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Abstract

Using a general equilibrium model with heterogeneous waste, this paper studies optimal waste policy when households have to exert separation effort to produce near-homogeneous waste streams suitable for recycling. Our model explicitly allows for changes in the composition (quality) of waste streams depending on how much effort households are willing to spend on separating different types of waste. Accordingly, we are able to generalize some earlier contributions to the waste management literature and demonstrate that with both mixing and effort included, a first-best optimum is feasible under reasonable conditions. In particular, we find that a (modified) deposit-refund system still provides the optimal incentives to guide recycling as well as legal disposal (landfilling) and illegal dumping. Both the number and level of taxes and subsidies needed to reach the first-best depend crucially on the socially optimal level of dumping as well as the socially optimal composition of the mix.

Key Words: Economics of Waste, Recycling, Deposit-Refund System,
General Equilibrium Theory

JEL Codes: H21, H23, Q53

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1 Introduction

Homogeneous waste streams are exceptional. Notably, household waste is heterogeneous and consists of a wide variety of waste streams such as paper, glass, organic waste, plastics, textiles, small chemical waste, etc. In order to recycle waste such as paper or glass, households are typically required to separate part of their waste into homogeneous streams and this is what governments in developed countries have typically tried to stimulate over the last couple of decades. The recycling programs introduced in many countries have been rather successful in the separation of different types of waste and by implication the reduction of its amount in the mixed waste stream. To illustrate, Figure 1 clearly shows the remarkable rise in recycled waste streams from municipal waste in the Netherlands since 1971: from less than 9% in 1971 to over 50% in 2002.[1] [INSERT FIGURE 1] In absolute terms, the amount of mixed waste peaked at an all-time high of 4,600 million tons in 1990 and decreased to a low of 3,432 million tons in 1995. This 'crowding-in' effect of several homogeneous waste streams is clearly demonstrated in Figure 2, which shows the development of the three major waste streams responsible for the rise in recycling volume in the Netherlands, i.e. paper, glass and organic waste. [INSERT FIGURE 2] Paper recycling rates have doubled since 1971, but in particular the introduction of glass recycling around 1980 and the separate collection of organic waste at the beginning of the 1990s have reduced the amount of waste in the trash bin.

However, separating waste into homogeneous streams requires a lot of effort that people are willing to expend only up to some level (Ackerman, 1997; Huhtala, 1999; Aadland and Caplan, 2003). Again, the Netherlands is illustrative here. As recycling is not subsidized, separation effort basically goes unpaid in this country. Nevertheless, the comprehensive recycling infrastructure for waste paper, glass and organic waste built by the Dutch government has contributed to the high recycling rates shown in Figure 2. However, rates for paper and organic waste have been decreasing slightly since 1997 (see AOO (2004)). For instance, the recycling rate for organic waste has dropped - on average - from 53.7% of all organic waste in 1997 to 49.6% in 2003. This is indicative of the fact that people are becoming less inclined to separate their waste stream at home. Moreover, this decline in recycling rates is masked by the fact that an increasing number of Dutch municipalities have introduced unit-based pricing systems to stimulate recycling since 1997. These municipalities, which make up 17% of the Dutch population, have seen recycling rates going up by 20 percentage points since (Dijkgraaf and Gradus, 2004). Supplementary evidence for the important role of effort in relation to the level of recycling from an entirely differ-

[1] Results of physical monitoring of the composition of mixed household waste in the Netherlands are available since 1971. However, in the early years, monitoring was done at five-year intervals. Since 1993, figures have been updated on a yearly basis (see AOO (2004)).

ent perspective is given by the study of Jenkins et al. (2003). They show that curbside recycling programs have a bigger effect on behavior than drop-off programs: the probability that the average household recycles over 95% increases by approximately 20% for a curbside program compared with a drop-off program.[2]

In this paper, we study household waste management in a world where households have to exert effort to separate specific waste streams from their overall mix of heterogeneous waste at home in the context of a general equilibrium model. In our model, the household decides whether to keep a given type of waste separate, and thus create a homogeneous waste stream, or to throw the same unit into the general waste bin, i.e. mix this unit with other types of waste. Thus our model recognizes that waste is heterogeneous in two dimensions: (i) waste of different types, such as paper and glass; (ii) waste of a given type (such as paper) that is either a *separate* homogeneous waste stream or part of a mixed basket of different types of waste streams, called 'the mix'. Only if a given waste stream is homogeneous can it also be used for recycling. Using this basic architecture of material waste flows in the economy, we study optimal waste policy when households have to exert separation effort to produce (near-)homogeneous waste streams suitable for recycling whereas mixing their waste at home is costless in terms of effort. In particular, we explore whether a deposit-refund system is still a first-best policy option for the government when the household may, apart from recycling, either legally or illegally dump its waste.

So far, the theoretical literature using general equilibrium analysis has not explicitly recognized the link between recycling of waste and the role of separation effort.[3] One part of the existing studies based on general equilibrium analysis has focused on the difference that illegal dumping would make to previous studies that did not recognize the option for households of getting rid of their waste by just dumping it illegally. In particular, Fullerton and Kinnaman (1995) started this line of research, showing that an important detrimental side-effect of any unit-based pricing system to address waste externalities is likely to be an increase in the amount of illicit burning. The solution they propose is a deposit-refund system: a tax on all output or consumption plus a rebate on proper disposal through recycling and proper disposal, such as landfilling, to prevent dumping.[4] Although they recognize the possibility of heterogeneous waste, the analysis is restricted to the first dimension mentioned in the previous paragraph. Indeed, homogeneous waste streams are available for recycling in their model without any cost of effort. Another important liter-

[2] This is consistent with the general picture emerging from Figure 2. In the Netherlands, recycled organic waste is collected by a curbside program, whereas bottles and paper are collected by a drop-off program.

[3] In practice, however, one of the more natural questions to ask is how much sorting to demand from households (Porter, 2002, p.167). Our results provide guidance on this question.

[4] The rebate on recycling is larger than the rebate on landfilling to reflect the external effect associated with landfilling.

ature has focused on green design and the explicit link between the decisions of firms to choose a given (material) composition of their products and the 'downstream' incentives for households to reduce their overall level of waste (Fullerton and Wu, 1998; Calcott and Walls, 2000; Eichner and Pethig, 2001 and 2003). These studies focus on optimizing the recyclability of products by changing their material composition or design. For instance, by taxing products in relation to their specific waste content, producers get an incentive to change the composition of their product. In contrast, our study focuses on the entirely different question of how to obtain homogeneous waste streams suitable for recycling when this requires effort from households and the recycling itself is not produced at home.

The role of effort in general equilibrium analysis of waste management has been studied in a seminal paper by Choe and Fraser (1999). Their model allows for - what they call - waste reduction effort by either firms in redesigning their products or households in reusing or composting their waste at home. They find that a first-best policy cannot be attained if waste reduction effort is significant, i.e. the effort for reducing waste is large. This increases the likelihood that households will dump their waste in the presence of a tax on landfilling or to stimulate recyclability. With significant waste reduction effort, the government should introduce an optimal fine policy as part of its optimal second-best policy in order to prevent dumping. The need for a fine arises because recycling is done at home in their model and hence (recycling) effort is unobservable. In our model, however, recycling is not done at home and hence (separation) effort can be observed through the volume of waste collected for recycling. This allows the government to reach the first-best once again without using the additional instrument of fining as part of its optimal recycling policy. Whether recycling should occur at home or not is another issue and depends on the costs and benefits of these options.

Thus the main feature of our model is that it explicitly allows for changes in the composition of waste streams depending on how much effort households are willing to spend on separating different types of waste. We endogenize what we call the mixing decision. By throwing waste into the trash bin, households avoid the trouble of keeping different types of waste separate. Hence, (avoiding) separation effort becomes an additional element in the trade-off between recycling on the one hand and landfilling (incineration) or dumping on the other hand.

