“It’s All in the Mix!” Internalizing Externalities with R&D Subsidies and Environmental Liability[1]

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Abstract

Extending previous “tales of two market failures”, we consider a setting in which firms generate environmental externalities and may invest in environmentally friendly technological advancement generating R&D spillovers. We analyze 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 emission levels and technical progress may be induced by combining either liability rule with an appropriate R&D subsidy. However, when the policy maker has incomplete information with respect to a firm’s productivity of R&D investments and non-discriminatorily sets a uniform liability rule and a uniform subsidy, only the so-called “double negligence” rule that imposes both an emission and a technology standard can induce the social optimum (if any one). The double negligence rule dominates strict liability with respect to the goal of minimizing social costs under modest conditions, also in cases in which none of the liability rules is capable of inducing first-best behavior among firms. Somewhat counterintuitively, a non-discriminatory double negligence rule can even dominate a (simple as well as double) negligence rule with type-specific norms and compliance-contingent type-specific subsidies.

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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, as modeled by two alternative rules: strict liability and negligence. In the case of strict liability, the polluter is responsible for any damages incurred, irrespective of fault. By contrast, under the negligence rule, the polluter must compensate the victim for any damage that has been caused when the polluter has neglected "due care". When polluters abide by the due care standard, they are exempt from liability. In the literature on environmental law and economics, due care is operationalized using an emissions norm. We address this traditional understanding of negligence below, referring to it as "simple negligence". In addition, we introduce a somewhat more sophisticated version of this rule in which due care is defined as a combination of an emission standard and a technology standard. We call this version of the liability rule the "double negligence rule".[2] In the present paper, technology spillovers are internalized by financial assistance for R&D, which is modeled as a constant per-unit subsidy.

In the main part of our paper (Sections II-V), our framework considers two asymmetric firms that select emission levels and R&D investment. The firms' asymmetry, which results from their different levels of R&D costs, creates different firm types. R&D is deterministic and lowers marginal abatement costs.[3] Firms interact via knowledge spillovers.[4] We consider both the case of complete information (in which the policy maker can observe and verify firm type and behavior) and the case of incomplete information (in which the policy maker observes firm behavior but not type). With complete information, the policy maker can implement first-best emissions and R&D investments under strict liability using R&D subsidies set at the optimal level. In the case of negligence, in addition to the condition regarding the level of the R&D subsidy, it is furthermore required that the behavioral standard be set at the first-best emission level. With incomplete information, the policy maker may induce first-best firm choices by using a double negligence rule that combines an emission norm with a technology norm, given that the requirements specified in this paper are fulfilled. This may be achieved by a kind of screening that differentiates firms according to their (non-)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 from the

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

[3] In Section VI.2, we consider an alternative stylization of technical change.

[4] In order to focus on the 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 addressed in, e.g., Puller 2006).

perspective of 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 double) negligence rule with type-specific norms and compliance-contingent type-specific subsidies. We stylize incomplete information using the traditional method for asymmetric information models, which dates back to Akerlof (1970). There are different types of agents, and the policy maker is aware of the characteristic feature of each type. He is also assumed to know the distribution of the types. However, he does not know the type of the individual agent with which he is dealing. In our model, each agent (polluting firm) i has a characteristic formally described by its per-unit cost of R&D coefficient, also denoted as i. In our model of incomplete information, we assume that the information asymmetry is confined to this cost of R&D coefficient. The reason behind this particular choice of stylization is that the focus of this paper is on inducing technical change through the use of public-policy instruments (liability and subsidies); in our model, the level of equilibrium technical change is determined by the equilibrium level of R&D. The differences between the firms' individual R&D decisions are due to the differences in their cost of R&D coefficients. Aside from the cost of R&D, there are three other important elements in our model: the benefit function, the damage function, and the spillover coefficient. However, these are assumed to be the same for all firm types. The regulatory agency is assumed to have full information on these latter aspects.

We analyze legal architectures to internalize externalities, i.e., different liability rules. Liability law is similar but not identical to property law.[5] On the basis of well-defined property rights regarding the resource through which the externality is mediated (and with zero transaction costs), the polluter and pollutee might negotiate and agree on a socially optimal allocation. Under certain conditions, this allocation is unique, independent of the initial allocation of property rights (the "Coase Theorem"). However, in the present paper, 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 the literature.[6]

This paper complements previous contributions describing "tales of two market failures",[7] namely environmental externalities and R&D spillovers. These papers have analyzed the joint use of various 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

[5] Differences are pointed out in Endres (2011), pp. 52-54.
[6] See, e.g., Chipman and Tian (2012) and Endres and Rundshagen (2008).
[7] Jaffe, Newell, and Stavins (2005) deserve credit for this expression, which was also referenced in the abstract above.

with performance standards.[8] In contrast to this paper, none of the analyses mentioned above considers environmental liability as a possible means of internalizing the double externality, either exclusively or jointly with another policy instrument. Moreover, none of these papers allows for asymmetric information.[9]

Environmental liability law as a means of addressing the double market failure generated by environmental externalities and research spillovers is addressed in Endres et al. (2008). In that contribution, however, environmental liability rules are not combined with any other policy instrument. Moreover, the paper does not allow for asymmetric information.[10]

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 in combination with a research subsidy. Section III analyzes the case in which the regulator has complete information, whereas Sections IV and V assume that the regulator has information only on firm behavior, not on firm type. 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.1 considers an extension with $N > 2$ firms. Section VI.2 explores the robustness of our results with respect to an alternative stylization of technical change. Section VII concludes.

