Meylan, Ami, & Spoerri, subm.; Meylan, Seidl, & Spoerri, 2013) with respect to their desirability and probability of occurrence. Scenarios with higher eco-efficiency than the current system are more desirable and considered more probable than those with lower eco-efficiency. A combination of inland recycling and downcycling to foam glass (insulation material) in Switzerland is desired by all stakeholders and is more eco-efficient than the current system. In contrast, institutions of MSW management such as national and regional environmental protection agencies judge a scenario in which nearly all cullet would be recycled in the only Swiss glass-packaging factory as more desirable than supply and demand stakeholders of waste glass-packaging. Such a scenario involves a monopsony rejected by many municipalities and scrap traders. We conclude that such an assessment procedure can provide vital information guiding the formulation of environmental policies.

4.1 INTRODUCTION

Recommendations from technical-environmental assessments of scenarios for municipal solid waste (MSW) management systems are often used to guide policies. The majority of MSW management professionals have a technical background; therefore, they tend to favor technical assessments. In this context, life cycle assessment (LCA), a method used to assess the environmental impacts of goods, products, or services over their entire life cycle (Pennington et al., 2004; Rebitzer et al., 2004), stands at the forefront of technical-environmental assessments for various reasons, for instance, the extension of system boundaries to energy and material supply chains, the aggregation of different environmental impacts to single indicators, and readily available databases (e.g., ecoinvent Centre, 2010), software (e.g., SimaPro and OpenLCA) and standards (ISO, 2006a, b). Cleary (2009) reviewed the current practice of LCAs of MSW management systems and found that there is a lack of transparency with respect to their methodological assumptions (e.g., a lack of clarity with respect to system boundaries). Despite these limitations, the popularity of LCAs among MSW

policy-makers has risen steadily in the two last decades. A prominent example is the European Union and its Waste Framework Directive (WFD) (European Parliament and Council, 2008), which states that the waste hierarchy can be bypassed on the condition that LCA-based evidence supports such a move. For policy-makers, LCA is particularly attractive in that it delivers seemingly clear-cut results (Lazarevic, Buclet, & Brandt, 2012). As the scope of LCA extends to a growing number of resources, pollutants, and ensuing environmental impacts, strives to include economic and social dimensions, and links more human activities and regions (Finnveden et al., 2009; Jeswani, Azapagic, Schepelmann, & Ritthoff, 2010), one might expect this popularity to continue if not to increase.

In the context of MSW management systems' transitions, LCA remains a method commonly used for technical-environmental assessments. However, it has failed to consider the human system inextricably associated with waste management infrastructure and flows, a human system taking the form of a regime of stakeholders with—possibly diverging—interests and preferences and operating in a broader context of societal evolution and technological innovation (Raven, 2007; Spoerri, Lang, Staeubli, & Scholz, 2010). In fact, policies informed by LCA could threaten the interests of key stakeholders and, as a result, policy implementation might be delayed or blocked due to their opposition. It is therefore striking that so few researchers have reported on the translation of LCA results into societally robust policies, e.g., addressing conflicting interests. Jeswani et al. (2010), reviewing options for broadening and deepening LCA approaches, suggested that LCA could be combined with strategic environmental assessment (SEA) to foster dialogue among stakeholders and identify conflicting interests, among others. SEA is a procedural method to support policies at an early stage of the planning process by combining analytical tools and the investigation of stakeholder concerns (Fischer, 2007; Ness, Urbel-Piirsalu, Anderberg, & Olsson, 2007; Salhofer, Wassermann, & Binner, 2007). On the level of policy-support organization, Scholz and colleagues (Scholz, 2011; Seidl et al., 2013) proposed the idea of transdisciplinary (TD) processes to provide robust orientations in contested societal decision processes. For societally robust orientations, the integration of various forms of knowledge, including stakeholders' views, can be necessary depending on the stage of the decision process (Krütli, Stauffacher, Flüeler, & Scholz, 2010; Stauffacher, Krütli, Flüeler, & Scholz, 2012). On the level of policy-support stages, Loorbach and colleagues (Loorbach & Rotmans, 2010; Rotmans & Loorbach, 2008, 2009) embed the collection of stakeholder views into a broader cycle of transition management implying stakeholder participation. After achieving consensus among stakeholders on long-term sustainability visions, the latter are translated into agendas; experiments are conducted on technologies foreseen by agendas in real-world settings. Eventually, the transition experiments are monitored and evaluated, which can lead to revising visions.

The goal of this paper is to identify and analyze stakeholders' views on MSW management transitions and thus to contribute in anticipating possible conflicts between alternative LCA-based policies and stakeholders' interests. The study hence shares the goals of combining LCA and SEA as proposed by Jeswani et al. (2010). The case at hand is Swiss waste glass-packaging disposal. The national environmental protection agency (EPA) is responsible for levying a tax on glass-packaging, the anticipated disposal fee (ADF), to financially compensate municipalities responsible for waste collection. It defines the amount raised and the compensation rates according to how waste glass-packaging is collected by

municipalities (i.e., color-mixed or separated) and what disposal option they choose (i.e., bottle-to-bottle recycling, various downcycling options). This is a case pertinent to the above-mentioned gap in the practice of LCA for supporting MSW management policies. ADF amounts and compensation rates have been contested ever since this policy tool was introduced in 2001, while the rates have been justified by means of LCA (e.g., Doka, 2006). The study is part of a broader TD process between the Swiss EPA, ETH Zurich, and the EPA of Canton Zurich focusing on reviewing present ADF rates. The results will serve to define an agenda of measures in the next stage of transition management. The following research questions are addressed:

- 1) How do stakeholders rate scenarios of an MSW management system with respect to desirability?
- 2) How do stakeholders react to LCA information?
- 3) Do stakeholder groups assess scenarios differently?

Stakeholder views were analyzed in a two-fold exploratory manner. First, a detailed individual assessment involved eliciting the stakeholders' assessment of scenarios. In the first assessment, stakeholders rated the desirability and probability of the occurrence of six Swiss waste glass-packaging disposal scenarios. The probability of occurrence was assessed to identify stakeholders' perceived barriers to transitions other than opposing interests. In a second assessment, stakeholders were provided with information on the environmental efficacy and economic efficiency of the six scenarios, two metrics of eco-efficiency determined by means of LCA. Stakeholders were again asked to rate the desirability and probability of the scenarios' occurrence. Second, a social conflict analysis served to identify rating differences between stakeholder groups.

4.1.1 DETAILED INDIVIDUAL ASSESSMENT

The purpose of the detailed individual assessment was to identify scenarios that are both desired by stakeholders and assessed as eco-efficient by means of LCA. Scenarios assessed as eco-efficient by means of LCA might be blocked due to low desirability ratings. Further, eco-efficient scenarios rated by stakeholders as desirable may not be pursued due to low ratings in the probability of occurrence. We explored whether differences in the scenarios' environmental and economic impacts determined by LCA lead to differences in the mean ratings of desirability and probability. We also analyzed whether the LCA information provided in the second scenario assessment leads to changes in the mean ratings of desirability and probability.

4.1.2 SOCIAL CONFLICT ANALYSIS

Social conflicts resulting from the perceived divergence of interest between different parties (Bügl, Stauffacher, Kriese, Lehmann Pollheimer, & Scholz, 2012; Button, 2002; Pruitt & Sung, 2004) have been well researched in the field of MSW management, yet mainly from an end-of-pipe perspective: e.g., waste managers and decision-makers against communities next to which waste treatment facilities (e.g., incinerators, landfills) are to be installed (Che et al., 2013; Contreras, Hanaki, Aramaki, & Connors, 2008; Srivastava, Kulshreshtha, Mohanty, Pushpangadan, & Singh, 2005). Conflicts within a supply/demand chain of an MSW system, i.e., between suppliers, purchasers of secondary raw materials, and institutions governing

the system, have less frequently been the object of research, albeit worthy of interest. Most MSW management policies are now targeting this relationship in addition to limiting local impacts of waste treatment facilities. In the case of Swiss waste glass-packaging disposal, supply, demand, and institutions framing this relationship can have different rationales or system knowledge, which can lead to social conflict and thereby hinder transitions (Meylan et al., 2013). Municipalities (representing supply) must provide waste disposal services at a low cost. Swiss producers of glass-packaging and foam glass as well as scrap traders (representing demand) are embedded in competitive national and international markets. The Swiss cullet market itself is very much embedded into the greater European cullet market. Scrap traders, which sell cullet either to Swiss processors or to buyers in neighboring countries, describe the Swiss market as a spot market. When the production of glass-packaging increases in neighboring countries, Swiss cullet is demanded first due to its quality (Meylan et al., 2013). Supply and demand stakeholders work in the framework of municipal, cantonal, and national waste legislations. Institutions are responsible for enforcing environmental regulations, designing strategy, and controlling the activities of public and private entities of MSW management. Scenarios that are highly desired by all stakeholder groups and that show high performance in terms of environmental efficacy and economic efficiency assessed by means of LCA can represent a way out of a social conflict (Bügl et al., 2012). In other words, we are searching for scenarios that both achieve high eco-efficiency and are desired by stakeholders.

4.2 METHODS

4.2.1 SCENARIOS OF SWISS WASTE GLASS-PACKAGING DISPOSAL

Table 1 gives an overview of the scenarios of Swiss waste glass-packaging disposal in terms of the percentages of green, white, brown, and mixed cullet collected and treated in Switzerland (recycling to new packaging glass in one factory, high-grade downcycling to foam glass for insulation purposes in two facilities operated by a single company, and low-grade downcycling to sand substitute used in public works) or recycled to new glass-packaging in neighboring countries. Export is characterized by three possibilities: the recycling of mixed cullet, of separated cullet, and of separated cullet following optic sorting (sorting facilities in neighboring countries). Scenarios S1 to S4 are the result of a scenario analysis based on expert and stakeholder knowledge and literature review (Meylan et al., 2013) and correspond to possible, future states in the year 2020. Scenarios S5 and S6 are prototypical systems (i.e., inland recycling, low-grade downcycling). In scenarios S1, S2, S4, and S6, glass-packaging is no longer produced in Switzerland. In scenarios S1, S4, S5, and S6, foam glass is no longer produced in Switzerland. All scenarios were the object of an LCA-based eco-efficiency assessment (Meylan et al., *subm.*). The difference between these scenarios and the current system was assessed in terms of their environmental impacts aggregated according to the Ecological Scarcity Method 2006 (Frischknecht, Steiner, & Jungbluth, 2009) as well as of their gross value added in Switzerland. These two indicators were meant to appraise the eco-efficiency of scenarios.

Identifying stakeholders' views on the eco-efficiency assessment
of a municipal solid waste management system

TABLE 1 SCENARIOS OF SWISS WASTE GLASS-PACKAGING DISPOSAL, INCLUDING THE ASSESSMENT OF THEIR ECO-EFFICIENCY (MEYLAN ET AL., SUBM.; MEYLAN ET AL., 2013).

		Current	S1: Export with optic sorting of mixed cullet	S2: High-grade downcycling	S3: Inland recycling and high-grade downcycling	S4: Export with partial optic sorting of mixed cullet	S5: Inland recycling	S6: Low-grade downcycling	
Percentage of total quantity in 2009	Collected	Mixed	29	29	29	29	0	29	
		Green	50	50	50	50	70	50	
		White	14	14	14	14	21	14	
		Brown	7	7	7	7	9	7	
	Export, separated	Green	23	50	0	0	50	0	
		White	11	14	14	11	11	14	
		Brown	4	7	7	4	4	7	
	Export, mixed	Mixed	14	0	0	0	14	0	
	Export, mixed, optic sorting	Mixed	0	29	0	0	14	0	
	Recycling, CH	Green	24	0	0	24	0	70	
		White	3	0	0	3	0	10	
		Brown	3	0	0	3	0	5	
	HG Downcycling	Mixed	14	0	29	29	0	0	
		Green	3	0	50	25	0	0	
	LG Downcycling	Mixed	0	0	0	0	0	29	
		Green	0	0	0	0	0	50	
	Environmental impacts compared to 2009 in %			106	-107	-100	106	-61	150
	Gross value added in CH compared to 2009 in %			-59	-17	19	-59	79	-66

4.2.2 SAMPLE DESCRIPTION

Stakeholders of Swiss waste glass-packaging disposal were selected after a thorough research process and according to the three predefined stakeholder groups: supply (municipalities and associations of municipalities for waste management purposes), demand (scrap traders/exporters and the two Swiss main cullet processors¹⁵), and institutional groups (national and all 26 cantonal EPAs¹⁶, recycling associations/lobbies, consultancy and other scientists). Great care was taken to identify the person responsible for the field of waste glass-packaging disposal within each organization. Stakeholders were informed beforehand by mail of the background and purpose of the online survey and that they would receive an invitation link to the survey by email in the next two weeks. The invitation email was sent out on May 17, 2013.

Table 2 gives an overview of the response and completion rates broken down by stakeholder groups. Response and completion refer to the initiation of the survey and the completion of it, respectively. The difference between participation and completion rates indicates the drop-out rate.

TABLE 2 RESPONSE AND COMPLETION RATES OF THE ONLINE SURVEY BROKEN DOWN BY STAKEHOLDER GROUPS.

	Supply		Demand		Institutions		Total	
	Total count	Percent	Total count	Percent	Total count	Percent	Total count	Percent
Contacted	59	100%	33	100%	37	100%	129	100%
Response	48	81%	21	64%	30	81%	99	77%
Drop-out	7	12%	4	12%	5	14%	16	12%
Completion	41	69%	17	52%	25	68%	83	64%

¹⁵ In the current system, a small quantity of sand substitute is produced. A public waste management entity using sand substitute as drainage material in engineered landfills was contacted, but did not participate in the survey.

