Investments in Recycling Technologies and the Effects of Tightened Environmental Policy

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Abstract

Recycling is seen as a means both for reducing the environmental impact of the residuals of production and consumption as well as a source for secondary resources. Thus, it may enable a company to adjust to environmental needs as being imposed either by nature itself, by consumers, or by government employing environmental policy instruments. This paper examines how the willingness to invest in such technologies is affected by tightening environmental policy. By employing a two-step evaluation approach, it will be possible to identify the determinants of the price ceiling of such an investment under imperfect market conditions. This price ceiling depends on the (corrected) net present values of the payments and on the interdependencies arising from changes in the optimal investment and production programmes. Although the well-established results of environmental economics for a single investment can be confirmed, tightening environmental policy may lead to sometimes contradictory and unexpected consequences for investments in recycling technologies. However, they can be interpreted in an economically comprehensible manner.

Keywords: *Recycling Technology, Environmental Policy, Investment Appraisal, Corrected Net Present Value, Price Ceiling, Imperfect Markets, Production Planning.*

1. Introduction

Over the last few decades, environmental protection has grown in importance. Since the reuse of materials allows for reduction of waste, and because the input of secondary raw material and energy recovery is able to help to protect environmental resources as well as contribute to reduce supply cost, recycling can be a major opportunity for coping with the requirements resulting from environmental policy (e.g. in form of constraints, taxes, licenses). In addition, legislation insists on an increase in the practice of recycling: For example, the German Bundes-Immissionsschutzgesetz (Federal Immissions Control Act) obliges operators of plants to avoid waste, to recover unavoidable waste and to dispose of non-recoverable waste without impairing public welfare. Moreover, the recycling resolution has even formed part of the nomenclature of laws since 1996, in the German Act for Promoting Closed Substance Cycle Waste Management and Ensuring Environmentally Compatible Waste Disposal (Kreislaufwirtschafts- und Abfallgesetz, KrW-/AbfG). Its § 4 constitutes a goal hierarchy: the first stipulation is that waste must be avoided. If this is impossible, material recycling or energy recovery is mandatory. Although not mentioned, disposal may only be considered as the last alternative. Furthermore, §§ 22-26 KrW-/AbfG, regarding product responsibility, authorise the Federal Government to set obligations to ensure the achievement of a closed substance cycle waste management (e.g. prohibitions, restrictions, labelling; obligations to return certain goods and to accept returned goods; obligations of holders after acceptance of returned goods) and to reach public-private goal agreements to return and accept certain goods.

In this context, this paper examines the degree to which environmental policy is actually able to provide incentives for investing in recycling technologies. For example, apart from the possibility of prescribing explicit recycling quotes, environmental constraints may also restrict the input and/or output of hazardous substances. In those cases, recycling may create the necessary space to still increase production. Moreover, since the time of Pigou's writing (Pigou, 1932: 172, 174, 183, 224) it has become commonplace in economic literature to indicate that social and later on, environmental policy may be made by using taxes and subsidies. According to related literature, setting a price for the use of environmental resources or capacities leads to their consideration in economic decisions: the individual compares the abatement cost to the cost of using these resources/capacities and, consequently, may avoid environmentally harmful behaviour or, conversely, extend environmentally beneficial behaviour. Hence, due to environmental taxes and subsidies, investments in recycling technologies may become economically significant as well.

Since investments of this type affect production, it is necessary that the payments and constraints required for a financial valuation are derived from production planning, with special regard to environmental taxes and joint production. On this basis, it is possible to develop a valuation model and to investigate the determinants of the price ceiling for an investment in recycling technologies. The proposed model considers activity-level-dependent and activity-level-independent payments and takes into account the indivisibility of the investment to be evaluated. Due to the fact that much of the impact of waste and pollution on the environment has yet to be explored and, because of changes in environmental policy and in ecological awareness (especially after accidents), this uncertainty is also taken into consideration.

Employing duality theory of linear programming, it can be demonstrated that the price ceiling depends on the (corrected) net present values of the payments and of the interdependencies due to changes in the optimal programme. Sensitivity analysis provides information about the (sometimes contradictory and unexpected) consequences of changes in environmental policy. Nevertheless, we are able to interpret them in an economically comprehensible manner. For better understanding, an example employing environmental taxes demonstrates these effects. A conclusion summarises the main results.

2. Financial Valuation of Investments in Recycling Technologies

2.1 Background – Financial Evaluation on Imperfect Markets under Uncertainty

In economics literature, several studies examine the consequences of environmental policy on investments in environmental protection technologies (Arguedas/van Soest, 2010; Blanco/Rodrigues, 2008; Buchner, 2007; Chakraborty, 2004; Hart, 2008; Hyder, 2008; Knutsson *et al.*, 2006; Laurikka, 2006; Laurikka/Koljonen, 2006; McGilligan *et al.*, 2010; Reinaud, 2003; Sekar *et al.*, 2007; Yang/Blyth, 2007; Zhao, 2003; for an overview of different environmental tax incentives in the European Union cf. Cansino *et al.*, 2010; Markandya *et al.*, 2009). While some of these refer to a single sector or to the whole economy, others take an enterprise point of view and employ different techniques for project appraisal such as cost-based approaches, discounted cash flow (DCF) models, which calculate the present value of an investment by discounting future cash flows at an appropriate discount rate, or real options analyses and simulations.
However, these models refer to perfect markets, a condition that does not apply to most companies: borrowing and lending conditions are restricted and differ and the best opportunity is not always determined on financial markets. Instead, the best opportunity for manufacturing companies will often be an investment in other technologies, producing more or less of the desired outputs, or trading of emissions allowances. Under these circumstances, neither "ordinary" (net) present values merely calculated with exogenous interest rates (even if adjusted to uncertainty) nor real options values are adequate methods for appraising technology investments – the more so because the characteristics of investments in recycling technologies normally may not fulfil all the other prerequisites for applying option pricing models either.[1]

[1] Nevertheless, it can be shown that certain discrete option pricing models may be derived as special cases of the model presented in this paper (Klingelhöfer, 2006: 76-77).

Consequently, to examine the effects of any environmental policy on investments in recycling technologies from a company's point of view, we have to consider the following restrictions:

Resulting from restricted capacities (due to budget constraints, production constraints or limited emissions allowances), every activity in imperfect markets may have interdependencies with other decisions. For instance, capital budget constraints may restrict the realisation of investment opportunities and limit production. On the other hand, the revenues of production may extend the possibilities for investments and finance and, thus, for environmentally beneficial investments as well. Hence, a financial valuation needs to derive the required payments and constraints from production theory and production planning, with special regard to environmental policy and joint production.

This makes it impossible to calculate the value of an investment solely by discounting its payments with a single market interest rate. Instead, a theoretically correct (partial) appraisal demands the endogenous marginal rates of return of the best alternatives. Also, it is not possible to determine the profitability of an additional object merely by calculating net present values: the realisation of additional objects may lead to capacity shortages and, therefore, to changes in the decision relevance of other objects or capacities (i.e. the binding restrictions may change). Consequently, assessing the degree of profitability of an additional single investment or activity within imperfect markets means a comparison of the situation after investing (i.e. the *valuation programme*) to the one before investing (i.e. the *basic programme*) (Hering, 2006: 57-59; Jaensch, 1966: 664-665; Klingelhöfer, 2006: 59-91; Matschke, 1975: 253-257, 387-390). If the maximum value of the valuation programme is greater than that of the basic programme, it is reasonable to invest. Ensuring this by means of a minimum withdrawal constraint, the valuation programme finds the maximum payable price p for the investment in recycling technologies.

