

Efficient and Sustainable Management of Product Durability and Recyclability

Thomas Eichner and Marco Runkel

University of Siegen
Department of Economics
Hoelderlinstr. 3
D-57068 Siegen
Germany

phone: ++49 271 740 3164 / 3152

fax: ++49 271 740 2732

e-mail: eichner@vwl.wiwi.uni-siegen.de

e-mail: runkel@wap-server.fb5.uni-siegen.de

Abstract

In a dynamic general equilibrium model we explicitly consider the relationship between the product attributes 'durability' and 'recyclability'. Both efficiency and sustainability aspects are taken into account. It turns out (a) that durability may be inefficient even in a perfectly competitive economy in which environmental externalities are absent, (b) that in case where markets for product design are absent the efficiency restoring tax-subsidy schemes may significantly differ from the sustainability restoring tax-subsidy schemes and (c) that changing the property rights for consumption goods and consumption residuals is a promising policy option to overcome market failure.

JEL classification: H21, Q28

key words: product design, recycling, durable good, efficiency, sustainability

1 Introduction

In recent years aspects of 'green' product design received increasing attention in economic studies. Focusing on recycling effects caused by green product attributes such as material mix, material weight, packaging rate or disassembly characteristics – all together denoted as recyclability – there are several authors who show that these design attributes cause externalities in the recycling activities if markets do not provide the right price signals: While Fullerton and Wu (1998) and Choe and Fraser (1999) concentrate on the failure in the market for spent consumption goods (also called residuals), Eichner and Pethig (1999b) investigate the allocative consequences of missing markets for green product design and Calcott and Walls (2000) and Eichner and Pethig (2000) analyse the case in which the markets for green product attributes and residuals break down simultaneously. All above mentioned papers derive policy recommendations which aim at internalizing the recycling externalities. The investigations are carried out in static general equilibrium models such that only the long-run is captured.

Moreover, there is an economic literature investigating product durability focusing on the conditions under which the market fails to provide the efficient level of durability. Basically, two reasons for market failure are identified namely selling the consumption goods under imperfect competition (see the discussion on the Swan's independence result in the survey article of Schmalensee (1978) or the original contributions of e.g. Swan (1970), Bulow (1986), Goering (1992) and Hendel and Lizzeri (1999)) and, more interestingly in the present context, environmental externalities due to production or consumption waste of durable goods (see Goering and Boyce (1999) and Runkel (1999a,b)).¹ The latter authors suggest regulatory policies for durability that restore the efficient allocation. All above durable good models are dynamic partial equilibrium models with the drawback that only the production and the consumption of the durable good are explicitly taken into account.

To sum up, previous articles both on recyclability and on durability derive interesting and important results. However, these lines of literature are characterized by two shortcomings. The first shortcoming is that none of the above articles captures the *relationship between recyclability and durability* which, in our view, is empirically significant. To clarify this relationship we provide two arguments. First, suppose the weight of a durable consumption good is held constant whereas the material mix (the share of different materials contained in the good) is varied. Different materials are more or less recyclable and more or less durable and thus the change in the material mix may affect both the recyclability and the durability of the products. An empirical example supporting this assertion are automobiles: Since the time automobile

¹Goering and Boyce (1999) concentrate on optimal taxation and do not explicitly address the question of market failure in the presence of production waste of durable goods. However, market failure in their model can be proven by extending their results in a straightforward manner.

manufacturer have designed full aluminium car bodies such as Audi's A8 or Honda's NSX there is a heated discussion among engineers about the optimal material or material mix for car bodies. The advantages and disadvantages of the two materials aluminium and steel in view of mechanical properties which determine the car's durability and in view of the car's recyclability are elaborated in Jambor and Beyer (1997) and Carle and Blount (1999). Another empirical example are water supply systems. The material composition of water pipes has changed from lead to copper alloys. On the one hand, that change reduced corrosion to increase the pipes lifespan and on the other hand also changed the recyclability, see McLaughlin et al. (1981, p. 397). Second, suppose the material mix of the good is fixed and the weight is varied, i.e. all material inputs vary in fixed proportions. The increasing weight enhances the recyclability since each unit of the durable contains more material but it typically also increases the product's durability since owing to the additional material the decay process of the good is retarded. An empirical case in point are again car bodies. Some mechanical properties of aluminium, especially the rigidity, are lower than that of steel. One possibility of compensating lower rigidity is to increase the wall thickness, see Carle and Blount (1999), which shows that increasing the amount of material improves the good's durability. In addition, the generation of recycled material is expected to increase if more mass of one material is available.

The second shortcoming of previous articles on green product design is that they concentrate solely on efficiency considerations and do not address the question of *intergenerational distribution*. Especially in durable good models with solid waste, however, such aspects are highly important as the following example clarifies. Suppose the production of a particular vintage of a durable good equals 100 units from which 60 units wear out in the first period and 40 units wear out in the second period of the vintage's life. If now durability of the vintage *ceteris paribus* increases then the amount of scrapped units in the first period and in the second period decreases, say to 50 and 30 units, respectively, but in at least one future period, say the third, the amount of scrapped units increases from 0 to 20 units. Hence, the 'present' decrease in the amount of scrapped units is only possible on the costs of 'future' generations since the sum of all changes in the amount of scrapped units has to be equal to zero. Whether the underlying increase in durability has a non-zero value for society depends on the weights which the well-being of present and future generations receives in the social welfare function. If present generations obtains relative more weight than future generations then the value of the shift in durability is non-zero because the present decrease in the amount of scrapped units is higher valued than the future increase. In contrast, if all generations are treated equally then the value of increasing durability is zero since the waste generation is only postponed to future periods and the society is indifferent between one scrapped unit today and one scrapped unit tomorrow. This example shows that the treatment of different generations in the social welfare function is a crucial aspect in durable good models.

The present paper aims to overcome these shortcomings of previous literature. The analysis is based on a dynamic general equilibrium model in which a durable good is produced by using the inputs labour and material where virgin and recycled material are considered homogeneous goods. The material input is embodied in the output, and the first aspect of product design we introduce is the material content or the weight of the goods which we also call recyclability since this variable influences the recycling productivity. The second attribute under consideration is product durability. We assume a functional relationship between the two product attributes in the sense that increasing recyclability (by increasing the weight or the material content) also enhances durability. Our analysis accounts for aspects of intergenerational distribution by distinguishing between the efficient allocation which is derived with the traditional utilitarian present-value criterion and the sustainable allocation which is derived with the recently developed criterion of Chichilnisky (1996). While the utilitarian approach gives more weight to the present generations, Chichilnisky's criterion treats all generations equally.

Our principal focus is to characterize the allocation when markets for green design fail and to propose policy recommendations which overcome possible market failure. With respect to the existing literature on product design our main results are (a) that product durability may be inefficient even in a perfectly competitive economy in which environmental externalities are absent, (b) that in case where markets for product design are absent the efficiency restoring tax-subsidy schemes may significantly differ from the sustainability restoring tax-subsidy schemes and (c) that changes in the property rights for consumption goods and consumption residuals turn out to be a promising policy option to overcome market failure in the present context.

The paper is organized as follows. In section 2 the dynamic general equilibrium model is developed. Section 3 characterizes the efficient and the sustainable allocation which are decentralized in section 4 by means of competitive prices. Section 5 investigates various policy recommendations in case some markets fail to be active and section 6 summarizes.

2 Durable Good Model with Recycling

The difference between durable and nondurable goods is that nondurable goods completely decay after a single use whereas durable goods may be used several times. Hence, analysing durable goods requires to employ a dynamic model which comprises more than one point in time. In order to map the whole lifecycle of the durable we develop a general equilibrium model

with different vintages of the durable good. For period t the model is given by:²

$$v^s(t) \leq V[\ell_v^d(t)] \quad \text{virgin material production} \quad (\text{A1})$$

$$x^s(t) \leq X[\ell_x^d(t), m^d(t)] \quad \text{production of the durable good} \quad (\text{A2})$$

$$q_x^s(t) = \frac{m^d(t)}{x^s(t)} \quad \text{recyclability of the durable good} \quad (\text{A3})$$

$$\phi^s(t) = \Phi[q_x^s(t)] \quad \text{durability of the durable good} \quad (\text{A4})$$

$$c(t) = \int_{-\infty}^t D[t-k, \phi^d(k)] x^d(k) dk \quad \text{stock of the durable good} \quad (\text{A5})$$

$$u(t) \leq U[c(t), \ell^s(t)] \quad \text{household's utility} \quad (\text{A6})$$

$$z^s(t) = - \int_{-\infty}^t D_a[t-k, \phi^d(k)] x^d(k) dk \quad \text{amount of residuals} \quad (\text{A7})$$

$$b(t) = - \int_{-\infty}^t D_a[t-k, \phi^d(k)] x^d(k) q_x^d(k) dk \quad \text{embodied material of residuals} \quad (\text{A8})$$

$$q_r^s(t) = \frac{b(t)}{z^s(t)} \quad \text{average recyclability of residuals} \quad (\text{A9})$$

$$r^s(t) \leq R[\ell_r^d(t), z^d(t), q_r^d(t)] \quad \text{recycling technology} \quad (\text{A10})$$

$$v^s(t) + r^s(t) \geq m^d(t), \quad x^s(t) \geq x^d(t),$$

$$z^s(t) \geq z^d(t), \quad \ell^s(t) \geq \ell_v^d(t) + \ell_x^d(t) + \ell_r^d(t),$$

$$\phi^s(t) \geq \phi^d(t), \quad q_x^s(t) \geq q_x^d(t), \quad q_r^s(t) \geq q_r^d(t) \quad \text{resource constraints} \quad (\text{A11})$$

The model (A1) - (A11) is compatible with two alternative interpretations. At the first interpretation we suppose that the economy under consideration uses and ultimately disposes of *two* virgin materials. For simplicity, the first material is assumed to be costless and is not explicitly introduced into the formal model. The second material is a scarce resource which in period t is extracted in quantity $v^s(t)$ with the help of labour input $\ell_v^d(t)$ (see (A1)). In the production sector described by (A2) the output $x^s(t)$ of a durable good (measured in kg or tons) is produced with labour $\ell_x^d(t)$ and with both materials where the explicitly modelled material is employed with quantity $m^d(t)$ (also measured in kg or tons). Each unit of the durable good is of constant

²Upper case letters denote functions and subscripts attached to them indicate first derivatives. A sign underneath an argument denotes the sign of the respective partial derivative. The superscripts s and d indicate quantities supplied (output) and demanded (input), respectively. Subscripts attached to variables characterize the good or process to which the variable belongs, e.g. ℓ_r^d is the input labour in recycling.

weight but the production process allows to vary the material composition which constitutes the first product design variable in form of the material-output ratio $q_x^s(t)$ defined in (A3). $q_x^s(t)$ measures the share of the (explicitly modelled) material per kg of vintage t , e.g. kg aluminium per kg of a car, and is denoted as *material content*. The material content, in turn, determines the second aspect of product design under consideration, the product's *durability* $\phi^s(t)$ defined in (A4). It is assumed that increasing the material content also enhances durability ($\Phi_q > 0$) at decreasing rates ($\Phi_{qq} < 0$).