¹⁶ Switzerland is constituted of 26 cantons enjoying large autonomy in various fields, e.g., MSW management.

Few representatives of cantonal EPAs admitted to not having sufficient knowledge to respond to the survey and either did not start or dropped out. These survey participants were kept in the sample, however. A small number of scrap traders did not begin the survey or dropped out for the following reasons (communicated to the authors during the survey):

- Waste glass-packaging was no longer part of their business.
- A negligible amount of waste glass-packaging was being traded (e.g., 20 tons per year).
- The participants' main activity was scrap transportation and not trading.

These participants were ruled out of the sample, i.e., are not included in the statistics of Table 2.

4.2.3 ONLINE SURVEY

An online survey consisting of a two-step rating of six scenarios of Swiss waste glass-packaging disposal was conducted from May 17 to June 14, 2013. The survey was developed in close consultation with the Swiss EPA and the EPA of Canton Zurich, members of the cooperation project in the framework of which the study was conducted. The software used for the online survey is Enterprise Feedback Suite (EFS) Survey by QuestBack, version 9.1/1.2 of March 28, 2013. Since stakeholders were selected in advance for the survey (see Section 4.2.2), a personalized survey was conducted. The survey was compiled in each of the stakeholders' languages: German, French, and Italian.

Prior to the ratings, stakeholders provided status information (e.g., their position in the organization) and expressed their opinion on the appropriateness of the ADF amounts as well as their level of satisfaction with respect to the ADF compensation rates. In the first assessment, stakeholders were familiarized with the current system of Swiss waste glass-packaging disposal as a geographical representation of waste glass-packaging percentages from the collection to different disposal options in Switzerland and abroad. They were then asked to rate scenarios with respect to the desirability and probability of their occurrence in 2020 on a scale from 1 (highly undesirable and highly unlikely, respectively) to 7 (highly desirable and highly probable, respectively). Scenarios were illustrated in a similar way as the current situation with a short summary (see Appendix A for a representation of the current system and an overview of the survey design). At the end of the first assessment, stakeholders were asked to select one among the six scenarios as the most desired and justify their choice. Prior to the second assessment, stakeholders were asked to weight the priority they give to environmental efficacy versus economic efficiency, while being briefly introduced to the LCA-based eco-efficiency assessment. Then, stakeholders were again asked to assess the desirability and probability of each scenario's occurrence given the new information (in addition to the same geographical representations). At the end of the second assessment, stakeholders were asked if their choice with respect to the most desired scenario had changed and if yes, to indicate their rationale.

4.2.4 DATA ANALYSES

All statistical analyses were carried out using R 3.0.1 for Mac. The assessment indicators were used as dependent variables in the analysis. Differences between the average scenario ratings depending on scenarios' environmental impacts and gross value added were

analyzed using two-way analysis of variance (ANOVA). Repeated measures ANOVA was used to test the influence of LCA-based eco-efficiency on stakeholders' views for each scenario. Differences between stakeholder groups were tested with univariate ANOVA for each scenario with stakeholder groups being the independent variable.

4.3 RESULTS

4.3.1 POLICY SATISFACTION

Figure 1 (a, b) shows the level of satisfaction of supply¹⁷ and demand stakeholders with the current policy of waste glass-packaging disposal, i.e., with the ADF amounts and rates. The mean and standard deviation of the 65 stakeholders are 3.8 and 1.1, respectively, for ADF amounts and 3.8 and 1.5, respectively, for ADF rates.

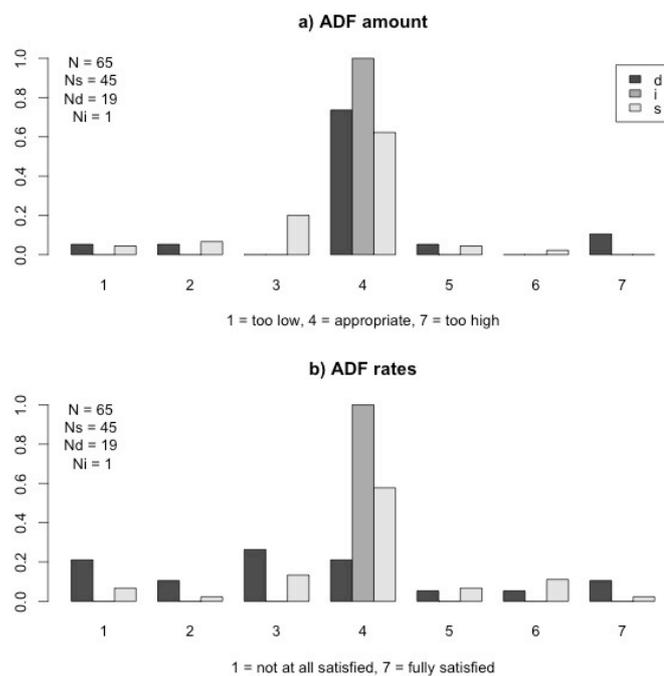


FIGURE 1 HISTOGRAMS OF SATISFACTION WITH ADF AMOUNTS (a) AND RATES (b) (d: DEMAND, s: SUPPLY, i: INSTITUTIONS).

4.3.2 DETAILED INDIVIDUAL ASSESSMENT

Figure 2 shows the mean ratings of scenarios' desirability and probability in the first and second assessments, i.e., without and with LCA information. The scenario with the highest mean ratings in both assessments is scenario S3 (Inland recycling and high-grade downcycling). It shows neither the highest environmental impact reduction nor the largest gain of gross value added in Switzerland when compared to the current system. Scenario S3 is one of the two scenarios achieving an environmental impact reduction and a gross value added gain together with scenario S5 (Inland recycling). The latter scores second best in desirability, but shows the same probability as scenario S2 (Inland downcycling) in the second assessment. Export scenarios involving the total or partial optic sorting of mixed cullet (S1,

¹⁷ The EPA of Canton Basel-City also answered this question, as it is responsible for waste collection.

S4) show similar mean ratings. Scenario S6 (low-grade downcycling) achieves similar desirability as the export scenarios, yet with lower probability.

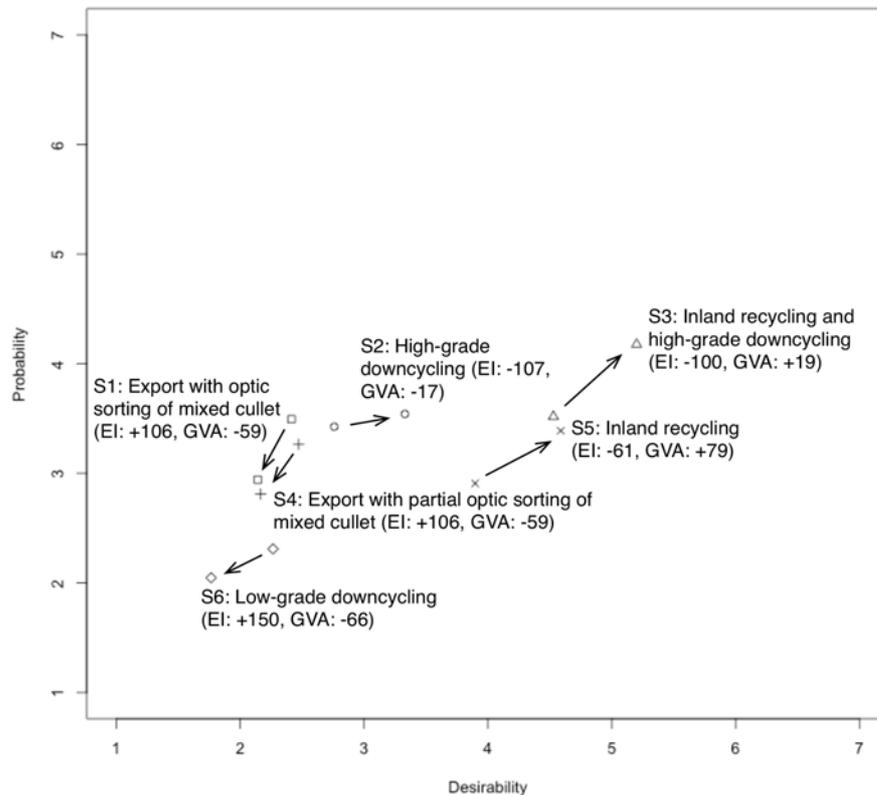


FIGURE 2 DETAILED INDIVIDUAL ASSESSMENT: THE MEAN VALUES OF DESIRABILITY VS. PROBABILITY RATINGS (ALL STAKEHOLDERS); THE ARROWS INDICATE THE SHIFT FROM MEAN RATINGS OF THE FIRST SCENARIO ASSESSMENT TO THOSE OF THE SECOND (EI: ENVIRONMENTAL IMPACTS, GVA: GROSS VALUE ADDED). NOTE: N = 85 (1020 OBSERVATIONS).

In the first assessment, without LCA information, differences in environmental impacts and gross value lead to significant differences in the mean ratings of desirability [$F_{d,env}(1) = 77.55$, $p_d < 0.001$, $F_{d,econ}(1) = 18.11$, $p_d < 0.001$, $F_{d,env:econ}(1) = 29.98$, $p_d < 0.001$]. This is not the case for probability [$F_{p,env}(1) = 1.93$, $p_p = 0.17$, $F_{p,econ}(1) = 0.44$, $p_p = 0.51$, $F_{p,env:econ}(1) = 0.31$, $p_p = 0.581$]. In the second assessment, differences in the mean ratings of desirability remain significant [$F_{d,env}(1) = 286.43$, $p_d < 0.001$, $F_{d,econ}(1) = 45.26$, $p_d < 0.001$, $F_{d,env:econ}(1) = 36.07$, $p_d < 0.001$], and become so for probability [$F_{p,env}(1) = 270.77$, $p_p < 0.001$, $F_{p,econ}(1) = 32.75$, $p_p < 0.001$, $F_{p,env:econ}(1) = 3.53$, $p_p = 0.061$].

Looking at the significance of the differences between ratings of the first and second assessments, the mean ratings of desirability increase for scenarios S2, S3, and S5 and decrease for scenario S6 [$F_{d,S2}(1) = 4.98$, $p_d < 0.05$, $F_{d,S3}(1) = 6.29$, $p_d < 0.05$, $F_{d,S5}(1) = 7.17$, $p_d < 0.01$, $F_{d,S6}(1) = 5.16$, $p_d < 0.05$]. The mean ratings of probability increase for scenarios S2, S3, and S5 and decrease for scenarios S1 and S4 [$F_{p,S2}(1) = 8.21$, $p_p < 0.005$, $F_{p,S3}(1) = 42.19$, $p_p < 0.001$, $F_{p,S5}(1) = 80.34$, $p_p < 0.001$, $F_{p,S1}(1) = 13.39$, $p_p < 0.001$, $F_{p,S4}(1) = 9.42$, $p_p < 0.005$].

4.3.3 SOCIAL CONFLICT ANALYSIS

Figure 3 (a, c) shows the most desired scenarios after the first and second scenario assessments by stakeholder groups. In the second scenario assessment, stakeholders were informed of the scenarios' LCA-based eco-efficiency. Results of supply and institution groups are similar. In the first assessment (a), these two stakeholder groups select scenarios S3 (Inland recycling and high-grade downcycling) and S5 (Inland recycling). Given the good LCA-based eco-efficiency of scenarios S3 and S5, it is not a surprise that selections do not change in the second assessment (c). Stakeholders in the demand group are less unanimous in the first selection, and there is no clear plebiscite for scenarios S3 and S5 in the second. Figure 3 (b) reveals how stakeholders weigh environmental efficacy against economic efficiency. The mean and standard deviation of all 87 stakeholders are 3.6 and 1.3 (supply: 3.9 and 1.2, demand: 3.9 and 1.7, institutions: 3.1 and 1.0).

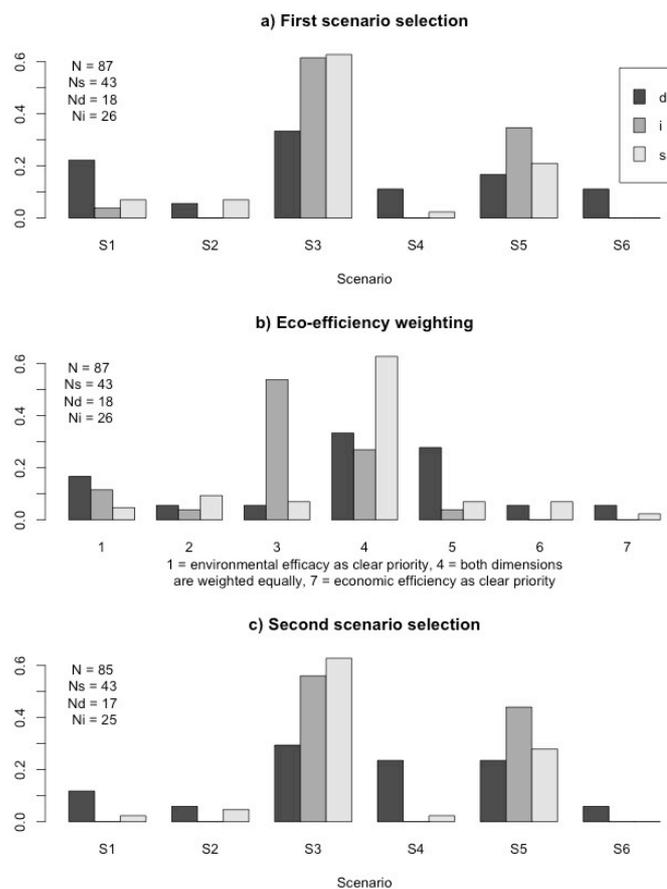


FIGURE 3 MOST DESIRED SCENARIO AFTER THE FIRST SCENARIO ASSESSMENT (a), WEIGHTING OF THE TWO DIMENSIONS OF ECO-EFFICIENCY (b), AND MOST DESIRED SCENARIO AFTER THE SECOND SCENARIO ASSESSMENT (c) (d: DEMAND, s: SUPPLY, i: INSTITUTIONS).