Uncertainty, as it results from either reiterative changes of environmental policy, shifts in ecological awareness or altered conditions on liberalised waste markets, etcetera, may be taken into account by using decision trees (Magee, 1964a; 1964b; Mao, 1969; and in the context of investment planning Klingelhöfer, 2006: 59-83; Laux, 1971: 19-22, 39-44). Starting with the realised and, therefore, known state s = 0 (denoting the state actually realised in t = 0), we obtain a set $\boldsymbol{S}$ = {0; 1; …; S} of possible states s, "organised" in a tree structure until time horizon t = T. However, the states being consecutively numbered from s = 0 to s = S, the two-dimensional tree of states for each point in time may be transformed into a one-dimensional mathematical structure. Hence, the valuation considers payments in *all* possible states. Information on probabilities, means or variances is not necessary, as simple dominance considerations are sufficient (we only have to know which states can possibly occur; the probability must be greater than zero, but smaller than 1). Therefore, the principle of *Bernoulli* and its axioms are not needed.

2.2 Derivation of the Payments from Production Theory and Production Planning

Every production, particularly with regard to the environment, is characterised as joint production: Using activity analysis of production (Debreu, 1959: 37-49; Klingelhöfer, 2000: 222-252, 417-442; Koopmans, 1957: 71-83; 1959; Nikaido, 1968: 180-185), a singular realisation of the production process β (for example, one hour), – the so-called *basic activity* B,β – consumes a combination of several kinds of m inputs r_μ (e.g., fuel, labour) and produces a combination of n wanted and unwanted outputs x_ν (e.g., products, electric power, heat, emissions, waste). Thus, a basic activity is defined as a vector of m input and n output commodities φ_ε:[2]

$$\text{(2.1)}\qquad \underline{\varphi}^{B,\beta} = \left(\varphi_1,\ \ldots,\ \varphi_{m+n}\right)' = \left(\underline{r}';\ \underline{x}'\right)' = \left(r_1,\ \ldots,\ r_m;\ x_1,\ \ldots,\ x_n\right)' \geq \underline{0}$$

[2] Underlining a variable denotes a vector and the prime (the symbol ´) the transposition of a vector.

Then, *every possible production* of a technology set ***T*** is a linear combination of the q basic activities with non-negative coefficients λ^{β} (the levels of the activities β):

$$(2.2) \qquad \forall \underline{\varphi} = \left(\underline{r}'; \; \underline{x}' \right)' \in \boldsymbol{T}: \quad \underline{\varphi} = \sum_{\beta=1}^{q} \underline{\varphi}^{B,\beta} \cdot \lambda^{\beta}$$

The Γ *production and environmental restrictions* can normally be written as follows:[3]

$$(2.3) \qquad \sum_{\beta=1}^{q} \sum_{\varepsilon=1}^{m+n} a_{\varepsilon\gamma} \cdot \varphi_{\varepsilon}^{B,\beta} \cdot \lambda_{s}^{\beta} \leq b_{\gamma s} \qquad \forall \gamma \in \{1; \; 2; \; \ldots; \; \Gamma\},$$

Introducing a *price system* with positive prices p_{ε} for the (desired) input of waste and the output of products, prices equal to zero for neutral inputs and outputs (e.g. air and water in certain cases) and negative prices for the input of (traditional) factors of production (primary commodities such as material, labour, or fuel) and the output of waste and emissions delivers the *contribution margin CM*:[4]

$$(2.4) \qquad CM(\underline{\varphi}) = \underline{p}' \cdot \underline{\varphi} = \underline{p}' \cdot \sum_{\beta=1}^{q} \underline{\varphi}^{B,\beta} \cdot \lambda^{\beta} = \sum_{\beta=1}^{q} \sum_{\varepsilon=1}^{m+n} p_{\varepsilon} \cdot \varphi_{\varepsilon}^{B,\beta} \cdot \lambda^{\beta} = CM(\underline{\lambda})$$

Under the conditions of joint production, this contribution margin CM is process specific. It has to be modified if the producer pays *taxes* $t_{\varepsilon s} \geq 0$ or if he receives *subsidies* $t_{\varepsilon s} \leq 0$ for the commodities φ_{ε}:[5,6]

$$(2.5) \qquad CM(\underline{\varphi}) = \left(\underline{p} - \underline{t} \right)' \cdot \underline{\varphi} = \sum_{\beta=1}^{q} \sum_{\varepsilon=1}^{m+n} \left(p_{\varepsilon} - t_{\varepsilon} \right)' \cdot \varphi_{\varepsilon}^{B,\beta} \cdot \lambda^{\beta} = CM(\underline{\lambda})$$

Recycling of the part $0 \leq rec_{\nu\mu} \leq 1$ of output x_{ν} as input r_{μ} of production will reduce the inputs obtained from outside to r_{μ}^{outs} and the outputs delivered to the outside to x_{ν}^{outs}:[7]

$$(2.6) \qquad x_{\nu}^{outs} = \left(1 - rec_{\nu\mu} \right) \cdot x_{\nu} = \left(1 - rec_{\nu\mu} \right) \cdot \sum_{\beta=1}^{q} x_{\nu}^{B,\beta} \cdot \lambda^{\beta}$$

$$(2.7) \qquad r_{\mu}^{outs} = r_{\mu} - rec_{\nu\mu} \cdot x_{\nu} = \sum_{\beta=1}^{q} \left(r_{\mu}^{B,\beta} - rec_{\nu\mu} \cdot x_{\nu}^{B,\beta} \right) \cdot \lambda^{\beta}$$

However, in most cases not an entire product is reused in production, but only (some or all of) its components ω. Since all the components $x_{\nu,\omega}$ of the n inputs x_{ν} can principally replace the *same* components $r_{\mu,\omega}$ of each of the m outputs r_{μ} and since the amounts of each input component $r_{\mu,\omega}$ can be replaced by the *same* components $x_{\nu,\omega}$ of each output, we obtain for the Ω components:

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3 In case of production constraints constituted by tradable permits (e.g. in an emissions trading system), (2.3) has to include the possibility of purchases and sales of tradable permits.

4 Since a linear programming approach (as applied starting from section 2.3) allows for the use of step-type demand and cost functions, nonlinearities may be introduced.

5 Variable tax/subsidy rates may be approximated by piecewise linear functions – the more so in that they usually do not tend to change continuously with the quantity of the charged/subsidised commodities φ_{ε} but in intervals.

6 In case of a system of tradable permits, terms for their trades have to be added.

7 For different forms of recycling in production planning cf. Klingelhöfer (2000): 252-305, 450-474.

$$(2.8) \qquad x^{outs}_{\nu,\omega} = \left(1 - \sum_{\mu=1}^{m} rec_{\nu\omega,\mu\omega}\right) \cdot x_{\nu,\omega} = \left(1 - \sum_{\mu=1}^{m} rec_{\nu\omega,\mu\omega}\right) \cdot \sum_{\beta=1}^{q} x^{B,\beta}_{\nu,\omega} \cdot \lambda^{\beta}$$

With

$$0 \le rec_{\nu\omega,\omega} = \sum_{\mu=1}^{m} rec_{\nu\omega,\mu\omega} = const. = rec_{\nu} \le 1 \quad \forall \nu \in \{1;\ldots;n\},\ \forall \omega \in \{1;\ldots;\Omega\}$$

(because entire objects x_{ν} as a bundle of their components $x_{\nu,\omega}$ are recycled), and

$$(2.9) \qquad r^{outs}_{\mu,\omega} = r_{\mu,\omega} - \sum_{\nu=1}^{n} rec_{\nu\omega,\mu\omega} \cdot x_{\nu,\omega} = \sum_{\beta=1}^{q} r^{B,\beta}_{\mu,\omega} \cdot \lambda^{\beta} - \sum_{\nu=1}^{n} \left(rec_{\nu\omega,\mu\omega} \cdot \sum_{\beta=1}^{q} x^{B,\beta}_{\nu,\omega} \cdot \lambda^{\beta} \right)$$
$$= \sum_{\beta=1}^{q} \left(r^{B,\beta}_{\mu,\omega} - \sum_{\nu=1}^{n} rec_{\nu\omega,\mu\omega} \cdot x^{B,\beta}_{\nu,\omega} \right) \cdot \lambda^{\beta}$$

Normally, entire objects are recycled; nevertheless, since components of several outputs can replace components of several different inputs, it is necessary to distinguish between

- On the one hand, objects (obj) for realising the cycle and its restrictions (and as well for object-related production and environmental constraints), and
- On the other hand, the recycled components (comp) for the components to be recycled (and as well for other, component-related production and environmental constraints).