The durability $\phi^d(t)$ of vintage t affects the decay process of that vintage determined by the decay function $D[a, \phi^d(t)]$. The decay function gives the share of the demanded quantity $x^d(t)$ of vintage t which is still in use when the vintage is a years old. We assume that this share is unity in the production period of vintage t ($D[0, \phi^d(t)] = 1$), that the share is decreasing in the age of the vintage ($D_a < 0$) and increasing in durability ($D_\phi > 0$) at decreasing rates ($D_{\phi\phi} < 0$). According to the example in the introduction two further assumptions on the amount $-D_a$ of scrapped units are imposed. First, we assume that for every vintage t there is a function $A[\phi(t)] > 0$ such that $-D_{a\phi}[a, \phi(t)] \stackrel{\leq}{\geq} 0$ if and only if $a \stackrel{\leq}{\geq} A[\phi(t)]$. This assumption states that an increase in durability decreases the amount of scrapped units at small ages of the vintage and increases the amount of scrapped units if the age exceeds a threshold value. Second, we assume that $\int_0^\infty D_{a\phi}[a, \phi(t)] da = 0$, i.e. if durability changes then the sum of all changes in the amount of scrapped units over the whole lifetime of the vintage equals zero.

The total stock $c(t)$ of the durable good in period t equals the sum of the remaining units of all vintages $k \leq t$ and hence is captured by the integral in (A5). In period t the representative household derives utility from the services of the good (e.g. trips with a car) which are assumed to be proportional to the physical stock $c(t)$ (see (A6)). After consumption in period t an amount $-D_a[t - k, \phi^d(k)]$ of every vintage $k \leq t$ wears out and is turned into consumption residuals. Hence the total amount of residuals in period t is described by (A7). The (explicitly modelled) material embodied in the residuals of period t is denoted by $b(t)$ defined in (A8). Dividing the embodied material of residuals by the amount of residuals yields the (weighted) average material content $q_r^s(t)$ of residuals in period t (see (A9)). The average material content $q_r^d(t)$ and the quantity $z^d(t)$ of residuals together with $\ell_r^d(t)$ units of labour are the inputs of the recycling process (A10) which generates the amount $r^s(t)$ of recycled material to be (re-)used in production. The description of the model is completed by the resource constraints (A11).³

The above interpretation of the model (A1) - (A11) is conform to the examples presented in the introduction in which the weight of the durables is constant and in which durability and the

³Note that we do not model the environmental pollution caused by the solid waste which is generated as a by-product of the recycling process since in the subsequent analysis we exclusively focus on the allocative consequences of product design. Therefore, as is done *explicitly* in Eichner and Pethig (2000), we implicitly assume that the environmental externality of solid waste is completely internalized e.g. by a Pigouvian tax.

recycling process are influenced by the mix of different materials. At the second interpretation we drop the costless material and assume that the economy under consideration disposes of only *one* material (or an aggregate of different materials with a fixed material mix). Then all equations have exactly the same meaning as in the first interpretation except for (A2) - (A4), (A8) and (A9). According to (A2), the durable is now produced with only one (aggregate) material where we measure the output $x^s(t)$ no longer in kg or tons but in quantity units. Consequently, $q_x^s(t)$ defined in (A3) states how much kg or tons of the material are contained in one unit of vintage t and hence it equals the *weight* of one unit of vintage t which is now our first product design variable. By (A4) the weight, in turn, determines the second product attribute, namely durability. Furthermore, $b(t)$ defined in (A8) denotes the total weight of residuals in period t whereas $q_r^s(t)$ defined in (A9) is the average weight of residuals in period t . This interpretation of our model is in accordance with the examples in the introduction in which the material mix is fixed and in which the durability and the recycling process are influenced by the weight of the products. The results of our subsequent analysis are compatible with both interpretations of the model. In order to avoid complicated phrases we will refer to q_x and q_r as the *recyclability* (instead of material content or weight) of the durable goods and the residuals, respectively.

As compared to previous literature our approach offers two innovations. First, we take into account the relationship between the product attributes recyclability and durability. Second, we use a dynamic general equilibrium approach considering different vintages and mapping the whole lifecycle of the durable good. Hence, the distinct feature of our framework with respect to the product design models of Fullerton and Wu (1998), Choe and Fraser (1999), Calcott and Walls (2000) and Eichner and Pethig (1999a,b, 2000) is that recyclability affects not only the recycling process via $R_q > 0$ but also determines product durability via $\Phi_q > 0$. Furthermore, while all these contributions concentrate on the long-run of the economy we are able to analyse short-run aspects of green product design owing to our dynamic vintage approach. The difference with respect to the durability literature as for example Goering and Boyce (1999) and Runkel (1999a,b) is that durability is not the only product design attribute under consideration but that it is closely linked to a second attribute of durable goods. Moreover, the above durable good models typically are partial equilibrium models without virgin material and recycling activities. In contrast, since our general equilibrium model maps the whole life-cycle of the durable we are able to discuss the relation between durability, material flows and recycling.

Bevor proceeding with the efficient and sustainable allocation a remark is in order. The economy (A1) - (A11) is based on a particular property rights regime defined by a specific sequence of transactions: In period t , the production sector supplies the bundle $[x^s(t), q_x^s(t), \phi^s(t)]$ to the household who demands $[x^d(t), q_x^d(t), \phi^d(t)]$ and who, in turn, offers the bundle $[z^s(t), q_r^s(t)]$ to the recycling sector whose demand is $[z^d(t), q_r^d(t)]$. Hence, when purchasing the durable the

household acquires the property rights for both the consumption goods and the residuals. This assignment of property rights will be referred to as *household property-rights rule* (H-rule). In section 5 we introduce another property rights regime called *rental rule* (R-rule) under which both the consumption goods and the residuals remain property of the production firm.

3 Efficient and Sustainable Allocation

As a point of reference we consider a social planner which aims to solve the problem of

$$\max \int_0^{\infty} U [c(t), \ell^s(t)] \gamma(t) dt \quad (1)$$

subject to (A1) - (A5), (A7) - (A11). In the subsequent analysis two specific functional forms of the discount factor $\gamma(t)$ are of interest. In the first case it is assumed that $\gamma(t) = e^{-\delta t}$ with $\delta > 0$. In this case, problem (1) is the conventional utilitarian approach to derive the *efficient* allocation in a dynamic framework: The social planner maximizes the present value of the household's utility which is calculated by discounting all future utilities with a positive and constant rate δ . This approach is widely used in economic theory since its rationale goes back to the axiomatic foundation of Koopmans (1960). He shows that for a constant discount rate the objective function (1) satisfies an undemanding set of axioms. However, in the last decade more and more articles emerge which questioned the suitability of the utilitarian approach since by using a constant discount rate it discriminates against future generations in favour of present generations. In our view, a promising approach to account for this problem is the sustainability framework developed by Chichilnisky and her co-authors (for a survey and recent developments see Chichilnisky et al. (1997)). By imposing two further axioms which require that neither present generations nor future generations 'dictate' the time path of the economy, Chichilnisky (1996) develops an objective function which gives more weight to the far distant future. Furthermore, Beltratti et al. (1997) show the solution to the dynamic maximization of Chichilnisky's objective function to be a solution to the maximization of the utilitarian objective function when the discount rate is not constant but converges to zero as time goes by. Hence, as a second case we consider the discount factor $\gamma(t) = e^{-\delta(t)t}$ with $\delta(t) > 0$ for all t and $\lim_{t \rightarrow \infty} \delta(t) = 0$. According to Chichilnisky's idea we call the solution to the problem (1) in this case the *sustainable* allocation. As will be seen, the distinction between efficiency and sustainability will have important implications in our durable good model.⁴

⁴It should be noted that there is a heated discussion whether efficiency or sustainability is the 'right' objective function of the social planner, see e.g. Chichilnisky et al. (1998). There are empirical and theoretical pro and cons for both approaches. However, it is *not* the task of the present paper to provide further arguments for one of the approaches. We simply apply both concepts, point out the differences in their implications for our durable good economy with recycling and left the question of the 'right' objective function for later research.

Independent of the functional form of the discount factor, problem (1) is an optimal control problem with the integral state constraints (A5), (A7) and (A8) where $c(t)$, $z^s(t)$ and $b(t)$ are the state variables and all other economic variables are the controls. In order to derive a solution to this problem we employ the current-value Hamiltonian and the associated Lagrangean

$$\begin{aligned}
\mathcal{L}(t) = & U [c(t), \ell^s(t)] + \pi_v(t) \left[V [\ell_v^d(t)] - v^s(t) \right] + \pi_x(t) \left[X [\ell_x^d(t), m^d(t)] - x^s(t) \right] \\
& + \lambda_q(t) \left[\frac{m^d(t)}{x^s(t)} - q_x^s(t) \right] + \lambda_{q\phi}(t) \left[\Phi [q_x^s(t)] - \phi^s(t) \right] \\
& + \int_t^\infty D[k-t, \phi^d(t)] x^d(t) \lambda_{cx}(k) \varepsilon(k, t) dk - \int_t^\infty D_a[k-t, \phi^d(t)] x^d(t) \lambda_{zx}(k) \varepsilon(k, t) dk \\
& - \int_t^\infty D_a[k-t, \phi^d(t)] x^d(t) q_x^d(t) \lambda_b(k) \varepsilon(k, t) dk + \lambda_{qq}(t) \left[\frac{b(t)}{z^s(t)} - q_r^s(t) \right] \\
& + \pi_r(t) \left[R [\ell_r^d(t), z^d(t), q_r^d(t)] - r^s(t) \right] + \lambda_m(t) [v^s(t) + r^s(t) - m^d(t)] \\
& + \lambda_x(t) [x^s(t) - x^d(t)] + \lambda_\phi(t) [\phi^s(t) - \phi^d(t)] + \lambda_{qx}(t) [q_x^s(t) - q_x^d(t)] \\
& + \lambda_z(t) [z^s(t) - z^d(t)] + \lambda_{qr}(t) [q_r^s(t) - q_r^d(t)] + \lambda_\ell(t) [\ell^s(t) - \ell_v^d(t) - \ell_x^d(t) - \ell_r^d(t)] \quad (2)
\end{aligned}$$

with $\varepsilon(k, t) := \gamma(k)/\gamma(t)$. λ_{cx} , λ_{zx} and λ_b represent the co-state variables associated with c , z^s and b , respectively, and all other λ 's and π 's are Lagrange multipliers. Following Kamien and Muller (1976), FOCs for an interior solution are obtained by setting the partial derivatives of (2) with respect to all control variables equal to zero, i.e. $\partial\mathcal{L}(t)/\partial\ell_v^d(t) = \partial\mathcal{L}(t)/\partial v^s(t) = \dots = 0$ for all $t \in [0, \infty[$, and the partial derivatives with respect to the state variables equal to the corresponding co-state variable, i.e. $\partial\mathcal{L}(t)/\partial c(t) = \lambda_{cx}(t)$, $\partial\mathcal{L}(t)/\partial z^s(t) = \lambda_{zx}(t)$ and $\partial\mathcal{L}(t)/\partial b(t) = \lambda_b(t)$ for all $t \in [0, \infty[$.⁵ The resulting expressions may be rearranged to yield

