"It's all in the Mix!"
– Internalizing Externalities with R&D Subsidies and Environmental Liability[1]

Alfred Endres[*], Tim Friehe[**] and Bianca Rundshagen[***]

Discussion paper No 479

March 08, 2012

[1] The manuscript was revised while Alfred Endres was a visiting scholar at La Trobe University. This author is indebted to the Economics Department for its hospitality and to the University of Hagen for granting a sabbatical. Special thanks go to Joanna Poyago-Theotoky, La Trobe University, for numerous helpful suggestions.
* Corresponding Author:

University of Hagen, Department of Economics, Profilstr. 8, 58084 Hagen and University of Witten/Herdecke, Germany, e-mail: Alfred.Endres@FernUni-Hagen.de, phone: +49-2331-987-301, Fax: +49-2331-987-302.

** University of Konstanz, Department of Economics, Box D 136, 78457 Konstanz, Germany.

*** University of Hagen, Department of Economics, Profilstr. 8, 58084 Hagen, Germany.

Abstract

This is one of the "tales of two market failures": we consider a setting where firms generate environmental externalities and may invest into environmentally friendly technical change generating R&D spillovers. We analyse the joint use of environmental liability law and R&D subsidies to internalize the double externality. Two alternative liability rules are considered, strict liability and negligence. In a complete information scenario, the social optimum in terms of pollution abatement and technical progress may be induced by combining either liability rule with an appropriate R&D subsidy. However, if the policy maker has incomplete information with respect to the firm's productivity of R&D investments and if he non-discriminatorily sets a uniform liability rule and a uniform subsidy, if at all only the so-called double negligence rule that uses an abatement and a technology standard may induce the social optimum. The double negligence rule dominates strict liability with respect to the goal of minimizing social costs under a mild condition also in those cases in which none of the liability rules is able to induce firstbest behavior of firms. Somewhat counterintuitively the non-discriminatory double negligence rule may even dominate a (simple as well as a double) negligence rule with type-specific norms and compliance-contingent type-specific subsidies.

JEL classification: K13, Q58

Keywords : Environmental liability law, R&D subsidies , induced technical change

I. Introduction

This paper considers the joint use of environmental liability law and R&D subsidies to address two market failures, a negative pollution externality and technology spillovers that represent a positive externality. In this paper, the pollution externality is addressed by environmental liability law. Liability law is modeled in two alternative types, strict liability and negligence. In the case of strict liability, the polluter is responsible for any damage caused, irrespective of fault. By contrast, under the negligence rule, the polluter has to compensate the victim for any damage that has been caused if the polluter has neglected "due care". If the polluter keeps the standard of "due care", he is exempt from liability. In the literature on environmental law and economics, "due care" is operationalized by a norm of pollution abatement. We deal with this traditional understanding of negligence below and call it "simple negligence". In addition, we introduce a somewhat more sophisticated version of this rule in which "due care" is defined as a combination of a pollution abatement standard and a technology standard. We call this version of the rule the "double negligence rule".[2] In the paper at hand, technology spillovers are internalized by financial assistance for R&D which is modeled by a constant per unit subsidy.

Our framework comprises two asymmetric firms that select pollution abatement and R&D investment. The firms' asymmetry is due to different levels of R&D costs, creating different firm types. R&D is deterministic and lowers abatement costs. Firms interact via knowledge spillovers.[3] We consider the case of perfect information, in which the policy maker can observe and verify firm type and behavior, and the case of imperfect information, in which the policy maker observes only firm behavior, but not the type.

With perfect information, the policy maker can implement first best pollution abatement and R&D investments under strict liability with R&D subsidies set at the optimal level. In the case of negligence, apart from the condition on the level of the R&D subsidy, it is furthermore required that the behavioral standard is set at the first best abatement level. In practical applications it usually holds true that policy makers cannot observe the firm type, as specifics of the firm, such as cost functions, are private information. With incomplete information the policy maker may induce first best firm choices with a double negligence rule that combines an abatement with a technology norm, given that the requirements specified in this paper are fulfilled. This may be achieved by a kind of screening that separates the firms according to their (non-

[2] An economic analysis of environmental liability law with the rules of simple negligence and strict liability can be found in Endres (2011).

[3] In order to focus on regulatory effects due to environmental liability law, we assume that firms do not compete in markets, ruling out strategic effects due to market interaction (which are dealt with in, e.g., Puller 2006).

)compliance with the norms. In any case under modest conditions (see section IV.4) the double negligence rule outperforms the simple negligence rule, which in turn dominates the strict liability rule, when evaluated by the benevolent policy maker. It can further be shown (see section V) that the double negligence rule combined with a uniform subsidy may even dominate a (simple as well as a double) negligence rule with type-specific norms and compliance-contingent type-specific subsidies.

We analyze legal architectures to internalize externalities – different liability rules. Liability law is similar but not identical to property law.[4] Having well defined property rights on the resource through which the externality is mediated (and with zero transaction costs) polluter and pollutee might negotiate, and agree on a socially optimal allocation. Under certain conditions, this allocation is unique, not depending on the initial allocation of property rights (the "Coase-Theorem"). However, in the paper at hand, we assume that polluter and pollutee do not negotiate on the extent of the externality (the level of pollution). This issue is dealt with in a different branch of literature.[5]

The paper at hand complements previous papers telling "tales of two market failures"[6], namely environmental externalities and R&D spillovers. These papers analyze the joint use of different policy instruments to address the double distortion, such as a Pigouvian tax combined with an R&D subsidy, or emission taxes and transferable discharge permits combined with performance standards.[7] In contrast to this paper, none of the analyses mentioned above considers environmental liability as a possible means to internalize the double externality, either exclusively or jointly with another policy instrument. Moreover, none of these papers allows for asymmetric information. [8]

Environmental liability law as a means to address the double market failure generated by environmental externalities and research spillovers is addressed in Endres et al. (2008). In this paper, however, environmental liability rules are not combined with any other policy instrument. Moreover, the paper does not allow for asymmetric information.[9]

---

[4] Differences are pointed out in Endres (2011), pp. 52-54.
[5] See Chipman and Tian (2011) for a recent exposition.
[6] Jaffe, Newell and Stavins (2005) deserve credit for this expression which has also been used in the abstract above.
[7] See Fischer et al. (2003), Fischer and Newell (2008), Jaffe et al. (2005), Katsoulacos und Xepapadeas (1996), Parry (1998), Ulph and Ulph (2007).
[8] Karp and Zhiang (2011) do also analyze the combination of an investment subsidy with an emission tax or emission quota, respectively, within the context of asymmetric information. However, it is "a tale of a single market failure", only, because the paper does not consider research spillovers.
[9] Endres and Bertram (2006), Endres et al. (2007) as well as Endres and Friehe (2011a, 2011b) analyze different environmental liability rules in a setting with negative externalities and induced technical change. However, these papers do not deal with R&D spillovers.

We proceed as follows: In section II, we derive the social optimum as a benchmark. Sections III, IV and V present the decentralization of decision-making under liability law when combined with a research subsidy. While section III analyzes the case in which the regulator has complete information, sections IV and V assume that the regulator has information only on firm behavior, but not on the type of the firm. Whereas in section IV uniform liability rules combined with a uniform subsidy are considered, section V deals with type-specific negligence rules combined with compliance-contingent subsidies. Section VI concludes.