Our basic findings are the following. Even though incentives to separate waste play an important role in the design of optimal waste policy in our model, they do not undermine the role of the deposit-refund system in guiding households' waste management as described by Fullerton and Kinnaman (1995). The optimal level of the deposit-refund scheme for the different types of waste still depends on the environmental cost structure of legal versus illegal dumping. The differences from earlier results are that the levels of the deposits and refunds now crucially depend on the level of *mixed dumping* in the social optimum and that the government may like to steer the composition of the mix in order to alleviate the detrimental effect of dumping. We consider two important cases. First, if mixed dumping for any imaginable composition is not considered to be socially optimal - for example, because the mix contains hazardous waste - the levels of the taxes and subsidies on all types of waste are determined by the externality associated with the most harmful type of waste.[5] Second, if (some) mixed dumping is socially optimal, the government's first-best policy rule follows the deposit-refund system where the rate of taxation is based on the volume-weighted average damage of the mix plus a 'composition tax'. The latter varies by the type of waste and is used by the government to change the composition of the mix towards a more environmentally friendly composition in order to reduce the impact of dumping the mix and thereby allow (some) dumping.

Our paper is organized as follows. In section 2, we introduce our general equilibrium model of household waste behavior allowing for a vector of consumption goods as well as effort. In section 3, we introduce the option of mixing waste streams. Accordingly, households are now allowed to avoid effort by throwing waste into the general waste bin and may choose from a menu of options that vary from separating all waste, at one extreme, to combining all streams in one mix, at the other. Next, section 4 discusses optimal policy in more detail, and section 5 discusses the limitations, extensions and policy implications of our approach.

2 A model of garbage characteristics without mixing

Modeling of household waste behavior is usually restricted to homogeneous garbage. This section illustrates how allowing for heterogeneity of garbage and separation effort affects solid waste behavior. The purpose of this section is not to break new ground, but to set up our (vector) notation and to generalize prior results to the world of heterogeneous garbage. We restrict the analysis to a single jurisdiction with n identical individuals or households. Each household buys a vector consumption good $\boldsymbol{c}$ with $\boldsymbol{c} \equiv (c_1, c_2, \ldots, c_N)'$.

We further assume that consumption of good c_i generates its own type of waste. The household separates waste, such as paper, glass and plastics, for reuse in production. We denote recycled waste by $\boldsymbol{r}$ with $\boldsymbol{r} \equiv (r_1, r_2, \ldots, r_N)'$. Alternative options are landfilling, $\boldsymbol{g}$, with $\boldsymbol{g} \equiv (g_1, g_2, \ldots, g_N)'$, and illegal dumping, $\boldsymbol{b}$, with $\boldsymbol{b} \equiv (b_1, b_2, \ldots, b_N)'$. In short,

[5] Fullerton and Wolverton (2000, p.241) also hint at this result when discussing potential generalizations of the deposit-refund system. They reason, in the context of firms producing multiple externalities, that 'the output tax has to be based on damages of the worst pollutant (and) the deposit would (then) be fully returned on all clean inputs and partially on other pollutants (at a rate equal to the difference in damages)'. In our case, both the output tax and all refunds are based on the damages of the worst pollutant.

the options for waste disposal can be described by the following 'mass balance' equation:[6]

$$\boldsymbol{c} = \boldsymbol{r} + \boldsymbol{g} + \boldsymbol{b} \tag{1}$$

Households derive utility from household consumption, $\boldsymbol{c}$, home production, h, the total amount of waste landfilled, G, and a vector of different types of waste disposed of illegally, $\boldsymbol{B}$. We assume that the physical effects of landfilled waste depend on its overall level but not on its composition, whereas these effects for illegal dumping depend on the type of waste dumped. The total amount of waste landfilled by a single household is given by $g = \boldsymbol{\iota g}$, were $\boldsymbol{\iota}$ is the vector of ones. Hence,

$$G = ng = n\boldsymbol{\iota g} \tag{2}$$

$$\boldsymbol{B} = n\boldsymbol{b} \tag{3}$$

Note that in this economy, households keep all waste separate before disposal, i.e. households do not have the option to mix waste. Keeping waste separate, however, is costly in terms of effort.[7] We model the effort of keeping waste separate as

$$\boldsymbol{e} = \boldsymbol{r} + \boldsymbol{g} + \boldsymbol{b} \tag{4}$$

Accordingly, the utility function reads

$$U = U[\boldsymbol{c}, h, \boldsymbol{e}, G, \boldsymbol{B}] \tag{5}$$

The social cost from dumping waste may differ according to the type of waste. For instance, the effect of dumping batteries is much more severe than the effect of dumping organic waste. We assume $U_{\boldsymbol{c}}, U_h > 0$, $U_{\boldsymbol{e}}, U_G, U_{\boldsymbol{B}} < 0$ and $U_{Bi} \leq U_G$. Garbage at the landfill causes negative utility due to aesthetic and health costs, but usually less so than illegal

[6] We restrict analysis to the 'mass balance' case for reasons that will become clear later (see section 3). Moreover, none of our results is changed in any fundamental respect by assuming a more general consumption-waste technology. Note furthermore that our vector notation allows for differences in quality of apparently 'homogeneous' waste streams such as glass or paper.

[7] Including effort at this stage in the model may look 'artificial' because households do not have the option of avoiding effort by mixing waste. We already include effort here for two reasons: (i) to illustrate a number of findings in the literature that only allow for separate waste streams; (ii) as a benchmark for the model in the next section which includes mixing.

dumping *for any levels of illegal dumping and landfilling.* Finally, we make the convention that $U_{B1} \leq U_{B2} \leq \ldots \leq U_{BN}$: more hazardous wastes have a lower index. Note that good h is produced and consumed at home.

Production is fairly straightforward. We assume output produced according to a constant-returns-to-scale production function

$$\boldsymbol{c} = F(\boldsymbol{k_c}, \boldsymbol{r}) \equiv (f_1(k_{c1}, r_1), f_2(k_{c2}, r_2), \ldots, f_N(k_{cN}, r_N))' \tag{6}$$

with input of resources $\boldsymbol{k_c}$=(k_{c1},k_{c2},...,k_{cN}) and recycled materials $\boldsymbol{r}$ from used consumption goods. We ignore peculiarities of the recycling process itself and simply assume that reuse is costless and smooth.[8] For simplicity, we assume that the production of consumption good i requires its own technology and only uses its 'own' recycled material, or $c_i = f_i(k_{ci}, r_i)$. We assume that $f_{kci} > 0$.

Garbage collection and processing at the landfill requires one input and uses a constant-returns-to-scale production function which is identical for each type of garbage. Household production uses resources k_h.

$$g_i = \gamma k_{gi} \Leftrightarrow \boldsymbol{g} = \gamma \boldsymbol{k_g}, \; h = k_h \tag{7}$$

Like Fullerton and Kinnaman (1995), we include an illegal dumping technology. In our case, this technology reads

$$\boldsymbol{k_b} = \boldsymbol{\Theta}(\boldsymbol{b}) \equiv (\theta_1(b_1), \theta_2(b_2), \ldots, \theta_N(b_N)) \tag{8}$$

with $\boldsymbol{\Theta_b} > 0$ and $\boldsymbol{\Theta_{bb}} > 0$. This captures positive and rising marginal costs of dumping waste. Note that the costs of illegal dumping may differ between types of waste. It is, for instance, more cumbersome to dump organic waste than paper. Finally, the model is closed by the resource constraint

$$k = k_h + \boldsymbol{\iota k_c} + \boldsymbol{\iota k_b} + \boldsymbol{\iota k_g} \tag{9}$$

where k is a fixed total resource such as capital or labor.

[8] Our focus is on the mixing behavior of households and not on firms' ability to change the material composition of given products as studied in the green design literature. See Fullerton and Wu (1998) and Eichner and Pethig (2001).

The social planner's problem is to maximize the utility of the representative household subject to the resource and production constraints. Most of the constraints except Eq. (6) can be substituted directly, to maximize

$$\begin{aligned}\mathcal{L} =& U[\boldsymbol{r}+\boldsymbol{g}+\boldsymbol{b}, k-\boldsymbol{\iota k_c}-\boldsymbol{\iota g}/\gamma-\boldsymbol{\iota}\boldsymbol{\Theta}(\boldsymbol{b}), \boldsymbol{r}+\boldsymbol{g}+\boldsymbol{b}, n\boldsymbol{\iota g}, n\boldsymbol{b}] \\ &+\boldsymbol{\delta}[F(\boldsymbol{k_c},\boldsymbol{r})-\boldsymbol{r}-\boldsymbol{g}-\boldsymbol{b}]\end{aligned} \tag{10}$$

with respect to $\boldsymbol{r}$, $\boldsymbol{g}$, $\boldsymbol{k_c}$ and $\boldsymbol{b}$.[9] Note that this optimization recognizes that every individual imposes costs on others through landfilling and illegal dumping.