Proposition 1. *The solution to (1) is characterized by⁶*

$$\begin{aligned}
\frac{1}{V_\ell(t)} - \frac{X_m(t)}{X_\ell(t)} + \Phi_q(t) \int_t^\infty D_{a\phi}(k) \frac{R_z(k)}{R_\ell(k)} \rho(k, t) dk = & -\Phi_q(t) \int_t^\infty D_\phi(k) \frac{U_c(k)}{U_\ell(k)} \rho(k, t) dk \\
& - \int_t^\infty \left[D_a(k) + \Phi_q(t) q_x(t) D_{a\phi}(k) - \Phi_q(t) q_r(k) D_{a\phi}(k) \right] \frac{R_q(k)}{z(k) R_\ell(k)} \rho(k, t) dk \quad (3)
\end{aligned}$$

⁵Actually, Kamien and Muller (1976) employ the *present-value* Lagrangean instead of the current-value counterpart. However, it can be shown that both approaches lead to the same FOCs.

⁶For notational convenience we mark functions and their derivatives only by the time index and suppress the other arguments, i.e. $U_c(t) := U_c[c(t), \ell^s(t)]$, $V_\ell(t) := V_\ell[\ell_v^d(t)]$, and so on. For the decay function define $D(k) := D[k-t, \phi(t)]$, $D_a(k) := D_a[k-t, \phi(t)]$ and so on. Furthermore, $\rho(k, t) := U_\ell(k) \varepsilon(k, t)/U_\ell(t)$ is a factor which discounts all values of period k down to period t and expresses the values in terms of period t labour.

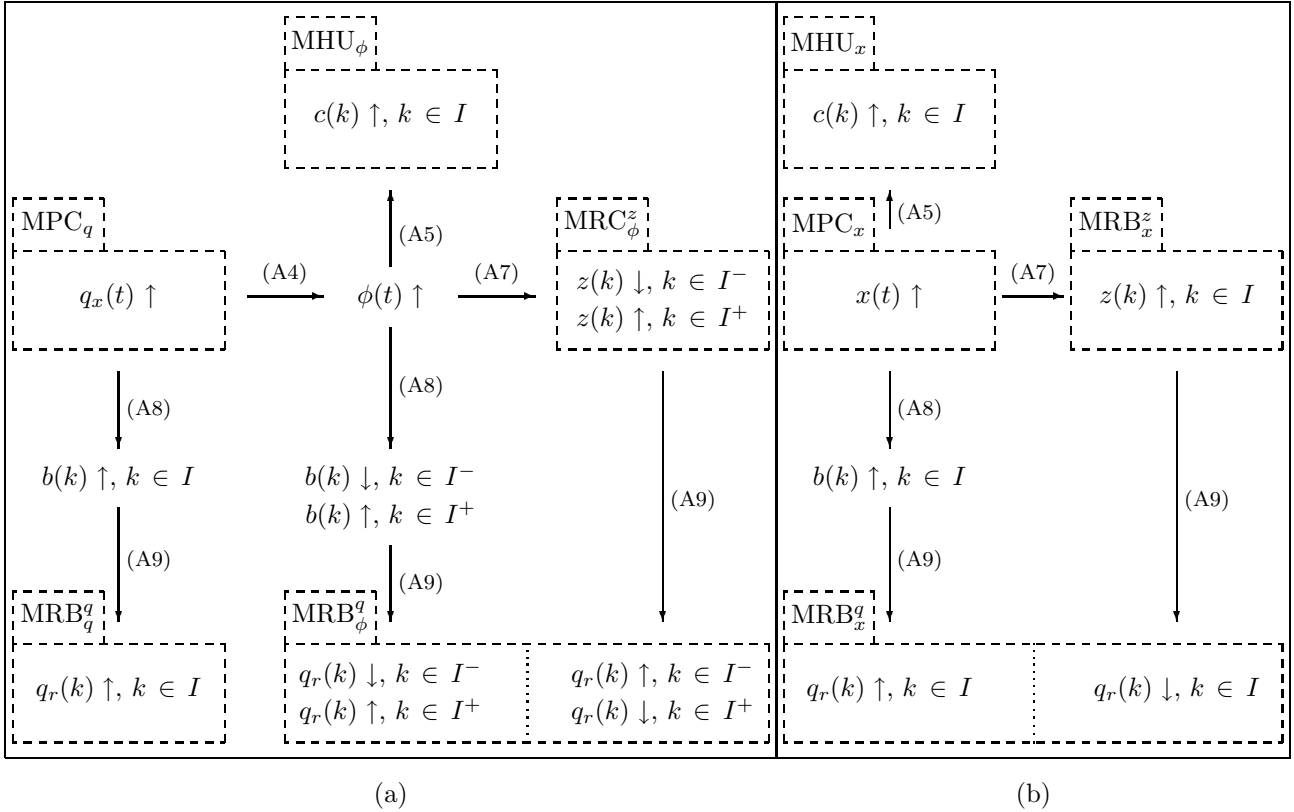
and

$$\begin{aligned} \frac{1}{X_\ell(t)} + q_x(t) \left[\frac{1}{V_\ell(t)} - \frac{X_m(t)}{X_\ell(t)} \right] = & - \int_t^\infty D(k) \frac{U_c(k)}{U_\ell(k)} \rho(k, t) dk \\ & - \int_t^\infty D_a(k) \frac{R_z(k)}{R_\ell(k)} \rho(k, t) dk + \int_t^\infty D_a(k) \left[q_r(k) - q_x(t) \right] \frac{R_q(k)}{z(k)R_\ell(k)} \rho(k, t) dk \end{aligned} \quad (4)$$

for all $t \in [0, \infty[$.

Equation (3) in proposition 1 is the allocation rule for recyclability $q_x(t)$ of the durable good. It states that in every period t marginal costs of the good's recyclability equal marginal benefits. Marginal costs and benefits comprises five components: First, the first two terms on the LHS indicate the (net) marginal production costs of the good's recyclability, MPC_q in figure 1a: For a given current production increasing durable's recyclability requires to substitute material for labour. This substitution causes additional material extraction costs $1/V_\ell(t)$, on the one hand, and saves labour costs $X_m(t)/X_\ell(t) = [d\ell_x(t)/dm(t)]|_{x(t)=const.}$ in the production sector, on the other hand. Second, the integral on the LHS of (3) may be denoted as the marginal recycling

Figure 1: Ceteris Paribus Effects of $q_x(t)$ and $x(t)$



costs/benefits of the good's durability due to changes in the amount of residuals, MRC_ϕ^z in figure 1a. It belongs to the marginal effects of the good's recyclability since a marginal increase

in the recyclability enhances product durability. The integral may have any sign, in general, since an increase in the good's durability (caused by a shift in the good's recyclability) reduces the amount of residuals in every period $k \in I^- := [t, A(\phi(t))]$ but raises the amount of residuals in every $k \in I^+ :=]A(\phi(t)), \infty[$. Third, the first integral on the RHS of (3) is the marginal household utility of durability, MHU_ϕ in figure 1a: Shifting durability in t to a higher level by increasing the good's recyclability enhances the stock $c(k)$ of the durable for all $k \in I := [t, \infty[$. Fourth, the part with D_a of the second integral on the RHS of (3) represents the marginal recycling benefits of the good's recyclability due to an increase in the residuals' recyclability, MRB_q^g in figure 1a: Enhancing the durable's recyclability in t increases the embodied material of the residuals which, in turn, shifts the residuals' recyclability to a higher level for all $k \in I$. Fifth, the remainder of the second integral on the RHS of (3) represents the marginal recycling benefits/costs of durability due to changes in the residuals' recyclability, MRB_ϕ^g in figure 1a. In general, this marginal effect is ambiguous in sign since residuals' recyclability is influenced through different channels: On the one hand, increasing durability in t by raising the good's recyclability in t decreases (increases) the embodied material of residuals which, in turn, exerts a negative (positive) effect on the residuals' recyclability for all $k \in I^-$ (for all $k \in I^+$). On the other hand, the improvement in durability decreases (increases) the amount of residuals and hence increases (decreases) residuals' recyclability for all $k \in I^-$ (for all $k \in I^+$).

Equation (4) in proposition 1 represents the allocation rule for the durable's production $x(t)$. It states that marginal costs of durable's production in period t equal marginal benefits. Marginal costs and marginal benefits comprise four components: First, the LHS of (4) captures the marginal production costs of the durable's output comprising the marginal labour costs $1/X_\ell(t)$ and the (net) marginal material costs $q_x(t)[1/V_\ell(t) - X_m(t)/X_\ell(t)]$, see MPC_x in figure 1b. Second, the first integral on the RHS of (4) equals the marginal household utility of the durable's output, MHU_x in figure 1b: Increasing the output in period t enhances the stock $c(k)$ of the durable good in every period $k \in I$. Third, the second integral on the RHS of (4) stands for the marginal recycling benefit of the durable good due to an increasing amount of residuals, MRB_x^z in figure 1b: Shifting the output in t to a higher level exerts a positive effect on the amount $z(k)$ of residuals in every period $k \in I$. Fourth, the third integral on the LHS of (4) represents the marginal recycling benefits/costs of the durable good due to changes in the residuals' recyclability, MRB_x^g in figure 1b. The sign of this integral is ambiguous since residuals' recyclability is influenced by the output through two channels. On the one hand, if the output in period t increases then the embodied material and the recyclability of residuals increase in every period $k \in I$, too. Second, raising durable's output increases the amount of residuals which, in turn, exerts a negative effect on residuals' recyclability in every period $k \in I$.