II. Socially optimal abatement and R&D investment

We consider a model of a risk-neutral society with two firms. Firm i's abatement level is given by $x_i(\geq 0)$, $i \in \{H, L\}$. The firm-specific (and verifiable) expected environmental damages are given by $D(x_i)$, with $D' < 0 < D''$, i.e., an increase in the abatement level lowers environmental damages at a diminishing rate. The abatement level x_i corresponds to abatement costs $C(x_i, T_i)$, where $C_x > 0$, $C_{xx} > 0$ holds, i.e., marginal abatement costs are positive and strictly increasing. T_i represents the state of the abatement technology used. The state of technology is determined by the firm's R&D level r_i and by that of the other firm r_j according to $T_i = r_i + \alpha r_j$, $i, j \in \{H, L\}$, $i \neq j$, with $\alpha \in (0,1)$ measuring the knowledge spillover between firms. The state of technology used affects abatement costs, with an improvement in the abatement technology lowering abatement costs $(C_T < 0)$ at a diminishing rate $(C_{TT} > 0)$. Additionally, we assume that marginal abatement costs are decreasing with regard to the state of the technology used ($C_{xT} < 0$).[10] A unit of R&D investment comes at costs i for firm i, where it holds that $H > L$.[11] Correspondingly, firm H is called a high-cost and firm L a low-cost firm.

The social planner minimizes expected social costs associated with pollution. These costs are composed of abatement costs, expected damages and R&D costs. Hence, the optimization problem faced by the social planner is given by

(1) $$\min_{x_i, r_i} SC = \sum_{i \in \{L,H\}} \sum_{j \neq i} \left(C(x_i, r_i + \alpha r_j) + D(x_i) + i r_i \right).$$

[10] Recent publications have acknowledged the empirical observation that some kinds of technical change exist that are associated with a reduction in marginal abatement costs only for a sub-range of abatement levels, while for another range marginal abatement costs are increasing (see e.g. Baker/Adu-Bonnah 2008; Baker et al. 2008; Bauman et al. 2008; Endres/Friehe 2011a, 2011b). Another way to stylize technical change is that it decreases emissions per unit of output (see, e.g., Ulph/Ulph 2007). However, we confine our analysis to the case in which technical progress induces an overall reduction of marginal abatement costs and ignore all other modeling possibilities.

[11] Since the cost parameter reflects the only difference between the two firms, we use the same symbols $i, j \in \{H, L\}$ for the names of the firms and the cost parameters.

The corresponding first-order conditions are

(1.a) $\partial SC/\partial r_i = C_T(x_i,T_i)+\alpha C_T(x_j,T_j)+i=0$,

(1.b) $\partial SC/\partial x_i = C_x(x_i,T_i)+D'(x_i)=0$.

We focus on interior solutions and thereby consider only cases in which the social planner seeks to induce positive abatement levels and technology investments from both firms. Equation (1.a) implies that the social planner acknowledges that R&D by firm i entails a marginal benefit not only with respect to the level of firm i 's abatement costs, but also regarding those of firm j. This is due to the fact that there is a technology spillover to the extent of α. Equation (1.b) states that in the social optimum, marginal abatement costs are equal to the marginal reduction of environmental harm. Both conditions together imply the following statement:

Proposition 1: ***First best abatement and investment levels***

For the socially optimal abatement and investment levels holds $x_L^{FB} > x_H^{FB}$ and $r_L^{FB} > r_H^{FB}$.[12]

Proof:

We first prove $x_L^{FB} > x_H^{FB}$ by showing that (i) $x_L^{FB} < x_H^{FB}$ as well as (ii) $x_L^{FB} = x_H^{FB}$ leads to a contradiction. (iii) We then show that $r_L^{FB} > r_H^{FB}$ follows from $x_L^{FB} > x_H^{FB}$.

(i) Assume that $x_L^{FB} < x_H^{FB}$ holds. Then it follows from (1.b):

$C_x(x_L^{FB},T_L^{FB}) = -D'(x_L^{FB}) > -D'(x_H^{FB}) = C_x(x_H^{FB},T_H^{FB}) > C_x(x_L^{FB},T_H^{FB})$ with $T_i^{FB} = r_i^{FB} + \alpha r_j^{FB}$.

Because of $C_{xT} < 0$ this however implies $T_H^{FB} > T_L^{FB}$ or equivalently $r_H^{FB} > r_L^{FB}$.

For the corresponding social costs would hold:

$$SC^{FB} = C(x_L^{FB}, r_L^{FB}+\alpha r_H^{FB}) + D(x_L^{FB}) + Lx_L^{FB} + C(x_H^{FB}, r_H^{FB}+\alpha r_L^{FB}) + D(x_H^{FB}) + Hx_H^{FB}$$

$$= C(x_L^{FB}, r_L^{FB}+\alpha r_H^{FB}) + D(x_L^{FB}) + Hx_L^{FB} + C(x_H^{FB}, r_H^{FB}+\alpha r_L^{FB}) + D(x_H^{FB}) + Lx_H^{FB} + (H-L)(x_H^{FB}-x_L^{FB})$$

$$> C(x_L^{FB}, r_L^{FB}+\alpha r_H^{FB}) + D(x_L^{FB}) + Hx_L^{FB} + C(x_H^{FB}, r_H^{FB}+\alpha r_L^{FB}) + D(x_H^{FB}) + Lx_H^{FB},$$

which is a contradiction since the last term represents social costs under the abatement and investment values $x_L := x_H^{FB}$, $r_L := r_H^{FB}$, $x_H := x_L^{FB}$, $r_H := r_L^{FB}$, which would be lower than the socially optimal ones.

(ii) Assume that $x_L^{FB} = x_H^{FB}$ holds. Then from (1.b) it follows

$C_x(x_L^{FB},T_L^{FB}) = -D'(x_L^{FB}) = -D'(x_H^{FB}) = C_x(x_H^{FB},T_H^{FB}) = C_x(x_L^{FB},T_H^{FB}) \Rightarrow T_H^{FB} = T_L^{FB} \Leftrightarrow r_H^{FB} = r_L^{FB}$.

Hence, from (1.a) follows

$C_T(x_H^{FB},T_H^{FB}) + H + \alpha C_T(x_L^{FB},T_L^{FB}) = C_T(x_L^{FB},T_L^{FB}) + L + \alpha C_T(x_H^{FB},T_H^{FB}) \Leftrightarrow H = L$, which is a contradiction.

---

[12] The upper index "FB" denotes the socially optimal (= first best) activity levels.

(iii) From $x_L^{FB} > x_H^{FB}$ **it** follows

$$C_x(x_L^{FB}, T_L^{FB}) = -D^{'}(x_L^{FB}) < -D^{'}(x_H^{FB}) = C_x(x_H^{FB}, T_H^{FB}) < C_x(x_L^{FB}, T_H^{FB}) \Rightarrow T_H^{FB} < T_L^{FB} \Leftrightarrow r_H^{FB} < r_L^{FB}.$$

(q.e.d.)

The intuition behind Proposition 1 is simply the following. Since firm L is able to invest in technical progress more efficiently than firm H, it should invest a larger amount of money, according to the criterion of social cost minimization. This results in a more advanced socially optimal technology level of firm L. Correspondingly, also firm L's optimal abatement level is higher than the optimal one of firm H.

III. Regulation with complete information

In the following, we will show that the joint use of environmental liability law and R&D subsidies can induce first best decision-making by firms if the policy maker has complete information. Complete information in our context in particular implies knowledge on firm type, i.e., the firms' R&D costs. As such information is unrealistic in most practical settings, the results obtained may be interpreted as a benchmark. In section IV, we will turn to the more realistic scenario in which firm type is no longer common knowledge. We assume throughout the paper that firms have no concern for social costs, but wish to minimize private costs.

III.1 Strict liability and R&D subsidies

In the case of strict liability, the requirement to compensate those harmed by the activity in question arises irrespective of the way in which the activity was undertaken (see, e.g., Shavell 2007). For our analysis of strict liability, we assume the following three-stage game: (i) The policy maker determines the level of R&D subsidies s_L and s_H. (ii) Firms simultaneously choose the extent of R&D investment. (iii) Firms simultaneously decide on their level of abatement. We solve the game backwards.

At stage 3, firm i minimizes private costs PC_i^{SL} with respect to the abatement x_i, given the abatement technology T_i.