The first-order conditions are

$$U_{ci}+U_{ei} = \delta_i(1-f_{ri}),\ i=1,\dots,N \tag{11a}$$

$$U_{ci}+U_{ei}-U_h/\gamma+nU_G = \delta_i \quad ,\ i=1,\dots,N \tag{11b}$$

$$U_h = \delta_i f_{kci} \quad ,\ i=1,\dots,N \tag{11c}$$

$$U_{ci}+U_{ei}-U_h\theta_{bi}+nU_{Bi} = \delta_i \quad ,\ i=1,\dots,N \tag{11d}$$

We assume second-order conditions hold, solutions are internal and a unique solution exists. Note that effort now enters marginal cost for all disposal options and plays a role in equating marginal social benefits and costs for any additional $\boldsymbol{r}$, $\boldsymbol{g}$ and $\boldsymbol{b}$. However, its role is very limited and only reduces the level of utility from consumption compared with a model without effort.

For the case of private markets, producers of consumption goods receive a unit price for selling $\boldsymbol{c}$ and receive the price paid by consumers, $\boldsymbol{p_r}$, for recycling good $\boldsymbol{r}$ which can be positive or negative. They maximize profits $\boldsymbol{c}+\boldsymbol{p_r r}-p_k\boldsymbol{\iota k_c}$ under perfect competition with constant returns to scale. Hence, $p_k = f_{kci}$ and $p_{ri} = -f_{ri}$ for $i=1,\dots,N$. Producers of landfilling services maximize $\boldsymbol{p_g g}-p_k\boldsymbol{\iota k_g}$, so $p_{gi} = p_k/\gamma$ for $i=1,\dots,N$. Households maximize utility in Eq. (5) subject to (1), (4) and the budget constraint

$$p_k(k-h) = (\boldsymbol{1}+\boldsymbol{t_c})\boldsymbol{c}+(\boldsymbol{p_r}+\boldsymbol{t_r})\boldsymbol{r}+(\boldsymbol{p_g}+\boldsymbol{t_g})\boldsymbol{g}+p_k\boldsymbol{\iota}\boldsymbol{\Theta}(\boldsymbol{b}) \tag{12}$$

where p_k is the price earned on resources, the price of consumption is equal to 1 since $\boldsymbol{c}$ is the numeraire, $\boldsymbol{p_r}$ is the price paid by the consumer for recycling, $\boldsymbol{p_g}$ is the price paid

[9]We closely follow the model structure of Fullerton and Kinnaman (1995) for ease of comparison, although our model does not include virgin material.

for garbage collection, and $\boldsymbol{t_c}$, $\boldsymbol{t_r}$ and $\boldsymbol{t_g}$ are the per-unit tax on respectively consumption, recycling and landfilling. Finally, note that the cost of illegal dumping is included and is assumed to be untaxable.

The first-order conditions are:

$$U_{ci} + U_{ei} = \lambda(1 + t_{ci} - f_{ri} + t_{ri}) \quad , \; i = 1, \ldots, N \tag{13a}$$

$$U_{ci} + U_{ei} = \lambda(1 + t_{ci} + f_{kci}/\gamma + t_{gi}), \; i = 1, \ldots, N \tag{13b}$$

$$U_h = \lambda f_{kci} \quad , \; i = 1, \ldots, N \tag{13c}$$

$$U_{ci} + U_{ei} = \lambda(1 + t_{ci} + f_{kci}\theta_{bi}) \quad , \; i = 1, \ldots, N \tag{13d}$$

where we have replaced the prices (p_k, p_{gi} and p_{ri}) with the marginal products (f_{kci}, f_{kci}/γ and $-f_{ri}$) and where λ is the marginal utility of income. These first-order conditions demonstrate the matching of private marginal utility (net of effort) with the cost of each activity. With all tax rates equal to zero, it is clear that no matching exists for the external cost of both landfilling, nU_G, and illegal dumping, nU_{Bi}, in equations (11b) and (11d) respectively.

It is easy to see that this model produces a deposit-refund system for each separate waste stream as the first-best optimal tax system. From (13c) and (11c), we have $\delta_i = \lambda$. Then using $\delta_i = \lambda$, we find the following set of optimizing tax rates:

$$t^*_{ci} = -nU_{Bi}/\lambda \quad , \; i = 1, \ldots, N \tag{14a}$$

$$t^*_{ri} = nU_{Bi}/\lambda \quad , \; i = 1, \ldots, N \tag{14b}$$

$$t^*_{gi} = n(U_{Bi} - U_G)/\lambda, \; i = 1, \ldots, N \tag{14c}$$

With these Pigouvian rates, private behavior in equations (13a-13d) matches the social optimum in equations (11a-11d). If there is no illegal dumping of separate waste streams, a simple first-best solution exist with taxes $t_{ci} = t_{ri} = 0$, which follows from using $\delta_i = \lambda$ and comparing (13a) and (11a).[10] Using $t_{ci} = 0$, we still need a $t_{gi} = -nU_G/\lambda$ on landfilled waste in order to compensate for the externality associated with landfilling. This Pigouvian tax is obviously > 0 since $U_G < 0$. The larger the externality and the number of people affected, the higher its rate. Note also that the introduction of disutility of effort has no effect on the level of the optimal rates at all.

[10] As noted by Fullerton and Kinnaman (1995), this is just one solution out of an infinite number of solutions. The only requirement is that the *net tax is zero.*

With illegal dumping the government lacks a tax base that could be used as an instrument to attain the optimal social composition of waste disposal. Interestingly, a deposit-refund system also induces optimal behavior by collecting $t_{ci} = -nU_{Bi}/\lambda$ on each purchase and rebating the corresponding amount upon proper disposal of that item, i.e. through either recycling or landfilling (net of its external effects). This follows from comparing (13a) and (11a) to find $t_{ri} = nU_{Bi}/\lambda$. Furthermore, we find $t_{gi} = n(U_{Bi} - U_G)/\lambda$ from comparing (13b) and (11b). Thus the tax on consumption is fully returned when waste is recycled and partially returned - i.e. after being corrected for the environmental externality - when it is landfilled. This result is similar to the result obtained by Fullerton and Kinnaman (1995) for their case of 'disaggregated goods and services'.

At this point, it is also useful to compare our model with the results obtained by Choe and Fraser (1999), who were the first to introduce effort explicitly in a general equilibrium context. They point out that a simple Pigouvian policy that uses a tax on waste collection would be suboptimal if effort by households to reduce waste through reuse or composting were significant. In their model, this tax would be necessary to induce waste reduction by households (and firms). However, households now also have an incentive to dump this waste illegally in order to avoid paying this tax. Thus the government lacks an instrument to steer both waste reduction and illegal waste disposal at the same time and a first-best optimum would no longer be attainable (see also Choe and Fraser (2001)). As a result, the government has to rely on the additional instrument of monitoring and fining to reach a second-best optimum. Interestingly, in our case, the effort involved in separating waste has no such effect.

This can be easily understood. Recycling in our model is fully observable and waste reduction through reuse is part of the formal economy.[11] By dropping the subsidy on recycling, $\boldsymbol{t_r}$, our model captures the result by Choe and Fraser (1999): if the government lacks an instrument to steer recycling explicitly, introducing effort destroys the benevolent effect of the deposit-refund system also in our model. This has been observed before by Shinkuma (2003) as well, who also demonstrated that the first-best can be achieved even if households have to exert significant effort. Nevertheless, one would expect effort to play a role in guiding optimal waste policy here because separation effort might become prohibitive if households are required to separate a large part of their waste. This, however, cannot be studied in the current framework and requires the additional possibility that the same type of waste could be either part of a homogeneous waste stream and part of a waste stream that consists of several different types of waste or what we call 'the mix'. The next section introduces this possibility explicitly in our model.