Figure 4 shows the mean ratings of desirability and probability by stakeholder groups. Stakeholder groups disagree on the desirability and probability of scenario S4 (Export with partial optic sorting of mixed cullet) [$F_{S4,d} (2) = 5.70, p_d < 0.005, F_{S4,p} (2) = 5.12, p_p < 0.01$]. The demand group desires scenario S4 more than supply and institution groups [$t_{d,S4}, (19.18) = 2.00, p_d < 0.05, t_{d,S4} (18.64) = 2.59, p_d < 0.05$, respectively]. The demand group also views scenario S4 as more probable than the supply group [$t_{p,S4}, (20.70) = 1.99, p_p < 0.05$]. Scenario S5 (Inland recycling) is also the object of dissent in terms of its desirability and probability

$[F_{S5,d} (2) = 4.90, p_d < 0.01, F_{S5,p} (2) = 4.01, p_p < 0.05]$. Institutions desire scenario S5 more than supply and demand groups [$t_{d,S5} (64.34) = 2.01, p_d < 0.005, t_{d,S5} (23.98) = 3.04, p_d < 0.005$, respectively]. Institutions consider scenario S5 more probable than supply and demand groups [$t_{p,S5} (62.63) = 3.28, p_p < 0.001, t_{p,S5} (22.59) = 1.75, p_p < 0.05$, respectively].

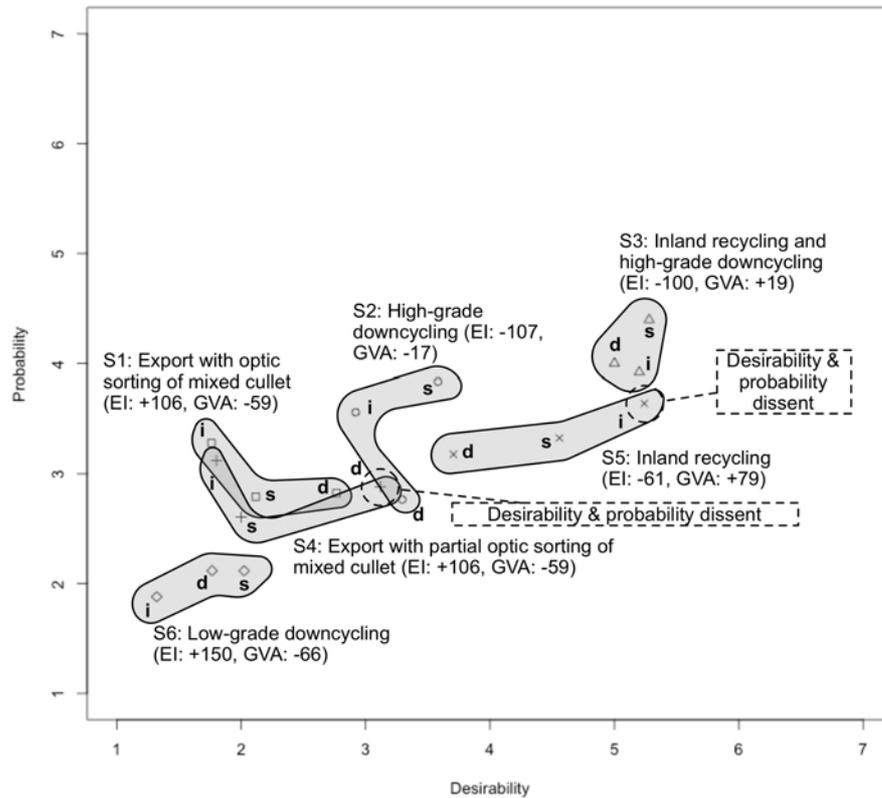


FIGURE 4 SOCIAL CONFLICT ANALYSIS: THE MEAN VALUES OF DESIRABILITY VS. PROBABILITY RATINGS IN THE SECOND SCENARIO ASSESSMENT (BY STAKEHOLDER GROUPS). AREAS OF DISSENT BETWEEN STAKEHOLDER GROUPS ARE INDICATED AS WELL (d: DEMAND, s: SUPPLY, i: INSTITUTIONS). NOTE: N = 85 (510 OBSERVATIONS).

Of the two scenarios achieving environmental impact reductions and gross value added gains compared to the current system, scenario S3 (Inland recycling and high-grade downcycling) shows no sign of substantial dissent between stakeholder groups. All stakeholder groups rate S3 as desirable (mean rating of 5.2 on a seven-point scale). The other scenario achieving environmental impact reductions and gross value added gains obtains lower desirability than scenario S3 and there are more differences between the stakeholder groups.

4.4 DISCUSSION

We start the discussion by answering the first two research questions, i.e., how stakeholders assess scenarios with respect to the desirability and probability of their occurrence (cf. research question 1) and whether LCA information influences their ratings (cf. research question 2). We then address rating differences between stakeholder groups (cf. research question 3). We also reflect on stakeholders' rationales for their ratings. Further, we provide an outlook on the next stage of transition management of Swiss waste glass-packaging

disposal. We close this section by reflecting on the method used to collect stakeholders' views on scenarios of Swiss waste glass-packaging disposal and their eco-efficiencies.

4.4.1 DETAILED INDIVIDUAL ASSESSMENT

Before elaborating on the differences in stakeholders' mean ratings of the various scenarios, it seems worthwhile to discuss their absolute average ratings. The highest average rating for desirability or probability is that of scenario S3's desirability (Inland recycling and high-grade downcycling) in the second assessment with mean ratings of 5.2 and 4.2, respectively (see Figure 2). We advance here a possible explanation for the simultaneously low desirability and probability ratings. In comparison to the current system, the six scenarios are extreme in the sense that at least one disposal path is completely ruled out in each scenario. Present disposal paths represent regional markets that stakeholders might consider sustainable. This argument is in line with the satisfaction expressed by stakeholders with ADF amounts and rates (see Figures 1a and 1b). It is not surprising, then, that scenarios in which green and mixed cullet is no longer exported get the highest average desirability and probability ratings. In recent years, this option has been plagued by increasingly low cullet prices¹⁸. To substantiate this argument, here are several stakeholders' rationales for selecting scenario S3, which most closely resembles the current system: "diversification allows for better management of waste glass-packaging," "[scenario S3 allows for] conservation of diversity and some independence from abroad," and "[scenario S3 allows for a] competitive environment, high-grade recycling is maintained."

In the second scenario assessment, stakeholders prefer and consider more probable scenarios with lower environmental impacts and/or higher gross value added than in the current system. Such ratings stand in line with the balanced weighting of environmental efficacy against economic efficiency most stakeholders make (see Figure 3b). Many stakeholders that select scenarios S2 (High-grade downcycling), S3 (Inland recycling and high-grade downcycling), and S5 (Inland recycling) following the first scenario assessment (i.e., prior to receiving LCA information) advance local circular flow economy, maintaining jobs and industry in Switzerland, independence, and/or reducing transport distances to recycling facilities as rationales. Interestingly, a previous and publicly available LCA has shown that transport distances to foreign glass-packaging factories are not an important parameter for environmental impacts (Doka, 2006). In the second assessment with LCA information, stakeholders see their views confirmed, yet for other reasons (e.g., lower environmental standards of glass-packaging factories in Europe than in Switzerland). Possible reasons for the low probability ratings for scenario S5 in comparison to scenario S3 are the possible closing of the only Swiss glass-packaging factory due to declining market shares¹⁹ and the structural challenges of the European glass-packaging sector (e.g., increasing energy prices, high labor costs)²⁰ as well as the high costs that would arise from transporting most Swiss cullet to this factory. Stakeholders seem to acknowledge that more radical—and thus improbable—policy interventions are needed if such a scenario is to occur.

At this stage, it is interesting to relate the results of the detailed individual assessment to recent research on stakeholders' views on goals to be pursued in future Swiss waste

¹⁸ See <http://www.gvzag.ch/preisindex-glas.html> for an index of cullet prices since 2009

¹⁹ http://www.vetropack.ch/htm/vetro_schweiz_3.htm

²⁰ <http://www.feve.org/index.php>

management (Scholz, Spoerri, & Lang, 2009). In a workshop framework, 48 experts of Swiss waste management reached a consensus on short-term and long-term priorities of upcoming waste management transitions. While experts attributed high short-term and long-term priorities to economic efficiency and resource management (from a life cycle perspective), respectively, they also gave high short-term priority to federalism, i.e., the principle by which different solutions should be found according to regional conditions. Waste logistics, including waste transportation, was assigned high short-term priority. Overall, stakeholders' ratings of this specific MSW management system are very much in line with Swiss waste management experts' generic priorities.

Additional LCA information impacts the mean ratings of desirability and probability differently. Desirability ratings change significantly for those scenarios that achieve environmental impact reductions compared to the current system (scenarios S2, S3, and S5) and for scenario S6 (Low-grade downcycling). Many stakeholders may not change their ratings for the two export scenarios (S1, S4) due to the regional importance of export. Probability ratings change significantly for all scenarios, with the exception of scenario S6. Although also significant, the change for scenario S2 (High-grade downcycling) is very small. A few stakeholders mention the limited market potential for foam glass, the product of high-grade downcycling, when rationalizing the selection of most desired scenarios. As for scenario S6, in the past, downcycling to sand substitute assessed by means of LCA as performing clearly worse than bottle-to-bottle recycling has been effectively eliminated through unfavorable ADF rates (Doka, 2006). In other words, stakeholders may think that the unfavorable LCA information for this scenario will not lead to a policy review making its revival even less probable. Generally, the differences between first and second assessments, albeit most of them statistically significant, remain low. We see here three possible explanations. First, for many stakeholders, the rating of scenarios in the first assessment was only confirmed with the additional LCA information. Second, stakeholders do not change ratings once additional information is provided in order to reduce cognitive dissonance (Festinger, 1962; Scholz, 2011). The last explanation may concern those stakeholders who believe recycling is from an environmental point of view better than downcycling, no matter where recycling is carried out and what type of downcycling is performed. To these, LCA information is rather counterintuitive, so that views are not changed in the second assessment.

4.4.2 SOCIAL CONFLICT ANALYSIS

Demand stakeholders rate scenario S4 (Export with partial optic sorting of mixed cullet) as more desirable than supply stakeholders and institutions. Demand stakeholders also rate scenario S4 as more probable than supply stakeholders. Demand stakeholders, among them scrap traders, seem to consider recycling mixed cullet abroad as a more sustainable outlet in terms of cullet prices than other stakeholder groups.

Institutions rate scenario S5 (Inland recycling) as more desirable and more probable than supply and demand stakeholders. The latter stakeholder groups seem to give weight to a balanced supply/demand relationship and be worried by a monopsony embodied by many municipalities or associations of municipalities with a single end cullet processor in Switzerland (Kinnaman, 2009; Kinnaman & Fullerton, 1999). Additionally, scenario S5 would entail high logistical costs for cullet transport that would inevitably arise from such a setting. Here are two quotes from supply and demand stakeholders fearing this monopsony situation:

"[...] the Swiss glass-packaging factory is far away (transport time and costs) and offers less competitive prices [than Italian glass-packaging factories] [...]" and "Swiss solution: monopsony danger, a competitive environment should be secured." In contrast, institutions seem to view scenario S5 as the role model of a circular flow economy.

Finally, stakeholder groups rate scenario S3 (Inland recycling and high-grade downcycling) similarly. In absolute figures, however, it does not score very high and most closely resembles the current system, which might ultimately be the reason for its success. The rating stakeholders, after all, are the constituents of the incumbent regime, which strives for stability. There might not be enough external pressure (e.g., environmental NGOs and regulation, rapid increases in waste glass-packaging collection in neighboring countries) and/or radical innovation in collection, sorting, and glass-based production technologies to create a window of opportunity for the reconfiguration of the regime (Geels, 2006; Geels & Schot, 2007). In this sense, LCA information will not lead to pressure on the regime, as it is quite in line with stakeholder ratings of the first assessment.

4.4.3 OUTLOOK

Results of the eco-efficiency assessment of Swiss waste glass-packaging disposal and of the stakeholder assessment will be presented at an upcoming workshop held by the Swiss EPA and gathering some 25–30 stakeholders who took part in the online survey. The main purpose of the workshop will be to discuss stakeholders' ratings of the scenarios proposed in this study and their rationales, to identify advantages and disadvantages of fostering/securing the most desired scenario, and to define measures to achieve such a scenario. For the latter purpose, stakeholders' knowledge will be integrated into backcasting methods (Carlsson-Kanyama, Carlsen, & Dreborg, 2013; Carlsson-Kanyama, Dreborg, Moll, & Padovan, 2008; Quist & Vergragt, 2006). Given the results of the stakeholder assessment, an important issue will certainly be the possibility of better considering regional conditions (i.e., local cullet markets) through a "regionalization" of the ADF rates or of any policy targeting the flows of waste glass-packaging. A new series of statistical analyses involving principal component analysis and cluster analysis may be conducted for this purpose.

4.4.4 STRENGTHS AND LIMITATIONS OF THE ONLINE SURVEY

We now reflect on the strengths and limitations of the online survey used to identify stakeholders' views on transitions within an MSW management system. The alternative to an online survey is an exploration parcours, in which stakeholders are physically confronted with scenario models and information and rate scenarios in face-to-face interviews (Bügl et al., 2012; Scholz & Tietje, 2002). In contrast to an exploration parcours, our online survey involved less sample bias arising from stakeholders' efforts to take part in the scenario assessment. An exploration parcours usually lasts two hours, while the average processing time for the online survey was 30 minutes. Additionally, stakeholders must travel for an exploration parcours. This would have been quite an issue in the case of rating scenarios of a national MSW management system. More generally, a larger number of stakeholders can be reached via online survey, thus increasing the robustness of results. There are also no interviewer effects in an online survey (Loureiro & Lotade, 2005) and data quality is thus expected to be higher. Finally, an online survey suits well a sample of stakeholders speaking different mother tongues.