(2) $$\min_{x_i} PC_i^{SL} = C(x_i, T_i) + D(x_i) + (i - s_i) r_i$$

The first-order condition for firm i

(2.a) $$\partial PC_i^{SL} / \partial x_i = C_x(x_i, T_i) + D'(x_i) = 0$$

implicitly defines the optimal abatement level $x_i(T_i)$ for a given technology level T_i. Because of $C_{xT} < 0$ the abatement choice is increasing with the technology level. Since equation (2.a) corresponds to (1.b), given T_i, the abatement level is not only optimal from the private, but also from the social point of view. In particular, this directly implies that the privately optimal level of abatement is equal to the first best level if the private decisions on R&D at the former stage are such that the state of technology is first best (i.e., that $x_i(T_i^{FB}) = x_i^{FB}$).

At stage 2, firm i minimizes private costs PC_i^{SL} with respect to the research investment r_i, given the research investment by the other firm and the anticipated level of abatement at stage 3, $x_i(T_i)$.

(3) $$\min_{r_i} PC_i^{SL} = C(x_i(T_i), r_i + \alpha r_j) + D(x_i(T_i)) + (i - s_i) r_i$$

The first-order condition for firm i is given by

(3.a) $$\partial PC_i^{SL} / \partial r_i = \underbrace{\left(C_x(x_i(T_i), T_i) + D'(x_i(T_i))\right)}_{=0} \frac{dx}{dT} + C_T(x_i(T_i), T_i) + i - s_i = C_T(x_i(T_i), T_i) + i - s = 0 .$$

Comparing condition (3.a) and (1.a) shows that in case of strict liability, firm i does not internalize the marginal benefit owing to the reduction in firm j 's abatement costs. However, this deficiency may be remediated by an appropriate selection of the R&D subsidy granted to firm i at stage 1.

At stage 1, the policy maker chooses the subsidy levels, whose optimal structure in the case of strict liability is discussed in Proposition 2.

Proposition 2: ***Strict liability with full information***

a) Assume that the firm type is public information. Then, the joint use of strict liability and an R&D subsidy $s_i^{FB} = -\alpha C_T(x_j^{FB}, T_j^{FB})$ *ensures that the socially optimal abatement and investment levels are also privately optimal.*

b) The R&D subsidy that is granted to firm L is higher than the one granted to firm H, $s_L^{FB} > s_H^{FB}$ *.*

c) A deviation from at least one of the subsidy levels specified in a) results in a deviation from the socially optimal activity levels.

Proof:

a) Using $s_i^{FB} = -\alpha C_T(x_j^{FB}, T_j^{FB})$, $i = H, L$, leads to a correspondence of private and social first-order conditions, from which directly follows the assertion.

b) Restating conditions (1.a) shows that
$L = -C_T(x_L^{FB}, T_L^{FB})[1 + \alpha C_T(x_H^{FB}, T_H^{FB}) / C_T(x_L^{FB}, T_L^{FB})]$ and
$H = -C_T(x_L^{FB}, T_L^{FB})[\alpha + C_T(x_H^{FB}, T_H^{FB}) / C_T(x_L^{FB}, T_L^{FB})]$, from which follows

$$L < H \Leftrightarrow 1 + \alpha C_T(x_H^{FB}, T_H^{FB}) / C_T(x_L^{FB}, T_L^{FB}) < \alpha + C_T(x_H^{FB}, T_H^{FB}) / C_T(x_L^{FB}, T_L^{FB})$$
$$\Leftrightarrow 1 - \alpha < (1-\alpha) C_T(x_H^{FB}, T_H^{FB}) / C_T(x_L^{FB}, T_L^{FB}) \Leftrightarrow 1 < C_T(x_H^{FB}, T_H^{FB}) / C_T(x_L^{FB}, T_L^{FB})$$
$$\Leftrightarrow C_T(x_L^{FB}, T_L^{FB}) > C_T(x_H^{FB}, T_H^{FB}) \Leftrightarrow -\alpha C_T(x_L^{FB}, T_L^{FB}) < -\alpha C_T(x_H^{FB}, T_H^{FB}) \Leftrightarrow s_H^{FB} < s_L^{FB}.$$

c) Given $r_j = r_j^{FB}$ and $s_i < (>) s_i^{FB}$ it follows from equation (3.a) that for the optimal activity levels of firm i holds $r_i < r_i^{FB}$ and $x_i < x_i^{FB}$. **(q.e.d.)**

The intuition behind Proposition 2 is quite straightforward.In principal, there are two kinds of externality that may cause a divergency of private choices and socially optimal ones. The first externality is due to pollution and is internalized by imposing social damages onto the polluting firm. The second externality arises from the technology spillover. The individual firm enjoys a private marginal benefit from research strictly below the social one. An appropriate adjustment of research costs by means of an R&D subsidy can align private and social incentives if it mirrors the additional social benefits of a higher R&D level of firm i.

Moreover, since research investments of firm L are more productive than research investments of firm H, the socially optimal subsidy of firm L is higher than the one of firm H.

III.2 Negligence and R&D subsidies

In the case of negligence, the requirement to compensate those harmed by an activity only arises if the undertaking of the activity is judged to be negligent by a court, i.e., if it breaches a defined behavioral standard. In our context, firms are required to take at least a predetermined level of abatement defined as $\overline{x}_i$. We assume that the behavioral standard is set at the first best abatement level, $\overline{x}_i = x_i^{FB}$. For our analysis of negligence, we model the following three-stage game: (i) The policy maker determines the level of R&D subsidy s_i and the abatement standard $\overline{x}_i$ for firm i. (ii) Firms simultaneously choose the extent of R&D investment. (iii) Firms simultaneously decide on their level of abatement. As in section III.1, we solve the game backwards.

At stage 3, firm i determines its level of abatement x_i, given the abatement technology and the abatement norm $\bar{x}_i$. Abatement is undertaken in order to minimize private costs:

(4) $$\min_{x_i} PC_i^N = \begin{cases} C(x_i, T_i) + D(x_i) + (i - s_i) r_i & \text{if} \quad x_i < \bar{x}_i = x_i^{FB}, \\ C(x_i, T_i) + (i - s_i) r_i & \text{if} \quad x_i \geq \bar{x}_i = x_i^{FB}. \end{cases}$$

Let $\tilde{x}_i(T_i)$ denote the abatement level that minimizes the first line of equation (4). Note that $\tilde{x}_i(T_i)$ is increasing in T_i and that $\tilde{x}_i(T_i^{FB}) = x_i^{FB}$ holds.

The second line of (4) is minimized by x_i^{FB}. Hence for the equilibrium of the third stage $x_i^*(T_i)$ we get $x_i^*(T_i) \in \{\tilde{x}_i(T_i), x_i^{FB}\}$, with $x_i^*(T_i) = x_i^{FB}$ iff

(5) $$C(x_i^{FB}, T_i) \leq C(\tilde{x}_i(T_i), T_i) + D(\tilde{x}_i(T_i)).$$

It is clear that this inequality will hold true if $T_i = T_i^{FB}$. Consequently, the negligence rule induces first best abatement decisions, contingent on having socially optimal R&D choices by firms.

At stage 2, firm i minimizes private costs PC_i^N with respect to the research investment r_i, given the research investment by the other firm and the anticipated level of abatement at stage 3, $x_i(T_i)$.

(6) $$\min_{r_i} PC_i^N = \begin{cases} C(x_i(T_i), T_i) + D(x_i) + (i - s_i) r_i & \text{if} \quad x_i(T_i) < \bar{x}_i = x_i^{FB}, \\ C(x_i^{FB}, T_i) + (i - s_i) r_i & \text{if} \quad x_i = \bar{x}_i = x_i^{FB}. \end{cases}$$

At stage 1, the policy maker chooses the subsidies whose optimal levels in the case of negligence also coincide with the socially optimal ones. In fact, Proposition 3 shows that given $\bar{x}_i = x_i^{FB}$, $s_i = s_i^{FB}$ (see Proposition 2) and $r_j = r_j^{FB}$, $j \neq i$, firm i chooses $r_i = r_i^{FB}$.