[11] Although unobservability of recycled waste at home may be a useful description of behavior up to some point, we think that our description fits reality better at least for densely populated areas. As is clear from our Figures 1 and 2, the volume of recycled waste in the formal economy is substantial and observable.

3 Sorting and mixing

In this section, we allow households to keep waste streams separate or to mix different types of waste. As noted in the introduction, waste such as glass or organic waste may either be separated (for recycling purposes) or be thrown away into the general waste bin. Accordingly, households typically face two interlinked decisions. The first decision is whether or not to put waste in the general waste box. By throwing their waste into one general waste bin, they save on effort because separating waste streams is costly. The second decision is about the actual disposal of the waste, through recycling, landfilling or dumping. Obviously, waste in the general waste bin, or mixed waste, is much more difficult to recycle because recycling requires separation.[12] In order to account for these alternative ways of disposing of waste, we introduce five modifications to the model described in the previous section. First, the mass balance equation is altered to allow for mixing:

$$\boldsymbol{c} = \boldsymbol{r} + \boldsymbol{g} + \boldsymbol{b} + \boldsymbol{m} \tag{1'}$$

where $\boldsymbol{m}$ with $\boldsymbol{m} \equiv (m_1, m_2, \ldots, m_N)$ denotes the composition of the waste in the general waste bin (the mix).

Second, mixed waste can be either landfilled or dumped. The total amount of mixed waste is given by $\boldsymbol{\iota m}$. The fraction of the mix that is dumped is given by α. Hence, the amount of waste that is dumped from the general waste bin (labelled mixed dumping) is equal to $b_0 = \alpha\boldsymbol{\iota m}$, whereas the amount of mixed landfilling is given by $g_0 = (1-\alpha)\boldsymbol{\iota m}$.[13] The total amount of waste landfilled is

$$G = n\boldsymbol{\iota g} + ng_0 = n\boldsymbol{\iota g} + n(1-\alpha)\boldsymbol{\iota m} \tag{2'}$$

Note that the external effect of mixed landfilling is determined only by the total amount landfilled - that is, G - and does not depend on the type of waste that is landfilled. Due to the asymmetry in information about the type of waste brought to the landfill, modern landfills are ignorant of the types of waste included and therefore introduce measures against leaking for the (mixed) waste stream as a whole. Similarly,

[12] For simplicity, we assume that recycling of mixed waste is not possible. One might also consider a cost-benefit analysis comparing savings on recycling effort by households using mixed waste for ex post recycling on the one hand and the loss in quality and productivity of this type of waste on the other hand.

[13] A subscript of zero denotes mixed streams of waste; subscripts larger than zero denote homogeneous (separate) streams of waste. Thus m_i is the amount of waste i thrown into the general waste bin, $\boldsymbol{m}$ represents the composition of (mixed) waste in the general waste bin and $\boldsymbol{\iota m}$ is the total amount of mixed waste (the mix).

$$\boldsymbol{B} = n\boldsymbol{b} + n\alpha\boldsymbol{m} \tag{3'}$$

The external effect of dumping is - in contrast to the external effect of landfilling - not determined by the total amount dumped, but by the separate amounts dumped of each (type of) waste.[14] Note that the external effect does not depend on the type of dumping (mixed or separate), i.e. there are no interaction effects ('cocktails'). Third, the mixed landfilling technology is similar to the technology for separate landfilling:

$$g_0 = \gamma k_{g0} \tag{15}$$

Dumping mixed garbage uses resources according to

$$k_{b0} = \theta_0(\alpha\boldsymbol{m})^{15} \tag{16}$$

Fourth, the resource constraint now includes resources used for mixed landfilling and mixed dumping:

$$k = k_h + \boldsymbol{\iota k_c} + \boldsymbol{\iota k_g} + k_{g0} + \boldsymbol{\iota k_b} + k_{b0} \tag{9'}$$

Note that nothing changes because of mixing on the production side.

The social planner's problem is again to maximize the utility of the representative household, Eq. (5), but now subject to the constraints (1′), (2′), (3′), (4), (6), (7), (9′), (15) and (16) with respect to the same instrument variables as in the previous section, $\boldsymbol{r}, \boldsymbol{g}, \boldsymbol{b}$ and $\boldsymbol{k_c}$, and the two additional variables $\boldsymbol{m}$ and α.

The Lagrangian (10) is replaced by a version that explicitly accounts for the effect of mixing on consumption and home production as well as for the external effects of mixed landfilling or mixed dumping, and now reads

$$\begin{aligned}\mathcal{L} =& U[\boldsymbol{r} + \boldsymbol{g} + \boldsymbol{b} + \boldsymbol{m}, k - \boldsymbol{\iota k_c} - \boldsymbol{\iota g}/\gamma - \boldsymbol{\iota \Theta}(\boldsymbol{b}) - (1-\alpha)\boldsymbol{\iota m}/\gamma - \theta_0(\alpha\boldsymbol{m}),\\ &\quad \boldsymbol{r} + \boldsymbol{g} + \boldsymbol{b}, n\boldsymbol{\iota g} + n(1-\alpha)\boldsymbol{\iota m}, n\boldsymbol{b} + n\alpha\boldsymbol{m}]\\ &+ \boldsymbol{\delta}[F(\boldsymbol{k_c}, \boldsymbol{r}) - \boldsymbol{r} - \boldsymbol{g} - \boldsymbol{b} - \boldsymbol{m}].\end{aligned} \tag{10'}$$

[14] This explains the absence of $\boldsymbol{\iota}$ in (3′) compared to (2′).

[15] This includes the special case in which the resources needed to dump mixed garbage would depend only on on the total amount of mixed waste that is dumped and not on the composition of the mix, i.e. $k_{b0} = \theta_0(\alpha\boldsymbol{\iota m})$.

Differentiation of the above Lagrangian yields, in addition to the first-order conditions equations (11a-11d), where the equality signs of (11b) and (11d) are replaced by inequality signs, the following extra first-order conditions:

$$U_{ci} - U_h((1-\alpha)/\gamma + \theta_{0i}\alpha) + nU_G(1-\alpha) + nU_{Bi}\alpha = \delta_i,\ i = 1, \dots, N \tag{11e}$$

$$\alpha \geq 0,\ U_h(\boldsymbol{\iota m}/\gamma - \boldsymbol{m}\nabla\boldsymbol{\theta_0}) - n\boldsymbol{\iota m}U_G + n\boldsymbol{m}\nabla U_{\boldsymbol{B}} \leq 0,\ \text{C.S.} \tag{11f}$$

The additional first-order conditions evaluate the marginal costs and benefits of mixing an additional unit of waste (Eq. (11e)) and of slightly enlarging the fraction of mixed waste that is dumped (see Eq. (11f)). In particular, the first additional condition guides the social planner as to how to weigh the utility of consumption because of mixing an additional unit of waste against an increase in the resources necessary for waste disposal and the external costs of mixed landfilling and dumping. Obviously, effort plays no role because mixing does not require separation. Indeed, both recycling and separate landfilling and dumping require (separation) effort and now become relatively expensive from the social perspective. If the waste is mixed, however, recycling is no longer an option and resources have to be spent to get rid of it through either mixed landfilling or dumping. The second additional equation (11f) guides the choice as to how much of the available mixed waste should be dumped (the fraction α). Clearly, a larger fraction of mixed waste being dumped saves the resources necessary for landfilling the same amount of waste, but also requires more resources for dumping. The overall balance also depends on the balance between the environmental externalities of landfilling that are saved and the additional externalities due to dumping. Note also that the overall effect may differ between types of waste as pollution profiles of waste categories typically tend to differ.

Before exploring optimal waste policy by the government, we state and prove three useful lemmas. The first establishes that when recycling is productive, in the sense that the marginal product, f_{ri}, of at least one type of waste is larger than zero, recycling dominates both separated landfilling and separated dumping as disposal options.