Then, an *investment I, in recycling technologies* for process q (w.l.o.g.) has the following effects:

- The input-/output vector $\underline{\varphi}^{q}$ of process q changes to $\underline{\varphi}^{outs,I}$ of the inputs and outputs directly obtained from or delivered to the outside.
- Sometimes, process I can be used with different recycling quotes. Therefore, Ik denotes its partial processes with constant recycling quotes $0 \le rec^{Ik}_{\mu\nu} \le 1$.
- We have to consider costs $p^{Rec,Ik}_{\nu}$ for recycling outputs x_{ν}.
- Recycling may be restricted, and production and environmental constraints have to take into account the recycled quantities.

Therefore,

- for the *contribution margin* CM of the new process I we obtain instead of (2.5):

$$(2.10) \qquad CM(\underline{\varphi}^{I}) = \sum_{k} (\underline{p} - \underline{t})' \cdot \underline{\varphi}^{Ik} = \sum_{k} \left(\sum_{\varepsilon=1}^{m+n} (p_{\varepsilon} - t_{\varepsilon}) \cdot \varphi^{B,outs,Ik,obj}_{\varepsilon} + \sum_{\nu=1}^{n} p^{Rec,Ik}_{\nu 0} \cdot rec^{Ik}_{\nu} \cdot x^{B,Ik,obj}_{\nu} \right) \cdot \lambda^{Ik}_{0},$$

- and the Γ *production and environmental restrictions* (2.3) will be replaced by:

$$(2.11) \qquad \sum_{\beta=1}^{q-1} \sum_{\varepsilon=1}^{m+n} a_{\varepsilon\gamma 1} \cdot \varphi^{B,\beta,obj}_{\varepsilon} \cdot \lambda^{\beta} + \sum_{k} \sum_{\varepsilon=1}^{m+n} a_{\varepsilon\gamma 1} \cdot \varphi^{B,outs,Ik,obj}_{\varepsilon} \cdot \lambda^{Ik} \le b_{\gamma 1}$$

$$\forall \gamma 1 \in \{1; 2; \ldots; \Gamma_{1}\}$$

$$(2.12)\quad \sum_{\beta=1}^{q-1}\sum_{\varepsilon=1}^{m+n}\sum_{\omega=1}^{\Omega} a_{\varepsilon,\omega,\gamma 2}\cdot\varphi_{\varepsilon,\omega}^{B,\beta,comp}\cdot\lambda^{\beta}+\sum_{k}\sum_{\varepsilon=1}^{m+n}\sum_{\omega=1}^{\Omega} a_{\varepsilon,\omega,\gamma 2}\cdot\varphi_{\varepsilon,\omega}^{B,outs,Ik,comp}\cdot\lambda^{Ik}\le b_{\gamma 2}$$

$$\forall\ \gamma 2\in\{1;2;\ldots;\Gamma_2\}$$

2.3 Model for the Financial Valuation of Investments into Recycling Technologies

According to section 0, the first step to assessing the degree of profitability of an investment on imperfect markets under uncertainty, the basic programme, calculates the maximum value of the situation without realising this investment. The maximum value may be operationalised by maximising the sum SWW of weighted withdrawals $w_s \cdot W_s$ subject to the constraints of investment and production, where $s \in \boldsymbol{S} = \{0; 1; 2; \ldots; S\}$ denotes the present state 0 and the S future states and the weights w_s express the decision maker's individual relative preferences for payments in the regarded states.[8] Deriving the constraint system, we have to consider the previously mentioned fact that investments in recycling technologies affect production. Therefore, it is necessary to integrate contribution margins, production constraints and the payments resulting from environmental policy. While the production constraints become directly part of the constraint system, the contributions margins CM according to (2.5) modify the investment programme's liquidity constraints: liquidity must be guaranteed with respect to all the payments resulting from production and environmental policy (e.g. taxes), z_{js} from the other projects inv_j (e.g. credits or loans), the payments uz_s which are independent from production quantities and the investment programme (e.g. additional individual deposits, fixed rents, taxes or fees determined in former periods, determined payments resulting from objects realised in former periods), and the withdrawals W_s; otherwise the company becomes insolvent. Thus, we receive the following basic programme as a linear programming problem:

$$(2.13)\quad \text{max. SWW},\qquad SWW := \sum_{s=0}^{S} w_s\cdot W_s$$

Subject to:

Liquidity constraints (capital budget constraints) for the S+1 states s (cp. (2.5)):

$$-\sum_{j=1}^{J} z_{js}\cdot inv_j-\sum_{\beta=1}^{q}\sum_{\varepsilon=1}^{m+n}\left(p_{\varepsilon s}-t_{\varepsilon s}\right)\cdot\varphi_{\varepsilon}^{B,\beta}\cdot\lambda_s^{\beta}+W_s\ \le\ uz_s\qquad \forall s\in\boldsymbol{S}$$

Γ_s production and environmental constraints γ for the S+1 states s (cp. (2.3)):[9]

$$\sum_{\beta=1}^{q}\sum_{\varepsilon=1}^{m+n} a_{\varepsilon\gamma 1s}\cdot\varphi_{\varepsilon}^{B,\beta,obj}\cdot\lambda_s^{\beta}\le b_{\gamma 1s}\qquad \forall\gamma 1\in\{1;\ 2;\ \ldots;\ \Gamma_{1s}\}\qquad \forall s\in\boldsymbol{S}$$

$$\sum_{\beta=1}^{q}\sum_{\varepsilon=1}^{m+n}\sum_{\omega=1}^{\Omega} a_{\varepsilon,\omega,\gamma 2s}\cdot\varphi_{\varepsilon,\omega}^{B,\beta,komp}\cdot\lambda_s^{\beta}\le b_{\gamma 2s}\qquad \forall\gamma 2\in\{1;\ 2;\ \ldots;\ \Gamma_{2s}\}\qquad \forall s\in\boldsymbol{S}$$

8 Although, at first sight, this seems to be similar to using expected values, weighting the payments of each possible state does not imply considering probabilities and, therefore, the sum of weights does not have to equal 1.