Proposition 3: ***Negligence with full information***

Assume that the firm type is public information. Then the joint use of negligence with $\bar{x}_i = x_i^{FB}$ and the first best R&D subsidy $s_i^{FB} = -\alpha C_T(x_j^{FB}, T_j^{FB})$ ensures that the socially optimal abatement and investment levels are also privately optimal.

Proof:

Assume that $\bar{x}_i = x_i^{FB}$, $s_i = s_i^{FB}$ and $r_j = r_j^{FB}$, $j \neq i$, holds.

Given x_i^{FB} (second line of equation (6)) the optimal technology investment of firm i is given by r_i^{FB}. In the range $x_i(T_i) < x_i^{FB}$ the cost minimizing investment level would be given by $r_i^{FB} - \varepsilon$

with $\varepsilon \to 0$. Since
$C(x_i(T_i^{FB}-\varepsilon),T_i^{FB}-\varepsilon)+D(x_i(T_i^{FB}-\varepsilon))+(i-s_i^{FB})(r_i^{FB}-\varepsilon) > C(x_i^{FB},T_i^{FB})+(i-s_i^{FB})r_i^{FB}$,
the overall optimal investment level is given by r_i^{FB}. **(q.e.d.)**

III.3 Comparing strict liability and negligence

We have shown that privately optimal decisions on R&D investment and abatement coincide with socially optimal levels in the case of both strict liability and negligence if respective liability rules are used jointly with an R&D subsidy set at the spillover level at optimal abatement and investment levels. As a consequence, neither liability rule is strictly preferable to the other one in the presence of complete information. However, the critical assumption maintained during this section, being that the policy maker can observe firm type and behavior, is restrictive as it is unlikely to hold in reality. Accordingly, in the next section, we analyze the ability of the two liability rules to induce socially optimal firm behaviour under the more realistic assumption of incomplete information.

IV. Regulation with incomplete information

In this section, we address the problem that policy makers cannot observe the firm type. Therefore, we make the following assumption, which is conventional in the literature on asymmetric information: the policy maker only knows that there are two firm types with different R&D costs but he does not know which cost function belongs to which firm. This precludes having subsidies and negligence standards being contingent on the observation of the firm type.

In this section we assume that the policy maker offers a unique subsidy to both firms and analyze whether the strict liability and/or the negligence rule are able to induce the socially optimal activity levels.[13] One might suspect that for any liability rule two distinct subsidy offers would be necessary to reach this goal. Indeed, this presumption turns out to be true for the strict liability rule (see section IV.1) and a (simple) negligence rule which makes liability dependent only on the level of abatement (see section IV.2). A double negligence rule with a combined abatement and technology standard, however, may be able to induce the socially optimal allocation even with a uniform subsidy (see section IV.3).

IV.1 Strict liability and R&D subsidy

In case of a uniform subsidy s, with the strict liability rule the individual payoff functions are given by

[13] A screening mechanism using differentiated subsidies and negligence norms is analyzed in section V.

(7) $$PC_i^{SL} = C\left(x_i, T_i\right) + D(x_i) + (i-s)r_i \, .$$

From Proposition 2, however, we know that the socially optimal activity levels can only be induced by firm-specific subsidy levels $s_i^{FB} = -\alpha C_T(x_j^{FB}, T_j^{FB})$ with $s_L^{FB} > s_H^{FB}$. Hence the strict liability rule combined with uniform subsidies is not able to induce first-best decision-making by firms.

IV.2 (Simple) Negligence and R&D subsidy

Whether the simple negligence rule combined with a uniform subsidy is able to induce the socially optimal activity levels is not as clear as for the strict liability rule, since Proposition 3 (in contrast to Proposition 2) does not make a statement with respect to the uniqueness of the specified socially optimal policy choices. Indeed, in the case of negligence the socially optimal policy levels are not unique, since the firms' socially optimal behavior might also be induced by abatement norms with which at least one firm does not comply. However, in the following we will demonstrate that under the restrictions of a uniform negligence rule and a uniform subsidy socially optimal firm behavior cannot be induced.

In the following, we will consider a negligence rule with abatement norm $\bar{x}$. The corresponding firm-specific payoff functions are given by

(8) $$PC_i^{N} = C\left(x_i, T_i\right) + \begin{Bmatrix} 0 & \text{if } x_i \geq \bar{x} \\ D(x_i) & \text{if } x_i < \bar{x} \end{Bmatrix} + (i-s)r_i \, .$$

With respect to the stringency of the abatement norm three cases are possible:

a) The abatement norm is "very tough", so that no firm is going to comply with it.
b) The abatement norm is "very mild", so that both firms are going to comply with it.
c) The abatement norm is "moderate" (which puts case (c) in between cases (a) and (b)), so that only the L-firm is going to comply with the norm.

Obviously neither in case (a) nor in case (b) the socially optimal activity levels can be induced. In case (a) the equilibrium activity levels correspond with those in case of strict liability. Hence the argumentation of section IV.1 applies. In case (b) both firms choose the same abatement levels, whereas in the social optimum firm L chooses a higher abatement level (see Proposition 1). Since in case (c) the L-firm complies with the abatement norm it has to be chosen according to the socially optimal abatement level of this firm, i.e., $\bar{x} = x_L^{FB}$. To induce that firm L chooses the socially optimal investment level r_L^{FB} the subsidy must equal s_L^{FB} (see section III.1). Given $s = s_L^{FB}$ and $r = r_L^{FB}$, however, firm H chooses a higher investment level than its socially optimal one because of $s_L^{FB} > s_H^{FB}$. In summary, also under case (c) the negligence rule with a single abatement norm is not able to induce the social optimum.

The results of the sections IV.1 and IV.2 are summarized in Proposition 4.

Proposition 4: ***Strict liability and negligence with incomplete information***

Assume that the firm type is private information. Then the combination of a subsidy with strict liability or (simple) negligence is not able to induce the socially optimal activity levels.

IV.3 Double Negligence and R&D subsidy

In the following we will consider a negligence rule that combines thresholds for abatement ($\overline{x}$) and technology ($\overline{T}$). The corresponding firm-specific payoff functions are given by

$$PC_i^{DN} = C\left(x_i, T_i\right) + \begin{Bmatrix} 0 & \text{if } x_i \geq \overline{x} \text{ and } T_i \geq \overline{T} \\ D(x_i) & \text{if } x_i < \overline{x} \text{ or } T_i < \overline{T} \end{Bmatrix} + (i-s)r_i \,. \tag{9}$$

With respect to the stringency of the two thresholds, we again distinguish the cases (a), (b) and (c) from section IV.2. As in the case of the simple negligence rule neither in case (a) nor in case (b) the socially optimal activity levels can be induced. In case (a) the equilibrium activity levels correspond with those of strict liability. Hence the argumentation of section IV.1 applies. In case (b) both firms choose the same activity levels, whereas in the social optimum firm L chooses higher activity levels. Hence, if at all, the social optimum can only be induced via threshold and subsidy levels that correspond with case (c).
Since in case (c) the L-firm complies with the thresholds they have to be chosen according to the socially optimal activity levels of this firm, i.e., $\overline{x} = x_L^{FB}$ and $\overline{T} = T_L^{FB}$. The subsidy, however, has to be chosen on the socially optimal level with respect to firm H, i.e. $s = s_H^{FB}$. (See the argumentation of section III.1).

Proposition 5 specifies the conditions under which the double negligence rule is able to induce the socially optimal activity levels.

Proposition 5: ***Double negligence with incomplete information***

Assume that the firm type is private information. Then the combination of the subsidy $s = s_H^{FB}$ with the double negligence rule specified in (9) with $\overline{x} = x_L^{FB}$ and $\overline{T} = T_L^{FB}$ is able to induce the socially optimal activity levels iff the following two conditions are fulfilled simultaneously:

a) $C\left(x_L^{FB}, T_L^{FB}\right) + (L - s_H^{FB})r_L^{FB} \leq \min\limits_{x_L, r_L} \left\{ C\left(x_L, r_L + \alpha r_H^{FB}\right) + D(x_L) + (L - s_H^{FB})r_L \right\}$,

b) $C\left(x_L^{FB}, T_L^{FB}\right) + (H - s_H^{FB})\left(T_L^{FB} - \alpha r_L^{FB}\right) \geq \min\limits_{x_H, r_H} \left\{ C\left(x_H, r_H + \alpha r_L^{FB}\right) + D(x_H) + (H - s_H^{FB})r_H \right\}$.