II. Socially optimal emission and R&D investment

We consider a model of a risk-neutral society with two firms. Firm *i*'s emission level is given by $E_i\ (\geq 0)$, $i \in \{H, L\}$. The firm-specific (and verifiable) expected environmental damages are given by $D(E_i)$, with $D', D'' > 0$, i.e., an increase in the emission level increases environmental damages at an increasing rate. The emission level E_i corresponds to benefits $B(E_i, T_i)$, where $B_E > 0$ for $E_i < E_i^{\max}(T)$ and $B_{EE} < 0$ holds, i.e., marginal benefits from emissions are positive and strictly decreasing in the relevant range $0 < E_i \leq E_i^{\max}(T)$. T_i represents the state of the technology in use. The state of technology is determined by the firm's R&D level, r_i, and by the level 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. A higher technology level increases the benefit level ($B_T > 0$) at a diminishing rate ($B_{TT} < 0$). Additionally, we assume that marginal

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[8] See Fischer et al. (2003), Fischer and Newell (2008), Jaffe et al. (2005), Katsoulacos and Xepapadeas (1996), Parry (1998), and Ulph and Ulph (2007).

[9] Karp and Zhang (2012) analyze the combination of an investment subsidy with an emission tax or emission quota within the context of asymmetric information. However, this represents a "tale of a single market failure", as the paper does not consider research spillovers.

[10] Endres and Bertram (2006), Endres et al. (2007), and 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 address R&D spillovers.

benefits from emissions and hence marginal abatement costs are decreasing with regard to the state of the technology used ($B_{ET} < 0$ for $E_i < E_i^{\max}(T)$).[11,12] A unit of R&D investment comes at a cost i for firm i , where it holds that $H > L$.[13] Correspondingly, firm *H* is called a high-cost firm, and firm *L* a low-cost firm.

The social planner maximizes the expected welfare associated with pollution. This welfare comprises the benefits from emissions minus expected damages and R&D costs. With respect to damages, we assume mono-causality, i.e., total damage is the sum of firm-specific damages.[14] An example of this scenario is local pollution, in which many polluting firms may exist but dispersion characteristics prevent emission interaction effects. Applications of this idea to a local externality include noise, odor, and vibrations but also more conventional pollutants, such as soot, dust, and heavy gases (e.g., xenon (Xe) and sulfur hexafluoride (SF_6)).

The optimization problem faced by the social planner is given by

(1) $$\max_{E_i, r_i} W = \sum_{i \in \{L,H\}} \left(B(E_i, r_i + \alpha r_{-i}) - D(E_i) - i r_i \right),$$

with $r_j = r_{-i}$ denoting the investment level of firm $j \neq i$.

The corresponding first-order conditions are

(1.a) $\partial W / \partial r_i = B_T(E_i, T_i) + \alpha B_T(E_j, T_j) - i = 0$ and

(1.b) $\partial W / \partial E_i = B_E(E_i, T_i) - D'(E_i) = 0$.

We focus on interior solutions and thereby consider only cases in which the social planner seeks to induce positive emission (abatement) levels and technology investments from both firms.

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11 Recent publications have acknowledged the empirical observation that certain kinds of technical change exist for which a reduction in marginal abatement costs results only for a sub-range of abatement levels, while marginal abatement costs increase for another range (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 in Sections II-V to the case in which technical progress induces an overall reduction in marginal abatement costs, turning to an alternative specification only in Section VI.2.

12 Note that $B_{ET} < 0$ for $E_i < E_i^{\max}(T)$ implies $dE_i^{\max} / dT \leq 0$. The border case $dE_i^{\max} / dT = 0$ occurs, if the solution of $B_E = 0$ is independent of T , which in particular applies to end-of-pipe-technologies. This case can graphically be represented. Because it is obvious, we do not show the graph here. In this graph, the reader is invited to imagine, a technology improvement results in a leftward rotation of B_E around $E_i^{\max}$.

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

14 For further elaboration, see, e.g., Calcott and Hutton (2006) and Endres and Friehe (2012), p. 63. The reason underlying this assumption is that in the case of multi-causality, strict liability is doomed to failure: Equilibrium pollution is not socially optimal. However, this “impossibility theorem” does not hold for the negligence rule. The two seminal sources for these fundamental insights in the field of law and economics are Landes and Posner (1980), p. 523, and Shavell (1987), Proposition 7.1, p. 178.