9 Of course, the constraints in the basic programme can be object and component related as well.

q activity level constraints for the S+1 states s:

$$\lambda_s^{\beta} \le \lambda_s^{\beta,\max} \qquad \forall \beta \in \{1; 2; ..., q\} \quad \forall s \in \boldsymbol{S}$$

Restrictions of quantity of J other investment objects and financial transactions:

$$\text{inv}_j \le \text{inv}_j^{\max} \qquad \forall j \in \{1, ..., J\}$$

Non-negativity conditions:

$$\text{inv}_j,\ \lambda_s^{\beta}, W_s \ge 0 \qquad \forall j \in \{j = 1; ...; J\} \quad \forall \beta \in \{1; ...; q\} \quad \forall s \in \boldsymbol{S}.$$

Using the known solution of the basic programme (2.13), the *valuation programme* calculates the maximum payable price p_I which can be paid for an investment I in recycling technologies for process q (w.l.o.g.) under the condition that the investor's utility may not be lower than in the basic programme (*minimum withdrawal constraint*). Besides this different objective function VAL, it exhibits nearly the same structure as the basic programme. However, we have to consider a few changes regarding investment I:

- In addition to the basic programme we have to take into account all the activity-level-dependent and -independent payments caused by this investment. This means that we have to consider not only the adjusted contribution margins according to (2.10) instead of (2.5), but also the price p_I of the investment and other activity-level-independent payments z_{Is} (e.g. for its installation).
- If process I can be used with different recycling quotes, its partial processes Ik denote its use with constant recycling quotes.
- The *production and environmental restrictions* consider the needs for realising the cycle as well as the recycled object and component quantities.
- A minimum withdrawal constraint ensures that the utility (= sum of weighted withdrawals) of the new investment programme (i.e. the *valuation programme*) is not less than before (= in the optimal solution SWW^{opt} of the basic programme).

Then, the valuation programme results as follows:

(2.14) $\max.\ VAL; \quad VAL := p_I$

Subject to:

Liquidity constraints (capital budget constraints) for the S+1 states s (cp. (2.10)):

$$-\sum_{j=1}^{J} z_{j0} \cdot \text{inv}_j - \sum_{\beta=1}^{q-1} \sum_{\varepsilon=1}^{m+n} (p_{\varepsilon 0} - t_{\varepsilon 0}) \cdot \varphi_{\varepsilon}^{B,\beta,obj} \cdot \lambda_0^{\beta} + W_0 + p_I$$
$$\le uz_0 + z_{I0} + \sum_k \left(\sum_{\varepsilon=1}^{m+n} (p_{\varepsilon 0} - t_{\varepsilon 0}) \cdot \varphi_{\varepsilon}^{B,outs,Ik,obj} + \sum_{\nu=1}^{n} p_{\nu 0}^{Rec,Ik} \cdot rec_{\nu}^{Ik} \cdot x_{\nu}^{B,Ik,obj} \right) \cdot \lambda_0^{Ik}$$

$$-\sum_{j=1}^{J} z_{js} \cdot \text{inv}_j - \sum_{\beta=1}^{q-1} \sum_{\varepsilon=1}^{m+n} (p_{\varepsilon s} - t_{\varepsilon s}) \cdot \varphi_{\varepsilon}^{B,\beta,obj} \cdot \lambda_s^{\beta} + W_s$$
$$\le uz_s + z_{Is} + \sum_k \left(\sum_{\varepsilon=1}^{m+n} (p_{\varepsilon s} - t_{\varepsilon s}) \cdot \varphi_{\varepsilon}^{B,auß,Ik,obj} + \sum_{\nu=1}^{n} p_{\nu s}^{Rec,Ik} \cdot rec_{\nu}^{Ik} \cdot x_{\nu}^{B,Ik,obj} \right) \cdot \lambda_s^{Ik}$$
$$\forall s \in \boldsymbol{S} \setminus \{0\}$$

$\Gamma_{1s} + \Gamma_{2s}$ production and environmental constraints γ1 and γ2 for objects and components (including also the restrictions for realising the cycle) for the S+1 states s (cp. (2.11) and (2.12)):

$$\sum_{\beta=1}^{q-1} \sum_{\varepsilon=1}^{m+n} a_{\varepsilon\gamma 1s} \cdot \varphi_{\varepsilon}^{B,\beta,obj} \cdot \lambda_s^{\beta} + \sum_{k} \sum_{\varepsilon=1}^{m+n} a_{\varepsilon\gamma 1s} \cdot \varphi_{\varepsilon}^{B,outs,Ik,obj} \cdot \lambda_s^{Ik} \leq b_{\gamma 1s}$$

$$\forall \gamma 1 \in \{1;\ 2;\ \ldots;\ \Gamma_{1s}\} \qquad \forall s \in \boldsymbol{S}$$

$$\sum_{\beta=1}^{q-1} \sum_{\varepsilon=1}^{m+n} \sum_{\omega=1}^{\Omega} a_{\varepsilon,\omega,\gamma 2s} \cdot \varphi_{\varepsilon,\omega}^{B,\beta,comp} \cdot \lambda_s^{\beta} + \sum_{k} \sum_{\varepsilon=1}^{m+n} \sum_{\omega=1}^{\Omega} a_{\varepsilon,\omega,\gamma 2s} \cdot \varphi_{\varepsilon,\omega}^{B,outs,Ik,comp} \cdot \lambda_s^{Ik} \leq b_{\gamma 2s}$$

$$\forall \gamma 2 \in \{1;\ 2;\ \ldots;\ \Gamma_{2s}\} \qquad \forall s \in \boldsymbol{S}$$

Minimum withdrawal constraint (ensuring that the utility is not less than before):

$$-\sum_{s=0}^{S} w_s \cdot W_s \leq -SWW^{opt}$$

q – 1 activity level constraints for the unchanged processes for the S+1 states s:

$$\lambda_s^{\beta} \leq \lambda_s^{\beta,max} \qquad \forall \beta \in \{1;\ 2;\ \ldots;\ q-1\} \qquad \forall s \in \boldsymbol{S}$$

Activity level constraints for process I allowing for different recycling quotes for the S+1 states s:

$$\sum_{k} \lambda_s^{Ik} \leq \lambda_s^{I,max} \qquad \forall s \in \boldsymbol{S}$$

Restrictions of quantity of other investment objects and financial transactions:

$$inv_j \leq inv_j^{max} \qquad \forall j \in \{1,\ \ldots,\ J\}$$

Non-negativity conditions:

$$\lambda_s^{\beta},\ \lambda_s^{Ik}, inv_j, W_s \geq 0 \qquad \forall \beta \in \{1;\ 2;\ \ldots,\ q-1\} \qquad \forall k \qquad \forall j \in \{1,\ \ldots,\ J\} \qquad \forall s \in \boldsymbol{S}$$

$$p_I \in \mathbb{R}$$

Besides the maximum payable price p_I for the investment and the activity levels λ_s^{Ik}, for using the partial processes Ik of the cleaned process I with constant recycling quotes (instead of λ_s^{q} in the basic programme), the basic programme and the valuation programme contain the same decision variables: the activity levels λ_s^{β} of the q – 1 old processes (before introducing recycling), the quantities inv_j of the other investment objects and financial transactions, and the withdrawals W_s. We find that the contribution margins (2.5) resp. (2.10) are part of the liquidity constraints, (2.6)-(2.9) deliver the object quantities $\varphi_{\varepsilon}^{B,outs,Ik,obj}$ and their component quantities $\varphi_{\varepsilon,\omega}^{B,outs,Ik,comp}$, and (2.3) respectively (2.11)-(2.12) are constraints of either programme.