These interpretations of the optimum conditions (3) and (4) are valid for both the efficient allocation and the sustainable allocation. The only difference between the two allocations is

that the present values of the various marginal costs and marginal benefits are computed with different discount rates. The optimality conditions simplify in a considerable way if the economy reaches its long-run stationary state. In the long-run all economic variables are independent of time. Then (A7), (A8) and (A9) become, respectively,⁷

$$z = x, \quad b = q_x x, \quad \text{and} \quad q_r = q_x \quad (5)$$

First, consider the steady state of the efficient allocation, i.e. $\gamma(t) = e^{-\delta t}$. Define $\Psi(\phi) := \int_0^\infty D(a, \phi) e^{-\delta a} da$ and $\Omega(\phi) := -\int_0^\infty D_a(a, \phi) e^{-\delta a} da$. The assumptions on the decay function imply $\Psi, \Psi_\phi, \Omega > 0$ and $\Omega_\phi < 0$. From (3) and (4) we then obtain (for the proof of corollary 1ii and corollary 2ii see the appendix)

Corollary 1. (i) *The steady-state of the efficient allocation is characterized by*

$$\frac{1}{V_\ell} - \frac{X_m}{X_\ell} - \Phi_q \Omega_\phi \frac{R_z}{R_\ell} = -\Phi_q \Psi_\phi \frac{U_c}{U_\ell} + \Omega \frac{R_q}{x R_\ell}, \quad (6)$$

$$\frac{1}{X_\ell} + q_x \left(\frac{1}{V_\ell} - \frac{X_m}{X_\ell} \right) = -\Psi \frac{U_c}{U_\ell} + \Omega \frac{R_z}{R_\ell}. \quad (7)$$

(ii) *Suppose $R_q > 0$. If the assumptions*

$$V \text{ is linear: } V(\ell_v) = \bar{v} \ell_v \quad \text{with} \quad \bar{v} > 0. \quad (B1)$$

$$X \text{ is linear homogeneous: } X(\theta \ell_x, \theta m) = \theta X(\ell_x, m) \quad \text{for all} \quad \theta. \quad (B2)$$

$$U \text{ is linear: } U(c, \ell^s) = \bar{c} c - \bar{\ell} \ell^s \quad \text{with} \quad \bar{c}, \bar{\ell} > 0. \quad (B3)$$

$$R \text{ is linear: } R(\ell_r, z, q_r) = \tilde{\ell} \ell_r + \bar{z} z + \bar{q} q_r \quad \text{with} \quad \tilde{\ell}, \bar{z}, \bar{q} > 0. \quad (B4)$$

$$\Omega \text{ is concave: } \Omega_{\phi\phi} < 0. \quad (B5)$$

$$\Phi \text{ is linear: } \Phi(q_x) = \bar{\phi} q_x \quad \text{with} \quad \bar{\phi} > 0. \quad (B6)$$

are satisfied then the efficient long-run recyclability and the efficient long-run durability are greater than they would be if $R_q \equiv 0$.

(6) and (7) are the allocation rules for efficient recyclability and efficient output of the durable good in the long-run. Their interpretation is analogous to that of the short-run allocation rules (3) and (4) with two simplifications: First, the MRB_ϕ^q and the MRB_x^q are zero since in the long-run the residuals' recyclability equals the good's recyclability. Second, the MRC_ϕ^z are unambiguously positive and hence represent marginal costs. It is important to note that the last simplification is solely based on the constant discount rate used in deriving the efficient

⁷Note that (A5) implies $\dot{c}(t) = x(t) + \int_{-\infty}^t D_a[t-k, \phi(k)] x(k) dk$ which in the long-run (i.e. $\dot{c}(t) = 0$ and $x(t) = x$ for all t) becomes $\int_{-\infty}^t D_a[t-k, \phi(k)] dk = -1$.

allocation: By discounting all changes with the same discount rate δ the present decreases in the amount of residuals obtain more weight than the future increases and hence $\Omega_\phi < 0$.

Corollary 1ii shows that under the condition $R_q > 0$ the efficient long-run recyclability and the efficient long-run durability are greater than they would be if the derivative is zero. Of course, the conditions under which this result is proven are quite restrictive but the result has a strong economic intuition since for $R_q > 0$ increasing recyclability (and hence increasing durability) has the additional benefits of increasing the recycling productivity represented by MRB_q^q . Therefore, we conjecture that the result remains valid under more general assumptions. It is not possible to establish a similar result for the case $\Phi_q \equiv 0$. In this case both the MRC_ϕ^z , represented by the term $-\Phi_q \Omega_\phi R_z / R_\ell$, and the MHU_ϕ , represented by $-\Phi_q \Psi_\phi U_c / U_\ell$, disappear and, consequently, it is not intuitively obvious whether the two product attributes are greater or smaller than they would be if $\Phi_q > 0$.

For the sustainable allocation (i.e. $\gamma(t) = e^{-\delta(t)t}$) observe first that there is no long-run steady state at all. There will always be changes in the sustainable allocation due to changes in the discount rate which is now a function of time. However, there is an asymptotic steady-state of the sustainable allocation since the discount rate converges to zero. To characterize this asymptotic steady-state define $\Gamma(\phi) := \int_0^\infty D(a, \phi) da$ with $\Gamma_\phi > 0$ and recognize that $\int_0^\infty D_a(a, \phi) da = -1$ (see footnote 7) and $\int_0^\infty D_{a\phi}(a, \phi) da = 0$ (by assumption). Using these information and $\lim_{t \rightarrow \infty} \delta(t) = 0$ in (3) and (4) yields

Corollary 2. (i) *The asymptotic steady-state of the sustainable allocation is characterized by*

$$\frac{1}{V_\ell} - \frac{X_m}{X_\ell} = -\Phi_q \Gamma_\phi \frac{U_c}{U_\ell} + \frac{R_q}{x R_\ell}, \quad (8)$$

$$\frac{1}{X_\ell} + q_x \left(\frac{1}{V_\ell} - \frac{X_m}{X_\ell} \right) = -\Gamma \frac{U_c}{U_\ell} + \frac{R_z}{R_\ell}. \quad (9)$$

(ii) *Suppose $\Phi_q > 0$ and $R_q > 0$. If (B1) - (B3) are satisfied then the sustainable long-run recyclability and the sustainable long-run durability are greater than they would be if $\Phi_q > 0$ and $R_q \equiv 0$ or if $\Phi_q \equiv 0$ and $R_q \equiv 0$. If additionally the assumption*

$$R \text{ is quasi-linear: } R(\ell_r, z, q_r) = \tilde{R}(z) + \tilde{\ell} \ell_r + \bar{q} q_r \text{ with } \tilde{R}_z > 0, \tilde{R}_{zz} < 0. \quad (\text{B7})$$

is satisfied then the sustainable long-run recyclability and the sustainable long-run durability are greater than they would be if $\Phi_q \equiv 0$ and $R_q > 0$.

(8) and (9) are the allocation rule for the sustainable recyclability and the sustainable production of the durable good in the asymptotic steady state.⁸ By contrast to the short-run

⁸In terms of Beltratti et al. (1997) these conditions describe the green golden rule. They may also be derived if we assume that the model (A1) - (A11) already has reached its steady state and if the utility of the representative household is then maximized subject to all other constraints with means of static optimization.

allocation rule (3) and (4) they contain the same two simplification already described in the long-run efficiency scenario. However, there is a further simplification. The MRC_{ϕ}^z become zero. The reason is obvious: For the efficient long-run durability this recycling effect is solely based on the constant discount rate whereas in the sustainable long-run steady state there is no discounting since the discount rate converges to zero. Therefore, in the sustainable steady state the present decreases in the amount of residuals obtain the same weight as the future increases and hence both effects cancel out.

An immediate consequence of this fundamental difference between long-run efficiency and long-run sustainability is revealed by corollary 2ii. The sustainable long-run recyclability and durability are greater for $R_q > 0$ and $\Phi_q > 0$ than they would be if at least one of the derivatives is zero. The result with respect to R_q holds also for the efficient long-run steady state whereas the result with respect to Φ_q is valid only in the sustainable long-run. Again the reason is obvious: For $\Phi_q > 0$ the sustainable long-run recyclability and durability only have the additional benefits of increasing households utility represented by the MHU_{ϕ} and not the additional costs of reducing the recycling productivity via changes in the amount of residuals (MRC_{ϕ}^z) as in the efficient long-run. Hence both product attributes are greater than for $\Phi_q \equiv 0$. This difference between efficiency and sustainability will be crucial in the subsequent analysis where we evaluate the capacity of markets to reach the efficient or the sustainable allocation.

4 A Benchmark Market System

Now we introduce a benchmark market economy consisting of a complete set of competitive markets to clarify if and how the efficient and sustainable allocation can be decentralized by prices. In this section all markets under consideration are assumed to operate frictionless. The prices p_{ℓ} and p_m for labour and material, respectively, are determined on conventional markets whereas the prices for the durable good and residuals are specified as hedonic price functions. The durable good's price $P^x(\phi, q_x)$ depends on the good's durability and its recyclability and the residuals price $P^z(q_r)$ reflects the household's and recycler's valuation of the residuals' recycling properties. In that sense there are *indirect markets* for product attributes. The Walrasian auctioneer determines the price function of the durable good such that the demand matches supply of the durable, its durability and its recyclability. The same holds for the residual price which has to equate the supply and demand for residuals and their recyclability.

According to section 3 we investigate both the case in which the agents discount future values by a constant rate and the case in which future values are discounted by a variable rate.⁹ Under the

⁹At first glance, a variable discount rate appears to be a strange behavioural assumption. However, there is an significant empirical evidence for declining discount rates. See for example Loewenstein and Thaler (1989).