The first limitation of our study was the non-representativeness of the survey. A study including all institutional and economic actors of Swiss waste glass-packaging disposal would have been difficult for several reasons. First, the scrap trade market is highly dynamic with entities merging while other are bought by larger firms and often international groups. On the supply side, a number of Swiss cantons are in the process of reducing the number of municipalities, while waste associations appear and disappear at a fast pace. Further, provided the number of survey participants can be increased, another approach could be adopted to measure the impact of LCA results on stakeholders. Two groups could rate scenarios with respect to their desirability and probability: one with LCA information and another without (i.e., the baseline group). This would prevent the cognitive dissonance that we believe may have taken place in our study.

4.5 CONCLUSION

A survey of stakeholder views on six scenarios of Swiss waste glass-packaging disposal in 2020 was conducted online to identify potential conflicts between stakeholder interests and the performance of scenarios with respect to environmental impacts and gross value added in Switzerland. The latter eco-efficiency metrics were informed by means of LCA (Meylan et al., *subm.*; Meylan et al., 2013). Besides desirability, N=85 stakeholders of Swiss waste glass-packaging disposal assessed the probability of scenarios' occurrence to identify stakeholders' perceived barriers to transitions other than opposing interests. Stakeholders were further divided into three groups of waste glass-packaging disposal: supply (municipalities), demand (scrap traders/exporters and the two Swiss main cullet processors), and institutional groups (mainly national and cantonal EPAs).

The online survey revealed which scenarios achieving high eco-efficiency lead to consensus among stakeholder groups. All stakeholder groups desire a scenario in which inland recycling to new glass-packaging is combined with high-grade downcycling to foam glass used as insulation material. They also consider it the most probable among the six scenarios assessed. In contrast, a scenario in which a large majority of Swiss cullet would be recycled in one Swiss glass-packaging factory leads to dissent with respect to desirability. Supply and demand stakeholders are significantly less enthusiastic about this scenario than institutions. Stakeholders also rate this scenario as less probable than the combination of inland recycling and high-grade downcycling, particularly supply and demand stakeholders. In light of the overall low ratings, the question remains whether stakeholders ultimately prefer the current system. This question will be addressed in a follow-up workshop with selected stakeholders.

Finally, our use of an online survey represents a novel way to confront stakeholders with results of LCAs informing policies. Instead of a presentation to a limited number of stakeholders, generally to those who provided data for life cycle inventories, a greater number of stakeholders first get to think about LCA results in a more intensive manner. This could allow them to be better prepared when the LCA, e.g., modeling assumptions, is presented in the follow-up workshop and, in turn, serve mutual learning between scientists performing LCAs and MSW management stakeholders.

ACKNOWLEDGEMENTS

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APPENDIX A. SUPPLEMENTARY MATERIALS

Figure SM 1 illustrates the current Swiss waste glass-packaging disposal system. Figure SM 2 details the survey design. Some sections are not the subjects of the present paper.

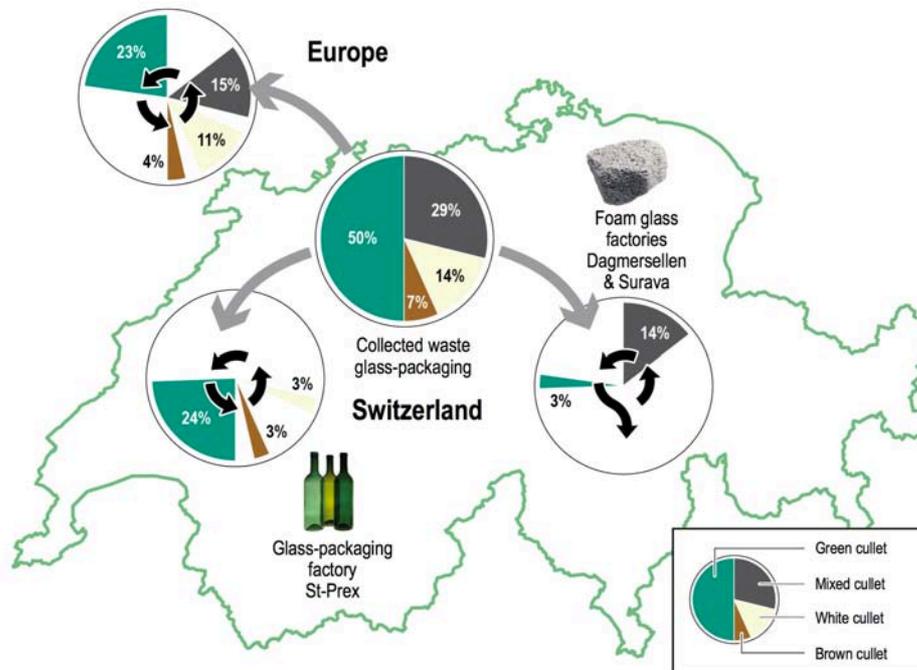


FIGURE SM 1 CURRENT SWISS WASTE GLASS-PACKAGING DISPOSAL SYSTEM.

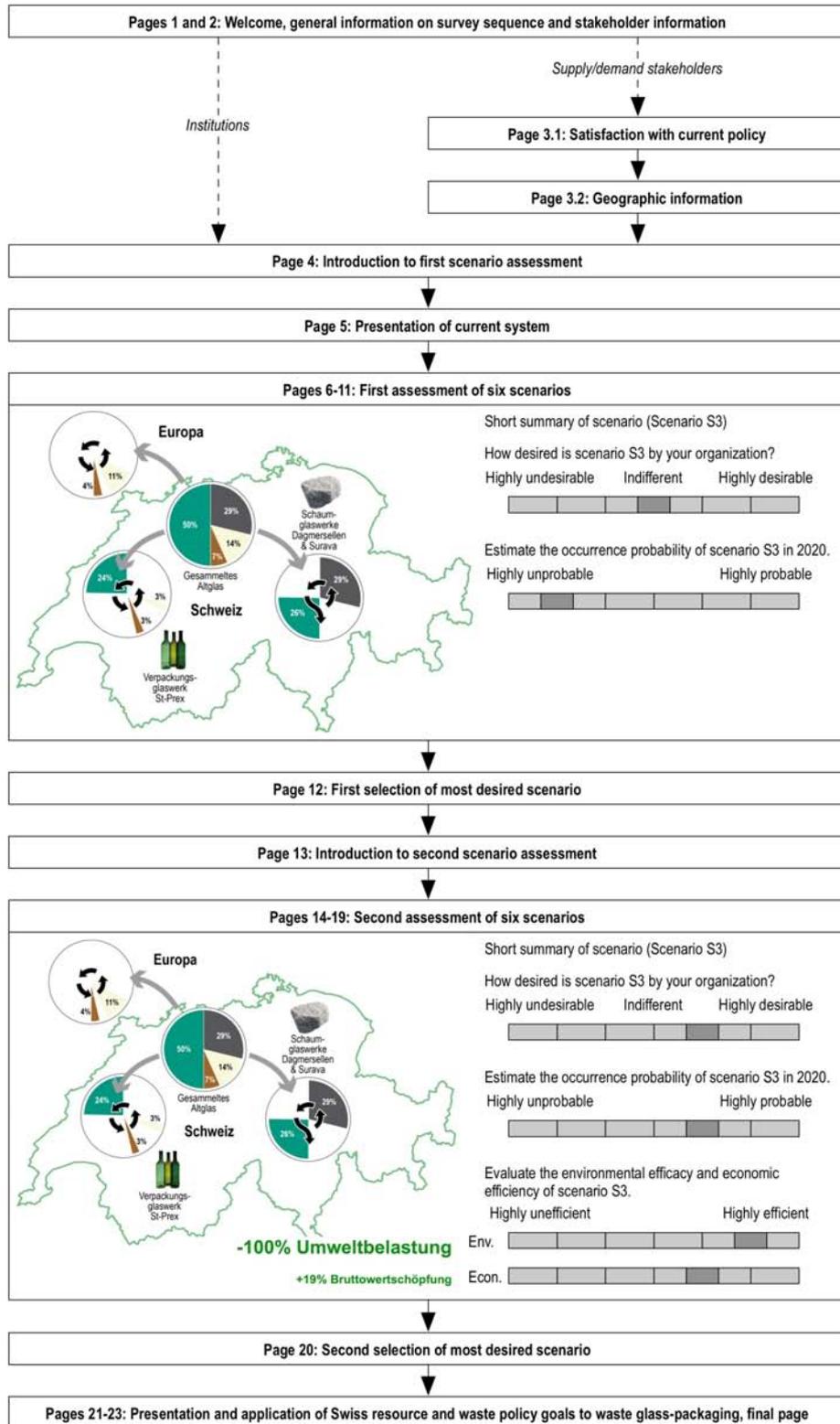


FIGURE SM 2 DESIGN OF THE ONLINE SURVEY ON SWISS WASTE GLASS-PACKAGING DISPOSAL.

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5 PAPER 4 – ECO-EFFICIENCY ASSESSMENT OF OPTIONS FOR METAL RECOVERY FROM INCINERATION RESIDUES: A CONCEPTUAL FRAMEWORK

Meylan, G., & Spoerri, A. (2014). *Waste Management*, 34, 93-100.

ABSTRACT

Residues from municipal solid waste (MSW) incineration in Switzerland have been a hot topic in recent years, both in the research and practice communities. Regarded by many as an economically and environmentally sound solution to this issue, technological retrofitting of existing grate incinerators has the dual purpose of enhancing the metal recovery of bottom and fly ashes and improving the inertization of residues to be landfilled. How does context influence the economic and environmental performance of this particular technological option? Under which conditions would this technological option be implemented nationwide in the future? What are stakeholders' views on sustainable transitions of MSW incineration? We propose a three-stage methodological procedure to address these questions.

5.1 INTRODUCTION

Switzerland's municipal solid waste (MSW) management history is characterized by environmental problem shifting (Laurent, Olsen, & Hauschild, 2012; Raadschelders, Hettelingh, van der Voet, & Udo de Haes, 2003; Saner, Blumer, Lang, & Koehler, 2011; Spoerri, 2009; Venkatesh & Brattebo, 2009). At the turn of the 20th century, uncontrolled dumping and soaring waste volumes brought about massive surface water pollution that threatened drinking water supplies and aquatic ecosystems as well as malodorous emanations that often reached inhabited areas in the vicinity of dumps. Surface water protection legislation was instrumental in the implementation of three alternative forms of waste treatment: composting, controlled landfilling, and incineration. However, composting quickly became obsolete due to the changing composition of residual waste (i.e., increasing shares of metals and plastics). As for controlled landfilling, the issue of waste volumes was obviously not solved and became more acute in a country with a paucity of land resources. At the same time, tougher landfill construction regulations led to higher landfill prices, which led to incineration getting the upper hand in the eighties. Yet this was not the panacea, as in addition to traffic and industry, grate incinerators with rudimentary filter technology became major emitters of specific air pollutants (e.g., heavy metals) in Switzerland. This time, new air pollution regulations forced operators to upgrade flue gas treatment (e.g., denitrification and acid washing systems) and a minimal energetic yield was imposed upon MSW incineration. With respect to metals, water- and airborne pollutants became incineration residues landfilled onto or into engineered compartments in Switzerland and abroad.

Today, with such practice, Swiss MSW management is facing a new, two-faced problem: first, a resource problem, as prices rise slowly yet steadily on world metal markets, and second, an environmental and human health problem, because of the long-term risk of heavy metal leaching from landfills. Two incineration residue types are targeted by retrofitting of existing

incinerators: (i) bottom ash through dry (instead of wet) discharge followed by a series of magnets and Eddy currents (Morf et al., 2012), and (ii) fly ash through acid washing (Nagib & Inoue, 2000; Pan, Huang, Kuo, & Lin, 2008; Youcai, Lijie, & Guojian, 2002). Today, of the 28 incinerators Switzerland counts, two have already implemented and are further developing dry discharge of bottom ash with enhanced metal recovery (e.g., Fe, Cu, Al, precious metals), while 13 others have different variants of acid washing of fly ash to recover various metals (Cd, Cu, Pb, Zn). There is a large consensus among key stakeholders and policy-makers of Swiss waste management that dry discharge of bottom ash and acid washing of fly ash are the best available technologies (BAT) with respect to Swiss conditions and context. However, an objective assessment of the performance of these two technologies in the Swiss context is yet to be conducted.

Based on our experience gathered on the case of disposal of waste glass-packaging in Switzerland (Meylan, Ami, & Spoerri, *subm.*; Meylan, Seidl, & Spoerri, 2013; Meylan, Stauffacher, Krütli, Seidl, & Spoerri, *in prep.*), we identify three reasons that might lead directly or indirectly to further problem shifting if assessments of waste management systems are conducted in their present form. We exemplify these reasons with the case described above.

First, in such assessments, the performance of waste management technologies is given on a unit level, e.g., the disposal of one kilogram of MSW. In reality, a single technology is unlikely to fit best an entire country. On the contrary, a mix of technologies, each corresponding to different local economic, geographic, political, and social conditions, characterizes most MSW management systems. For instance, household organic waste is either collected separately prior to composting or anaerobic digestion or co-incinerated with other household wastes as a result of various factors. There is a need to assess systems at their real scale, i.e., the scale of total waste quantities to deliver credible policy support (Ekvall, Assefa, Björklund, Eriksson, & Finnveden, 2007).