3. Tightening Environmental Policy, Values and the Willingness to Invest in Recycling Technologies

3.1 (Corrected) Net Present Values and the Maximum Payable Price for the Investment

In the case of the existence of a finite positive solution of the basic programme and the valuation programme, according to duality theory of linear programming, we obtain information about the determinants of the maximum payable price by inserting the optimal solution to the dual problem into the optimal solution to the primal one. Using complementary slackness conditions enables us to interpret the mathematical formula in an economic manner:

By introducing the dual variables

- l_s for the liquidity constraints (and the resulting endogenous discount factors $\rho_{s,0} = l_s/l_0$ to discount payments in state s to state 0),
- $\pi_{\gamma 1s}$ and $\pi_{\gamma 2s}$ for the production and environmental constraints (including the restrictions for realising the cycle as well as to the recycled object and component quantities),
- ζ_s^{β} and ζ_s^{I} for the activity level constraints and
- ξ_j for the quantity restrictions of the other investment objects and financial transactions,

and dividing the dual constraints of the decision variables by l_0, we obtain the **(corrected) net present values NPV$^{\text{(corr)}}$** of:[10]

- Using the partial process Ik of the cleaned process I with constant recycling quotes in the states s:

$$(3.1)\quad NPV_{\lambda,Iks}^{corr} := \underbrace{\left(\sum_{\varepsilon=1}^{m+n}(p_{\varepsilon s}-t_{\varepsilon s})\cdot\varphi_{\varepsilon}^{B,outs,Ik,obj}+\sum_{\nu=1}^{n}p_{\nu s}^{Rec,Ik}\cdot rec_{\nu}^{Ik}\cdot x_{\nu}^{B,Ik,obj}\right)\cdot\frac{l_s}{l_0}}_{NPV_{\lambda,Iks}}$$

$$-\underbrace{\left(\sum_{\gamma 1=1}^{\Gamma_{1s}}\sum_{\varepsilon=1}^{m+n}a_{\varepsilon\gamma 1s}\cdot\varphi_{\varepsilon}^{B,outs,Ik,obj}\cdot\frac{\pi_{\gamma 1s}}{l_0}+\sum_{\gamma 2=1}^{\Gamma_{2s}}\sum_{\varepsilon=1}^{m+n}\sum_{\omega=1}^{\Omega}a_{\varepsilon,\omega,\gamma 2s}\cdot\varphi_{\varepsilon,\omega}^{B,outs,Ik,comp}\cdot\frac{\pi_{\gamma 2s}}{l_0}\right)}_{Correction}$$

$$\leq \frac{\zeta_s^{I}}{l_0}\qquad\forall k\qquad\forall s\in\boldsymbol{S}$$

[10] Except for (3.1), all the following (corrected) net present values NPV are able to be derived from both the basic programme (2.13) and the valuation programme (2.14). However, the dual variables, and consequently the endogenous discount factors $\rho_{s,0} = l_s/l_0$ to discount payments in state s to state 0, normally differ between the two programmes. In the case of an existing finite positive solution $p_I > 0$ of both the primal and dual valuation programme in particular, we can deduce $l_0 = 1$ and, therefore, $\rho_{s,0} = l_s$ for all the (corrected) NPVs derived from the valuation programme. This results for $p_I > 0$ from the complementary slackness condition $p_I \cdot (1 - l_0) = 0$.

$NPV^{corr}_{\lambda,Iks}$:= discounted contribution margin (incl. recycling costs)
– discounted monetary equivalent of the required capacity of the production and environmental constraints (object and component related)

- Using the q (in the valuation programme: q – 1) other processes β in the states s:

$$(3.2)\quad NPV^{corr}_{\lambda,\beta s} := \underbrace{\sum_{\varepsilon=1}^{m+n}\left(p_{\varepsilon s}-t_{\varepsilon s}\right)\cdot\varphi_{\varepsilon}^{B,\beta,obj}\cdot\frac{l_s}{l_0}}_{NPV_{\lambda,\beta s}}$$

$$-\underbrace{\left(\sum_{\gamma 1=1}^{\Gamma_{1s}}\sum_{\varepsilon=1}^{m+n}a_{\varepsilon\gamma 1s}\cdot\varphi_{\varepsilon}^{B,\beta,obj}\cdot\frac{\pi_{\gamma 1s}}{l_0}+\sum_{\gamma 2=1}^{\Gamma_{2s}}\sum_{\varepsilon=1}^{m+n}\sum_{\omega=1}^{\Omega}a_{\varepsilon,\omega,\gamma 2s}\cdot\varphi_{\varepsilon,\omega}^{B,\beta,comp}\cdot\frac{\pi_{\gamma 2s}}{l_0}\right)}_{Correction}$$

$$\leq\frac{\zeta_s^{\beta}}{l_0}\qquad\forall\beta\in\{1;\ 2;\ \ldots,\ q-1\}\qquad\forall s\in\boldsymbol{S}$$

- Realisation of other investment objects and financial transactions j:

$$(3.3)\quad NPV_{inv,j} := \sum_{s=0}^{S}z_{js}\cdot\frac{l_s}{l_0}=\sum_{s=0}^{S}z_{js}\cdot\rho_{s,0}\ \leq\ \frac{\xi_j}{l_0}$$

$NPV_{inv,j}$:= discounted payments

Since according to (3.1), all the different NPV^{corr} of *all* partial processes k of the new process I are restricted by the *same* dual variable ζ_s^I of the *common* activity level constraints for all the partial processes Ik of process I with different recycling quotes $rec^{Ik}_{\mu\nu}$, and since ζ_s^I is independent of the intervals k and can only be positive if the corresponding primal constraint $\sum_k \lambda_s^{Ik}\leq\lambda_s^{I,max}$ is satisfied as an equation, it defines the corrected net present value of *all* these partial processes Ik in state s together. Therefore, we can deduce the following for the partial processes employed used in the optimal solution of the valuation programme:

- *Either only one* partial process Ik of process I has a positive corrected net present value (meaning that process I is not divided into partial processes, but is used only with *one* constant recycling quote $rec^{Ik}_{\mu\nu}$ at the activity level $\lambda_s^{Ik}=\lambda_s^{I,max}$ in state s);

- *Or* – in the case of more than one partial process with $NPV^{corr}_{\lambda,Iks}>0$ – *all* chosen partial processes Ik of one process I have the *same positive corrected net present value which is also the corrected net* *present value of the whole process I*, and the sum of all activity levels λ_s^{Ik} reaches exactly the maximum activity level $\lambda_s^{I,max}$:[11]

$$\text{(3.4)}\quad NPV_{\lambda,Is}^{corr} = NPV_{\lambda,Iks}^{corr} = \zeta_s^I \qquad \forall\, NPV_{\lambda,Iks}^{korr} > 0$$

It is possible to understand this outcome, since the net present value is a *partial model* calculated by using *marginal values*. Similar to communicating tubes where the pressure is equal in each of them, it does not matter *which* of the used partial processes Ik (partially) replaces the best opportunity or which of the used partial processes Ik is (partially) replaced by the best opportunity – the result is the same (and therefore even the *same for the whole process I*) because it is always the *same* best opportunity.

Using these results, it is also possible to obtain the desired information about the determinants of the maximum payable price. According to the duality theory of linear programming in case of an existing finite positive solution, the optimal solutions of the primal and the dual problem are equal. Therefore, the optimal solution of the dual problem of the valuation programme provides information concerning the price ceiling.

Furthermore, because the withdrawal constraint is part of the constraint system of the valuation programme, it also takes the optimal solution SWW^{opt} of the basic programme into account. Ergo, in case of an existing finite positive solution of this programme, the optimal solution of its dual can substitute SWW^{opt} in the minimum withdrawal constraint of the valuation programme. Consequently, the equation of the price ceiling, which results from the optimal solution of the dual valuation programme, contains several corresponding dual variables of both programmes.