H-rule the household maximizes the present value of her utility subject to the budget constraint and the integral constraints for the state variables c and z^s and b . Hence, she solves an optimal control problem by maximizing the current-value Lagrangean

$$\begin{aligned} \mathcal{L}^H(t) = & U[c(t), \ell^s(t)] + \mu_h(t) \left[p_\ell(t) \ell^s(t) + \alpha(t) + P^z[q_r^s(t)] z^s(t) - P^x[\phi^d(t), q_x^d(t)] x^d(t) \right] \\ & + \int_t^\infty D[k-t, \phi^d(t)] x^d(t) \mu_{cx}(k) \varepsilon(k, t) dk - \int_t^\infty D_a[k-t, \phi^d(t)] x^d(t) \mu_{zx}(k) \varepsilon(k, t) dk \\ & - \int_t^\infty D_a[k-t, \phi^d(t)] x^d(t) q_x^d(t) \mu_b(k) \varepsilon(k, t) dk + \mu_{qq}(t) \left[\frac{b(t)}{z^s(t)} - q_r^s(t) \right] \end{aligned} \quad (10)$$

where $\alpha(t)$ is a lumpsum transfer of profits and net tax revenue to the household in period t . μ_{cx} , μ_{zx} and μ_b are the co-state variables and all other μ 's are Lagrange multipliers. The virgin material sector and the recycling sector maximize the present value of profits subject to their technologies without taking into account any dynamic restriction for state variables. Hence, the dynamic problem of these sectors reduces to an infinite number of static optimization problems each of which maximizes the periodical profits for a particular $t \in [0, \infty[$. The pertinent Lagrangeans for the virgin material sector and the recycling sector are, respectively,

$$\mathcal{L}^V(t) = p_m(t) v^s(t) - p_\ell(t) \ell_v^d(t) + \mu_v(t) \left[V[\ell_v^d(t)] - v^s(t) \right], \quad (11)$$

$$\mathcal{L}^R(t) = p_m(t) r^s(t) - p_\ell(t) \ell_r^d(t) - P^z[q_r^d(t)] z^d(t) + \mu_r(t) \left[R[\ell_r^d(t), z^d(t), q_r^d(t)] - r^s(t) \right]. \quad (12)$$

It remains to specify the profit maximization problem of the producer. In addition to the market prices we include in the producer's Lagrangean (13) a tax $\tau_x(t)$ on the supply of the durable good and a subsidy $\sigma_m(t)$ on the demand for material in period t .¹⁰ With respect to other possible tax-subsidy schemes the instruments τ_x and σ_m have the advantage of lower administration costs due to two reasons: First, they are levied solely on producers which in literature is denoted as 'upstream' regulation, see e.g. Calcott and Walls (2000), and applying upstream instruments typically requires to tax/subsidize less agents than in case of downstream regulation. Second, they are superior to direct taxes/subsidies on recyclability and durability since they are based on inputs and outputs which in contrast to product attributes are easier to measure and to monitor. Moreover, regulating product attributes may cause non-concavity problems in the producer's profit function with the consequence that no profit maximum may exist (see Eichner and Pethig (1999b)). Such problems do not emerge if material and output are regulated. In view of these convincing advantages we focus exclusively on the policy (τ_x, σ_m) . Analogously to the virgin material and recycling sectors, the profit maximization of the producer reduces to an infinite number of static optimization problems since the producer does not recognize any

¹⁰The introduction of the two policy parameters follows the convention that on condition they are positive (negative) σ_m identifies a subsidy (a tax) and τ_x identifies a tax (a subsidy).

dynamic constraints. Hence, the pertinent Lagrangean reads

$$\begin{aligned} \mathcal{L}^P(t) = & \left[P^x[\phi^s(t), q_x^s(t)] - \tau_x(t) \right] x^s(t) - p_\ell(t) \ell_x^d(t) - \left[p_m(t) - \sigma_m(t) \right] m^d(t) \\ & + \mu_x(t) \left[X[\ell_x^d(t), m^d(t)] - x^s(t) \right] + \mu_q(t) \left[\frac{m^d(t)}{x^s(t)} - q_x^s(t) \right] + \mu_{q\phi}(t) \left[\Phi[q_x^s(t)] - \phi^s(t) \right]. \end{aligned} \quad (13)$$

The price path $p^H(t) \in M^H := \{p(t) \mid p(t) := [p_\ell(t), p_m(t), P^x[q_x(t), \phi(t)], P^z[q_r(t)]]\}$, $t \in [0, \infty[$ and the allocation resulting from (10) - (13) constitute a *competitive H-equilibrium* if all constraints in (A1) - (A11) hold as equalities. Our analysis is restricted to interior solutions.

Maximization of the Lagrangeans (10) - (13) yields FOCs which may be rearranged to

$$p_m(t) - \sigma_m(t) - p_\ell(t) \frac{X_m(t)}{X_\ell(t)} = P_\phi^x(t) \Phi_q(t) + P_q^x(t), \quad (14)$$

$$\frac{p_\ell(t)}{X_\ell(t)} + q_x(t) \left[p_m(t) - \sigma_m(t) - p_\ell(t) \frac{X_m(t)}{X_\ell(t)} \right] = P^x(t) - \tau_x(t) \quad (15)$$

for all $t \in [0, \infty[$ where

$$p_m(t) = \frac{p_\ell(t)}{V_\ell(t)}, \quad P^z(t) = p_\ell(t) \frac{R_z(t)}{R_\ell(t)}, \quad P_q^z(t) = p_\ell(t) \frac{R_q(t)}{z(t)R_\ell(t)}, \quad (16)$$

$$\begin{aligned} P^x(t) = & -p_\ell(t) \int_t^\infty D(k) \frac{U_c(k)}{U_\ell(k)} \rho(k, t) dk - p_\ell(t) \int_t^\infty D_a(k) \frac{P^z(k)}{p_\ell(k)} \rho(k, t) dk \\ & + p_\ell(t) \int_t^\infty D_a(k) \left[q_r(k) - q_x(t) \right] \frac{P_q^z(k)}{p_\ell(k)} \rho(k, t) dk, \end{aligned} \quad (17)$$

$$\begin{aligned} P_\phi^x(t) = & -p_\ell(t) \int_t^\infty D_\phi(k) \frac{U_c(k)}{U_\ell(k)} \rho(k, t) dk - p_\ell(t) \int_t^\infty D_{a\phi}(k) \frac{P^z(k)}{p_\ell(k)} \rho(k, t) dk \\ & + p_\ell(t) \int_t^\infty D_{a\phi}(k) \left[q_r(k) - q_x(t) \right] \frac{P_q^z(k)}{p_\ell(k)} \rho(k, t) dk, \end{aligned} \quad (18)$$

$$P_q^x(t) = -p_\ell(t) \int_t^\infty D_a(k) \frac{P_q^z(k)}{p_\ell(k)} \rho(k, t) dk. \quad (19)$$

To check the performance of our benchmark market economy, suppose the government abstains from imposing any taxes and subsidies. Then the capacity of the market economy to achieve the efficient or the sustainable allocation follows from comparing the market equilibrium conditions (14) - (19) with the conditions for efficiency or sustainability in (3) and (4).

Proposition 2. *Set τ_x and σ_m equal to zero. In case of $\gamma(t) = e^{-\delta t}$ there exists a price path $p^{HE}(t) \in M^H$ such that the competitive H-equilibrium is efficient. In case of $\gamma(t) = e^{-\delta(t)t}$ there exists a price path $p^{HS}(t) \in M^H$ such that the competitive H-equilibrium is sustainable. $p^{HE}(t)$*

and $p^{HS}(t)$ both contain the prices $p_\ell(t) = -U_\ell(t)$ and (16) - (19) for $t \in [0, \infty[$ where all functions and variables are evaluated at their efficient or sustainable levels, respectively.

Proposition 2 states that our benchmark economy is capable to provide either an efficient or a sustainable allocation according to what discount rate the agents use. Moreover, proposition 2 together with (16) - (19) provides information about how prices guide the allocation in the market economy efficient and sustainable, respectively. The price for labour, $p_\ell(t)$, captures the marginal disutility of labour. The price for material, $p_m(t)$, reflects the marginal extraction costs of primary material.¹¹ The price for residuals, $P^z(t)$, and the indirect price for their recyclability, $P_q^z(t)$, equals the marginal recycling benefit of residuals and the marginal recycling benefit of the residuals' recyclability, respectively. The price for the durable good in period t , $P^x(t)$, comprises the MHU_x , the MRB_x^z and the MRB_x^q . The indirect price for durability in period t , $P_\phi^x(t)$, contains the MHU_ϕ , the MRC_ϕ^z and the MRB_ϕ^q . The price for the durable's recyclability in period t , $P_q^x(t)$, reflects the MRB_ϕ^q . In summary, all marginal costs and benefits of the various variables are captured by market prices and hence the competitive H-equilibrium provides an efficient and sustainable allocation, respectively.

In general, it is not possible to specify the sign of all above prices. While the prices for labour, material, residuals and recyclability of residuals are positive in every period, the prices for the durable good, its durability and its recyclability are ambiguous in sign. Focussing on the long-run steady state yields more clear-cut results. For the case of a constant discount rate the efficient prices in proposition 2 simplify to

$$p_\ell = -U_\ell > 0, \quad p_m = \frac{p_\ell}{V_\ell} > 0, \quad P^z = p_\ell \frac{R_z}{R_\ell} > 0, \quad P_q^z = p_\ell \frac{R_q}{xR_\ell} > 0, \quad (20)$$

$$P^x = -p_\ell \frac{U_c}{U_\ell} \Psi + P^z \Omega > 0, \quad P_\phi^x = -p_\ell \frac{U_c}{U_\ell} \Psi_\phi + P^z \Omega_\phi \gtrless 0, \quad P_q^x = P_q^z \Omega > 0. \quad (21)$$

Hence, the efficient long-run prices in our benchmark economy are all positive except for the price of durability. The latter price may also be negative since the MHU_ϕ , represented by $-p_\ell U_c \Psi_\phi / U_\ell > 0$, and the MRC_ϕ^z , represented by $P^z \Omega_\phi < 0$, are opposite in sign. In contrast, the sustainable long-run prices are captured by (20) and

$$P^x = -p_\ell \frac{U_c}{U_\ell} \Gamma + P^z > 0, \quad P_\phi^x = -p_\ell \frac{U_c}{U_\ell} \Gamma_\phi > 0, \quad P_q^x = P_q^z > 0. \quad (22)$$

Thus, the sustainable price for durability is also unambiguously positive. The reason is that in the long-run sustainability scenario the MRC_ϕ^z disappear and the remaining MHU_ϕ are positive.

¹¹Both virgin material and recycled material have the same price due to the assumption that they are homogeneous, see (A11) especially $v^s + r^s \geq m^d$. An investigation of inhomogeneous recycled material caused by 'downcycling' goes beyond the scope of our paper.

5 Market Failures and Corrections

For the design of an effective policy it is crucial to assess the empirical relevance of the market economy discussed above. From an empirical point of view it is quite obvious that markets for labour, material and the durable good exist. Thus, candidates for missing markets are the markets for residuals, recyclability and durability. The consequences of absent markets for residuals are extensively discussed in literature, e.g. by Dinan (1993), Fullerton and Kinnaman (1995), Kohn (1995), Palmer and Walls (1997), Calcott and Walls (2000) and Eichner and Pethig (2000). Therefore we restrict our investigations to missing price signals for recyclability and durability, i.e. we assume that the prices are independent of the commodities' attributes.