Proof:

Given $r_H = r_H^{FB}$, firm L complies with the abatement- and investment norm if (a) holds. On the other hand, given $r_L = r_L^{FB}$, firm H prefers 'liability' if (b) is fulfilled. If both conditions hold simultaneously the socially optimal allocation is an equilibrium in the case of the double negligence rule. **(q.e.d.)**

The two conditions specified in Proposition 5 ensure a successful screening that separates the firms with respect to non-compliance and compliance of the combined abatement-technology-norm. Condition (a) ensures that firm L chooses compliance with the double norm and condition (b) ensures that firm H chooses non-compliance (given the equilibrium choices of the other firms). Even though the subsidy level is lower than s_L^{FB} it may be attractive to firm L to comply with the double norm in order to avoid liability. Since the "compliance costs" of firm H are higher than those of firm L it may be unattractive to firm H to comply with the double norm, even if it is attractive to firm L.

Example 1 demonstrates that the two conditions (a) and (b) can indeed be fulfilled simultaneously and hence the double negligence rule may be able to induce the socially optimal activity levels.

Example 1:

Let the abatement costs be given by $C(x,T) = cx^2 / \left(\sqrt{T} + 1\right)$, and environmental harm by $D(x) = d / x$.

a) For the parameter values $\alpha = 0.1, c = 2500, d = 50, L = 1$ and $H = 5$ we get the following results.

The first best abatement and R&D levels for the low-cost and high-cost firm are given by $(x_L^{FB}, r_L^{FB}) = (0.43, 50.11)$ and $(x_H^{FB}, r_H^{FB}) = (0.32, 0.48)$, respectively. The corresponding first best levels for the R&D subsidy are given by $s_L^{FB} = 0.495$ and $s_H^{FB} = 0.051$.

In the case of the double negligence rule with $\bar{x} = x_L^{FB}$, $\bar{T} = T_L^{FB}$ and $s = s_H^{FB}$ the costs of firm L (under the assumption that $r_H = r_H^{FB}$ holds) are given by $PC_L^{compliance} = 105.4$ if it complies with the standards. Under non-compliance the optimal activity levels of firm L would be given by $(x_L, r_L) = (0.40, 27.80)$. (Note that since the subsidy is lower than the socially optimal level for firm L, its abatement and investment levels are also lower than the corresponding socially optimal ones.) Corresponding private costs of firm L would be given by $PC_L^{non-compliance} = 215.1$ and hence would be higher than in the case of compliance.

The costs of firm H (under the assumption that $r_L = r_L^{FB}$ holds) are given by $PC_H^{compliance} = 281.9$ if it complies with the standards. With non-compliance the optimal activity levels of firm H would be given by $(x_H, r_H) = (0.32, 0.48) = (x_H^{FB}, r_H^{FB})$. Corresponding private costs of firm H are

given by $PC_H^{non-compliance} = 235.2$. Summing up, in equilibrium only firm L complies with the standards and both firms choose the socially optimal activity levels.
b) Note that for a smaller difference between *H* and *L*, e.g., in case of $H = 4$ both firms would comply with the standards and hence the socially optimum could not be induced.

IV.4 Welfare comparison

In sections IV.1-IV.3 it could be seen that the double negligence rule may induce the social optimum for appropriate parameter specifications, which is not possible in the case of the strict liability or the simple negligence rule. Of course in these cases the negligence rule is welfare superior to the strict liability rule and the simple negligence rule.
For those cases in which the double negligence rule is also not able to induce socially optimal firm behavior, it can be argued that the socially optimal variant of the negligence rule performs at least as well as the strict liability rule with respect to social costs if abatement costs for total abatement are infinite, i.e., if $C(x,T) \to \infty$ for $x \to x_{\max}$, where $x_{\max}$ is the abatement level that corresponds with no pollution at all, holds. The simple reason behind this claim is that the policy maker may always choose an abatement (and investment) norm that is strict enough to ensure that both firms do not comply with the norm, which, however, implies that the corresponding activity levels coincide with those in the case of the strict liability rule.
Similarly the double negligence rule also dominates the simple negligence rule, since in the case of the double negligence rule the technology level can always be chosen to such a low extent that it is not binding. In other words, the set of social costs that can be induced by the double negligence rule comprises the sets of social costs that can be induced by the strict liability and the simple negligence rule, respectively. Hence the minimum level of social costs in the case of the double negligence rule is at least as low as the minima in the cases of the strict liability and the simple negligence rule.

V. Screening of firms using compliance-contingent subsidies

In section IV, we assumed that the regulator is restricted to uniform policy measures, i.e., he uses uniform subsidies and an identical liability rule for each firm. However, it is well known from the theory of asymmetric information that the offer of type-specific *contracts* may be conducive to a successful screening. Hence, in this section, we assume that the policy maker offers two variants of negligence which differ in the requested levels of care and between which the firms may choose.[14] To make the more demanding negligence rule potentially attractive, we assume that the two negligence rules are combined with differentiated compliance-contingent subsidy levels, i.e., the unattractiveness of a stricter norm is

[14] In a related analysis Friehe (2009) discusses a policy maker seeking to screen accident victims with different harm levels in a tort setting.

compensated by a higher subsidy. As in section IV we consider two variants of negligence: a simple negligence rule with an abatement norm and a double negligence rule with an abatement and technology norm.

Since the goal of the differentiated policy variants is a successful screening of firms with both firms choosing their socially optimal activity levels, we assume that the firms may choose between

- the higher subsidy s_L^{FB} combined with the abatement norm x_L^{FB} (and the additional technology norm T_L^{FB} under the double negligence rule) and
- the lower subsidy s_H^{FB} combined with the weaker abatement norm x_H^{FB} (and the additional technology norm T_H^{FB} under the double negligence rule).

We henceforth abbreviate the first contract by L-contract and the second one by H-contract.

The corresponding private cost functions can be represented by equation (10) in the case of simple negligence and by equation (11) in the case of double negligence.[15]

(10) $$PC_i^{N(C)} = C\left(x_i, T_i\right) + \left\{ \begin{array}{ll} (i - s_L^{FB}) r_i & \text{if } x_i \geq x_L^{FB} \\ (i - s_H^{FB}) r_i & \text{if } x_i \in [x_H^{FB}, x_L^{FB}) \\ D(x_i) + i r_i & \text{if } x_i < x_H^{FB} \end{array} \right\}.$$

(11) $$PC_i^{DN(C)} = C\left(x_i, T_i\right) + \left\{ \begin{array}{ll} (i - s_L^{FB}) r_i & \text{if } x_i \geq x_L^{FB} \text{and } T_i \geq T_L^{FB} \\ (i - s_H^{FB}) r_i & \text{if } x_i \geq x_H^{FB}, T_i \geq T_H^{FB} \text{ and } (x_i < x_L^{FB} \text{ or } T_i < T_L^{FB}) \\ D(x_i) + i r_i & \text{if } x_i < x_H^{FB} \text{ or } T_i < T_H^{FB} \end{array} \right\}.$$

We first consider the optimal choice of firm L, given that firm H chooses the socially optimal activity levels x_H^{FB} and r_H^{FB}. First note that non-compliance with both contracts (= third line of equations (10) and (11)) cannot be the best option for firm L, since this choice is dominated by compliance with the L-contract. The reasoning given in section III.2 applies. Hence firm L chooses one of the following two options:

i) Firm L may choose its type-specific L-contract and comply with it (=first line of equation (10) or (11)). Irrespective of the negligence rule being of the simple or double type, in this case firm L chooses the socially optimal activity levels (x_L^{FB}, r_L^{FB}). Its corresponding costs are given by $C(x_L^{FB}, T_L^{FB}) + (L - s_L^{FB}) r_L^{FB}$.

ii) Alternatively firm L might choose the H-contract and comply with it (= second line of equations (10) and (11)). Accordingly in the case of the simple negligence rule firm L chooses x_H^{FB} and the technology level r_L that minimizes $C(x_H^{FB}, r_L + \alpha r_H^{FB}) + (L - s_H^{FB}) r_L$. In the case of the double negligence rule firm L would comply with both standards. Whereas it would exactly fulfill the abatement norm, it might pay off for firm L to overfulfill the technology norm due to

[15] The upper index C indicates compliance-contingent subsidies.

its lower investment costs (see example 2, below). Hence firm L would choose $(x_H^{FB}, r_L \geq T_H^{FB} - \alpha r_H^{FB})$.