Nevertheless, using the (corrected) net present values (3.1)-(3.4) allows one to interpret this equation in an economic context. If one of the primal variables λ_s^{Ik} and λ_s^{β} of the activity levels or inv_j of the other investment objects and financial transactions is positive, then, by reason of "complementary slackness", the corresponding inequality (3.1)-(3.4) is satisfied as an equation. Therefore, we may use the (corrected) net present values $NPV^{(corr)}$ to substitute the corresponding *positive* dual variables ζ_s^I, ζ_s^{β} and ξ_j of the valuation (VP) and the basic programme (BP).[12] Introducing the dual variable δ of the withdrawal constraint, we then obtain the price ceiling for an investment in recycling technologies as a sum of several (partly corrected) net present values:[13]

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11 This (possibly confusing) result can be clarified from a mathematical point of view, since

- On the one hand (3.1), by reason of "complementary slackness" to λ_s^{Ik}, must be satisfied as an equation for each partial process Ik employed and
- On the other hand, by reason of "complementary slackness", ζ_s^I can only be positive if process I is used at its maximum activity level $\lambda_s^{I,max}$. Nevertheless, production with several recycling quotes $rec_{\mu\nu}^{Ik}$ can simply be enforced by non-monetary restrictions of production (e.g. by environmental constraints), but need not be.

12 Compare footnote 10.

13 The dual variable δ of the withdrawal constraint calculates the value of a marginal increase in SWW^{opt} referring to the objective function of the valuation programme (the price ceiling).

$$(3.5)\quad p_I^{opt} = \underbrace{\sum_{s=0}^{S} z_{Is}\cdot l_s^{VP}}_{I} + \underbrace{\sum_{s=0}^{S} \lambda_s^{I,max}\cdot \zeta_s^{VP,I}}_{II} + \underbrace{\sum_{s=0}^{S} uz_s\cdot\left(l_s^{VP}-\delta\cdot l_s^{BP}\right)}_{III}$$

$$+\underbrace{\sum_{s=0}^{S}\left(\sum_{\gamma1=1}^{\Gamma_{1s}^{VP}} b_{\gamma1s}^{VP}\cdot\pi_{\gamma1s}^{VP} + \sum_{\gamma2=1}^{\Gamma_{2s}^{VP}} b_{\gamma2s}^{VP}\cdot\pi_{\gamma2s}^{VP} - \sum_{\gamma1=1}^{\Gamma_{1s}^{BP}} b_{\gamma1s}^{BP}\cdot\delta\cdot\pi_{\gamma1s}^{BP} - \sum_{\gamma2=1}^{\Gamma_{2s}^{BP}} b_{\gamma2s}^{BP}\cdot\delta\cdot\pi_{\gamma2s}^{BP}\right)}_{IV}$$

$$+\underbrace{\sum_{s=0}^{S}\lambda_s^{\beta,max}\cdot\left(\sum_{\beta=1}^{q-1}\zeta_s^{VP,\beta}-\sum_{\beta=1}^{q}\delta\cdot\zeta_s^{BP,\beta}\right)}_{V} + \underbrace{\sum_{j=1}^{J} inv_j^{max}\cdot\left(\xi_j^{VP}-\delta\cdot\xi_j^{BP}\right)}_{VI}$$

$$= \underbrace{\sum_{s=0}^{S} z_{I,s}\cdot\rho_{s,0}^{VP}}_{(I)} + \underbrace{\sum_{NPV_{\lambda,Is}^{corr,VP}>0}\lambda_s^{I,max}\cdot NPV_{\lambda,Is}^{corr,VP}}_{(II)} + \underbrace{\sum_{s=0}^{S} uz_s\cdot\left(\rho_{s,0}^{VP}-\delta\cdot l_s^{BP}\right)}_{(III)}$$

$$+\underbrace{\sum_{s=0}^{S}\left(\sum_{\gamma1=1}^{\Gamma_{1s}^{VP}} b_{\gamma1s}^{VP}\cdot\pi_{\gamma1s}^{VP} + \sum_{\gamma2=1}^{\Gamma_{2s}^{VP}} b_{\gamma2s}^{VP}\cdot\pi_{\gamma2s}^{VP} - \delta\cdot\sum_{\gamma1=1}^{\Gamma_{1s}^{BP}} b_{\gamma1s}^{BP}\cdot\pi_{\gamma1s}^{BP} - \delta\cdot\sum_{\gamma2=1}^{\Gamma_{2s}^{BP}} b_{\gamma2s}^{BP}\cdot\pi_{\gamma2s}^{BP}\right)}_{(IV)}$$

$$+\underbrace{\sum_{NPV_{\lambda,\beta s}^{corr,VP}>0}\lambda_s^{\beta,max}\cdot NPV_{\lambda,\beta s}^{corr,VP} - \delta\cdot\sum_{NPV_{\lambda,\beta s}^{corr,BP}>0}\lambda_s^{\beta,max}\cdot l_0^{BP}\cdot NPV_{\lambda,\beta s}^{corr,BP}}_{(V)}$$

$$+\underbrace{\sum_{NPV_{inv,j}^{VP}>0} inv_j^{max}\cdot NPV_{inv,j}^{VP} - \delta\cdot\sum_{NPV_{inv,j}^{BP}>0} inv_j^{max}\cdot l_0^{BP}\cdot NPV_{inv,j}^{BP}}_{(VI)}$$

p_I^{opt} = NPV of all activity-level-independent payments of the investment in recycling technologies (without p_I^{opt}) (I)

+ NPV^{corr} of operating the profitable new processes at their maximum activity levels $\lambda_s^{I,max}$ (II)
+ NPV of the changes between VP and BP regarding the valuation of the payments that are independent from production quantities and from the investment programme (III)
+ NPV of the changes between VP and BP regarding the monetary equivalents of the production and environmental constraints (incl. the restrictions for realising the cycle) (IV)
+ NPV^{corr} of the changes between VP and BP regarding the use of the other production processes β (V)

+ NPV of the changes between VP and BP regarding the realised other investment objects and financial transactions (VI)

This maximum payable price for an investment in recycling technologies depends on the (corrected) NPVs of its payments and on the interdependencies occurring because of changes in the optimal investment programme. Under uncertainty it includes the *discounted payments of all states* – even those which, in fact, will not occur.

3.2 Tightening Environmental Policy and the Willingness to Invest in Recycling Technologies

Examining term (IV) of Eq. (3.5) shows that *environmental constraints* restrict production in the same way as any other constraint. Using sensitivity analysis, right-hand-side ranging can assess the impact of changes of the allowed quantities on the maximum payable price for an investment in recycling technologies in the same way as the impact of other production constraints: if the constraint is valid for production after the investment in the same way as before and, if a variation of the allowed quantities neither affects the structure of the optimal solution of the basic programme nor of the valuation programme, then p_I^{opt} changes at the same amount as term (IV).[14]

Furthermore, the economic interpretation of the terms (II) and (V) of (3.5) in connection with (3.1) and (3.2) demonstrates that *environmental taxes and subsidies* affect the *price ceiling* for recycling technology investments via the corrected net present values of the (partial) processes. The known results of environmental economics (e.g. the effect of *Pigou* taxes) are confirmed for a single investment. Nevertheless, sensitivity analysis of the left-hand-side coefficients of both the basic programme and the valuation programme demonstrates that these instruments may be *counterproductive, even for environmentally beneficial recycling investments*. The maximum payable price p_I^{opt} may increase, decline or remain constant if taxes or subsidies change. There are several reasons for this:

- Taxes and subsidies are coefficients for a decision variable which is a basis or non-basis variable. This may differ between the basic programme and the valuation programme.
- The minimum withdrawal constraint connects the basic and the valuation programme.
- Negative (corrected) NPVs are not part of the optimal solution: neither in the basic nor in the valuation programme.