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 benefit, but also to that 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, the marginal benefit from emissions is equal to the marginal reduction in environmental harm. Together, the two conditions imply the following statement:

Proposition 1: ***First-best emission and investment levels***

For the socially optimal emission and investment levels, it holds that $E_L^{FB} < E_H^{FB}$ and $r_L^{FB} > r_H^{FB}$.[15]

Proof:

We first prove $E_L^{FB} < E_H^{FB}$ by showing that both (i) $E_L^{FB} > E_H^{FB}$ and (ii) $E_L^{FB} = E_H^{FB}$ result in a contradiction. (iii) We then show that $r_L^{FB} > r_H^{FB}$ follows from $E_L^{FB} < E_H^{FB}$.

(i) Assume that $E_L^{FB} > E_H^{FB}$ holds. Then, it follows from (1.b) that

$B_E(E_L^{FB},T_L^{FB}) = D'(E_L^{FB}) > D'(E_H^{FB}) = B_E(E_H^{FB},T_H^{FB}) > B_E(E_L^{FB},T_H^{FB})$, with $T_i^{FB} = r_i^{FB} + \alpha r_j^{FB}$.

However, because $B_{ET} < 0$, this implies that $T_H^{FB} > T_L^{FB}$, or equivalently $r_H^{FB} > r_L^{FB}$.

For the corresponding welfare level, it holds that

$$\begin{aligned} W^{FB} &= B(E_L^{FB}, r_L^{FB} + \alpha r_H^{FB}) - D(E_L^{FB}) - Lr_L^{FB} + B(E_H^{FB}, r_H^{FB} + \alpha r_L^{FB}) - D(E_H^{FB}) - Hr_H^{FB} \\ &= B(E_L^{FB}, r_L^{FB} + \alpha r_H^{FB}) - D(E_L^{FB}) - Hr_L^{FB} + B(E_H^{FB}, r_H^{FB} + \alpha r_L^{FB}) - D(E_H^{FB}) - Lr_H^{FB} - (H-L)(r_H^{FB} - r_L^{FB}) \\ &< B(E_L^{FB}, r_L^{FB} + \alpha r_H^{FB}) - D(E_L^{FB}) - Hr_L^{FB} + B(E_H^{FB}, r_H^{FB} + \alpha r_L^{FB}) - D(E_H^{FB}) - Lr_H^{FB}. \end{aligned}$$

This is a contradiction, since the last term represents social welfare under the emission and investment values $E_L := E_H^{FB}$, $r_L := r_H^{FB}$, $E_H := E_L^{FB}$, $r_H := r_L^{FB}$, which would be higher than the socially optimal level.

(ii) Assume that $E_L^{FB} = E_H^{FB}$ holds. Then, from (1.b), it follows that

$B_E(E_L^{FB},T_L^{FB}) = D'(E_L^{FB}) = D'(E_H^{FB}) = B_E(E_H^{FB},T_H^{FB}) = B_E(E_L^{FB},T_H^{FB}) \Rightarrow T_H^{FB} = T_L^{FB} \Leftrightarrow r_H^{FB} = r_L^{FB}$.

Hence, from (1.a), we obtain

$B_T(E_H^{FB},T_H^{FB}) + \alpha B_T(E_L^{FB},T_L^{FB}) - H = B_T(E_L^{FB},T_L^{FB}) + \alpha B_T(E_H^{FB},T_H^{FB}) - L \Leftrightarrow H = L$, which is a contradiction.

(iii) From $E_L^{FB} < E_H^{FB}$**,** it can be determined that

$B_E(E_L^{FB},T_L^{FB}) = D'(E_L^{FB}) < D'(E_H^{FB}) = B_E(E_H^{FB},T_H^{FB}) < B_E(E_L^{FB},T_H^{FB}) \Rightarrow T_H^{FB} < T_L^{FB} \Leftrightarrow r_H^{FB} < r_L^{FB}$.

(q.e.d.)

The intuition behind Proposition 1 is simple: Since firm *L* is able to invest in technical progress more efficiently than firm *H*, it should purchase more technical progress, according to the criterion of welfare maximization. This results in a more advanced socially optimal technology level for firm *L*. Consequently, firm *L*'s optimal emission level is also lower than the optimal level for firm *H*.

[15] The superscript "FB" denotes the socially optimal (= first-best) activity levels.

III. Regulation with complete information

In the following section, we will show that the joint use of environmental liability law and R&D subsidies can induce first-best decision-making by firms when the policy maker has complete information. In our context, complete information implies knowledge about firm type, i.e., 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 seek 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 is 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 their R&D investment. (iii) Firms simultaneously decide on their emission level. We solve the game backwards.