Lemma 1 *When recycling of type i waste is productive in the sense that $f_{ri} > 0$, separated waste of type i is neither dumped nor landfilled in equilibrium.*

Proof. The proof follows directly from the first-order conditions. Consider separated dumping first. Substituting (11a) into (11d), we get from our assumptions on the derivatives of the utility function, private costs of dumping and $f_{ri} > 0$ that $-\delta_i f_{ri} - U_h\theta_{Bi} + nU_{Bi} < 0$. The proof for separated landfilling is similar. □

The intuition is that with productive recycling, waste produces resources when it is recycled, whereas it consumes resources when it is landfilled or dumped. Note that the case where $\boldsymbol{r} = 0$ does not add anything interesting to our problem, because in that case all waste will be mixed.[16] Therefore we will assume subsequently that $\boldsymbol{r} > 0$.

The second lemma discusses the role of economies of scope in the landfilling and dumping technology. This lemma shows that in the absence of economies of scope in mixing waste, it is not optimal to have both landfilling and dumping of mixed waste.

Lemma 2 *If* $\theta_0(\alpha \boldsymbol{m}) = \boldsymbol{\iota\Theta}(\alpha \boldsymbol{m})$, *then* $\boldsymbol{b}^* \boldsymbol{g}^* = 0$.

Proof. The proof follows by contradiction. Observe that in the absence of economies of scope, we have $\theta_{0i} = \theta_{bi}$. Substituting this into (11e), we see immediately that equations (11d), (11b) and (11e) cannot hold simultaneously with equality. □

This is intuitive as mixing waste is a policy that can be interpreted as a linear combination of separate landfilling and separate dumping without the need to spend effort on separation. In the absence of economies of scope, the combination of separated landfilling and separated dumping is then dominated by mixing. In a world without separate dumping ($\boldsymbol{b} = 0$), this lemma reduces to the case that $\boldsymbol{g}^* = 0$ always holds in the absence of economies of scope.

The third lemma establishes that when mixed dumping is not an optimal policy, separate landfilling is not an optimal policy either.

Lemma 3 *If* $\alpha^* = 0$, *then* $\boldsymbol{g}^* = 0$.

Proof. The proof follows directly from the first-order conditions. Substituting $\alpha^* = 0$ into (11e), we get $\forall i : U_{ci} - U_h/\gamma + nU_G = \delta_i$. From this, it follows by substitution that (11b) must hold with strict inequality. Hence, $\boldsymbol{g}^* = 0$. □

The intuition is that whenever mixed dumping is not optimal, mixing becomes identical to (mixed) landfilling. Since, compared to separate landfilling, mixed landfilling saves on effort, separate landfilling cannot occur in any equilibrium without mixed dumping.

4 Modified deposit-refund systems

This section explores whether the deposit-refund system survives in a world where households can mix their waste and avoid separation effort. Note, first of all, that for the case of private markets, nothing changes on the production side. Households, however, maximize

[16] This requires $f_i(k_{ci}, c) > 0$, which is indeed satisfied.

utility in Eq. (5) subject to (4), $g_0 = (1-\alpha)\boldsymbol{\iota m}$, the modified mass balance equation (1′) and the modified budget constraint

$$p_k(k-h) = (\mathbf{1}+\boldsymbol{t_c})\boldsymbol{c}+(\boldsymbol{p_r}+\boldsymbol{t_r})\boldsymbol{r}+(\boldsymbol{p_g}+\boldsymbol{t_g})\boldsymbol{g}+(p_{g0}+t_{g0})g_0+p_k\boldsymbol{\iota\Theta}(\boldsymbol{b})+p_k\theta_0(\alpha\boldsymbol{m}) \quad (12')$$

Note that the asymmetry in tax instruments available to the government because of dumping now extends to the mixed categories of waste as well: the government may use a tax on mixed landfilling, t_{g0}, but has no direct instrument to control the level of mixed dumping. In addition to the set of first-order conditions (13a-d) with inequality signs (≤ 0) instead of the equality signs of (13d) and (13b), we now have the following extra first-order conditions:

$$U_{ci} = \lambda(1 + t_{ci} + (1-\alpha)f_{kci}/\gamma + \alpha f_{kci}\theta_{0i} + t_{g0}(1-\alpha)),\ i = 1,\ldots,N \quad (13e)$$

$$\alpha \geq 0,\ \lambda(f_{kci}/\gamma + t_{g0})\boldsymbol{\iota m} - \lambda f_{kci}\boldsymbol{m}\nabla\boldsymbol{\theta_0} \leq 0,\ \text{C.S.} \quad (13f)$$

where the price p_{g0} is replaced with its marginal product f_{kci}/γ. We are now in the position to discuss different policy options that can attain the first-best allocation of resources. Equations (13a-f) are the Kuhn-Tucker conditions for the household problem. Notice that the optimal solution to (13a-f) may be a corner solution. However, not each of these solutions is equally interesting or viable. In order to reduce the number of cases, we assume that we have interior solutions for household production, $h^* > 0$, and recycling, $\boldsymbol{r^*} > 0$.[17] However, we explicitly consider corner solutions for landfilling, $\boldsymbol{g^*}$, and illegal dumping, α^* and $\boldsymbol{b^*}$. Finally, in this section, we restrict our attention to interior solutions for mixing, $\boldsymbol{m^*} > 0$, as we have already discussed the case without mixing, $\boldsymbol{m^*} = 0$, in section 2.[18] We include this result as case 1 in Table 1 for the sake of reference. [INSERT TABLE 1]

Let us now discuss the cases with mixing, i.e. $\boldsymbol{m}^* > 0$. Remember that mixed waste, separate waste or a combination of both may exist in equilibrium. In this section, we restrict the analysis to the cases where it is not optimal to have dumping of separate waste streams in equilibrium, for reasons that will become clear in the last section, i.e. we assume $\boldsymbol{b}^* = 0$ throughout this section. We start with the case where, in addition, no mixed dumping is optimal and therefore $\alpha^* = 0$. The optimal solution is then given by equating (11a), (11c) and (11e) with (13a), (13c) and (13e) respectively. Again, the case where all taxes are zero is illustrative. Comparing (13e) with (11e) and substituting

[17] The analysis of these cases is straightforward and provides no further insight.

[18] In the case without mixing, there is only separate dumping and separate landfilling. Hence, $\alpha^* = 0$ in that case and the instrument targeting mixed landfilling, t_{g0}, has no meaning in that case.

$\alpha = 0$, we see that only (11e) would account for the external cost of landfilling. At zero taxes, there would be too much mixed waste in the private optimum.

Again it appears that with Pigouvian tax rates, private behavior in (13) can be induced to match the unique social optimum in (11) in this case.[19] From the second column in Table 1, it appears that the deposit-refund system survives although in a modified way. The subsidy on recycling is still equal to the tax on consumption and can easily be derived by comparing (11a) and (13a). Furthermore, comparing (11e) and (13e), we find that any tax scheme that induces private behavior to match the social optimum has now to satisfy $t_{ci} + t_{g0} = -nU_G/\lambda$. Although the tax (subsidy) rates are similar, i.e. the tax on consumption has to be returned to the consumer up to the external effect of landfilling ($-nU_G/\lambda$), the tax base now shifts towards mixed waste only. In other words, we need a tax (refund) on mixed waste that goes to the landfill only in order to compensate for the externality associated with landfilling. Indeed, it makes little sense to expend effort on first separating waste and then taking it to a landfill where it is mixed anyway.

Finally, we show in appendix section A.1 that $t^*_{g0} < n(U_{B1} - U_G)/\lambda$.[20] Consequently, $t^*_{ci} > -nU_{B1}/\lambda$ and $t^*_{ri} = -t^*_{ci} < nU_{B1}/\lambda$. Because the household must be induced not to dump at all and spending effort on landfilling is suboptimal (lemma 3), the refund on mixed waste must prevent dumping.[21] Hence, both the consumption tax and the subsidies on recycling and mixed landfilling are higher for all less detrimental wastes than in the case where households do not have the option to mix wastes: for waste of type i, any refund on separate landfilling higher than $n(U_{Bi} - U_G)/\lambda$ would ensure no dumping.[22] Since $U_{B1} \leq \ldots \leq U_{BN}$, the tax on mixed landfilling must be smaller than $n(U_{B1} - U_G)/\lambda$: the environmentally most detrimental waste now sets the minimum level of tax on consumption for each good and the subsidies on recycling and landfilling for each type of waste.