Summing up, in the case of simple negligence (double negligence) firm L chooses its type specific L-contract if and only if equation (12) (equation (13)) holds:

(12) $C(x_L^{FB}, T_L^{FB}) + (L - s_L^{FB}) r_L^{FB} \leq \min_{r_L} \left\{ C(x_H^{FB}, r_L + \alpha r_H^{FB}) + (L - s_H^{FB})(r_L) \right\}$ and

(13) $C(x_L^{FB}, T_L^{FB}) + (L - s_L^{FB}) r_L^{FB} \leq \min_{r_L \geq T_H^{FB} - \alpha r_H^{FB}} \left\{ C(x_H^{FB}, r_L + \alpha r_H^{FB}) + (L - s_H^{FB}) r_L \right\}$.

Let us now consider the optimal choice of firm H, given that firm L complies with its type-specific norms and hence chooses x_L^{FB} and r_L^{FB}. Also for firm H non-compliance cannot be the best option, since this choice is dominated by compliance with the H-contract. Hence firm H either complies with the H- or the L- contract.

i) If firm H chooses the H-contract its optimal activity levels coincide with the socially optimal ones (x_H^{FB}, r_H^{FB}) (irrespective of whether there is simple or double negligence). Its corresponding costs are given by $C(x_H^{FB}, T_H^{FB}) + (H - s_H^{FB}) r_H^{FB}$.

ii) Under the L-contract firm H chooses x_L^{FB} and the technology level r_H that minimizes $C(x_L^{FB}, r_H + \alpha r_L^{FB}) + (H - s_L^{FB}) r_H$ in the case of simple negligence and $(x_L^{FB}, T_L^{FB} - \alpha r_L^{FB})$ in the case of double negligence. Summing up, with simple negligence (double negligence) firm H chooses the H-contract if and only if equation (14) (equation (15)) holds with

(14) $C(x_H^{FB}, T_H^{FB}) + (H - s_H^{FB}) r_H^{FB} \leq \min_{r_H} \left\{ C(x_L^{FB}, r_H + \alpha r_L^{FB}) + (H - s_L^{FB})(r_H) \right\}$ and

(15) $C(x_H^{FB}, T_H^{FB}) + (H - s_H^{FB}) r_H^{FB} \leq C(x_L^{FB}, T_L^{FB}) + (H - s_L^{FB})(T_L^{FB} - \alpha r_L^{FB})$.

Since the L- and H-contract are tailored to the particular cost functions of firm L and H, respectively, one might assume that at least one of the two condition pairs (12 and 14) or (13 and 15) are less restrictive than the conditions for social optimality of the double negligence rule with uniform subsidies specified in Proposition 5 (see section IV.3). However, from Proposition 6.c it follows that this expectation can be refuted. E.g., in Example 2 below only double negligence with uniform subsidies may induce socially optimal activity.

Proposition 6: *Differentiated simple and double negligence rules with compliance-contingent subsidies*

Assume that firm type is private information.

a) Simple negligence with two type-specific negligence contracts, each being composed of the abatement norm x_i^{FB} and a compliance-contingent subsidy $s_i^{FB}, i \in \{L, H\}$, is able to induce the socially optimal activity levels iff equations (12) and (14) are fulfilled.

b) Double negligence with two type-specific negligence contracts, each being composed of the pair of abatement and technology norm (x_i^{FB}, T_i^{FB}) *and a compliance-contingent subsidy* $s_i^{FB}, i \in \{L, H\}$*, is able to induce the socially optimal activity levels iff equations (13) and (15) are fulfilled.*

c) Double negligence with uniform subsidies may lead to higher welfare than any of the two type-specific negligence rules with compliance-contingent subsidies.

Proof:

Propositions 6.a and 6.b directly follow from the analysis presented above.

Proposition 6.c is proven by the following example. **(q.e.d.)**

Example 2:

Consider again the functions and parameter specifications of Example 1.a, i.e, $C(x,T) = cx^2 / \left(\sqrt{T} + 1\right)$, $D(x) = d / x$, $\alpha = 0.1, c = 2500, d = 50, L = 1$ and $H = 5$. In section IV.3 it has been shown that for these parameter values both firms choose their socially optimal activity levels in the case of the double negligence rule with a uniform subsidy. For the type-specific negligence rules with compliance-contingent subsidies the following results can be found:

a) *Simple negligence*: With simple negligence the firms have the choice between the abatement norm $x_L^{FB} = 0.43$ combined with the subsidy $s_L^{FB} = 0.495$ (L-contract) and the abatement norm $x_H^{FB} = 0.32$ combined with the subsidy $s_H^{FB} = 0.051$.

Given that firm L chooses its socially optimal activity levels, firm H would prefer complying with the H-contract with corresponding total costs given by $C(x_H^{FB}, T_H^{FB}) + (H - s_H^{FB}) r_H^{FB} = 79.99$. (If it would instead choose the L-contract its optimal investment level would be given by $r_H = 4.56$ instead of $r_H^{FB} = 0.48$ under the H-contract. Corresponding total costs would be given by $\min_{r_H} \left\{ C(x_L^{FB}, r_H + \alpha r_L^{FB}) + (H - s_L^{FB})(r_H) \right\} = 134.70$.)

However, given that firm H chooses the socially optimal activity levels the L-contract is not the optimal choice of firm L. If firm L chose the L-contract its total costs would be given by $C(x_L^{FB}, T_L^{FB}) + (L - s_L^{FB}) r_L^{FB} = 83.13$ and hence, they would be even higher than firm H's costs under the H-contract. This is due to its higher abatement requirements and higher investment (which costs are only partially compensated by the subsidy). Hence it would pay off for firm L to choose the H-contract. (Under the H-contract and given that firm H would choose the socially optimal activity levels firm L would choose $r_L = 20.26$ with corresponding total costs $\min_{r_H} \left\{ C(x_L^{FB}, r_H + \alpha r_L^{FB}) + (H - s_L^{FB})(r_H) \right\} = 66.36$.) This implies that in our example the type-specific simple negligence rule with compliance-contingent subsidies is not able to induce both firms to choose their socially optimal activity levels and hence, is inferior to the double negligence rule with a uniform subsidy. In fact, in equilibrium, none of the firms choose the socially optimal investment level, since also firm H would take into account that the investment level of firm L under the H-contract is lower than r_L^{FB}. Hence in equilibrium firm H receives lower technology spillovers and reacts with a higher investment than r_H^{FB}. If both firms make their investment decisions simultaneously firm L chooses $r_L = 19.69$ and firm H $r_H = 3.50$. Corresponding equilibrium costs are $C(x_H^{FB}, r_H + \alpha r_L) + (H - s_H^{FB}) r_H = 94.92$ for firm H and $C(x_H^{FB}, r_L + \alpha r_H) + (L - s_H^{FB}) r_L = 66.08$ for firm L.

b) *Double negligence*:

With double negligence the firms have the choice between the pair of norms (x_L^{FB}, T_L^{FB}) combined with the subsidy s_L^{FB} (L-contract) and the pair of norms (x_H^{FB}, T_H^{FB}) combined with the subsidy s_H^{FB} (H-contract).