At stage 3, firm i maximizes profits π_i^{SL} with respect to the emission level E_i, given the technology T_i.[16]

(2) $$\max_{E_i} \pi_i^{SL} = B(E_i, T_i) - D(E_i) - (i - s_i) r_i$$

The first-order condition for firm i

(2.a) $$\partial \pi_i^{SL} / \partial E_i = B_E(E_i, T_i) - D'(E_i) = 0$$

implicitly defines the optimal emission level $E_i(T_i)$ for a given technology level T_i. Because $B_{ET} < 0$, the emission choice is decreasing in the technology level. Since equation (2.a) corresponds to (1.b), given T_i, the emission level is optimal not only from the private point of view but also from the social perspective. In particular, this directly implies that the privately

[16] Equation (2) implies that firms perfectly account for all damage to society. Alternatively, it could be assumed that the firms expect compensation payments to differ from (in particular: be lower than) the actual damages caused – i.e., the firms might assume that they will not be sued every time they cause harm or that the courts will make mistakes in determining the amount of the actual harm caused (see, e.g., Friedman 2001, pp. 204-206). The consequences of a deviation from harm in compensation payments on investment and abatement incentives under environmental liability law are analyzed in Endres and Friehe (2011a). However, this paper does not consider technology spillovers; consequently, it does not consider the combination of liability law and R&D subsidies, either.

optimal emission level is equal to the first-best level if the private decisions on R&D at stage 2 are such that the state of technology is first-best (i.e., that $E_i(T_i^{FB}) = E_i^{FB}$).

At stage 2, firm i maximizes profits π_i^{SL} with respect to the research investment r_i, given the research investment by the other firm and the anticipated emission level at stage 3, $E_i(T_i)$.

(3) $$\max_{r_i} \pi_i^{SL} = B(E_i(T_i), r_i + \alpha r_j) - D(E_i(T_i)) - (i - s_i) r_i$$

The first-order condition for firm i is given by

(3.a) $$\partial\pi_i^{SL} / \partial r_i = \underbrace{\left(B_E - D'\right)}_{=0} \frac{dE_i}{dT} + B_T(E_i(T_i), T_i) - (i - s_i) = B_T(E_i(T_i), T_i) - i + s_i = 0 \ .$$

A comparison of conditions (3.a) and (1.a) shows that firm i does not internalize the marginal benefit resulting from the increase of firm *j*'s benefit under strict liability. 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. The optimal structure of these levels in the case of strict liability is discussed in Proposition 2.

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

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

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

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

Proof:

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

b) Restating condition (1.a), we find that
$L = B_T(E_L^{FB}, T_L^{FB})[1 + \alpha B_T(E_H^{FB}, T_H^{FB}) / B_T(E_L^{FB}, T_L^{FB})]$ and
$H = B_T(E_L^{FB}, T_L^{FB})[\alpha + B_T(E_H^{FB}, T_H^{FB}) / B_T(E_L^{FB}, T_L^{FB})]$, from which follows

$L < H \Leftrightarrow 1+\alpha B_T(E_H^{FB},T_H^{FB}) / B_T(E_L^{FB},T_L^{FB}) < \alpha + B_T(E_H^{FB},T_H^{FB}) / B_T(E_L^{FB},T_L^{FB})$
$\Leftrightarrow 1-\alpha < (1-\alpha)B_T(E_H^{FB},T_H^{FB}) / B_T(E_L^{FB},T_L^{FB}) \Leftrightarrow 1 < B_T(E_H^{FB},T_H^{FB}) / B_T(E_L^{FB},T_L^{FB})$

$\Leftrightarrow B_T(E_L^{FB},T_L^{FB}) < B_T(E_H^{FB},T_H^{FB}) \Leftrightarrow \alpha B_T(E_L^{FB},T_L^{FB}) < \alpha B_T(E_H^{FB},T_H^{FB}) \Leftrightarrow s_H^{FB} < s_L^{FB}$.

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*, it holds that $r_i < (>)\ r_i^{FB}$ and hence $E_i > (<)\ E_i^{FB}$. **(q.e.d.)**

The intuition behind Proposition 2 is straightforward. In principal, there are two kinds of externality that may cause a divergence between private and socially optimal choices. The first externality is due to pollution; this is internalized by imposing social damages on the polluting firm. The second externality arises from the technology spillover. An individual firm enjoys a private marginal benefit from research that is strictly less than the social benefit. An appropriate adjustment of research costs by means of an R&D subsidy can align private and social incentives when this subsidy reflects the additional social benefits of the higher R&D level of firm i.

Moreover, since the research investments of firm *L* are more productive than the research investments of firm *H*, the socially optimal subsidy of firm *L* is higher than that granted to 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 when 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 not exceed a predetermined emission level (defined as $\overline{E}_i$). We assume that the behavioral standard is set at the first-best emission level, $\overline{E}_i = E_i^{FB}$. For our analysis of negligence, we model the following three-stage game: (i) The policy maker determines the level of the R&D subsidy s_i and the emission standard $\overline{E}_i$ for firm i. (ii) Firms simultaneously choose the extent of their R&D investment. (iii) Firms simultaneously decide on their emission level. As in Section III.1, we solve the game backwards.