5.1 No Indirect Markets for Recyclability

The first case we pay attention to is that no prices emerge that depend on recyclability, i.e. $P_q^x(t) = P_q^z(t) = 0$ for all $t \in [0, \infty[$. Without any corrective policy the consequences are (i) that the production firm determines the level of recyclability without any regard of the household's and the recycler's needs or wants and (ii) that the household and the recycler take recyclability as exogeneously given. Recyclability then represents an externality for the household and the recycling firm. For this scenario we obtain¹²

Proposition 3. *Suppose there are no markets for recyclability, i.e. $P_q^x(t) = P_q^z(t) = 0$.*

(i) *Set τ_x and σ_m equal to zero. Then, in case of $\gamma(t) = e^{-\delta t}$ the competitive H-equilibrium is characterized by an inefficient recyclability and durability for all $t \in [0, \infty[$, in general. In case of $\gamma(t) = e^{-\delta(t)t}$ the competitive H-equilibrium is characterized by an unsustainable recyclability and durability for all $t \in [0, \infty[$, in general.*

(ii) *Set all remaining prices as in proposition 2 and set*

$$\begin{aligned}\sigma_m(t) &= U_\ell(t) \int_t^\infty \left[D_a(k) + \Phi_q(t)q_x(t)D_{a\phi}(k) - \Phi_q(t)q_r(k)D_{a\phi}(k) \right] \frac{R_q(k)}{z(k)R_\ell(k)} \rho(k, t) dk \\ \tau_x(t) &= U_\ell(t) \int_t^\infty \left[q_r(k)D_a(k) - \Phi_q(t)q_x(t)D_{a\phi}(k) [q_r(k) - q_x(t)] \right] \frac{R_q(k)}{z(k)R_\ell(k)} \rho(k, t) dk\end{aligned}\quad (23)$$

Then, in case of $\gamma(t) = e^{-\delta t}$ the competitive H-equilibrium is efficient for all $t \in [0, \infty[$ and in case of $\gamma(t) = e^{-\delta(t)t}$ the competitive H-equilibrium is sustainable for all $t \in [0, \infty[$.

The reason for the market failure identified in proposition 3i is that in the absence of missing markets for recyclability there are no prices which capture the MRB_q^q , the MRB_ϕ^q and the MRB_x^q . The producer of the durable good determines the recyclability inappropriately low or high

¹²To prove proposition 3 set $P_q^x(t) = P_q^z(t) = 0$ in (14) - (19) and compare them with (3) and (4).

because she does not receive any prices signals accounting for the productivity of recyclability in the recycling process. Since recyclability is positively related to durability the latter product attribute is also set inappropriately. Placing these results into the context of the available literature two remarks are in order. First, the *inefficiency* with respect to recyclability has already been demonstrated by Eichner and Pethig (2000), even in a static general equilibrium framework. The *inefficiency* with respect to durability, however, represents an extension of the durability literature: As already mentioned in the introduction, the previous literature identified imperfect competition and environmental externalities as reasons for an inefficient provision of product durability in unregulated markets. Proposition 3i reveals that durability may be inefficient even in a perfectly competitive market in which environmental externalities are absent (or, equivalently, perfectly internalized). In our model durability is inefficient since it is related to recyclability which in turn is distorted by the recyclability externality. Second, previous articles are not able to provide informations about the ability of markets to generate the *sustainable* product design. In contrast, proposition 3i establishes that in case of missing markets for recyclability the unregulated H-equilibrium does not provide sustainable levels of the product attributes.

Proposition 3ii proposes a tax-subsidy scheme which is capable to overcome market failure identified in proposition 3i. This policy option influences the product design of the producer in an indirect way since it suggest to regulate the output of the durable good together with the material input instead of the product attributes recyclability and durability. The instruments reflects the MRB_q^q , the MRB_ϕ^q and the MRB_x^q which in the benchmark economy are reflected by competitive prices but which in the present scenario do not emerge in the price system since markets for recyclability are absent. In general, it is not possible to determine the signs of the tax-subsidy rates but more specific results are obtained if we concentrate on the steady state.¹³

Corollary 3. *Suppose there are no markets for recyclability, i.e. $P_q^x(t) = P_q^z(t) = 0$.*

(i) *Suppose (B1) - (B6) are satisfied and set τ_x and σ_m equal to zero. Then, in case of $\gamma(t) = e^{-\delta t}$ the steady state of the competitive H-equilibrium is characterized by an inefficiently low recyclability and an inefficiently low durability.*

(ii) *Set all remaining prices as in the price path p^{HE} of proposition 2 and set*

$$\sigma_m q_x = \tau_x = -q_x \Omega \frac{R_q}{x R_\ell} U_\ell > 0.$$

Then, in case of $\gamma(t) = e^{-\delta t}$ the long-run competitive H-equilibrium is efficient.

In the long-run the durable's recyclability and the residuals recyclability are the same. The MRB_ϕ^q and the MRB_x^q then becomes zero and the MRB_q^q is the only effect which is not repre-

¹³To prove corollary 3 compare the pertinent conditions for the market equilibrium and the efficient allocation and note that the long-run laissez-faire allocation for $P_q^x = P_q^z = 0$ equals the efficient allocation for $R_q \equiv 0$ which is characterized in corollary 1ii.

sented by prices if the market for recyclability is absent. Based on these simplifications, corollary 3 specifies the result of proposition 3 with respect to efficiency in two directions. First, the unregulated H-equilibrium in the long-run generates inefficiently low product attributes if the markets for recyclability break down. Although the underlying assumptions (B1) - (B6) are quite restrictive we conjecture that the result is valid also under less restrictive conditions since the missing MRB_q^g represented by $\Omega R_q/xR_\ell$ are unambiguously positive. Second, in the steady state the efficiency restoring tax-subsidy rates of proposition 3 are both positive because the product attributes are expected to fall short of its efficient levels in this scenario. Hence, the sales tax $\tau_x > 0$ on the durable good induces the producer to reduce her supply of the good and the subsidy $\sigma_m > 0$ on material input stimulates her demand for material. The net effect of both instruments is to shift recyclability up to its efficient long-run level and thus also rendering the long-run durability efficient. In recycling literature this policy option is well known as deposit-refund system (see Palmer and Walls (1997)).

The (asymptotic) steady state in case of $\gamma(t) = e^{-\delta(t)t}$ differs from the steady state in case of a constant discount rate since also the MRC_ϕ^z disappears and since the functions Ψ and Ω are replaced by Γ and unity, respectively. However, these changes do not alter the result of corollary 3 in a qualitative way if we move from a constant to a variable discount rate. The only difference lies in the magnitude of the tax-subsidy scheme since the function Ω becomes unity. Consequently, to achieve sustainability in the steady state of the H-equilibrium a deposit-refund system has to be implemented to overcome the unsustainably low recyclability and the unsustainably low durability. A qualitative difference between efficiency restoring and sustainability restoring policies is derived in the next section.

5.2 No Indirect Markets for Durability

Suppose now that the indirect markets for recyclability are working well but the market fails to provide price signals for durability. As a consequence the price functions depend on recyclability but not on durability, i.e. $P_\phi^x(t) = 0$ for all $t \in [0, \infty[$. In this scenario three marginal effects are not captured by market prices: the MHU_ϕ , the MRC_ϕ^z and the MRB_ϕ^g . Analogous to missing markets for recyclability investigated in proposition 3, the unregulated H-equilibrium can then be shown to be neither efficient nor sustainable, in general. In contrast to section 5.1, however, the market failure now no longer rests on the recyclability externality but on the durability externality. Since markets for durability fail to be active the production sector does not obtain the correct price signal for durability and hence she sets this product attribute together with the closely related recyclability inappropriately. As opposed to the durability literature as e.g. Bulow (1986), Goering and Boyce (1999a) and Runkel (1999a,b) this result identifies missing markets for durability as a further reason why durability may be inefficient even in the absence

of environmental externalities and imperfect competition. In contrast to Eichner and Pethig (2000) this result proves that recyclability may be inefficient even if markets for that product attribute are present.

It can be shown that the signs of the pertinent tax-subsidy rates which restore efficiency and sustainability, respectively, are ambiguous, in general. This arise the question whether more clear-cut results are again obtained if we concentrate on the long-run steady state. Let us start with the case of a constant discount rate.

Corollary 4. *Suppose there are no markets for durability, i.e. $P_\phi^x(t) = 0$.*

(i) *Set τ_x and σ_m equal to zero. Then, in case of $\gamma(t) = e^{-\delta t}$ recyclability and durability in the steady state of the competitive H-equilibrium may deviate from their efficient levels in either direction even under the special assumptions (B1) - (B6).*

(ii) *Set all remaining prices as in the price path p^{HE} of proposition 2 and set*

$$\sigma_m q_x = \tau_x = q_x \Phi_q \Psi_\phi U_c - q_x \Phi_q \Omega_\phi \frac{R_z}{R_\ell} U_\ell \begin{matrix} \geq \\ < \end{matrix} 0.$$

Then, in case of $\gamma(t) = e^{-\delta t}$ the long-run competitive H-equilibrium is efficient.

For the case of a variable discount rate we obtain

Corollary 5. *Suppose there are no markets for durability, i.e. $P_\phi^x(t) = 0$.*

(i) *Suppose (B1) - (B3), (B7) are satiesfied and set τ_x and σ_m equal to zero. Then, in case of $\gamma(t) = e^{-\delta(t)t}$ the (asmyptotic) steady state of the competitive H-equilibrium is characterized by an unsustainably low recyclability and an unsustainably low durability.*

(ii) *Set all remaining prices as in the price path p^{HS} of proposition 2 and set*

$$\sigma_m q_x = \tau_x = q_x \Phi_q \Gamma_\phi U_c > 0.$$

Then, in case of $\gamma(t) = e^{-\delta(t)t}$ the long-run competitive H-equilibrium is sustainable.

If the discount rate is constant and if markets for durability are absent then there are still *two* marginal effects of product design not captured by prices in the long-run H-equilibrium: the MHU_ϕ and the MRC_ϕ^z . These effects are opposite in sign and, consequently, it is not clear whether recyclability and durability are inefficiently low or high (see corollary 4i). It follows that the tax-subsidy rates which restore efficiency are not unique in sign even in the long-run steady state (see corollary 4ii) - a result which is opposed to the result if markets for recyclability are absent (see corollary 3). In contrast, if the discount rate is variable and if there are no markets for durability then in the long-run H-equilibrium only the MHU_ϕ are not reflected by the price system. The MRC_ϕ^z becomes zero. Consequently, the unregulated product attributes are unsustainably low (see corollary 5i) and sustainability is restored by

subsidizing the material input and by taxing the output of the production sector (see corollary 5ii). This result is qualitative the same as in the case of missing markets for recyclability.

So far our analysis was based on the H-rule. We now wish to elaborate the consequences of changing the property rights regime from the H-rule to the R-rule. Under the institutional arrangement of the R-rule the producer rents the durable good and sells the services (instead of the good itself) at price p_c while the durables remain her property. Moreover, the producer is the owner of the residuals since at the end of the good's life the household hands the good over to the producer who sells the residuals at price $P^z(q_r^s)$ to the recycler.¹⁴ It can be shown that the efficient (sustainable) allocation under the H-rule and the R-rule are the same. This is in accordance with Coasean economics since we abstained from introducing regime specific transaction costs. Hence, (3) and (4) are the efficiency (sustainability) conditions not only under the H-rule but also under the R-rule.