Given that firm L chooses its socially optimal activity levels, the L-contract is even more unattractive for firm H with double negligence than with simple negligence due to the higher investment requirement. (Firm H's total costs under compliance of the L-contract would be given by $C(x_L^{FB}, T_L^{FB}) + (H - s_L^{FB})(T_L^{FB} - \alpha r_L^{FB}) = 261.22$.)

However, given that firm H chooses the socially optimal activity levels the L-contract is not the optimal choice for firm L. If firm L chose the L-contract its total costs would (as under simple negligence) be given by $C(x_L^{FB}, T_L^{FB}) + (L - s_L^{FB}) r_L^{FB} = 83.13$. Hence it would pay for firm L to choose the H-contract. (Under the H-contract and given that firm H would choose the socially optimal activity levels firm L would have to invest only $T_H^{FB} - \alpha r_H^{FB} = 5.46$. Corresponding total costs would be given by 81.74. However firm L could further lower its total costs by overfulfilling the technology norm. Given $r_H = r_H^{FB}$ its optimal investment level would be given by $r_L = 20.26$ with corresponding total costs given by 66.36. (Note that similar to the argumentation for the simple negligence rule the equilibrium investment levels of both firms would have to be determined simultaneously.)

Summing up, opposed to the double negligence rule with a uniform subsidy neither the type-specific simple negligence rule nor the type-specific double negligence rule is able to induce the social optimum.

The intuition for the potentially better outcome in the case of the double negligence rule with uniform subsidies compared to the type-specific negligence rules may be explained as follows: In the case ofdouble negligence with a uniform subsidy firm L has to "pay" for a deviation from its socially optimal activity levels by bearing environmental harm. In the case of the type-specific negligence rules with compliance contingent subsidies the firm pays (only) with the abdication of the higher subsidy, whereas on the other hand the requirements with respect to abatement are decreasing. In the case of the type-specific negligence rule firm L (as well as firm H) has not only two but three options and this widening of its scope of actions may lead to a destabilization of the social optimum.

VI. Conclusion

This paper analyzes abatement and technology choices by two asymmetric polluting firms that are subject to environmental liability law and are granted R&D subsidies. The two externalities, the pollution externality and the externality due to knowledge spillovers, can be exactly offset if the policy maker has complete information. In that case, the two liability rules considered both can induce first-best decisions by private actors. This symmetry no longer holds as soon as the reality of incomplete information about firms' costs is addressed.

In the case of asymmetric information between the policy maker and firms, the former may potentially induce the socially optimal activity levels by screening the firms using a double negligence rule with abatement and investment norms that are tailored to the firm with low investment costs and a subsidy that is tailored to the firm with high investment costs, whereas it is not possible to induce the social optimum via strict liability. In those cases in which the double negligence rule is not able to induce the social optimum it performs at least as well as the strict liability and the simple negligence rule. In addition, it has been shown that the double negligence rule with uniform subsidy may even outperform a simple and double negligence rule with type-specific subsidies, abatement (and technology) norms. Hence screening via compliance and non-compliance of a simple negligence rule combined with a uniform subsidy may be more efficient than screening via type-specific negligence norms and subsidies.

References

Baker, E. and K. Adu-Bonnah, 2008. Investment in Risky R&D Programs in the Face of Climate Uncertainty. Energy Economics 30, 465-486.

Baker, E., Clarke, L., and E. Shittu, 2008. Technical Change and the Marginal Cost of Abatement. Energy Economics 30, 2799-2816.

Bauman, Y., Lee, M., and K. Seeley, 2008. Does Technological Innovation Really Reduce Marginal Abatement Costs? Some Theory, Algebraic Evidence, and Policy Implications. Environmental and Resource Economics 39, 507-527.

Chipman, J.S. and G. Tian, 2011. Detrimental Externalities, Pollution Rights, and the "Coase Theorem". Forthcoming in Economic Theory.

Endres, A., 2011. Environmental Economics – Theory and Policy. Cambridge and New York: Cambridge University Press.

Endres, A. and R. Bertram, 2006. The Development of Care Technology Under Liability Law. International Review of Law and Economics 26, 503-518.

Endres, A., Bertram, R., and B. Rundshagen, 2007. Environmental Liability and Induced Technical Change - The Role of Discounting. Environmental and Resource Economics 36, 341-366.

Endres, A. and T. Friehe, 2011a. R&D and Abatement under Environmental Liability Law: Comparing Incentives under Strict Liability and Negligence if Compensation Differs from Harm. Energy Economics 33, 419-422.

Endres, A. and T. Friehe, 2011b. Incentives to Diffuse Advanced Abatement Technology Under Environmental Liability Law. Journal of Environmental Economics and Management 62, 30-40.

Endres, A., Rundshagen, B., and R. Bertram, 2008. Environmental Liability Law and Induced Technical Change - The Role of Spillovers. Journal of Institutional and Theoretical Economics 164, 254-279.

Fischer, C. and R.G. Newell, 2008. Environmental and Technology Policies for Climate Mitigation. Journal of Environmental Economics and Management 55, 142-162.

Fischer, C., Parry, I.W.H., W.A. Pizer, 2003. Instrument Choice for Environmental Protection when Technological Innovation is Endogenous. Journal of Environmental Economics and Management 45, 523-545.

Fischer, C., Parry, I.W.H., W.A. Pizer, 2003. Instrument Choice for Environmental Protection when Technological Innovation is Endogenous. Journal of Environmental Economics and Management 45, 523-545.

Friehe, T., 2009. Screening Accident Victims. International Review of Law and Economics 29, 272-280.

Jaffe, A.B., Newell, R.G., and R.N. Stavins, 2005. A Tale of Two Market Failures: Technology and Environmental Policy. Ecological Economics 54, 164–174.

Karp, L. and J. Zhang, 2011. Taxes versus Quantities for a Stock Pollutant with Endogenous Abatement Costs and Asymmetric Information. Forthcoming in Economic Theory.

Katsoulacos, Y. and A. Xepapadeas, 1996. Environmental Innovation, Spillovers and Optimal Policy Rules. In: Carraro, C., Katsoulacos, Y., and A. Xepapadeas (eds.), Environmental Policy and Market Structure, Kluwer: Dordrecht, 143–150.

Martin, S. and J.T. Scott, 2000. The Nature of Innovation Market Failure and the Design of Public Support for Private Innovation. Research Policy 29, 437-447.

Parry, I.W.H., 1998. Pollution Regulation and the Efficiency Gains from Technological Innovation. Journal of Regulatory Economics 14, 229-254.

Puller, S.L., 2006. The Strategic Use of Innovation to Influence Regulatory Standards. Journal of Environmental Economics and Management 52, 690-706.

Shavell, S., 2007. Liability for Accidents. In: Polinsky, A.M., and S. Shavell (Eds.). Handbook of Law and Economics 1. Amsterdam: Elsevier, 139-182.

Ulph, A. and D. Ulph, 2007. Climate Change - Environmental and Technology Policies in a Strategic Context. Environmental and Resource Economics 37, 159-180.

Die Diskussionspapiere ab Nr. 183 (1992) bis heute, können Sie im Internet unter
http://www.fernuni-hagen.de/FBWIWI/ einsehen und zum Teil downloaden.
Ältere Diskussionspapiere selber erhalten Sie nur in den Bibliotheken.