Second, most assessments lack an explicitly prospective nature that makes the anticipation of future trade-offs possible. Practitioners of life cycle assessment (LCA) tend to focus more on the uncertainty of data representing present systems than the uncertainty arising from future developments (Höjer et al., 2008; Spielmann, Scholz, Tietje, & de Haan, 2005). This contradicts the reality of growing waste amounts and the changing demand for energy and secondary raw materials, i.e. structural change, whose extent depends in turn on various factors. Over the last 20 years, Switzerland experienced a major restructuring of its metal industry with a shift to processing stages generating high added value (e.g., watch industry), while smelting activities were left to neighboring or distant countries. The impacts of further possible structural change on the performance of waste management should thus be part of the scope of an assessment of options for MSW incineration.

The need for prospective and integrative assessments, as described above, was already acknowledged by waste experts and policy-makers almost 30 years ago in the Guidelines for Swiss waste management (FOEN, 1986): (i) explicit modeling of upstream and downstream economic sectors linked to waste management processes (e.g., energy production) as well as imports of goods, services, and waste; and (ii) consideration of material flows in quantity and quality.

Third and last, the main output of assessments is usually a set of recommendations to policy-makers, e.g., the ban of a packaging material or the adaptation on a national level of heavy metal thresholds of incineration residues. Based on our own experience, we feel a structured and inclusive process that allows for a societally robust translation of assessment results to policies (Fan, 2012; Kruetli, Stauffacher, Pedolin, Moser, & Scholz, 2012), e.g., avoiding further problem-shifting, is lacking. This can result in misunderstanding/rejection by one or more waste management stakeholders of the assessment results e.g., due to an insufficient transparency of assumptions, or of policies based on these results. Ultimately, the policy might fail to yield desired impacts due to opposition by powerful stakeholders. Further, the scientific community dealing with waste management itself recognizes that it must go beyond recommendations and enter decision-making processes as a prerequisite to establish sustainable waste management systems (Hering, 2012).

In this paper, we present a three-step methodological procedure to meet these needs. First, a prospective analysis of MSW management systems by means of scenario analysis serves to construct possible, future MSW management systems. Second, these possible, future systems are assessed with a novel variant of LCA. Third, a method for conveying assessment results to stakeholders and identifying their views on sustainable transitions of MSW management is proposed. Before presenting this methodological procedure, we detail the two Swiss BATs at stake.

5.2 BEST AVAILABLE TECHNOLOGIES

5.2.1 DRY DISCHARGE OF BOTTOM ASH AND ENHANCED METAL RECOVERY

Wet discharge of bottom ash assumes two functions. First, it allows the incineration residue to cool down. Second, the furnace is airtight so that no tertiary air can penetrate into it. However, such a procedure presents the major inconvenience of agglutinating bottom ash, thus obstructing metal recovery. With dry discharge, the potential for metal recovery is significantly increased. Tertiary air cools down the ashes and improves the burning processes, i.e., enhances the afterburning of organic compounds, whereas an equivalent amount of secondary air is retrieved from incineration. Furthermore, a study commissioned by the Swiss EPA and other organizations investigated the quality of bottom ash at a Swiss MSW incineration plant equipped with dry discharge (Fierz & Bunge, 2007). One finding was that, despite longer cooling times, concentrations of asbestos and dioxin in fine bottom ash not conveyed back to the furnace by tertiary air (where it ends up as fly ash) are negligible.

Figure 1 details the process diagram of bottom ash treatment at one of the two plants implementing this technology, a grate incinerator in Hinwil in the Canton of Zurich (Boeni, 2011; Buechi, Boeni, & Di Lorenzo, 2012). Coarse bottom ash (>0.5 mm) is treated conventionally prior to landfilling, i.e., undergoes off-site metal recovery through magnetic separation (Morf et al., 2012). Fine bottom ash (<0.5 mm) is lead to a conveyor where it cools down. At its end, a first magnet recovers ferrous metals. The remaining ash is then collected in a silo prior to being separated on a screen into two fractions: fine (0.7–5.0 mm) and finest ash (0.1–0.7 mm). The fine fraction goes through a second magnet before non-ferrous metals (NE) are recovered through a series of two Eddy currents and sent to a new screen. The resulting fractions then land on a separating table, where copper- and aluminum-rich fractions are recovered. As for the finest fraction, it directly undergoes a second screen and is then processed through a series of three Eddy currents. Then, copper- and aluminum-rich

fractions are recovered on a separating table. For the fine fraction, whose recovery has taken place since 2008 in Hinwil, a separation rate of 90% is achieved for metals such as Al, Cu, Pb, Sn, and Zn. The content of non-ferrous metals in fine ash (0.7-5.0 mm) amounts to more than 5%. Finally, the NE metals recovered from this fine fraction present minimal mineral contents.

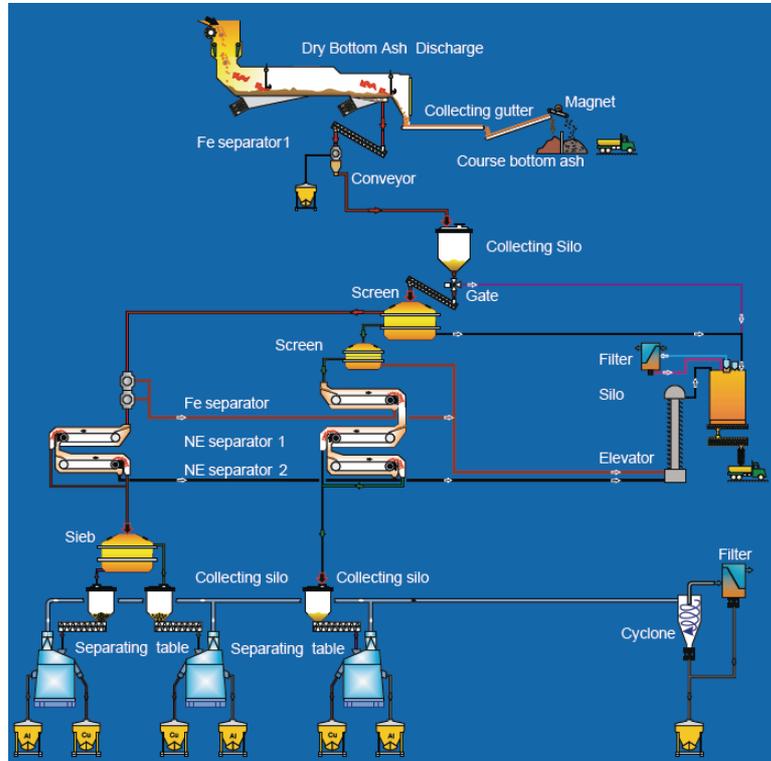


FIGURE 1 PROCESS DIAGRAM OF BOTTOM ASH TREATMENT AT HINWIL GRATE INCINERATOR, AS OF MARCH 2012. SOURCE: BUECHI, BOENI ET AL. (2012).

5.2.2 ACID WASHING OF FLY ASH

Fly ash accumulates in the boiler pipework and at the various downstream dust filters (electrostatic precipitators, fabric filters, etc.). In most MSW incinerators of Switzerland, fly ash is either exported to underground deposits in Germany or cemented prior to its disposal into domestic residual landfills. This results in a loss of 2,200 tons of zinc per year (Schlumberger, 2011). In 13 other plants, 1,800 tons of zinc per year are recycled thanks to the FLUWA process (FLUWA: Flugaschewäsche or washing of fly ash). Table 1 gives a detailed chemical analysis of fly ash.

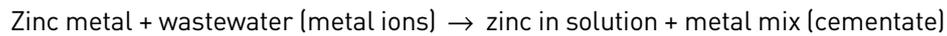
TABLE 1 AVERAGE ELEMENTAL COMPOSITION OF FLY ASH, CONCENTRATE OBTAINED BY MECHANICAL FILTRATION OF THE FLY ASH WASHED WITH ACID SCRUBBER WASTEWATER, AND FILTRATE AFTER NEUTRALIZATION WITH LIME MILK FROM SEVERAL MSW INCINERATORS IN SWITZERLAND (NOT THE EXACT SAME INCINERATORS FOR EVERY PRODUCT) (ABC: ACID BINDING CAPACITY; DM: DRY MATTER; OC: ORGANIC CARBON; WSF: WATER SOLUBLE FRACTION). SOURCE: BUEHLER AND SCHLUMBERGER (2010).

Element	Fly ash		Concentrate		Filtrate after neutralization	
	Unit	Concentration	Unit	Concentration	Unit	Concentration
WSF	g/kg	260-300	g/L	8-12		
ABC			mol/kg	0.75		
OC			%	0.4-0.6		
Chlorine					g/kg DM	80-100
Cadmium		550-650		40-70		3'000-6'000
Chrome		270-300		240-280		30-70
Copper	mg/kg DM	1,200-1,350	mg/kg DM	1,030-2,560	mg/kg DM	200-1,000
Lead		15,000-18,000		5,000-12,000		7,000-36,000
Mercury		0.5-0.9		0.7-0.9		0.7-0.9
Nickel		80-90		50-70		20-80
Zinc		40,000-44,000		11,000-17,000		150,000-300,000

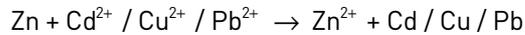
FLUWA produces a filtrate and, after wastewater treatment, hydroxide sludge, from which cadmium, copper, lead, and zinc are recovered in foreign zinc smelters. As a retrofitting of the FLUWA process, FLUREC is currently being implemented in one of these MSW incinerators (FLUREC: Flugaschenrecycling or fly ash recycling). There, the FLUWA filtrate is processed to three products: (i) pure zinc that is directly purchased by the domestic zinc processing industry, (ii) a cementate containing cadmium, copper, and lead as well as (iii) gypsum sludge. It is estimated that FLUWA/FLUREC could serve to substitute 25 to 30% of imports to Switzerland of zinc as raw material (Schlumberger, 2011).

Figure 2 details the process diagram of fly ash treatment through FLUWA and FLUREC. In FLUWA (Figure 2, left), a synergy is obtained between the high contents of heavy metals in fly ash and the acidity of flue gas treatment wastewater. Acid wastewater is the product of the scrubber located downstream from the dust filters to remove nitrogen oxide from the flue gas. Acidity increases as the wastewater is conducted through an ion exchanger to remove mercury. In a stirred-tank reactor located downstream from the ion exchangers, the heavy metals are extracted, i.e., dissolved. The heavy metal-rich liquid is then filtered on a vacuum band. The semisolid concentrate (see chemical analysis in Table 1) is disposed of together with bottom ash onto reactor landfills. In the second stage, the filtrate is neutralized with lime milk. The resulting, heavy metal-rich hydroxide sludge is exported to zinc smelters (see chemical analysis in Table 1), while the new filtrate is freed from remaining heavy metals through an ion exchanger and directly discharged into receiving water bodies. In the FLUREC process (Figure 2, right), instead of being directly neutralized with lime milk, the FLUWA filtrate undergoes a two-step treatment. First, zinc powder is added to the filtrate to precipitate cadmium, lead, and copper as cementate, as indicated in Equations 1 and 2. All three metal elements are then recovered in lead smelters.

EQUATION 1



EQUATION 2



Second, zinc is recovered as pure metal through solvent extraction involving three stages. In the first stage, extraction, zinc is transferred from the aqueous solution into the organic phase thanks to a selective complexing agent. The aqueous solution, free from heavy metals, is discharged into receiving water bodies after its neutralization with lime milk and the absorption of the remaining organic compounds from the organic phase through activated carbon filter. Lime sludge with a very low metal content is sent back to the furnace without influencing its performance. In the second stage, the wash stage, organic contaminants are eliminated to optimize the third stage: reextraction. Here, diluted acid, in the form of sulfuric acid, is added to regenerate the complexing agent for a new cycle, while zinc returns as cation to the aqueous solution. Finally, pure zinc (> 99.99%) is recovered by electrolysis. The FLUREC process thus allows only high-grade secondary raw materials to be produced out of fly ash. Economic profitability of the FLUREC process is achieved through marketing recovered metals, avoiding costs of neutralization of the filtrate entailed in the FLUWA process, and the possibility of treating ash from other facilities, which further reduces needs of lime milk (Schlumberger, 2010).

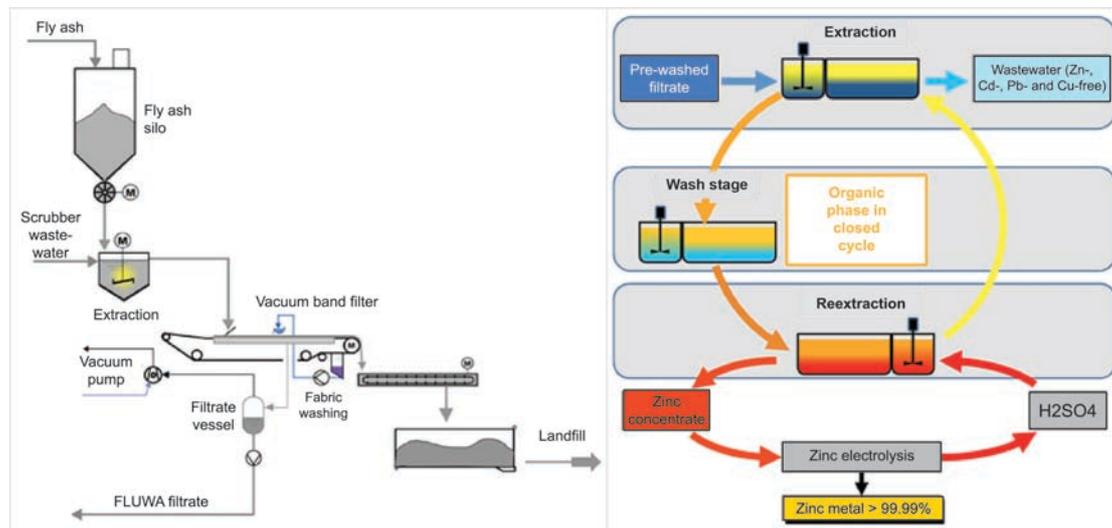


FIGURE 2 PROCESS DIAGRAM OF FLY ASH TREATMENT WITH FLUWA (LEFT) AND FLUREC (RIGHT). ADAPTED FROM: BUEHLER AND SCHLUMBERGER (2010), SCHLUMBERGER (2010).