At stage 3, firm i determines its emission level E_i, given the technology and the emission norm $\overline{E}_i$. The optimal emission level follows from a maximazition of the profit function:

$$(4) \qquad \max_{E_i} \pi_i^N = \begin{cases} B(E_i,T_i) - D(E_i) - (i-s_i)r_i & \text{if} \quad E_i > \overline{E}_i = E_i^{FB}, \\ B(E_i,T_i) - (i-s_i)r_i & \text{if} \quad E_i \le \overline{E}_i = E_i^{FB}. \end{cases}$$

Let $\tilde{E}_i(T_i)$ denote the emission level that maximizes the first line of equation (4). Note that $\tilde{E}_i(T_i)$ is decreasing in T_i and that $\tilde{E}_i(T_i^{FB}) = E_i^{FB}$ holds.

The second line of (4) is maximized by E_i^{FB}. Hence, for the equilibrium of the third stage $E_i^*(T_i)$, we obtain $E_i^*(T_i) \in \{\tilde{E}_i(T_i), E_i^{FB}\}$, with $E_i^*(T_i) = E_i^{FB}$, if

(5) $$B(E_i^{FB}, T_i) \geq B(\tilde{E}_i(T_i), T_i) - D(\tilde{E}_i(T_i)).$$

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

At stage 2, firm i maximizes profits π_i^N with respect to the research investment r_i, given the research investment by the other firm and the anticipated emission level at stage 3, $E_i(T_i)$.

(6) $$\max_{r_i} \pi_i^N = \begin{cases} B(E_i(T_i), T_i) - D(E_i) - (i - s_i) r_i & \text{if} \quad E_i(T_i) > \bar{E}_i = E_i^{FB}, \\ B(E_i^{FB}, T_i) - (i - s_i) r_i & \text{if} \quad E_i = \bar{E}_i = E_i^{FB}. \end{cases}$$

At stage 1, the policy maker chooses the subsidies whose optimal levels in the case of negligence coincide with the socially optimal level. In fact, Proposition 3 shows that given $\bar{E}_i = E_i^{FB}$, $s_i = s_i^{FB}$ (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 firm type is public information. Then, the joint use of negligence with $\bar{E}_i = E_i^{FB}$ and the first-best R&D subsidy $s_i^{FB} = \alpha B_T(E_j^{FB}, T_j^{FB})$ ensures that the socially optimal emission and investment levels are also privately optimal.

Proof:

Assume that $\bar{E}_i = E_i^{FB}$, $s_i = s_i^{FB}$, and that $r_j = r_j^{FB}$, $j \neq i$, holds.
Given E_i^{FB}, the optimal technology investment of firm i is given by r_i^{FB}. In the range $E_i(T_i) > E_i^{FB}$, the cost-minimizing investment level would be given by $r_i^{FB} - \varepsilon$, with $\varepsilon \to 0$.
Since $B(E_i(T_i^{FB} - \varepsilon), T_i^{FB} - \varepsilon) - D(E_i(T_i^{FB} - \varepsilon)) - (i - s_i^{FB})(r_i^{FB} - \varepsilon) < B(E_i^{FB}, T_i^{FB}) - (i - s_i^{FB}) r_i^{FB}$, 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 concerning R&D investment and emissions coincide with socially optimal levels in the case of both strict liability and negligence when these liability rules are used jointly with an R&D subsidy equal to the value of the spillover at optimal emission and investment levels. As a consequence, neither liability rule is strictly preferable to the other in the presence of complete information. However, the critical assumption maintained during this section – that the policy maker can observe firm type and behavior – is restrictive. Accordingly, in the next section, we analyze the ability of the two liability rules to induce socially optimal firm behavior under the more realistic assumption of incomplete information.

IV. Regulation with incomplete information with respect to firm-specific R&D costs

In this section, we address the problem of the policy maker's inability to observe firm type. We make the following assumption, which is conventional in the literature on asymmetric information: The policy maker knows that there are two firm types with different R&D costs, but does not know which cost function belongs to which firm.[17] This precludes the use of subsidies or negligence standards that are contingent on the observation of firm type.