Therefore, (over-) compensation of the effects of tax/subsidy changes between the two programmes is possible. To give an example, rising taxes may initially ameliorate the conditions of recycling in comparison to the older processes of the basic programme (with the result that an investment in recycling technologies would be encouraged). However, if taxes continue to rise, parts of the optimal solution of the basic programme may lose their profitability faster than in the valuation programme. Since processes and other objects with (corrected) NPVs which are becoming negative will no longer be chosen in the optimal solution, they will not diminish SWW^{opt} any longer. The optimal solution of the dual valuation programme (and consequently p_I^{opt}) may then decline. In particular, this situation may be found when production is stopped in the situation without recycling and, therefore, is no longer affected by rising taxes (with the consequence that harm to the environment will no longer occur), while it still delivers a positive

[14] If a variation of the allowed quantities affects the structure of the basic and/or the valuation programme as well, then an influence might also exist, especially via the correction terms to the corrected net present values (3.1) and (3.2), and, therefore, via the terms (II) and (V) of (3.5); sometimes even via other terms as well.

contribution margin when using recycling technologies. Thus, in the valuation programme there would still be production to cover fixed costs and, consequently, there would be still *harm to the environment*, while *profitability* would be more and more affected by higher taxes.

Accordingly, a tightened scheme of environmental taxes may sometimes even lead to the paradoxical situation that: 1. it is unprofitable to invest in recycling technologies, 2. the marginal incentive to invest is negative, and 3. the danger/harm to the environment even increases. Or, if viewed the other way round, situations may even exist where subsidies on environmentally harmful substances lead to environmental protection.

Since a system of tradable permits (e.g. similar to tradable emissions allowances) exhibits similarities to both environmental constraints as well as – with regard to the permit trade e.g. at rising prices – taxes/subsidies, it should be stated that the effects on the price ceiling for an investment in recycling technologies described just above, may occur there as well.[15]

4. Example: Effects of Increasing Environmental Taxes on the Willingness to Invest in Recycling Technologies

Given an imperfect market under certainty with lending opportunity at the interest rate i_L = 50% (investment object inv_L), but without the possibility of borrowing money, an investor with the initial amount of cash uz_0 = 50 [$] in t = 0 wants to maximise his withdrawals in t =1.[16] Producing with the basic activities

$$\underline{\varphi}^{B,old1} = \left(r_1^{B,old1}, r_2^{B,old1}; x_1^{B,old1}, x_2^{B,old1}\right)' = (4, 5; 8, 10)' \quad \text{and}$$

$$\underline{\varphi}^{B,old2} = \left(r_1^{B,old2}, r_2^{B,old2}; x_1^{B,old2}, x_2^{B,old2}\right)' = (10, 4; 10, 8)'$$

at the activity level λ^{old} = 1 with the current prices $\underline{p}$ = $(p_{r1}; p_{r2}; p_{x1}; p_{x2})'$ = (–4; –2; 10; 0)´ enables him to receive the following contribution margins CM:

$$\text{(4.1)} \qquad CM(\lambda^{old1} = 1) = \underline{p}' \cdot \underline{\varphi}^{B,old1} \cdot 1 = -4 \cdot 4 - 2 \cdot 5 + 10 \cdot 8 + 0 \cdot 10 = 54 \text{ [\$]}$$

$$\text{(4.2)} \qquad CM(\lambda^{old2} = 1) = \underline{p}' \cdot \underline{\varphi}^{B,old2} \cdot 1 = -4 \cdot 10 - 2 \cdot 4 + 10 \cdot 10 + 0 \cdot 8 = 52 \text{ [\$]}$$

Now, the government wants to establish a tax system for output 2. Therefore the producer considers an investment in recycling for process old1. This will change $\underline{\varphi}^{B,old1}$ to the vector $\underline{\varphi}^{B,outs,I}$ = $\left(r_1^{B,outs,I}, r_2^{B,outs,I}; x_1^{B,outs,I}, x_2^{B,outs,I}\right)'$ = (3, 3; 7, 7)´ of inputs and outputs, which the combination of the cleaned process I and recycling directly obtains from outside or delivers to the outside.

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[15] For a derivation cf. analogously Klingelhöfer (2006): 211-242, 255-263.

[16] The reader may consider that these assumptions are not very realistic. However, similar results may be derived with other numbers, a longer time horizon, a different structure for the desired withdrawals, more complex assumptions regarding the borrowing and lending conditions in the market, and by introducing more states to deal with uncertainty as well. The purpose of choosing i_L = 50% and not allowing for credits, is merely to simplify the example as much as possible, while still focussing on demonstrating the main outcomes, which were derived in chapter 3.

This means: recycling of 3 [QU] (quantity units) of output 2 reduces the quantity needed of input 1 by 1 [QU] and the quantity needed of input 2 by 2 [QU]. From realising recycling, there $p_2^{Rec,I}$ = –1 [\$/QU] will accrue. Consequently, at the activity level λ^I = 1 after making the investment, the producer receives the contribution margin:

$$\text{(4.3)} \quad CM(\lambda^I = 1) = \underline{p}' \cdot \underline{\varphi}^{B,outs,I} \cdot 1 + p_2^{Rec,I} \cdot x_2^{B,Rec,I} \cdot 1$$

$$= (-4 \cdot 3 - 2 \cdot 3 + 10 \cdot 7 + 0 \cdot 7) + (-1 \cdot 2) = 50 \ [\$]$$

In all cases, with and without recycling, the maximum activity levels are $\lambda^{old1,max} = \lambda^{old2,max} = \lambda^{I,max}$ = 10. For the installation of recycling and the change of production in t = 0, the investor has to spend $z_{I,0}$ = –50 [\$]. Then, even without employing the simplex algorithm, we can calculate the *maximum utility* (the maximum sum of weighted withdrawals) of the *basic programme* by compounding with the lending rate i_L = 50% – e.g., if output 2 is not object to taxes, i.e. if $t_{x2} = t_{x20} = t_{x21} = 0$ [\$/QU]:[17]

$$\text{(4.4)} \quad SWW^{opt} = (50 + 54 \cdot 10 + 52 \cdot 10) \cdot 1.5 + (54 \cdot 10 + 52 \cdot 10) = 2{,}725 \ [\$]$$

To realise these withdrawals in t = 1, the investor needs to use the processes at their (maximum) activity levels $\lambda_t^{old1} = \lambda_t^{old2} = \lambda^{old1,max} = \lambda^{old2,max}$ = 10 in t = 0 and in t = 1. He transfers the money earned in t = 0 to t = 1 by using the lending opportunity inv_L. Hence, the shadow prices of the liquidity constraints are l_0^{BP} = 1.5 and l_1^{BP} = 1 (money in t = 1 can be withdrawn directly).

For this initial situation, it is obvious that the investment is not sensible: at both points in time, the resulting contribution margin is smaller (50 [\$] instead of 54 [\$]), and the initial amount of cash (plus the interest) for installing the recycling technology and changing production is lost. Thus, the maximum payable price p_I^{opt} for realising the investment is negative, i.e., the investor only installs recycling technologies if someone else pays for them. Solving the *valuation programme* confirms this result: p_I^{opt} = –116 2/3 [\$]. It can be proven by equation (3.5):

With δ = 2/3 (the basic programme maximises withdrawals in t = 1, but the valuation programme refers to t = 0), l_0^{VP} = 1 (more money in t = 0 allows for paying more for the investment) and l_1^{VP} = 1/1.5 = 2/3 (more money in t = 0 for less lending at i_L = 50%), we obtain from (3.5) if output 2 is not subject to taxes, i.e. if $t_{x2} = t_{x20} = t_{x21} = 0$ [\$/QU]:[18]

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[17] After 7 iterations, the simplex algorithm provides the optimal solution SWW^{opt} and the values for l_0^{BP} and l_1^{BP}. That (4.4) is true, can be confirmed by the following considerations: Because lending is not limited, inv_L is the marginal investment opportunity. Therefore, SWW^{opt} can be calculated by compounding the payments resulting from production (the contribution margins) and the initial amount of cash with i_L.