5.3 METHODOLOGICAL PROCEDURE

The proposed methodological procedure to reduce the risk of problem shifting in the upcoming transition of Swiss MSW incineration consists of three stages of knowledge integration (cf. Figure 3). In the first stage, a prospective analysis is conducted to yield future, possible MSW management systems including disposal schemes (i.e., scenarios) derived from stakeholder and expert knowledge. In the second stage, an integrative assessment of the scenarios is performed referring to environmental and economic criteria. For this, a

model of waste management is set up which allows to account for direct and indirect impacts of waste management systems in Switzerland and abroad. By indirect impacts, we mean impacts that occur through the provision of goods or services needed by processes of MSW management. In the third and final stage, results from the two previous steps (i.e. prospective and integrative assessment) are communicated to stakeholders with the double aim of creating transparency regarding, e.g., underlying assumptions, and sampling stakeholders' views on the results. Stakeholder views should in turn help policy-makers of MSW management anticipate conflicts arising from new policies.

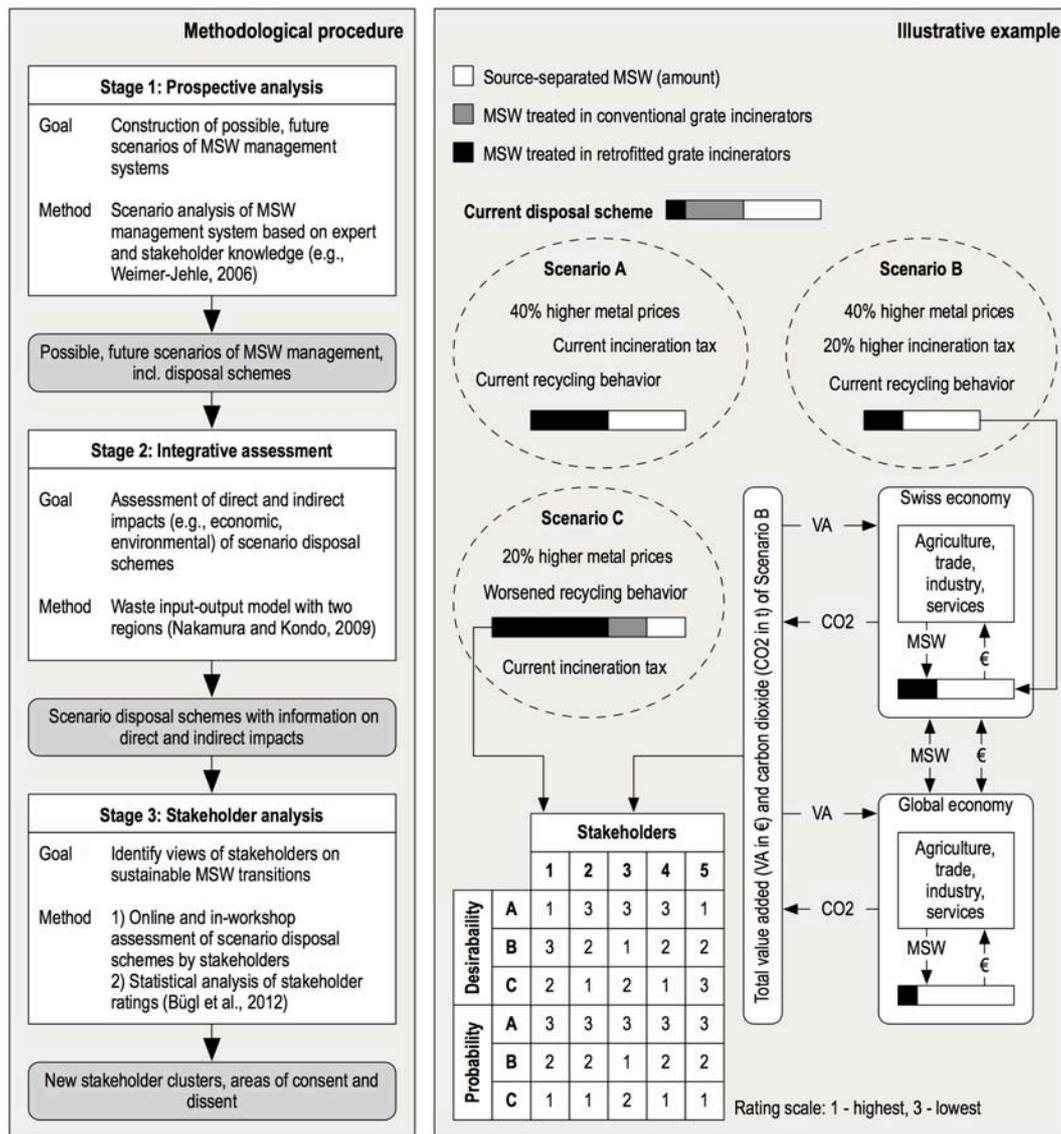


FIGURE 3 METHODOLOGICAL PROCEDURE FOR THE ASSESSMENT OF MSW MANAGEMENT TRANSITIONS AND AN ILLUSTRATIVE EXAMPLE FROM THE CASE OF GRATE INCINERATION RETROFITTING IN SWITZERLAND.

5.3.1 PROSPECTIVE ANALYSIS

Scenario analyses can fulfill different functions, one of them being the construction of possible, future states of a system through knowledge integration (Wiek, Binder, & Scholz, 2006). Methods of scenario analysis have in common the definition of a time horizon

(generally at least 10 years), impact variables (also referred to as descriptors) and their states (or levels) at the time horizon. A set of future states of all impact variables is one future state of a system or a scenario. The procedure for selecting scenarios based on their plausibility varies depending on the methods used. In formative scenario analysis (Scholz & Tietje, 2002), stakeholders and/or experts define impact variables and rate the consistency between two states of different variables. Stakeholders/experts defining the impact variables and future states are not necessarily the same (Spoerri, Lang, Binder, & Scholz, 2009). Scenarios are selected based on their consistency score, i.e., sum of pairwise consistency ratings in one scenario, and on further criteria, e.g., the distance between scenarios (Tietje, 2005). In cross-impact balance analysis (Weimer-Jehle, 2006), stakeholders/experts rate only mutual (positive or negative) influences of impact variables. The consistency of scenarios is defined at the level of individual impact variables as the matching of the state of a scenario and the state receiving the highest total influence. Scenarios are either consistent or inconsistent with respect to one impact variable, two impact variables, etc. A criterion to further select consistent scenarios is the size of their basin of attraction (see Weimer-Jehle, 2006, for more detail on this methodological step).

In a scenario analysis of Swiss MSW incineration, the impact variables consist of drivers of disposal schemes and the disposal schemes themselves. In the first variable category, one can find policies (e.g., incineration tax) besides economic (e.g., metal prices) and socio-cultural variables (e.g., recycling behavior). Disposal schemes consist of flows of waste (including composition) and secondary raw materials to different treatment technologies in Switzerland and abroad – from waste sorting to final treatment or supply of final products based on secondary raw materials – as well as the treatment technologies' efficacy with respect to various parameters (e.g., energy efficiency). The key result of the scenario analysis is a set of consistent (i.e., possible, future) scenarios of Swiss MSW incineration reflecting total burnable MSW quantities, the share of incinerators having implemented the retrofitting technologies by the target horizon, and the location and technology for the downstream refining of recovered metals.

5.3.2 INTEGRATIVE ASSESSMENT

5.3.2.1 GOAL AND SCOPE

The goal of the integrative assessment is to assess the economic and environmental performance of scenarios. This is accomplished by linking the possible, future disposal schemes with a model of waste management. Defining the following functional unit permits the scenario disposal schemes to be compared: disposal of the total scenario quantity of MSW and an amount of recovered energy and functionally-equivalent secondary raw materials per kilogram of MSW equal to that of the current waste management system. For instance, an increased MSW quantity combined with enhanced metal recovery in grate incinerators in the future results in higher total air emissions due to incineration but also in a higher amount of recovered metals per kilogram of MSW. The recovered metals displace metals of other production sources, e.g., of primary production. The environmental and economic implications of displacement are accounted for in the assessment by means of system expansion (ISO, 2006a, b).

5.3.2.2 INTERREGIONAL WASTE INPUT-OUTPUT MODEL

An Isard-type waste input-output model as a model of waste management is developed for two regions, i.e. Switzerland (*a*) and the rest of the world (*b*) (Nakamura & Kondo, 2009). The model is characterized by Equations 3, 4, and 5.

EQUATION 3

$$x^r = \begin{pmatrix} x_I^r \\ x_{II}^r \end{pmatrix} (r = a, b)$$

EQUATION 4

$$f^{rs} = \begin{pmatrix} f_I^{rs} \\ S^r W_f^{rs} \end{pmatrix} (r, s = a, b)$$

EQUATION 5

$$A^{rs} = \begin{pmatrix} A_{I,I}^{rs} & A_{I,II}^{rs} \\ S^r G_I^{rs} & S^r G_{II}^{rs} \end{pmatrix} (r, s = a, b)$$

The vector x^r refers to the total output of economic sectors (I) and waste quantities to waste management processes (II) in region r . The vector f^{rs} denotes the final demand of goods and services produced in region r and consumed in region s (f_I^{rs}) and the waste produced by the final demand treated by waste management processes in region r ($S^r W_f^{rs}$), as W_f^{rs} is the vector of waste types produced by the final demand in region s and treated in region r and S^r is the allocation matrix of waste types to waste management processes in region r . The matrix A^{rs} refers to the input coefficients of regional economies and waste management systems. The matrix $A_{I,I}^{rs}$ corresponds to the requirements purchased by economic sectors in region s from the sectors of region r , while $A_{I,II}^{rs}$ denotes the requirements purchased by waste management sectors in regions s from the economic sectors of region r . The matrix G_I^{rs} is the matrix of waste produced by economic sectors in region s and treated in region r . The matrix G_{II}^{rs} refers to waste produced by waste management processes in region s and treated in region r . Waste management processes are different from economic sectors in that emissions and products of the former (i.e., energy and/or secondary raw materials) are a function of waste inputs and technology. Total outputs are given by Equation 6 where I is the identity matrix.

EQUATION 6

$$\begin{pmatrix} x_1^a \\ x_{II}^a \\ x_1^b \\ x_{II}^b \end{pmatrix} = I - \begin{pmatrix} A_{1,I}^{aa} & A_{1,II}^{aa} & A_{1,I}^{ab} & A_{1,II}^{ab} \\ S^a G_1^{aa} & S^a G_{II}^{aa} & S^a G_1^{ab} & S^a G_{II}^{ab} \\ A_{1,I}^{ba} & A_{1,II}^{ba} & A_{1,I}^{bb} & A_{1,II}^{bb} \\ S^b G_1^{ba} & S^b G_{II}^{ba} & S^b G_1^{bb} & S^b G_{II}^{bb} \end{pmatrix}^{-1} \begin{pmatrix} f_1^{aa} + f_1^{ab} \\ S^a W_f^{aa} + S^a W_f^{ab} \\ f_1^{ba} + f_1^{bb} \\ S^b W_f^{ba} + S^b W_f^{bb} \end{pmatrix}$$

5.3.2.3 IMPACT ASSESSMENT

The inverse matrix on the right side of Equation 6 is commonly known as the Leontief-inverse matrix (Leontief, 1936), which we denote by L . By multiplying the total outputs with the environmental and economic intensities of economic sectors and waste management processes (e.g., CO₂ emissions to air R_{1,CO_2}^r and value added $E_{1,VA}^r$ per economic output/CO₂ emissions to air R_{II,CO_2}^r and value added $E_{II,VA}^r$ per amount of treated waste), one can calculate the total environmental and economic impacts for a given final demand or change in this final demand (e.g. r_{CO_2} and e_{VA}) [see Equation 7]. Moreover, different methods are readily available to aggregate environmental impacts to mid-point indicators or single scores (Frischknecht, Steiner, & Jungbluth, 2009; Goedkoop et al., 2009).

EQUATION 7

$$\begin{pmatrix} r_{CO_2} \\ e_{VA} \end{pmatrix} = \begin{pmatrix} R_{1,CO_2}^a & R_{II,CO_2}^a & R_{1,CO_2}^b & R_{II,CO_2}^b \\ E_{1,VA}^a & E_{II,VA}^a & E_{1,VA}^b & E_{II,VA}^b \end{pmatrix} L \begin{pmatrix} f_1^{aa} + f_1^{ab} \\ S^a W_f^{aa} + S^a W_f^{ab} \\ f_1^{ba} + f_1^{bb} \\ S^b W_f^{ba} + S^b W_f^{bb} \end{pmatrix}$$

5.3.2.4 DATA

The environmentally extended input-output table (EE-IOT) of Switzerland was compiled for the year 2005 (Jungbluth, Nathani, Stucki, & Leuenberger, 2011). In this table, imports are disaggregated into 65 goods and 15 services, while exports are aggregated into a single figure for each sector of the Swiss economy. Hence, the first step towards the Isard model is the breakdown of imports and exports to produce matrixes $A_{1,I}^{ab}$ and $A_{1,II}^{ba}$. The second step is the disaggregation of waste management processes from the economic sectors they originally belonged to in the Swiss EE-IOT as well as from the foreign economic sectors. This is done by using either existing data sets or primary data from the waste treatment plants themselves (e.g., Hinwil plant for dry discharge of bottom ash). Here, all matrixes $A_{1,II}^{rs}$ are concerned. An important question at this stage is: Which waste management processes should be disaggregated? The answer is: Every process that can assume different shares of waste to primary raw materials and, depending on this, can show either different input coefficients (e.g., energy requirements) or different environmental impacts. Hence, processes like metal smelting will also be disaggregated. In the third stage, data must be collected on waste production and allocation (G_1^{rs} , G_{II}^{rs} , S^r). Waste is to be characterized according to its origin (from which economic or waste management sectors?), quality (How

much copper does steel scrap from public tin can collections contain?), and treatment destination (Is the waste in question incinerated or prepared prior to recycling?). Quality permits the understanding of which recycling process can accept the secondary raw material and to what extent it is affected in terms of e.g., energy consumption.