Notice that our result for the case without dumping is much simpler than the *set* of taxes and refunds necessary in the model with heterogeneous waste but without mixing. Not only do consumers face a more straightforward deposit-refund system (on fewer waste streams), but also the government may save on administration and enforcement costs because it no longer has to organize a separate deposit-refund system for each type of waste. Consider, for instance, the case where households discard solvents (thinner) or batteries. If the hazards of either of these streams are such that dumping them separately or in the mix should be avoided, these hazards also guide the level of the deposit-refund for all other (potential) waste streams. In contrast to Fullerton and Kinnaman (1995),

[19] Note that if we impose $\alpha^* = 0$, we also have $\boldsymbol{g^*} = 0$ as part of our optimal policy because of lemma 3.

[20] This condition comes from the requirement that the taxes must satisfy not only the equality conditions but also the inequality conditions.

[21] Remember that we are analyzing the case in which $\boldsymbol{b^*} = \boldsymbol{g^*} = \alpha^* = 0$.

[22] Remember that $U_{Bi} \leq U_G$ and $U_{Bh} \leq U_{Bi}$ for $h < i$.

the complexities of a fully differentiated deposit-refund system are now (endogenously) avoided as the effort involved in separating waste streams makes mixing of waste streams attractive. To guarantee that all waste is properly handled, the government now has to 'hedge' against the potentially worst option, which only raises the level of the deposit-refund.[23]

This result is intuitive, as mixing provides the household with the option of evading differentiated subsidies on the components of the mix. This insight also enables us to generalize Choe and Fraser's (1999) condition that the total costs of landfilling (including effort) must be smaller than the total costs of dumping for the household in order for dumping not to occur in equilibrium. In the presence of mixing and the absence of separate landfilling (lemma 3), this condition now reads: for the household, the total costs of landfilling mixed waste must be smaller than both the total costs of dumping mixed waste and the total costs of dumping each type of waste separately.[24]

The next, and perhaps more interesting, case allows for mixed dumping, $\alpha^* > 0$. Note that up to some extent, mixed dumping can be optimal for the government. For instance, the environmental effects of dumping the most hazardous waste present in household waste may not be large either because the most hazardous waste is not 'too hazardous' or because it is only a very small part of household (mixed) waste. First, we focus on the subcase where $\boldsymbol{g}^* > 0$, i.e. the optimal policy of the government includes landfilling of separate waste streams. The optimum is now given by equations (11a-11c) and (11e) and (11f). The case of zero taxes now shows that we have too little separate landfilling in the optimum because households do not want to spend the effort to separate part of the waste for separate landfilling (compare (11b) and (13b)). Consequently, there is too much mixing, which can be verified from (11e) and (13e). Finally, from (11f) and (13f), we have that there is too much dumping in the absence of taxation.

Again compare equations (11c) and (13c) to find $\delta_i = \lambda$, i.e. the social marginal utility equals the private marginal utility of the resource. Next, define $U_{Bw} = \boldsymbol{m}\nabla\boldsymbol{U_B}/\boldsymbol{\iota m}$ as the weighted disutility of dumping mixed waste where the weights are given by the quantity (or share) of each waste in the mix. Next, from (11f) and (13f) and using $\delta_i = \lambda$, we find $t^*_{g0} = n(U_{Bw} - U_G)/\lambda$ to guide the optimal level of dumping mixed waste. Since $U_{Bw} \leq U_G$, this Pigouvian 'tax' is ≤ 0. So the more detrimental - in terms of its externality - it is to dump the mix compared with landfilling, the higher the refund on proper disposal should be. Accordingly, the subsidy on proper disposal through landfilling rises with the disutility

[23] Interestingly, proper disposal of mixed waste streams does not depend on the hazards of each waste stream separately, but on the (overall) externalities of the landfill. Modern landfills are designed in such a way that ambient quality of the environment is guaranteed by securing against leakage of the worst potential toxic combination of mixed waste streams (Dijkgraaf and Vollebergh, 2004).

[24] It is shown in appendix section A.1 that the tax scheme in Table 1 satisfies this property.

of dumping the mix and no longer depends on - as in the previous case - the disutility of dumping the most hazardous type of waste.

Apart from guiding the optimal level of the mix being dumped, the first-best solution also guides households as to what waste should be thrown into the general waste bin. As before, the choice of how much waste should be mixed in the optimum is likely to depend on the various externalities involved in dumping a specific waste stream, either separate or mixed. Indeed, by substituting t^*_{g0} and comparing (11e) and (13e), we find $t^*_{ci} = -n((1-\alpha)U_{Bw} + \alpha U_{Bi})/\lambda$, which is greater than or equal to zero given $U_{Bi}, U_{Bw} \leq 0$. Households now pay a tax that is a weighted average of the environmental effect of dumping the good separately, U_{Bi}, and the environmental effect of dumping the mix in which the waste is contained, U_{Bw}. The weights are given by the share of the mix, α, that is being dumped. Whether the tax increases or decreases with the share, α, depends on the detrimental effect of dumping the mix compared with dumping waste of type i. With $U_{Bi} < U_{Bw} < 0$, the consumption tax increases when the share of mixed waste that is dumped increases. This reflects the fact that when waste of type i is environmentally more damaging than the mix, its consumption is discouraged and therefore the quality of the mix is improved, reducing the effect of dumping the mix. For $U_{Bi} > U_{Bw}$, the reverse holds. As before, the refund for recycling is symmetric with the deposit: comparing (11a) and (13a), we see that $t^*_{ri} = -t^*_{ci} \leq 0$. When $U_{Bi} < U_{Bw}$, the recycling subsidy increases when the share of mixed waste that is dumped, α, increases. Environmentally more detrimental wastes are to be refunded at a higher rate.

Finally, the tax structure should also induce households to *separate* waste streams, after which they are properly disposed of (landfilled) instead of being recycled. This requires an additional instrument, which is a deposit t^*_{gi}. Its level is derived from comparing (11b) and (13b), yielding $t^*_{gi} = n((1-\alpha)U_{Bw} + \alpha U_{Bi} - U_G)/\lambda$. This raises the fundamental question of why the government would ever induce households to spend effort on separating waste after which that waste is again mixed at the landfill. The answer is that, in this way, the government is able to shift the composition of the mix, such that it becomes socially optimal to dump (a larger part of) the mix as its most hazardous elements are reduced. Indeed, the larger the negative effect of dumping, U_{Bi}, the higher the refund on separate landfilling. Moreover, with $U_{Bi} < U_{Bw}$, the refund on separate landfilling rises with the share of mixed waste that is dumped (again reducing the amount of hazardous waste in the mix). Note that to have separate landfilling at all, the refund on separate landfilling is (must be) larger than the refund on mixed landfilling.[25]

[25] A final check that has to be made is whether, at the above tax rates, there is no separate dumping, $\boldsymbol{b}^* = 0$. It turns out that this condition is satisfied as long as the private costs of separate dumping are not too low compared with the private costs of landfilling and the private costs of mixed dumping. See appendix section A.2.

Note that this modified deposit-refund scheme still provides a first-best solution for this (local) optimum. The refund on mixed landfilling provides proper incentives against separate and (potentially) suboptimal mixed dumping. It is also clear from this case that mixing has an effect only when the environmental effects of dumping differ between different types of waste. Indeed, if all wastes have identical environmental effects, $\forall i : U_{Bi} = U_B$, we are back in the original deposit-refund scheme found by Fullerton and Kinnaman (1995). However, we now much better understand when it is optimal to apply different taxes. The difference in taxes on individual goods and wastes is larger when (i) the difference in environmental effects is larger and (ii) the share of mixed waste that is dumped is larger. The option of throwing goods and wastes with different-sized externalities into the same tax category in order to reduce administration costs (see Fullerton and Kinnaman (1995, p.88)) works better the smaller the difference between the environmental effects of dumping *and* the smaller the amount of mixed dumping. This is intuitive as well, because at higher levels of mixed dumping, grouping types of waste together becomes more detrimental as the most hazardous type of waste in the group is dumped more as well.