In this section, operating on the assumption that the policy maker offers a uniform subsidy to both firms, we analyze the ability of the strict liability and the negligence rule to induce the socially optimal activity levels.[18] One might suspect that for any liability rule, two distinct subsidy offers would be necessary to achieve this goal. Indeed, this hypothesis turns out to be true for the strict liability rule (see Section IV.1) and for a (simple) negligence rule that makes liability dependent only on the emission level (see Section IV.2). However, a double negligence rule with a combined emission and technology standard 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 subsidies

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

(7) $$\pi_i^{SL} = B\left(E_i, T_i\right) - D(E_i) - (i-s)r_i .$$

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[17] Famous examples of analogous formalizations in other contexts are Akerlof (1970) and Spence (1974). Alternative (or additional) specifications of incomplete information on the part of the regulator might consider imperfect knowledge of the abatement cost and damage functions or incomplete information with respect to the spillover parameter. This issue goes back to Weitzman (1974); in our context, it would require the benefit and damage functions to be replaced by expected benefits and damages (as well as expected technology spillovers) in the optimization problem (1) of the regulator. Regarding the reasons for uncertainty with respect to benefits and costs and the implications for the optimal choice of price versus quantity policy instruments, see also Pindyck (2007). With respect to liability law, it can be expected that in these kinds of incomplete information scenarios, in general neither the chosen subsidy and liability norm(s) nor the equilibrium emission and investment levels will coincide with the ex-post socially optimal levels. Moreover, the relative performance of the liability rules might change in favor of strict liability if the divergence between the emission (technology) norm and the ex-post socially optimal emission (technology) level is sufficiently large. Additionally, the relative performance of simple and double negligence might shift in favor of simple negligence if the divergence between the emission norm and the socially optimal emission level (given the technology level set in the technology norm) is sufficiently large.

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

From Proposition 2, however, we know that the socially optimal activity levels can only be induced by firm-specific subsidy levels $s_i^{FB} = \alpha B_T(E_j^{FB}, T_j^{FB})$, with $s_L^{FB} > s_H^{FB}$. Thus, the strict liability rule combined with uniform subsidies is unable to induce first-best decision-making by firms.

IV.2 Simple negligence and R&D subsidies

Whether the simple negligence rule combined with a uniform subsidy can induce the socially optimal activity levels is not as clear as it was in the case of the strict liability rule, since Proposition 3 (in contrast to Proposition 2) does not specify the uniqueness of the derived 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 emission norms with which at least one firm does not comply. However, in the following section, 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 analysis, we will consider a negligence rule with an emission norm $\overline{E}$. The corresponding firm-specific profit functions are given by

$$(8) \qquad \pi_i^N = B\left(E_i, T_i\right) - \begin{Bmatrix} 0 & \text{if } E_i \leq \overline{E} \\ D(E_i) & \text{if } E_i > \overline{E} \end{Bmatrix} - (i-s)r_i .$$

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

a) The emission norm is "very tough", such that no firm will comply with it.
b) The emission norm is "very mild", such that both firms will comply with it.
c) The emission norm is "moderate" (i.e., case (c) is situated in between cases (a) and (b)), such that only firm *L* will comply with the norm.

Obviously, neither in case (a) nor in case (b) can the socially optimal activity levels be induced. In case (a), the equilibrium activity levels correspond with those in the case of strict liability. Hence, the argumentation from Section IV.1 applies. In case (b), both firms choose the same emission levels, whereas in the social optimum, firm *L* chooses a lower emission level (see Proposition 1). Since in case (c) firm *L* complies with the emission norm, this norm must be chosen in accordance with the socially optimal emission level for this firm, i.e., $\overline{E} = E_L^{FB}$. To induce firm *L* to choose 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 lower emission level than its socially optimal level because $s_L^{FB} > s_H^{FB}$. In summary, even in case (c), the negligence rule with a single emission norm is unable to induce the social optimum.

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

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

Assume that firm type is private information. Then, the combination of a subsidy with strict liability or (simple) negligence is unable to induce the socially optimal activity levels.

IV.3 Double negligence and R&D subsidies

In the following section, we will consider a negligence rule that combines thresholds for emissions ($\bar{E}$) and technology ($\bar{T}$). The corresponding firm-specific profit functions are given by

$$\text{(9)} \qquad \pi_i^{DN} = B\left(E_i, T_i\right) - \begin{cases} 0 & \text{if } E_i \le \bar{E} \text{ and } T_i \ge \bar{T} \\ D(x_i) & \text{if } E_i > \bar{E} \text{ or } T_i < \bar{T} \end{cases} - (i-s)r_i \,.$$

With respect to the stringency of the two thresholds, we again examine 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) can the socially optimal activity levels be induced. In case (a), the equilibrium activity levels correspond with those of strict liability; thus, the argumentation from Section IV.1 applies. In case (b), both firms choose the same activity levels, whereas in the social optimum firm *L* chooses a higher investment level and a lower emission level than firm *H*. Therefore, if any of these cases can induce the social optimum, it must be via the threshold and subsidy levels that correspond to case (c).
Since in case (c) firm *L* complies with the thresholds, these levels must be chosen according to the socially optimal activity levels of the firm, i.e., $\bar{E} = E_L^{FB}$ and $\bar{T} = T_L^{FB}$. The subsidy, however, must be chosen according to the socially optimal levels for firm *H*, i.e., $s = s_H^{FB}$. (See the argumentation from 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 firm type is private information. Then, the combination of the subsidy $s = s_H^{FB}$ *with the double negligence rule specified in (9) with* $\bar{E} = E_L^{FB}$ and $\bar{T} = T_L^{FB}$ *is able to induce the socially optimal activity levels when the following two conditions are simultaneously fulfilled:*
a) $B\left(E_L^{FB}, T_L^{FB}\right) - (L - s_H^{FB})r_L^{FB} \ge \max_{E_L, r_L} \left\{ B\left(E_L, r_L + \alpha r_H^{FB}\right) - D(E_L) - (L - s_H^{FB})r_L \right\},$
b) $B\left(E_L^{FB}, T_L^{FB}\right) - (H - s_H^{FB})\left(T_L^{FB} - \alpha r_L^{FB}\right) \le \max_{E_H, r_H} \left\{ B\left(E_H, r_H + \alpha r_L^{FB}\right) - D(E_H) - (H - s_H^{FB})r_H \right\}.$