To derive the conditions characterizing a competitive equilibrium under the R-rule note that the Lagrangeans (11) and (12) of the extraction and recycling firm remain unchanged. The state variables are now taken into account by the producer since she owns the stock of the durable stock. She solves an optimal control problem with the present-value Lagrangean

$$\begin{aligned}
\mathcal{L}^P(t) = & \left[p_c(t) - \tau_c(t) \right] c^s(t) + P^z [q_r^s(t)] z^s(t) - p_\ell(t) \ell_x^d(t) - \left[p_m(t) - \sigma_m(t) \right] m^d(t) \\
& + \mu_x(t) \left[X [\ell_x^d(t), m^d(t)] - x(t) \right] + \mu_q(t) \left[\frac{m^d(t)}{x(t)} - q_x(t) \right] + \mu_{q\phi}(t) \left[\Phi [q_x(t)] - \phi(t) \right] \\
& + \int_t^\infty D[k-t, \phi(t)] x(t) \mu_{cx}(k) \varepsilon(k, t) dk - \int_t^\infty D_a[k-t, \phi(t)] x(t) \mu_{zx}(k) \varepsilon(k, t) dk \\
& - \int_t^\infty D_a[k-t, \phi(t)] x(t) q_x(t) \mu_b(k) \varepsilon(k, t) dk + \mu_{qq}(t) \left[\frac{b(t)}{z^s(t)} - q_r^s(t) \right] \quad (24)
\end{aligned}$$

where $\tau_c(t)$ is a tax on the durable's stock in period t . The representative household does not take into account any state variable and hence her pertinent Lagrangean reads

$$\mathcal{L}^H(t) = U [\ell^s(t), c^d(t)] + \mu_h(t) \left[p_\ell(t) \ell^s(t) + \alpha(t) - p_c(t) c^d(t) \right]. \quad (25)$$

The price path $p^R(t) \in M^R := \{p(t) \mid p(t) := [p_\ell(t), p_m(t), p_c(t), P^z[q_r(t)]]\}$, $t \in [0, \infty[$ and the allocation resulting from solving (11), (12), (24) and (25) constitute a *competitive R-equilibrium* if all constraints in (A1) - (A11) hold as equalities. Again, only interior solution are of interest.

The FOCs related to (11), (12), (24) and (25) may be rearranged to yield

$$\begin{aligned}
\frac{p_m(t) - \sigma_m(t)}{p_\ell(t)} + \Phi_q(t) \int_t^\infty D_{a\phi}(k) \frac{P^z(k)}{p_\ell(t)} \varepsilon(k, t) dk = \Phi_q(t) \int_t^\infty D_\phi(k) \frac{p_c(k) - \tau_c(k)}{p_\ell(t)} \varepsilon(k, t) dk \\
+ \frac{X_m(t)}{X_\ell(t)} - \int_t^\infty \left[D_a(k) + \Phi_q(t) q_x(t) D_{a\phi}(k) - \Phi_q(t) q_r(k) D_{a\phi}(k) \right] \frac{P_q^z(k)}{p_\ell(t)} \varepsilon(k, t) dk \quad (26)
\end{aligned}$$

¹⁴Note that under the R-rule there exists no price for the durable good ($P^x = P_q^x = P_\phi^x = 0$).

and

$$\begin{aligned} \frac{1}{X_\ell(t)} + q_x(t) \left[\frac{p_m(t) - \sigma_m(t)}{V_\ell(t)} - \frac{X_m(t)}{X_\ell(t)} \right] &= \int_t^\infty D(k) \frac{p_c(k) - \tau_c(k)}{p_\ell(t)} \varepsilon(k, t) dk \\ &\quad - \int_t^\infty D_a(k) \frac{P^z(k)}{p_\ell(t)} \varepsilon(k, t) dk + \int_t^\infty D_a(k) \left[q_r(k) - q_x(t) \right] \frac{P_q^z(k)}{p_\ell(t)} \varepsilon(k, t) dk \end{aligned} \quad (27)$$

for all $t \in [0, \infty[$ where

$$p_m(t) = \frac{p_\ell(t)}{V_\ell(t)}, \quad p_c(t) = -p_\ell(t) \frac{U_c(t)}{U_\ell(t)}, \quad P^z(t) = p_\ell(t) \frac{R_z(t)}{R_\ell(t)}, \quad P_q^z(t) = p_\ell(t) \frac{R_q(t)}{xR_\ell(t)}. \quad (28)$$

By comparing (26) - (28) with the efficiency conditions (3) and (4) we obtain

Proposition 4. *Suppose the durable is rented. Set τ_c and σ_m equal to zero. In case of $\gamma(t) = e^{-\delta t}$ there exists a price path $p^{RE}(t)$ such that the competitive R-equilibrium is efficient. In case of $\gamma(t) = e^{-\delta(t)t}$ there exists a price path $p^{RS}(t)$ such that the R-equilibrium is sustainable. $p^{RE}(t)$ and $p^{RS}(t)$ both contain the prices $p_\ell(t) = -U_\ell(t)$ and (28) for $t \in [0, \infty[$ where all functions and variables are evaluated at their efficient or sustainable levels, respectively.*

The unregulated competitive R-equilibrium with rental markets for durable goods provides an efficient and sustainable allocation, respectively. Comparing the H-rule under failing indirect markets for durability (corollary 4 and 5) and the R-rule if price signals for durability are missing, too (proposition 4), offers an important insight for policy options: The market failure due to missing markets for durability may be either corrected by means of tax-subsidy schemes or, alternatively, through the introduction of the R-rule under which the producer rents (voluntarily or through regulatory force) rather than sells her goods. The reason for this result is straightforward: By reassigning the property rights for the consumption goods from the household to the producer the durability externality is internalized since the 'durable's stock production' (represented by (A5), (A7) and (A8)) is vertically integrated into the production sector. Hence, the producer takes into account the marginal effects of durability on the stock of the durable good and on the recycling process via the amount and the recyclability of residuals.

In fact, the obligation to rent the durable good has an important advantage over the tax-subsidy scheme. The information requirements for implementing the optimal tax-subsidy schemes proposed in case of the H-rule are quite sophisticated. The policy maker has to assess the marginal utility of the durable good, the marginal recycling productivity of residuals and of their recyclability, the decay function and the relationship between recyclability and durability of the consumption good. Moreover, she has to find out whether the economy has already reached its long-run steady state or is still on the adjustment path and whether individuals discount future values with a constant or a variable rate. In contrast, the policy option of reassigning the property rights does not require *any* of these informations. The policy maker simply obligates

the producer to rent the durable good and then the appropriate allocation is established by market forces. This measure is successful independent of the discount behaviour of individuals and independent of the position which the economy hold on the time path. Hence, we conclude that in case of missing price signals for durability the reassignment of property rights by switching from the H-rule to the R-rule is a very powerful instrument to overcome market failure.

5.3 No Indirect Markets for Recyclability and Durability

After having investigated the consequences of missing markets for recyclability and durability separately, we now analyse both cases simultaneously and hence assume that the price function P^x and P^z neither depend on recyclability nor on durability. Therefore, the market economy is now distorted by a recyclability externality and a durability externality. Not surprisingly, for this scenario it can be shown that under the H-rule qualitatively the same result hold as in the previous section since the durability externality of the previous section is merely augmented by the recyclability externality. The only difference to corollary 4 and 5 lies in the fact that the tax-subsidy rates additionally contains the MRB_q^q . Hence, the unregulated H-equilibrium can be shown to provide an inappropriate product design and the tax-subsidy rates which are capable to overcome the market failure are ambiguous in sign except for the steady state in case of a variable discount rate.

More interestingly, we finally address the question whether the R-rule is also a suitable measure to cope with a break down of indirect markets for both recyclability and durability. For the steady state this question is answered with the help of¹⁵

Corollary 6. *Suppose the durable consumption good is rented and there are no markets for recyclability and durability, i.e. $P_q^x(t) = P_q^z(t) = P_\phi^x(t) = 0$.*

(i) *Suppose (B1) - (B6) are satisfied and set τ_c and σ_m equal to zero. Then, in case of $\gamma(t) = e^{-\delta t}$ the steady state of the competitive R-equilibrium is characterized by an inefficiently low recyclability and an inefficiently low durability.*

(ii) *Set all remaining prices as in p^{RE} of proposition 4 and set*

$$\sigma_m q_x = \tau_c \Phi_q \Psi = - \frac{q_x \Omega \Psi}{\Psi - q_x \Phi_q \Psi_\phi} \frac{R_q}{x R_\ell} U_\ell > 0. \quad (29)$$

Then, in case of $\gamma(t) = e^{-\delta t}$ the long-run competitive R-equilibrium is efficient.

For the case of a variable discount rate we obtain the same result except for the fact that the

¹⁵To prove the sign of the tax-subsidy rates, note that owing to $\Psi_{\phi\phi}, \Phi_{qq} \leq 0$ the function Ψ is concave in q and hence we obtain $\Psi/q > \Psi_\phi \Phi_q$ or, equivalently, $\Psi - \Psi_\phi \Phi_q q > 0$. The same is true for the function Γ .

sustainability restoring tax-subsidy scheme changes to

$$\sigma_m q_x = \tau_c \Phi_q \Gamma = -\frac{q_x \Gamma}{\Gamma - q_x \Phi_q \Gamma_\phi} \frac{R_q}{x R_\ell} U_\ell > 0 \quad (30)$$

Relating these results to the above question it must be noted that adopting the R-rule alone is not sufficient to provide the appropriate allocation in case of missing price signals for recyclability and durability. An additional tax-subsidy scheme (σ_m, τ_c) is needed which consists of a material subsidy and a tax on the rented durables which captures the marginal recycling benefits of product design. In view of the relation of durability and recyclability corollary 6 has to be judged as surprising result. The explanation, however, is the following: If the producer rents the products then she keeps the property rights for both the consumption goods and the residuals and therefore it is in the producer's self interest to take into account the influence the durability exerts on the stock of the durable good and on the residual's recyclability. Thus, as in proposition 4 the 'durable stock production' is vertically integrated in the production sector and the durability externality is internalized. But shifting the property rights of residuals from households to producers has no impact on the recyclability externality since the R-rule does not integrate the recycling activity into the production sector. As a consequence the recyclability externality has to be internalized by a tax-subsidy combination.