The second subcase of mixed dumping is with $\boldsymbol{g}^* = 0$ and yields results identical to the case in which $\boldsymbol{g}^* > 0$ except for the tax on separate landfilling. This tax must now be strictly larger than $n(1-\alpha)U_{Bw}/\lambda + n\alpha U_{Bi}/\lambda - nU_G/\lambda$ in order to induce the household not to landfill separately. Since $n(1-\alpha)U_{Bw}/\lambda + n\alpha U_{Bi}/\lambda - nU_G/\lambda < 0$, we have that $t^*_{gi} = 0$. This subcase may, for example, arise when the most hazardous types of waste are recycled (almost) completely, as in that case there is no need for an instrument to shift the composition of the mix.

5 Extensions, limitations and conclusion

The previous section has shown that the deposit-refund system survives in a world where wastes can be mixed and illegal dumping is possible. Indeed, separated waste streams are more costly than mixed waste streams because of the effort of households in sorting waste streams from each other. Throwing all waste into the trash bin is the easiest way to get rid of waste as it avoids the trouble of keeping different boxes at home or walking or driving to the separate waste collection points. What is surprising, however, is not that mixing influences the design of optimal waste policy, but that it does not make first-best policy options impossible. Our results show that the deposit-refund system still produces a first-best outcome and that only the level and number of deposits and refunds needed to reach the first-best are affected. Its structure now depends on the question of whether the regulator would like to allow for mixed dumping or not in the first place. If mixed dumping is not optimal, the deposit-refund system should be designed so that it avoids the likelihood of mixed dumping. In that case, only one subsidy on mixed waste, t_{g0}, is necessary and sufficient to reach the first-best, whereas in the model of Fullerton and Kinnaman (1995), n subsidies for landfilling (t_{gi}) have to be implemented. A subsidy on mixed waste is also sufficient in the case where the mix does not contain hazardous waste and mixed dumping is optimal. However, if the mix does contain hazardous waste, it may be optimal to steer the composition of the mix towards a more environmentally friendly composition by implementing n additional subsidies on separate landfilling. In that case, we would have $3n + 1$ taxes.

Thus our model nicely captures the well-known fact that different waste streams can be mixed and that mixing is the natural way to describe household waste decisions as well as an essential requirement to understanding waste management policy. Our model also shows that recycling of waste streams of given quality is possible but cumbersome because of the effort involved for households at home. This nicely corroborates the difference in recycling effort found by Jenkins et al. (2003) between households subject to a drop-off program or a curbside recycling program. Also, the data for the Netherlands reflect this: the implementation of some large recycling programs for particular waste streams has reduced their presence in the mix, but a significant percentage of these streams remains present. Our model not only nicely fits this basic characteristic of actual waste policy and household behavior in many countries, but also contains interesting lessons for practical policy.

First of all, what makes waste 'hazardous' may depend not only on the characteristics of the type of waste, but also on the location where the mix might be dumped. Within densely populated areas, any level of dumping may be considered to be suboptimal as it may cause outbreaks of infectious diseases. On the other hand, in rural areas, some level of dumping may be socially optimal. Hence, one might expect government waste policy to differ between countries and even between municipalities because of differences in population density and degrees of urbanization. For instance, effort to keep waste that is useful for composting separate is more likely to be higher for tenants of apartment buildings than for households in suburban dwellings. Therefore, a lower than 100% recycling rate does not necessarily signal suboptimality as is sometimes suggested. Moreover, differences in effort might also explain why no correlation exists between actual recycling rates (as well as recycling targets) and population density across US states (see Porter (2002, p.157)). Indeed, one might expect that recycling is easier in more densely populated areas than in remote areas because of economies of scale in collecting waste for recycling. However, our model recognizes that separation effort might also be more substantial if the higher density is the result of households residing in urban dwellings rather than in suburban or less densely populated areas. Obviously, both forces may work against each other and thus explain the lack of correlation at state level.

Second, our model illustrates that the composition of the mix could be influenced by government policy in order to reduce its hazard. Indeed, some specific waste streams may have serious repercussions when being part of the mix and deserve special treatment. In many countries, special programs have been introduced to keep small hazardous waste separate from other waste. In some countries, such as the Netherlands, the government has stimulated the development of a drop-off system for hazardous waste (batteries, paint, thinner, etc.) from households. Under this program, a fine network of special collection facilities has been developed. In addition, it is possible to drop off one's small chemical waste at so-called 'chemo-cars'. Such policies could be seen as aiming to shift the composition of the mix towards a less hazardous mix.

Third, the government should take appropriate notice of the separation effort involved in recycling policies, including the previously mentioned policies that aim to influence the composition of the mix. Our findings provide additional explanation for the well-known fact that recycling programs are difficult to implement even though households are willing to spend effort 'for free'. In particular, separation effort will be higher the more time is involved in sorting and separating. This is likely to be the case the more complex it is to get rid of one's separated waste stream and the higher the percentage of waste of a given type already recycled as well as the higher the number of waste streams the household is supposed to keep separate. Indeed, the complexity of some specific policies is likely to thwart effort by governments to steer household behavior. For instance, the policies just mentioned that aim to keep small chemical waste separate are likely to require too much effort from households. In particular, a drop-off program such as a chemo-car that shows up only at a few places once a week is very demanding of households in terms of effort. Such a program is likely to fail even if households are highly motivated to join the program and mixing is available as a convenient legal way to get rid of this waste.

As far as the level and number of recycled waste streams are concerned, separation effort is likely to be rising at the margin. Indeed, a certain limit seems to exist for the number of waste streams that households are willing to keep separate for recycling purposes. Taking an even closer look at relatively homogeneous recycled waste streams, such as glass, reveals that such streams generally still comprise several different qualities - for example, white, brown and green glass. In addition, they often contain impurities, i.e. minor fractions of other waste streams. This thwarts efforts for recycling as well, because an important condition for (economically) viable recycling is that the recycled streams are sufficiently pure. Whereas the production of colored glass requires separation of heat-resistant glass from other glass, the production of white glass requires additional separation of glass according to color.[26] Thus the government should be aware of how much effort it would like households to spend on which types of recycling. It might also consider policies under which separation of waste takes place *after* the (mixed) waste has been collected. This type of recycling policy, however, produces recycled waste with many impurities, as Dutch experience has shown, which makes the processing of the recycled material even more problematic. As noted by Porter (2002, p.122), the choice between the recycling bin and the trash bin is not guided by any proper price signalling the difference in social cost between different disposal options. So introducing a deposit-refund system to support some of these recycling programs is likely to be more effective.

As a final remark, we would like to point to an interesting extension of our paper. We have deliberately limited the discussion to cases without *separate* dumping, i.e. $\boldsymbol{b}^* = 0$. The omitted case is rather unlikely, however, because households will typically be better off by dumping their waste mixed. This will not only save on effort (separation), but will in general also save on the (higher) resources needed for illegal dumping, i.e. illegal dumping is characterized by increasing returns to scale. However, for the treatment of waste not produced at home (i.e. litter), the case of separate dumping may have relevance. This will require a different type of model as the effort will typically be 'reversed'. For waste not produced at home, instantaneous littering will save on effort, whereas choosing not to litter but to put the waste into a bin, i.e. mixing, will require effort from the household. These and other interesting issues are left to another paper.

[26] In the Netherlands, impurities in recycled paper and glass are respectively 5% and 1.2% of total weight. Also, a substantial part of organic waste does not meet environmental standards due to pollution with other types of waste and is therefore declared unfit for recycling (see AOO (2004a)).