Nr	**Jahr**	**Titel**	**Autor/en**
420	2008	Stockkeeping and controlling under game theoretic aspects	Fandel, Günter Trockel, Jan
421	2008	On Overdissipation of Rents in Contests with Endogenous Intrinsic Motivation	Schlepütz, Volker
422	2008	Maximum Entropy Inference for Mixed Continuous-Discrete Variables	Singer, Hermann
423	2008	Eine Heuristik für das mehrdimensionale Bin Packing Problem	Mack, Daniel Bortfeldt, Andreas
424	2008	Expected A Posteriori Estimation in Financial Applications	Mazzoni, Thomas
425	2008	A Genetic Algorithm for the Two-Dimensional Knapsack Problem with Rectangular Pieces	Bortfeldt, Andreas Winter, Tobias
426	2008	A Tree Search Algorithm for Solving the Container Loading Problem	Fanslau, Tobias Bortfeldt, Andreas
427	2008	Dynamic Effects of Offshoring	Stijepic, Denis Wagner, Helmut
428	2008	Der Einfluss von Kostenabweichungen auf das Nash-Gleichgewicht in einem nicht-kooperativen Disponenten-Controller-Spiel	Fandel, Günter Trockel, Jan
429	2008	Fast Analytic Option Valuation with GARCH	Mazzoni, Thomas
430	2008	Conditional Gauss-Hermite Filtering with Application to Volatility Estimation	Singer, Hermann
431	2008	Web 2.0 auf dem Prüfstand: Zur Bewertung von Internet-Unternehmen	Christian Maaß Gotthard Pietsch
432	2008	Zentralbank-Kommunikation und Finanzstabilität – Eine Bestandsaufnahme	Knütter, Rolf Mohr, Benjamin
433	2008	Globalization and Asset Prices: Which Trade-Offs Do Central Banks Face in Small Open Economies?	Knütter, Rolf Wagner, Helmut
434	2008	International Policy Coordination and Simple Monetary Policy Rules	Berger, Wolfram Wagner, Helmut
435	2009	Matchingprozesse auf beruflichen Teilarbeitsmärkten	Stops, Michael Mazzoni, Thomas
436	2009	Wayfindingprozesse in Parksituationen - eine empirische Analyse	Fließ, Sabine Tetzner, Stefan
437	2009	ENTROPY-DRIVEN PORTFOLIO SELECTION a downside and upside risk framework	Rödder, Wilhelm Gartner, Ivan Ricardo Rudolph, Sandra
438	2009	Consulting Incentives in Contests	Schlepütz, Volker

439	2009	A Genetic Algorithm for a Bi-Objective Winner-Determination Problem in a Transportation-Procurement Auction"	Buer, Tobias Pankratz, Giselher
440	2009	Parallel greedy algorithms for packing unequal spheres into a cuboidal strip or a cuboid	Kubach, Timo Bortfeldt, Andreas Tilli, Thomas Gehring, Hermann
441	2009	SEM modeling with singular moment matrices Part I: ML-Estimation of time series	Singer, Hermann
442	2009	SEM modeling with singular moment matrices Part II: ML-Estimation of sampled stochastic differential equations	Singer, Hermann
443	2009	Konsensuale Effizienzbewertung und -verbesserung – Untersuchungen mittels der Data Envelopment Analysis (DEA)	Rödder, Wilhelm Reucher, Elmar
444	2009	Legal Uncertainty – Is Hamonization of Law the Right Answer? A Short Overview	Wagner, Helmut
445	2009	Fast Continuous-Discrete DAF-Filters	Mazzoni, Thomas
446	2010	Quantitative Evaluierung von Multi-Level Marketingsystemen	Lorenz, Marina Mazzoni, Thomas
447	2010	Quasi-Continuous Maximum Entropy Distribution Approximation with Kernel Density	Mazzoni, Thomas Reucher, Elmar
448	2010	Solving a Bi-Objective Winner Determination Problem in a Transportation Procurement Auction	Buer, Tobias Pankratz, Giselher
449	2010	Are Short Term Stock Asset Returns Predictable? An Extended Empirical Analysis	Mazzoni, Thomas
450	2010	Europäische Gesundheitssysteme im Vergleich – Effizienzmessungen von Akutkrankenhäusern mit DEA –	Reucher, Elmar Sartorius, Frank
451	2010	Patterns in Object-Oriented Analysis	Blaimer, Nicolas Bortfeldt, Andreas Pankratz, Giselher
452	2010	The Kuznets-Kaldor-Puzzle and Neutral Cross-Capital-Intensity Structural Change	Stijepic, Denis Wagner, Helmut
453	2010	Monetary Policy and Boom-Bust Cycles: The Role of Communication	Knütter, Rolf Wagner, Helmut
454	2010	Konsensuale Effizienzbewertung und –verbesserung mittels DEA – Output- vs. Inputorientierung –	Reucher, Elmar Rödder, Wilhelm
455	2010	Consistent Modeling of Risk Averse Behavior with Spectral Risk Measures	Wächter, Hans Peter Mazzoni, Thomas

456	2010	Der virtuelle Peer – Eine Anwendung der DEA zur konsensualen Effizienz-bewertung –	Reucher, Elmar
457	2010	A two-stage packing procedure for a Portuguese trading company	Moura, Ana Bortfeldt, Andreas
458	2010	A tree search algorithm for solving the multi-dimensional strip packing problem with guillotine cutting constraint	Bortfeldt, Andreas Jungmann, Sabine
459	2010	Equity and Efficiency in Regional Public Good Supply with Imperfect Labour Mobility – Horizontal versus Vertical Equalization	Arnold, Volker
460	2010	A hybrid algorithm for the capacitated vehicle routing problem with three-dimensional loading constraints	Bortfeldt, Andreas
461	2010	A tree search procedure for the container relocation problem	Forster, Florian Bortfeldt, Andreas
462	2011	Advanced X-Efficiencies for CCR- and BCC-Modell – Towards Peer-based DEA Controlling	Rödder, Wilhelm Reucher, Elmar
463	2011	The Effects of Central Bank Communication on Financial Stability: A Systematization of the Empirical Evidence	Knütter, Rolf Mohr, Benjamin Wagner, Helmut
464	2011	Lösungskonzepte zur Allokation von Kooperationsvorteilen in der kooperativen Transportdisposition	Strangmeier, Reinhard Fiedler, Matthias
465	2011	Grenzen einer Legitimation staatlicher Maßnahmen gegenüber Kreditinstituten zur Verhinderung von Banken- und Wirtschaftskrisen	Merbecks, Ute
466	2011	Controlling im Stadtmarketing – Eine Analyse des Hagener Schaufensterwettbewerbs 2010	Fließ, Sabine Bauer, Katharina
467	2011	A Structural Approach to Financial Stability: On the Beneficial Role of Regulatory Governance	Mohr, Benjamin Wagner, Helmut
468	2011	Data Envelopment Analysis - Skalenerträge und Kreuzskalenerträge	Wilhelm Rödder Andreas Dellnitz
469	2011	Controlling organisatorischer Entscheidungen: Konzeptionelle Überlegungen	Lindner, Florian Scherm, Ewald
470	2011	Orientierung in Dienstleistungsumgebungen – eine explorative Studie am Beispiel des Flughafen Frankfurt am Main	Fließ, Sabine Colaci, Antje Nesper, Jens

471	2011	Inequality aversion, income skewness and the theory of the welfare state	Weinreich, Daniel
472	2011	A tree search procedure for the container retrieval problem	Forster, Florian Bortfeldt, Andreas
473	2011	A Functional Approach to Pricing Complex Barrier Options	Mazzoni, Thomas
474	2011	Bologna-Prozess und neues Steuerungsmodell – auf Konfrontationskurs mit universitären Identitäten	Jost, Tobias Scherm, Ewald
475	2011	A reduction approach for solving the rectangle packing area minimization problem	Bortfeldt, Andreas
476	2011	Trade and Unemployment with Heterogeneous Firms: How Good Jobs Are Lost	Altenburg, Lutz
477	2012	Structural Change Patterns and Development: China in Comparison	Wagner, Helmut
478	2012	Demografische Risiken – Herausforderungen für das finanzwirtschaftliche Risikomanagement im Rahmen der betrieblichen Altersversorgung	Merbecks, Ute
479	2012	"It's all in the Mix!" – Internalizing Externalities with R&D Subsidies and Environmental Liability	Endres, Alfred Friehe, Tim Rundshagen, Bianca