5.3.3 STAKEHOLDER ANALYSIS

The goal of the stakeholder analysis is identifying diverging views of stakeholders (including policy-makers) on sustainable transitions of MSW incineration by use of the assessment results (cf. Sections 5.3.1 and 5.3.2). A prerequisite is the transparent communication of the assessment results to key stakeholders. By key stakeholders, we mean organizations (e.g., private companies, representative bodies of municipalities and cantons, lobbying groups) that alone have enough power to bear significant weight on a particular waste management system but are at the same time representative of the interests of a larger group of stakeholders. Next is the sampling of views of a wider group of stakeholders (including, e.g., waste management services of municipalities, cantonal EPAs, scrap traders) on the assessment results (Bügl, Stauffacher, Kriese, Lehmann Pollheimer, & Scholz, 2012). For instance, which scenarios are viewed as most desirable or probable by the different stakeholders? We propose a mixed methods approach to achieve these two tasks:

1. The selection of key stakeholders and validation through a project steering board.
2. Two-stage assessment of scenarios by the large group of stakeholders (including key stakeholders) by means of an online survey, i.e., scenarios (i) with and (ii) without economic and environmental impacts.
3. The presentation of the study (including assumptions) to key stakeholders in a dedicated workshop, the assessment of scenarios by key stakeholders, the identification of barriers, drivers, and needed instruments and other means to reach the best scenario (e.g., that scenario rated by a majority of key stakeholders as highly desirable).

The approach generates two kinds of insights that are useful for anticipating conflicts. First, a mapping of stakeholder views on sustainable transitions of MSW incineration allows for the identification of consent and dissent areas within and between stakeholder groups and potentially the creation of stakeholder clusters going beyond classical stakeholder grouping (e.g., clusters reflecting regions or sectors). Second, the double assessment of scenarios by key stakeholders helps to improve our understanding of the effects of a transparent presentation of a policy-support study and improve communication.

5.4 METHODOLOGICAL CONCLUSION

The main strengths of the methodological procedure are its explicitly prospective nature, the up-scaling approach allowing for the consideration of cross-boundary waste flows and regionalization of waste treatment, and the consideration of different assessment dimensions (e.g., environmental and economic criteria) and stakeholder views. However, several limitations are inherent to the methods of knowledge integration applied in each stage of the procedure, while others result from their combination. Here are some that we deem important and to which future research should be dedicated.

Results from the scenario analysis are sensitive to the judgments of stakeholders and experts (Weimer-Jehle, 2006). Depending on the case, there can be a large number of stakeholders necessitating a selection prior to knowledge integration, while expert and stakeholder judgments might vary diametrically. Moving to the stakeholder analysis, how do we judge whether an organization is a key stakeholder and should participate in the workshop? Avelino and Rotmans (2011) provide a framework (see also Avelino, 2009; Avelino & Rotmans, 2009) that allows, among others, powerful stakeholders in socio-technical sustainability transitions to be identified. What about the representativeness of interests? Is formal membership sufficient, e.g., municipalities as members of Swiss cities' and municipalities' associations?

The presented waste input-output model is conceived for two regions. Considering the sheer diversity of European energy systems in terms of production technology mixes, extending the model to more than two regions would help reduce the share of uncertainty in the assessment results arising from the waste input-output model. A regionalization within Switzerland itself might also make sense depending on the case. The interregional waste input-output model does not consider technological change in sectors providing future processes of MSW management with energy, ancillaries, and services. Coupling the scenarios of MSW management and more generic scenarios (Höjer et al., 2008), e.g., of energy production, could fill this gap and enhance the credibility of the integrative assessment results. In short, we need a small set of multi-regional input-output models reflecting different scenarios of economic and technological development as basis for societally robust assessment of MSW management systems.

ACKNOWLEDGEMENTS

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6 CONCLUDING REMARKS

In this thesis, I presented a methodological procedure for policy support of municipal solid waste management (MSW) integrating stakeholder perspectives and its application to two Swiss case studies. Relying on the integration of expert knowledge for scenario analysis, technical environmental-assessments, and the survey of stakeholder views, it can be assimilated to the first stage of transition management (TM): the generation of scenarios of an MSW management system, including their impacts, and what stakeholders and stakeholder groups think of them. To enhance the adequateness and societal robustness of the procedure, MSW management was conceptualized as a coupled human-environment system (HES), and the policy support was conducted in a genuinely transdisciplinary (TD) process, a HES-based TD process. The latter was steered by a committee composed of policy-makers, scientists, and stakeholders, the Consulting Committee of the cooperation project "Options Management for Sustainable Waste Management (Options-Management Nachhaltige Abfallwirtschaft, OMNA)." For instance, the OMNA Consulting Committee was responsible for selecting case studies.

I start these concluding remarks by summarizing the key findings of each methodological step for waste glass-packaging disposal. I then briefly present the procedural outcomes with respect to this case study, i.e., what came out of the TD process but was not reported in the previous chapters. Only then do I critically assess the methodological procedure. Here, I emphasize the need for a comprehensive evaluation of the TD process. Finally, I sketch possible next steps of TM of Swiss waste glass-packaging disposal and outline further research. The possible next steps will, of course, undergo discussion within and approval by the Consulting Committee.

6.1 SUMMARY OF KEY FINDINGS

6.1.1 SCENARIO ANALYSIS

Waste glass-packaging is one of the first MSW fractions to have been collected separately in Switzerland in the 1970s. The introduction of separate collection and cullet recycling is the result of economic interests of municipalities and the packaging industry as well as the mounting awareness of waste issues within Swiss public opinion and resulting pressure. Since as early as the 1970s, the state (both federal and cantonal) has enforced the diversion of waste glass-packaging from landfills and incinerators to recycling through legal prescriptions and institutions of environmental protection. One result was the increasing rates of waste glass-packaging collection. Simultaneously, beverage and food markets in Europe opened up and imports rapidly soared in Switzerland. The packaging industry closely followed with fewer and larger production facilities over the continent. Because of these developments, Switzerland no longer had the capacity to recycle its waste glass-packaging. Alternative solutions were exporting to neighboring countries (and corresponding recycling capacities) and downcycling to construction materials. With this move, collection costs, largely borne by the Swiss glass-packaging industry until then, increased and were soon transferred to municipalities. Eventually, the federal state introduced an anticipated disposal fee (ADF) on glass-packaging to compensate municipalities for their collection activities.

Another function of the ADF was the environmentally sound processing of collected waste glass-packaging, i.e., providing an economic incentive to reuse or recycle over downcycling through differentiated compensation rates. In 2009, one third of Swiss cullet was recycled in Switzerland, half was exported for recycling to neighboring countries, and the rest was downcycled to foam glass as insulation material in Switzerland.

Possible, future scenarios for the year 2020 were derived from the present system's characteristics as described above and alternative compensation rates of the ADF. The alternative ADF compensation rates were set based on a prioritization of different policy goals (e.g., environmental efficacy). Even though not compensating a disposal option is possible, no rate was set lower than 20% in order to simulate the current practice of the Swiss EPA. The scenario analysis revealed that the ADF has quite a limited impact on driving waste glass-packaging flows to desired processing options, i.e., reuse, recycling, and downcycling. On the one hand, what crucially affected the system in the past, e.g., foreign markets for cullet recycling and limited recycling capacity in Switzerland, will continue to do so in the foreseeable future. On the other hand, new factors, e.g., energy prices, might dramatically influence the system by obstructing recycling and promoting downcycling in Switzerland. Because the Swiss packaging market is stable and is expected to remain so in the foreseeable future by case experts, prices of competing packaging materials are not deemed crucial in upcoming transitions. The scenario analysis resulted in four different possible, future disposal schemes: the export of all Swiss cullet to neighboring countries with color optic sorting for all mixed cullet (some 30% of collected cullet) (S1), the downcycling of all green and mixed cullet to foam glass in Switzerland and the export of brown and white cullet (S2), inland recycling and downcycling to foam glass as insulation material in Switzerland as of 2009 in addition to downcycling to foam glass of green and mixed cullet, which was exported for recycling in 2009 (S3); and the export of all Swiss cullet to neighboring countries with some color optic sorting of mixed cullet (S4). In scenarios S1, S2, and S4, glass-packaging is no longer produced in Switzerland. In scenarios S1 and S4, foam glass is no longer produced in Switzerland. As a result of the limited influence of the ADF, pursuing a specific policy goal by setting corresponding compensation rates does not necessarily lead to a scenario in which this goal is achieved. For instance, depending on other factors, pursuing "disposal security" promotes export to neighboring countries (S1), a reinforcement of inland processing (performed by only two companies, S3), or downcycling to foam glass (S2). Neither of these scenarios corresponds to a diversified demand for Swiss cullet.

6.1.2 IMPACT ASSESSMENT

The difference in the direct and indirect impacts between the four possible future disposal schemes and the current state (2009) was assessed from the perspective of the Guidelines for Swiss Waste Management (FOEN, 1986). Environmental impacts (i.e., resource consumption and emissions) arise from the processing of Swiss waste glass-packaging to new products including from the supply chain of glass-packaging production. The substitution by glass-based products of alternative products providing functional equivalence allows reducing environmental impacts caused by these alternative products. Environmental impacts were aggregated to a single score according to the Ecological Scarcity Method 2006 (Frischknecht, Steiner, & Jungbluth, 2009). Environmental impacts in Switzerland and abroad were considered. The gross value added of an economic sector is equal to its total economic

output minus intermediary consumption. Gross value added is generated by the processing of Swiss waste glass-packaging to new products including by the supply chain of glass-packaging production. The substitution by glass-based products of alternative products providing functional equivalence causes losses of gross value added by these alternative products. Only gross value added in Switzerland was considered. The two assessment dimensions provide a metric of eco-efficiency. To enrich the comparison, two prototypic systems were assessed as well: the inland recycling of all Swiss cullet, except brown and white cullet exported in 2009 (S5), and the downcycling of all green and mixed cullet to sand substitute in Switzerland and the export of brown and white cullet (S6). In scenario S5, foam glass is no longer produced in Switzerland. In scenario S6, neither glass-packaging nor foam glass production takes place in Switzerland.

Disposal schemes in which more waste glass-packaging is processed in Switzerland either to new glass-packaging or to foam glass as insulation material (S2, S3, S5) perform better from an environmental point of view than the current state. Disposal schemes in which all cullet is exported (S1, S4) or all mixed and green cullet is downcycled to sand substitute (S6) perform worse. European glass-packaging production is on average much dirtier than its Swiss counterpart (i.e., different fuel mixes and emission filter technologies). Alternatives to foam glass, i.e., oil-based insulation systems produced in Switzerland and foam glass produced in Europe, show higher environmental impacts because of their fossil fuel consumption and fossil fuel and uranium-based power, respectively. Substituting foreign foam glass generates more environmental benefits than locally produced oil-based insulation systems. A slightly different pattern was observed for the economic impacts. Downcycling all green and mixed cullet to foam glass (S2) generates less value added than in the current state. Maintaining inland recycling is a necessary condition to achieve at least as much gross value added in Switzerland as in the current state. Hence, the ADF compensation rates should be designed with consideration of the location of waste glass processing (i.e., Switzerland vs. abroad) and substituted products (e.g., oil-based insulation system vs. foreign foam glass). In this way, the ADF will provide an economic incentive for the environmental soundness and economic profitability of Swiss waste glass-packaging disposal.

6.1.3 STAKEHOLDER ASSESSMENT

In the last step of the methodological procedure, the six scenarios were assessed by N=85 stakeholders from supply, demand, and institutions of Swiss waste glass-packaging disposal. Stakeholders rate differently the two scenarios performing better both from the environmental and economic points of view than the current system: scenarios S3 (Inland recycling and high grade downcycling) and S5 (Inland recycling). Scenario S3 is rated as more desirable, and its occurrence in 2020 is considered more probable than scenario S5. The lower desirability rating might come from the monopsony situation that scenario S5 would entail. Also, stakeholders seem to be aware of the highly competitive environment the only glass-packaging factory in Switzerland is facing, which would make such a growth unlikely. Additionally, stakeholders disagree on the desirability and probability of occurrence of scenario S5. Institutions consider the latter more desirable and more probable than supply and demand. Institutions, which are responsible for implementing environmental protection, seem to view scenario S5 as best suiting the concept of circular flow economy.

In a follow-up workshop, key stakeholders will meet to discuss the results of the three methodological steps. Focus will be laid on how the occurrence probability of scenarios

assessed as eco-efficient by means of LCA and rated as desirable by stakeholders can be increased.