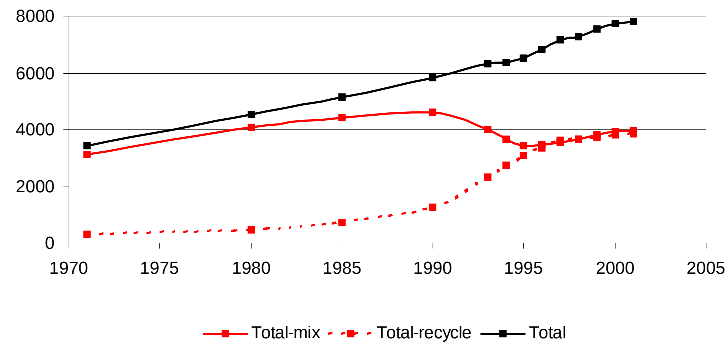

Figure 1: Waste supply and recycling of municipal waste in the Netherlands (in millions of tons)

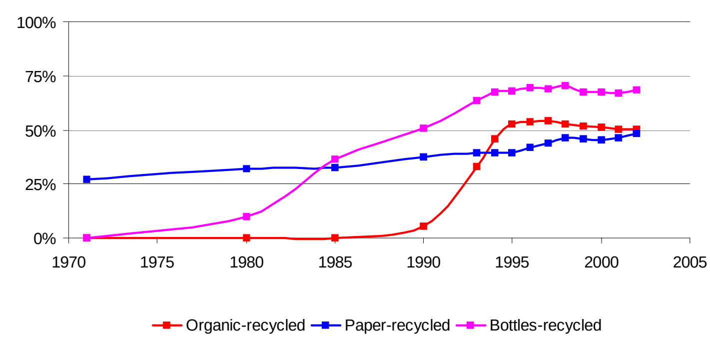

Figure 2: Recycling as a percentage of the total amount of waste in that category in the Netherlands

Table 1: Comparison of various tax schemes to achieve the first-best

Case 1: No mixing with dumping	Case 2: Mixing without dumping	Case 3: Mixing with mixed dumping
$t_{ci}^* = -nU_{Bi}/\lambda$	$t_{ci}^* = -nU_G/\lambda - t_{g0}^* > -nU_{B1}/\lambda$	$t_{ci}^* = -n((1-\alpha)U_{Bw} + \alpha U_{Bi})/\lambda$
$t_{ri}^* = nU_{Bi}/\lambda$	$t_{ri}^* = -t_{ci}^* < nU_{B1}/\lambda$	$t_{ri}^* = n((1-\alpha)U_{Bw} + \alpha U_{Bi})/\lambda$
$t_{gi}^* = n(U_{Bi} - U_G)/\lambda$	$t_{gi}^* = 0$	$t_{gi}^* = n((1-\alpha)U_{Bw} + \alpha U_{Bi} - U_G)/\lambda$
$t_{g0}^* = 0$	$t_{g0}^* < n(U_{B1} - U_G)/\lambda$	$t_{g0}^* = n(U_{Bw} - U_G)/\lambda$

Note 1: t_{ci}^*, t_{ri}^*, t_{gi}^* and t_{g0}^* are, respectively, tax rates on consumption, recycling, landfilling separate waste and landfilling mixed waste. U_{Bi} and U_G are the (negative) externalities of each illegally dumped waste stream and landfilling respectively, U_{B1} is the externality of the waste stream with the worst profile (cases 2 and 3) and U_{Bw} is the environmental effect of dumping the mix in which the waste stream is contained (case 3 only). α is the fraction of the mix that is dumped, λ is the private marginal utility of income, n is the number of individuals and i is the index for each separate waste stream.

Note 2: $t_{gi}^* = 0$ if $g_i^* = 0$.

6 Literature

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A Appendix

A.1 Mixing without dumping

From (11e) and (13e), we have that $t^*_{ci} + t^*_{g0} = -nU_G/\lambda$. We have to check whether there exist taxes t^*_{ci} and t^*_{g0} such that equations (13d), (13b) and (13f) are satisfied with inequality. First, check (13d). Substituting (13e) into (13d), we must have

$$U_{ei} + \lambda f_{kci}/\gamma - \lambda f_{kci}\theta_{bi} + \lambda t^*_{g0} < n(U_G - U_{Bi}) + \lambda t^*_{g0} < 0 \tag{17}$$

where the first inequality follows from the observation that (11d) and (11e) must hold with inequality and equality respectively, since $b^*_i = 0$ and $m^*_i > 0$. Separate dumping will be zero when the second inequality in (17) is satisfied. This is the case as long as $t^*_{g0} < n(U_{Bi} - U_G)/\lambda$. Since this condition must hold for all types of waste, we have

$$t^*_{g0} < \min_i \; n(U_{Bi} - U_G)/\lambda = n(U_{B1} - U_G)/\lambda \tag{18}$$

Second, check under what conditions the first-order condition for g_i is satisfied with strict inequality. Substituting (13e) into (13b), we must have

$$U_{ei} + \lambda t^*_{g0} - \lambda t^*_{gi} < 0 \tag{19}$$

Since $U_{ei} < 0$, a sufficient condition is that $t^*_{g0} < t^*_{gi}$. Finally, check under what conditions the first-order condition for α is satisfied with inequality. Rearranging terms in (13f), we must have

$$t^*_{g0} < f_{kci}\left(\frac{\boldsymbol{m}\nabla\boldsymbol{\theta}_0}{\boldsymbol{\iota m}} - \frac{1}{\gamma}\right) \equiv t^* \tag{20}$$

From $\alpha^* = 0$, we have that Eq. (11f) must hold with inequality. Rearranging terms, we have $t^* > n(U_{Bw} - U_G)/\lambda$. Setting t^*_{gi} equal to zero, we find that any $t^*_{g0} < n(U_{B1} - U_G)/\lambda$ will satisfy the conditions formulated in (17) and (19). Such a t^*_{g0} will also satisfy the condition formulated in (20) as $t^*_{g0} < n(U_{B1} - U_G)/\lambda < n(U_{Bw} - U_G)/\lambda < t^*$.

A.2 Mixing with mixed dumping

We have to check whether there is no separate dumping at taxes

$$
\begin{aligned}
t^*_{ci} &= -n(1-\alpha)U_{Bw}/\lambda - n\alpha U_{Bi}/\lambda \\
t^*_{ri} &= \ \ n(1-\alpha)U_{Bw}/\lambda + n\alpha U_{Bi}/\lambda \\
t^*_{gi} &= \ \ n(1-\alpha)U_{Bw}/\lambda + n\alpha U_{Bi}/\lambda - nU_G/\lambda \\
t^*_{g0} &= \ \ n(U_{Bw} - U_G)/\lambda
\end{aligned}
$$

First, assume that $U_{Bw} < U_{Bi}$. We will prove that the household prefers separate landfilling over separate dumping at these taxes. Substituting (13b) and the expression for t^*_{gi} into (13d), we find

$$
\begin{aligned}
U_{ci} + U_{ei} - \lambda(1 + t^*_{ci} + f_{kci}\theta_{bi}) &= \lambda f_{kci}(\frac{1}{\gamma} - \theta_{bi}) + n(1-\alpha)U_{Bw} + n\alpha U_{Bi} - nU_G \\
&< n(U_G - U_{Bi}) + n(1-\alpha)U_{Bw} + n\alpha U_{Bi} - nU_G \\
&= n(1-\alpha)(U_{Bw} - U_{Bi}) < 0
\end{aligned}
$$

where the first inequality follows from the fact that $b^*_i = 0$ and $g^*_i > 0$ and the last inequality follows from our assumption that $U_{Bw} < U_{Bi}$.

Second, consider relatively environmentally detrimental wastes ($U_{Bi} < U_{Bw}$). Separate dumping will not occur if the household prefers either separate landfilling or mixing waste to separate dumping. Separate landfilling is preferred over separate dumping if (substitute (13b) into (13d)):

$$
\lambda f_{kci}/\gamma - \lambda f_{kci}\theta_{bi} + \lambda t^*_{gi} < 0 \tag{21}
$$

Rearranging terms, we find

$$
f_{kci}(\frac{1}{\gamma} - \theta_{bi}) < -t^*_{gi} \tag{22}
$$

As long as the marginal costs for separate dumping of environmentally detrimental waste, θ_{bi}, are relatively large, separate dumping will not occur. This is, for example, the case if the marginal costs of separate dumping are much higher than the marginal costs of landfilling.

Separate dumping will also not occur when the household prefers mixing over separate dumping. This occurs when (substitute (13e) into (13d) and rearrange terms):

$$(1-\alpha)f_{kci}(\frac{1}{\gamma}-\theta_{bi})+\alpha f_{kci}(\theta_{0i}-\theta_{bi}) < -(1-\alpha)t^*_{g0}-U_{ei}/\lambda \tag{23}$$

Again when the marginal costs for separate dumping of environmentally detrimental waste, θ_{bi}, are relatively large compared with the marginal costs of separate landfilling and mixed dumping, separate dumping will not occur.