[18] The values for δ, l_0^{VP}, and l_1^{VP} are part of the optimal solution of the valuation programme that results after 7 dual simplex iterations. However, they can be proven by the given considerations in parentheses.

$$(4.5)\ p_I^{opt} = \underbrace{-50\cdot 1}_{(I)} + \underbrace{10\cdot 50\cdot\left(1+\frac{1}{1.5}\right)}_{(II)} + \underbrace{50\cdot\left(1-\frac{2}{3}\cdot 1.5\right)}_{(III)}$$

$$\underbrace{+10\cdot 52\cdot\left[\left(1+\frac{1}{1.5}\right)-\frac{2}{3}\cdot(1.5+1)\right]-10\cdot 54\cdot\frac{2}{3}\cdot(1.5+1)}_{(VI)}$$

$$= \mathbf{-116\frac{2}{3}}$$

Therefore, the investor has to produce at the maximum activity level $\lambda^{I,max} = \lambda^{old2,max} = 10$ at both points in time again. Lending the resulting contribution margin of 1,020 [$] in t = 0 together with the subvention $p_I^{opt} = -116\ 2/3$ [$] at the interest rate $i_L = 50\%$ allows for the same utility $SWW^{opt} = 2{,}725$ [$] of withdrawals as in the basic programme. However, rising taxes for output 2 change this solution: the net present values of the production in the terms (II) and (VI) of equation (3.5) will decline according to (3.1) and (3.2) – although (VI) faster than (II) due to more output 2. Depending on the taxes $t_{x2} = t_{x20} = t_{x21}$ on this output, we obtain the new optimal solutions SWW^{opt} of the basic programme and p_I^{opt} of the valuation programme as presented in Table 1:

Table 1: Optimal solutions of BP and VP with respect to the taxes on product 2

t_{x2}	SWW^{opt}	p_I^{opt}	Undesired output of x_2	
			without recycling	with recycling
0	2,725	–116 2/3	180	150
1	2,275	–66 2/3	180	150
2	1,825	–16 1/3	180	150
2 1/3	1,675	0	180	150
3	1,375	33 1/3	180	150
4	925	83 1/3	180	150
5	475	133 1/3	180	150
5,4	295	153 1/3	80	150
6	175	83 1/3	80	150
6,5	75	25	0	70
6 5/7	75	0	0	70
7	75	–33 1/3	0	70
7 1/7	75	–50	0	0
8	75	–50	0	0
9	75	–50	0	0

Since the lending opportunity is not limited and no additional constraint restricts production, the corrected net present values of the processes are equal to the discounted contribution margins, and the terms (IV) and (V) of (3.5) do not exist.

As may be expected, rising taxes t_{x2} affect the maximum payable price for the investment in recycling technologies, although not always in the politically desired way, as indicated in section 3.2. Starting from t_{x2} = 0 [$/QU], the contribution margins of production will decline in the basic programme as well as in the valuation programme. Since production with the cleaned process leads to less output than production without recycling, the contribution margin of the uncleaned process declines faster, and therefore, the *investment becomes increasingly more profitable*, reaching its break-even point at t_{x2} = 2 1/3 [$/QU] already. Now, the investor is willing to pay for it. Up to t_{x2} = 5,4 [$/QU], this advantage is growing, so that the investor is able to pay increasing amounts for the investment and still receives, at the least, the same sum of weighted withdrawals as in the situation where recycling is not installed.

For t_{x2} > 5,4 [$/QU], the contribution margin of uncleaned production, with process old1, is now too low to continue producing with $\lambda_t^{old1} > 0$. As a result, this part of production is stopped in the basic programme, and only production with old2 allows for SWW^{opt}. In the valuation programme, however, production with old2 as well as production with the cleaned process I is still advisable. Thus, since (in both situations) there is no difference in the use of process old2, while rising taxes t_{x2} still diminish contribution margins of production with I (without equivalent in the basic programme) – the *maximum payable price* p_I^{opt} for an investment in recycling technologies must *begin to fall*.

For t_{x2} > 6,5 [$/QU], production with old2 also becomes unprofitable, and the sum of weighted withdrawals SWW^{opt} remains constant (yet, the initial amount of cash uz_0 = 50 [$/QU] can be invested at the lending opportunity inv_L). For this reason, only production using the cleaned process I is taxed at rising rates t_{x2} at both points in time. Consequently, constant withdrawals in the situation without investment, together with decreasing contribution margins in the situation with investment, cause the *maximum payable price* p_I^{opt} for the recycling investment to *continue to decline*.

For t_{x2} > 6 5/7 [$/QU], the investment will even lose its profitability: though production with process I is still worthwhile because the contribution margins are still positive, they do not cover the activity-level-independent payments $z_{I,0}$ = –50 [$/QU] for the installation of recycling, and the change of production in t = 0. If finally t_{x2} > 7 1/7 [$/QU], there will not be any production in the valuation programme either. For this reason, the investor *will lose $z_{I,0}$ = –50 [$/QU] overall*.

Nevertheless, although rising environmental taxes in this example may lead the investment in recycling technologies to becoming unprofitable, it could be argued that environmental protection sometimes costs money. But even this *argument does not hold*: Starting at t_{x2} = 5.4 [$/QU], investing in recycling leads to *more undesired output* (cf. hatching in Table 1), and for 6 5/7 [$/QU] < t_{x2} < 7 1/7 [$/QU], it has a *negative outcome, not only in terms of profitability, but also for environmental protection* (cf. dark shading in Table 1). With other words: tightening of environmental policy may lead to counterproductive effects and missing the intended targets. Taking into account that Table 1 furnishes information on the maximum payable price for an investment in recycling technologies, but that the actual price to be paid will normally be greater than 0 [$/QU] (the difference between both therefore leads to the actual profitability of the investment)[19], this dark shaded area of negative outcome for both – the investment's profitability and environmental protection – will be even greater.

5. Conclusion

This paper has offered a two-step evaluation approach for investments in recycling technologies under imperfect market conditions with particular regard to the effects of environmental policy. Since recycling affects production, the payments required for a financial valuation have to be derived from production planning. This should consider that all the different components $x_{\nu,\omega}$ of the n inputs x_ν can principally replace the *same* components $r_{\mu,\omega}$ of each of the m outputs r_μ and that the amounts of each input component $r_{\mu,\omega}$ can be replaced by the *same* components $x_{\nu,\omega}$ of each output. With respect to the environment, production processes are characterised by joint production. Environmental policy may modify the contribution margins (such as taxes) and/or the constraint system. The model considers activity-level-dependent and -independent payments and handles the indivisibility of the investment in two steps.

Applying duality theory allows one to *exactly* identify the determinants of the price ceiling for an investment with regard to applied schemes of environmental policy and uncertainty. This price ceiling may be interpreted as a sum of (sometimes corrected) net present values. Information on probabilities, means and variances is not required. Surprisingly, if a process I can be used with different recycling quotes and if more than only one of its partial process Ik with constant recycling quotes is chosen, then *all* these partial processes have the *same* nonnegative corrected net present value, which is also the corrected net present value of the whole process I. (Thus, the corrected net present values of the partial processes are *not value additive.*)

Using sensitivity analysis, we have been able to show that tightening environmental policy does not always encourage environmentally beneficial investments such as recycling. In particular cases, e.g. increasing environmental taxes may even lead to the *paradoxical situation* that: 1. It is unprofitable to invest in environmental protection; 2. The marginal incentive to invest is negative and 3. The harm for the environment even increases.

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[19] Therefore, since the NPV of an investment in perfect markets shows how much an investor can gain in s = 0 by realising the investment and financing it at market conditions, this difference between the actual price to be paid and the maximum payable price (according to the investor's objective function and decision field) may be interpreted as an equivalent to the net present value NPV of an investment in perfect markets.

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