Proof:

Given $r_H = r_H^{FB}$, firm *L* complies with the emission and investment norm if (a) holds. On the other hand, given $r_L = r_L^{FB}$, firm *H* prefers non-compliance 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 or compliance with the combined emission-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 though compliance is attractive to firm *L*.

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

Example 1:

Let the benefit function be represented by $B(E_i, T_i) = aE_i - b\left(\sqrt{T_i}+1\right)E_i^2 + \frac{1}{4}\frac{a^2}{b}\left(\sqrt{T_i}+1\right)$, and environmental harm by $D(E_i) = dE_i^2$.

For the parameter values $\alpha = 0.01, a = 10000, b = 100, d = 500, L = 100000$, and $H = 200000$, we obtain the following results.

The first-best emission and R&D levels for the low-cost and high-cost firms are given by $(E_L^{FB}, r_L^{FB}) = (6.895, 1.562)$ and $(E_H^{FB}, r_H^{FB}) = (7.560, 0.361)$, respectively. The corresponding first-best levels for the R&D subsidy are given by $s_L^{FB} = 1990.2$ and $s_H^{FB} = 980.1$.

Under the double negligence rule with $\bar{E} = E_L^{FB}$, $\bar{T} = T_L^{FB}$, and $s = s_H^{FB}$, the profit for firm *L* (assuming that $r_H = r_H^{FB}$ holds) is given by $\pi_L^{compliance} = 466392.8$ when it complies with the standards. Under non-compliance, the optimal activity levels of firm *L* would be given by $(E_L, r_L) = (6.908, 1.530)$. (Note that since the subsidy is lower than the socially optimal level for firm *L*, its investment level is also lower and its emission level higher than the corresponding socially optimal levels.) The corresponding profits for firm *L* would be given by $\pi_L^{non-compliance} = 442635.2$, and thus would be lower than in the case of compliance.

The profit for firm *H* (assuming that $r_L = r_L^{FB}$ holds) is given by $\pi_H^{compliance} = 312611.7$ when it complies with the standards. With non-compliance, the optimal activity levels of firm *H* would be given by $(E_H, r_H) = (E_H^{FB}, r_H^{FB})$. The corresponding profits of firm *H* would be

$\pi_H^{non-compliance} = 369377.0$. In summary, in equilibrium only firm L complies with the standards, and both firms choose the socially optimal activity levels.

IV.4 Welfare comparison

From Sections IV.1-IV.3, it is evident that the double negligence rule may induce the social optimum for appropriate parameter specifications, which is not possible under the strict liability or the simple negligence rule. Of course, in these cases, the double negligence rule is welfare-superior to the strict liability rule and the simple negligence rule.

For the cases in which the double negligence rule is also unable to induce socially optimal firm behavior, it can be argued that under the additional assumption that abatement costs for total abatement are infinite, the socially optimal variant of the negligence rule performs at least as well as the strict liability rule with respect to social costs. The simple reason behind this claim is that the policy maker can always choose an emission (and investment) norm that is strict enough to ensure that neither firm will comply with the norm; however, this implies that the corresponding activity levels will 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 be set so low that it does not represent a constraint. In other words, the set of welfare levels that can be induced by the double negligence rule encompasses the sets of welfare levels that can be induced by the strict liability and the simple negligence rule. Thus, the maximum welfare level in the case of the double negligence rule is at least as high as the maxima in the cases of strict liability and the simple negligence rule.

V. Screening of firms using compliance-contingent subsidies

In Section IV, we assumed that regulators are restricted to uniform policy measures, i.e., they use 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 successful screening. Therefore, in this section, we assume that the policy maker offers two variants of negligence that differ in terms of the required emission levels and that the firms may choose between them.[19] 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 compensated by a higher subsidy. As in Section IV, we consider two variants of negligence: a simple negligence rule with an emission norm and a double negligence rule with both an emission and a technology norm.

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

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

- the higher subsidy s_L^{FB} combined with the emission norm E_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 emission norm E_H^{FB} (and the additional technology norm T_H^{FB} under the double negligence rule).