Regardless of this restriction in the effectiveness of the R-rule it is worth to emphasize that the policy of changing the property righty still has an advantage with respect to information requirements. The tax-subsidy scheme which under the H-rule are necessary to overcome market failure requires to asses the marginal utility of durability, the marginal recycling productivity of residuals' and their recyclability, the decay function and the relation between recyclability and durability. In contrast, the tax-subsidy scheme which under the R-rule is necessary to overcome market failure does not require any informations about the marginal utility of durability and the marginal recycling productivity of the amount of residuals. Hence, with respect to information requirements the reassignment of property rights is still superior to the tax-subsidy scheme under the H-rule.

6 Summary

Previous articles on the economics of green product design ignores the relation between the product attributes recyclability and durability. Moreover, they concentrate solely on efficiency aspects while ignoring issues of intergenerational distribution. Our paper overcomes these deficits and points out product attributes' market levels in comparison to their efficient and their sustainable level. Furthermore, policy recommendations in case green design markets fail are offered. We employed a durable good model with different vintages and with recycling in

which the material content or the weight determines both the product durability as well as the product recyclability. Our main findings can be summarized as follows:

- If indirect markets for at least one of the product attributes are absent then both recyclability and durability of the consumption goods are inefficient and unsustainable, respectively. Hence, with respect to durability our analysis shows that besides imperfect competition and environmental externalities there are further sources for inefficiency in the durability allocation, namely missing markets for product design.
- If markets for recyclability are absent and if the economy has reached its steady state then a deposit-refund system, i.e. a tax on the output and a subsidy on the material input of the durable good producer, is capable to restore efficiency in case of a constant discount rate. If individuals use a variable discount rate then the deposit-refund system is a suitable policy option to restore sustainability, too.
- If markets for durability are absent then the signs of the efficiency restoring tax-subsidy scheme are ambiguous even in the steady state and hence in this case the deposit-refund system is not necessary an appropriate policy. In contrast, for the case of a variable discount rate the deposit-refund system remains a suitable instrument to restore long-run sustainability.
- Focusing on property rights reveals another promising policy recommendation which impresses by its low information requirements for the policy maker: In case of absent markets for durability the obligation that producers have to rent rather than to sell the durables turns out to overcome market failure and that independent of the discounting behaviour of individuals and independent of whether the steady state is already reached.
- The benefit of the property rights regulation is limited since in case that both indirect markets for product attributes are absent an additional deposit-refund system is needed. However, with respect to information requirements changing property right is still superior to the deposit-refund system in the case where the durables are sold.

Finally, in our view it is desirable to know whether and, if so, which indirect markets for product attributes are missing in reality. We think that there are empirical examples for each case: durable goods markets which account for both, for only one or for none of the two product attributes. However, answering this question in a serious way will require to estimate the pertinent markets with polished econometric methods – a task which is beyond the scope of our paper. Hence, we hope that our analysis stimulates future research in this area.

References

- Beltratti, A., G. Chichilnisky and G. Heal (1997), 'Sustainable Use of Renewable Resources', in: Chichilnisky, G., G. Heal and A. Vercelli (Eds.), *Sustainability: Dynamics and Uncertainty*, Dordrecht: Kluwer Academic Publisher
- Bulow, J. (1986), 'A Theory of Planned Obsolescence', *Quarterly Journal of Economics* 101, 729-49.
- Calcott, P. and M. Walls (2000), 'Can Downstream Waste Disposal Policies Encourage Upstream „Design for Environment?“', forthcoming in *American Economic Review*.
- Carle, D. and G. Blount (1999), 'The Suitability of Aluminium as an Alternative Material for Car Bodies', *Materials and Design* 20, 267-72.
- Chichilnisky, G. (1996), 'Sustainable Development: An Axiomatic Approach', *Social Choice and Welfare* 13, 219-48.
- Chichilnisky, G., G. Heal and A. Vercelli (1997), *Sustainability: Dynamics and Uncertainty*, Dordrecht: Kluwer Academic Publisher
- Choe, C. and I. Fraser (1999), 'An Economic Analysis of Household Waste Management', *Journal of Environmental Economics and Management* 38, 234-46.
- Dinan, T.M. (1993), 'Economic Efficiency Effects of Alternative Policies for Reducing Waste Disposal', *Journal of Environmental Economics and Management* 25, 242-56.
- Eichner, T. and R. Pethig (1999a), 'Product Design and Alternative Markets for Solid Waste Treatment and Disposal', *Volkswirtschaftliche Diskussionsbeiträge* 73-99, University of Siegen.
- Eichner, T. and R. Pethig (1999b), 'Recycling, Producer Responsibility and Centralized Waste Management', *Volkswirtschaftliche Diskussionsbeiträge* 83-99, University of Siegen.
- Eichner, T. and R. Pethig (2000), 'Product Design and Efficient Management of Recycling and Waste Treatment', forthcoming in *Journal of Environmental Economics and Management*.
- Fullerton, D. and A. Kinnaman (1995), 'Garbage, Recycling, and Illicit Burning or Dumping', *Journal of Environmental Economics and Management* 29, 78-91.
- Fullerton, D. and W. Wu (1998), 'Policies for Green Design', *Journal of Environmental Economics and Management* 36, 131-48.
- Goering, G.E. (1992) 'Oligopolies and Product Durability', *International Journal of Industrial Organization* 10, 55-63.

- Goering, G.E. and J.R. Boyce (1999), 'Emissions Taxation in Durable Goods Oligopoly', *Journal of Industrial Economics* 47, 125-43.
- Hendel, I. and A. Lizzeri (1999), 'Interfering with Secondary Markets', *Rand Journal of Economics* 30, 1-21
- Jambor, A. and M. Beyer (1997), 'Technical Report: New Cars - New Materials ', *Materials and Design* 18, 203-09.
- Kamien, M.I. and E. Muller (1976), 'Optimal Control with Integral State Equation', *Review of Economic Studies* 43, 469-473
- Kohn, R.E. (1995), 'Convex Combination of Recycling Incentives', *Mathematical Computation Modelling* 21, 13-21.
- Koopmans, T.C. (1960), 'Stationary Ordinal Utility and Impatience', *Econometrica* 28, 287-309.
- Loewenstein, G. and R.H. Thaler (1989), 'Intertemporal Choice', *Journal of Economic Perspective* 3, 181-193.
- McLaughlin, R.K., R.C. McLean and W.J. Banthron (1981), *Heating Services Design*, Butterworth & Co, London, Boston, Toronto.
- Palmer, P. and M. Walls (1997), 'Optimal Policies for Solid Waste Disposal: Taxes, Subsidies, and Standards', *Journal of Public Economics* 65, 193-205.
- Runkel, M. (1999a), 'Product Durability, Solid Waste Management and Market Structure', *Volkswirtschaftliche Diskussionsbeiträge* 78-99, University of Siegen.
- Runkel, M. (1999b), 'First-Best and Second-Best Regulation of Solid Waste under Imperfect Competition in Durable Good Industry', *Volkswirtschaftliche Diskussionsbeiträge* 81-99, University of Siegen.
- Schmalensee, R. (1978), 'Market Structure, Durability, and Quality: A Selective Survey', *Economic Inquiry* 42, 177-196.
- Swan, P. (1970), 'Durability of Consumption Goods', *American Economic Review* 60, 884-94.

Appendix (not to be published)

In this appendix we prove the corollaries 1ii and 2ii. Start with corollary 1ii. Under the assumptions (B1) - (B6) equation (6) may be rewritten as

$$A(q_x) := 1/\bar{v} - B(q_x) - C(q_x) = \Omega\bar{q}/x\tilde{l} \quad (31)$$

with $B(q_x) := X_m/X_\ell$ and $C(q_x) := \bar{\phi}\Omega_{\phi\bar{z}}/\bar{\ell} + \bar{\phi}\Psi_{\phi\bar{c}}/\bar{\ell}$. Assumption (B3) ensures that there exists a function $G(k) := X(k, 1) = 1/q_x$ with $k := \ell_x/m$. Consequently, we obtain $X_\ell = G_k$, $X_m = G - kG_k$ and $X_{\ell k} = G_{kk} = X_{\ell\ell} < 0$, $X_{mk} = -kG_{kk} > 0$. The signs of the second derivative of X with respect to k imply that B is increasing in k and, since $k = G^{-1}(q_x)$, decreasing in q , i.e. $B_q < 0$. Furthermore, owing to the concavity of Ω and Ψ we obtain $C_q := \bar{\phi}^2\Omega_{\phi\phi\bar{z}}/\bar{\ell} + \bar{\phi}^2\Psi_{\phi\phi\bar{c}}/\bar{\ell} < 0$. In summary under (B1) - (B6) the function $A(q)$ is increasing in q . Recognizing that $\bar{\Phi}_q \equiv 0$ and $R_q \equiv 0$ are equivalent to $\bar{\phi} = 0$ and $\bar{q} = 0$, respectively, proves corollary 1ii.

Next turn to corollary 2ii. Under (B1) - (B3) equation (8) simplifies to

$$\tilde{A}(q_x) := 1/\bar{v} - B(q_x) - \tilde{C}(q_x) = R_q/xR_\ell \quad (32)$$

with $\tilde{C}(q_x) := \Phi_q\Gamma_{\phi\bar{c}}/\bar{\ell} > 0$ and $\tilde{C}_q = \Phi_{qq}\Gamma_{\phi\bar{c}}/\bar{\ell} + \Phi_q^2\Gamma_{\phi\phi\bar{c}}/\bar{\ell} < 0$. Hence \tilde{A} is increasing in q_x which proves the results for $R_q \equiv 0$, $\Phi_q > 0$ and $R_q \equiv \Phi_q \equiv 0$. In order to establish the statement for $R_q > 0$, $\Phi_q \equiv 0$ we introduce the shift parameter β with $\Phi_{q\beta} > 0$ for all β and $\Phi_q = 0$ for $\beta = 0$. If the assumptions (B1) - (B3) and (B7) are satisfied then (8) and (9) simplify to a system of equations which depends on the variables q_x and $x(=z)$ and on the shift parameter β . Totally differentiating these equations and using Cramer's rule yields

$$\frac{\partial q_x}{\partial \beta} = -\frac{1}{|J|} \frac{\bar{c}\Gamma_{\phi}\Phi_{q\beta}\tilde{R}_{zz}}{\bar{\ell}}, \quad \frac{\partial q_x}{\partial \bar{q}} = -\frac{1}{|J|} \frac{\tilde{R}_{zz}}{x\bar{\ell}^2} \quad (33)$$

where $|J|$ is the pertinent Jacobian determinant. From the fact that recyclability for $\Phi_q > 0$, $R_q > 0$ is greater than for $\Phi_q > 0$, $R_q \equiv 0$ (see the proof of the first statement above) it follows $\partial q_x/\partial \bar{q} > 0$ and hence the Jacobian determinant has to be positive, $|J| > 0$. Consequently, from (33) we obtain $\partial q_x/\partial \beta > 0$ which completes the proof of corollary 2ii.