6.1.4 THREE RECOMMENDATIONS

I derive three concrete recommendations for an eco-efficient Swiss waste glass-packaging disposal. First, specific socio-economic factors significantly affect Swiss waste glass-packaging disposal schemes. Monitoring these factors could help achieve goals of resource and waste policy by anticipating the effects of rising energy prices and varying cullet export prices on disposal options or schemes as a whole. Second, the ADF and its compensation rates are not a means to foster a diversified demand for waste glass-packaging. Other policy tools are needed for this purpose. Among the existing tools, legislation on cartels could provide the necessary legal basis to dismantle the oligopsony constituted by Vetropack and Misapor. The responsible institution for such an investigation is the Competition Commission (COMCO). However, there is a need for new policy tools, which reconcile an eco-efficient disposal scheme with fair cullet prices for Swiss municipalities. Third, the compensation rates should better reflect the actual alternatives to products of Swiss waste glass-packaging disposal. The rate for cullet recycling should reflect the mix of countries recycling Swiss cullet, as environmental standards vary from one country to another. The rate for downcycling to foam glass should reflect the mix of foam glass uses, as alternatives can show different economic and environmental characteristics. Because both mixes might change in the future, the corresponding rates should be updated on a regular basis.

6.2 PROCEDURAL OUTCOMES

A first significant outcome of the TD process is mutual learning within the OMNA Consulting Committee. On one hand, scientists of the OMNA Consulting Committee learned what motivates practice in investigating a case. Significant investments in and organizational commitment to large-scale trials of waste treatment technologies as in the case of incineration residues strongly impact research interests of practice. In other words, research questions can be “exciting” at one point in time for practice, but no longer be of relevance a couple of years later, although for scientists, they are still according to literature and their own understanding of practice. Considering investments and commitments can help clarify the research scope within a TD process. The research scope is indeed very much debated within the TD research community, as freedom of research possibly opposes the provision of societally relevant contributions (Scholz, 2011). More generally, stakeholders have different timeframes than researchers (Pohl & Hadorn, 2007). For instance, Vetroswiss, the organization responsible for collecting and redistributing the ADF, wished to advertise the OMNA case study in its yearly newsletter, although results were not available yet. Understanding research interests and timeframes of practice can help scientists to reflect on how to contribute meaningfully to societally relevant problems, from formulating appropriate research questions to deciding or not to enter a TD process. On the other hand, members of the Consulting Committee from practice gained insights into links between interesting research questions and the limited availability of methods and data. This indeed led to a joint refining of research questions.

Mutual learning also took place in the broader TD process, i.e., with decision-makers and stakeholders of Swiss waste glass-packaging disposal. Remember that consultants were involved in the TD process because they had in the past performed a life cycle assessment

(LCA) on Swiss waste glass-packaging disposal as a decision-base for the ADF rates. During the TD process, they acknowledged the benefits of combining scenario analysis with methods of life cycle thinking. Scaling up the functional unit to yearly waste quantities was considered particularly useful by LCA consultants to assess the environmental and economic effects of limited waste treatment capacities within a country. A dialogue was launched between scientists of the TD process and the LCA consultants to understand differences in results of the respective studies and communicate them to the Swiss environmental protection agency (EPA) and stakeholders in a sound manner. On the scientists' side, the repeated interaction with stakeholders (i.e., interviews for scenario analysis, data collection for impact assessment, stakeholder assessment of scenarios) allowed frontrunners to be identified in terms of their openness to change (Loorbach & Rotmans, 2010; Rotmans & Loorbach, 2009). Frontrunners could become instrumental in advancing a transition agenda and participating in transition experiments later on (see Section 6.4). More generally, knowledge about stakeholders acquired in the TD process could serve to define a transition arena responsible, e.g., of elaborating such an agenda. However, I expect the bulk of mutual learning in the broader TD process to take place in the upcoming Workshop on Waste Glass-Packaging (see Chapter 4).

6.3 CRITICAL ASSESSMENT OF THE METHODOLOGICAL PROCEDURE

The results of the methodological procedure constitute an extensive discussion base for the next steps of TM, i.e., setting an agenda to secure eco-efficient and desired scenarios and proposing experiments with alternative policies (see Section 6.4). The procedure allows policy-makers to go beyond generic visions as a base for planning (i.e., reuse vs. recycling vs. downcycling), which potentially mask stakeholder interests as potential barriers to transitions. Limiting the amount of concrete scenarios to a small set makes this possible in the first place. Unlike visions, scenarios can be characterized with respect to different performance criteria (e.g., environmental impacts, gross value added). The methodological procedure thus delivers societally robust orientations in the first phase of TM.

The methodological procedure combines the intrinsically prospective scope of scenario analysis with a static life cycle assessment. Concretely, possible, future combinations of disposal options are assessed from a life cycle perspective. The possible, future combinations result from internal dynamics and external constraints of Swiss waste glass-packaging disposal as elicited from case experts. The models and data used for the life cycle assessment are those of the last 15 years. Another prospective aspect of the methodological approach lies in the analysis of sensitivity of the scenario eco-efficiencies to alternative products of Swiss waste glass-packaging disposal. Such sensitivity analysis does not say whether Swiss glass-packaging (originally produced by Vetropack in Switzerland) would be replaced entirely by German glass-packaging or by a mix from different European factories. Nor does it indicate whether environmental standards of glass-packaging production will rise in Europe in a foreseeable future. However, it does say that such aspects are crucial for the eco-efficiency of the whole disposal system and provide the motivation for extending the scenario analysis to the alternative products of Swiss waste glass-packaging disposal. A scenario analysis extended on the basis of sensitivity analysis would lay the foundation for a system dynamics model (Scholz & Tietje, 2002), an alternative to the static life cycle assessment.

Besides the limitations of the three methods already discussed in the previous chapters, the methodological procedure introduced in this thesis introduces a new uncertainty dimension in addition to those of technical-environmental assessments performed in a consultancy setting. Let us remember that a subset of stakeholders was selected and interviewed for the scenario analysis (methodological step 1). The stakeholders interviewed in the first methodological step thus influenced the small set of possible future scenarios, which later underwent impact and stakeholder assessments. The selection was done in an informal way, upon the recommendation of members of the OMNA Consulting Committee or of interviewees themselves. Care was given to interview key stakeholders of supply, demand, and institutions. A retrospective look at the scenario analysis allows the selected stakeholders to be described as “loud” and/or “powerful,” i.e., those voicing complaints about the current policy to representatives of the Swiss EPA and those holding constitutive power in Swiss waste glass-packaging disposal, respectively. Constitutive power is the capacity of an actor to redistribute resources (e.g., financial, material) within a sociotechnical system (Avelino, 2009; Avelino & Rotmans, 2009, 2011). For the conducted scenario analysis, the main criteria for stakeholder selection should be system knowledge if one strives to reduce the uncertainty arising from the generation of a small set of scenarios to be later assessed. In other words, stakeholders’ involvement should be more functional (Krütli, Stauffacher, Flüeler, & Scholz, 2010; Reed et al., 2009). Of course, a remaining alternative to stakeholder interviews for scenario analysis is group brainstorming (Spoerri, Lang, Binder, & Scholz, 2009). Thereby, the process of exchange between stakeholders itself serves to create a comprehensive system representation.

A critical assessment of the methodological procedure should take place in the form of an ex-post evaluation of the corresponding TD process, yet this lies beyond the scope of this thesis. Walter, Helgenberger, Wiek, and Scholz (2007) proposed a framework to evaluate the effects of a TD process on society. They distinguish three types of measurable societal effects: outputs, impacts, and outcomes. First, stakeholders’ degree of involvement with immediate outputs of the TD process (e.g., consideration of EPA reports, participation in workshops) is measured. Here, the high completion rate of the online survey (see Chapter 4) hints at a high level of involvement. Second, impacts are “changes in knowledge, attitude, or behaviors (caused by their involvement)” (Walter et al., 2007, p. 328), e.g., network building, trust in others, understanding of others (e.g., of their interests), increasing system knowledge, all of which could take place in the upcoming Workshop on Waste Glass-Packaging (see Chapter 4). Third, outcomes are measured by identifying the decisions arising from or influenced by the TD process. Concretely, the transition agenda defined by and potential future transition experiments planned by the Swiss EPA and other stakeholders are among such decisions. I now give an outlook on the next stages of TM of Swiss waste glass-packaging disposal.

6.4 OUTLOOK ON TRANSITION MANAGEMENT OF SWISS WASTE GLASS-PACKAGING DISPOSAL

6.4.1 SETTING A TRANSITION AGENDA

An outcome of the upcoming Workshop on Waste Glass-Packaging (see Chapter 4) could be the constitution of a transition arena of stakeholders, defining in turn “content objectives, process objectives, and learning objectives” (Rotmans & Loorbach, 2009, p. 193), i.e., a

transition agenda. Ultimately, the transition agenda must serve the overarching long-term goal of securing eco-efficient and desirable scenarios of Swiss waste glass-packaging disposal.

The main content objectives are the maintenance of inland recycling (i.e., the only glass-packaging factory in Switzerland) and high-grade downcycling of Swiss cullet. A balanced cullet supply/demand relationship must be fostered as well to guarantee fair prices for collecting municipalities. Inland processing and a balanced cullet supply/demand relationship seem to be in opposition, so that experimentation in real-world settings is necessary (see Section 6.4.2). Concretely, innovations in policy, technology, etc. making inland processing (i.e., glass-packaging and foam glass production) more competitive while benefiting the cullet supply/demand relationship should be given protected space for further development (Geels & Schot, 2007). I see the emergence of a new relationship between policy-makers and other stakeholders on one side and an MSW management system on the other, that of system stewardship, as an overarching process objective (Chapin III et al., 2010). Stakeholders should go beyond their own interests in order to ensure that key eco-efficiency parameters of the system (e.g., maintaining inland processing) endure. For this, limited collaboration between potential competitors (e.g., scrap traders) might become necessary (Pohl, 2008). Finally, learning objectives for transition experiments should be defined. The results of experiments might lead to new options to secure the content objective or to revise the learning objectives (Rotmans, Kemp, & Van Asselt, 2001).

6.4.2 CONDUCTING TRANSITION EXPERIMENTS

Transition experiments involve learning about innovations in policy, technology, etc. in real-world settings. Van den Bosch (2010) distinguishes three learning mechanisms: deepening, broadening, and scaling-up. Deepening entails learning as much as possible about an innovation in a single context. Broadening refers to understanding how different contexts affect an innovation. Scaling-up consists of identifying barriers and drivers of an innovation breakthrough.

Besides transition experiments that have yet to be defined in an agenda, there is one experiment that might be of immediate interest to stakeholders of Swiss waste glass-packaging disposal. The color optic sorting of mixed cullet is on the rise in neighboring countries where brown and white glass-packaging materials are produced (e.g., Germany). It is not a regime technology since in Switzerland and elsewhere, color separate collection is dominant and has been fostered by MSW management policies. The purpose of a transition experiment on optic sorting should be to understand the effects of a policy favoring the optic sorting of mixed cullet on the system's key eco-efficiency parameters. In other words, one would seek to better understand the nature and implications of scaling up optic sorting.

6.5 FURTHER RESEARCH

A first line of future research concerns the Swiss national accounting matrix with environmental accounts (NAMEA, see Chapter 3 and Jungbluth, Nathani, Stucki, & Leuenberger, 2011). More economic sectors and public services related to MSW management could be disaggregated. The Swiss NAMEA could be broken down into regions or cantons. Gross value added could be broken down into subsidies, taxes, wages, etc. A Swiss NAMEA with higher economic and regional resolutions and detailed components of

gross value added would inform all three debates of Swiss MSW management described in the introduction of this thesis (Section 1.2.2). By definition, a NAMEA contains extensive information on monetary flows between the private sector and public services and between these economic players and the state (taxes). For instance, yearly amounts from ADFs or anticipated recycling contributions (ARCs) as components of the gross value added of a recycling sector in a particular region could easily be compared to revenues from this sector. Going beyond the direct costs of littering borne by municipalities and public transportation companies, one could investigate the economic costs and environmental benefits of options designed to reduce different MSW fractions' littering. Finally, the NAMEA is an ideal tool to monitor the effects of policies aiming at greening the Swiss economy as called for by the Green Party of Switzerland in its popular initiative.

A second line of future research concerns TD processes in which scientists produce knowledge resembling that previously delivered by consultants to the same policy-makers. This is the case of the TD process on Swiss waste glass-packaging disposal. The relevant knowledge entails LCA results. I believe that the dialogue between scientists of the TD process and LCA consultants described in Section 6.2 started too late. The lack of early exchange possibly entailed the risk of LCA losing credibility in the eyes of policy-makers and stakeholders due to different results. Research should be conducted on how providers of technical-environmental analyses and assessments (i.e., potential competitors) could exchange at an early stage to secure knowledge that is no longer contested between them. Only then would this knowledge, robust with respect to methods of technical-environmental analyses and assessments applied to a specific case, be brought into societally contested decision-making processes. The challenge is quite similar to that of originally competing private companies involved in the co-production of knowledge within a TD process (Pohl, 2008).

A final line of future research concerns the participatory aspects of the conducted research. The broader public was not included in the online survey (see Chapter 4). The main reason was the assumption that surveyed stakeholders should possess sufficient knowledge on such a complex system and show clear interests, e.g., economic interests. Integrating the perspectives of the broader public might bring further societal robustness in the form of e.g., the acceptance or not of higher ADFs ultimately borne by consumers to finance environmentally sound, yet expensive disposal schemes. Such research would focus on how to elicit the broader public's preferences on a specific MSW management scheme and integrate them with stakeholders' perspectives (e.g., desirability and probability ratings of supply, demand, and institutions of Swiss waste glass-packaging disposal). Combining visions (e.g., reuse, recycling, downcycling), their tangible consequences for the broader public (e.g., changes in ADF amounts, convenience of collection schemes), as well as broadly known and accepted indicators (e.g., CO₂ footprint, jobs) to elicit the broader public's preferences seems to be the first avenue worth testing.

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