Hereafter, we will refer to the first set of conditions as the "*L*-contract" and the second one as the "*H*-contract".

The corresponding profit functions can be represented by equation (10) in the case of simple negligence and by equation (11) in the case of double negligence.[20]

$$(10) \qquad \pi_i^{N(C)} = B(E_i,T_i) - \begin{cases} (i-s_L^{FB})r_i & \text{if } E_i \le E_L^{FB} \\ (i-s_H^{FB})r_i & \text{if } E_i \in (E_L^{FB},E_H^{FB}] \\ D(E_i)+ir_i & \text{if } E_i > E_H^{FB} \end{cases}$$

$$(11) \qquad \pi_i^{DN(C)} = B(E_i,T_i) - \begin{cases} (i-s_L^{FB})r_i & \text{if } E_i \le E_L^{FB} \text{and } T_i \ge T_L^{FB} \\ (i-s_H^{FB})r_i & \text{if } E_i \le E_H^{FB},\, T_i \ge T_H^{FB} \text{ and } (E_i > E_L^{FB} \text{ or } T_i < T_L^{FB}) \\ D(E_i)+ir_i & \text{if } E_i > E_H^{FB} \text{ or } T_i < T_H^{FB} \end{cases}$$

We first consider the optimal choice for firm *L*, given that firm *H* chooses the socially optimal activity levels E_H^{FB} and r_H^{FB}. First, it should be noted that non-compliance with both contracts (= the 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. Thus, firm *L* chooses one of the following two options:

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

ii) Alternatively, firm *L* might choose the *H*-contract and comply with it (= the second line of equations (10) and (11)). Under the simple negligence rule, firm *L* chooses E_H^{FB} and the technology level r_L that maximizes $B(E_H^{FB},r_L+\alpha r_H^{FB})-(L-s_H^{FB})r_L$. Under the double negligence rule, firm *L* would comply with both standards. Although the firm would opt to exactly fulfill the emission norm, it might pay off for firm *L* to over-fulfill the technology norm, due to its lower investment costs (see Example 2 below). Hence, firm *L* would choose $(E_H^{FB},r_L \ge T_H^{FB}-\alpha r_H^{FB})$.

In summary, 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:

$$(12) \qquad B(E_L^{FB},T_L^{FB})-(L-s_L^{FB})r_L^{FB} \ge \max_{r_L}\left\{B(E_H^{FB},r_L+\alpha r_H^{FB})-(L-s_H^{FB})(r_L)\right\},$$

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[20] The superscript "C" indicates compliance-contingent subsidies.

(13) $$B(E_L^{FB},T_L^{FB})-(L-s_L^{FB})r_L^{FB} \geq \max_{r_L \geq T_H^{FB}-\alpha r_H^{FB}} \left\{B(E_H^{FB},r_L+\alpha r_H^{FB})+(L-s_H^{FB})r_L\right\}.$$

Let us now consider the optimal choice of firm *H*, given that firm *L* complies with its type-specific norms and thus chooses E_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. Consequently, 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 (E_H^{FB},r_H^{FB}), irrespective of whether simple or double negligence is applied. The firm's corresponding profits are given by $B(E_H^{FB},T_H^{FB})-(H-s_H^{FB})r_H^{FB}$.

ii) Under the *L*-contract, firm *H* chooses E_L^{FB} and the technology level r_H that maximizes $B(E_L^{FB},r_H+\alpha r_L^{FB})-(H-s_L^{FB})r_H$ in the case of simple negligence and $(E_L^{FB},T_L^{FB}-\alpha r_L^{FB})$ in the case of double negligence. Thus, under simple negligence (double negligence), firm *H* chooses the *H*-contract if and only if equation (14) (equation (15)) holds:

(14) $$B(E_H^{FB},T_H^{FB})-(H-s_H^{FB})r_H^{FB} \geq \max_{r_H} \left\{B(E_L^{FB},r_H+\alpha r_L^{FB})-(H-s_L^{FB})(r_H)\right\},$$

(15) $$B(E_H^{FB},T_H^{FB})-(H-s_H^{FB})r_H^{FB} \geq B(E_L^{FB},T_L^{FB})-(H-s_L^{FB})(T_L^{FB}-\alpha r_L^{FB}).$$

Since the *L*- and *H*-contract are tailored to the specific cost functions of firms *L* and *H*, respectively, one might assume that at least one of the two condition pairs (12 and 14) or (13 and 15) would be less restrictive than the conditions for the social optimality of the double negligence rule with uniform subsidies specified in Proposition 5 (see Section IV.3). However, Proposition 6.c demonstrates that this expectation can be refuted. In Example 2 below, only double negligence with uniform subsidies is capable of inducing 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 consisting of the emission norm E_i^{FB} *and a compliance-contingent subsidy* $s_i^{FB}, i \in \{L,H\}$, *is able to induce the socially optimal activity levels if equations (12) and (14) are fulfilled.*

b) Double negligence with two type-specific negligence contracts, each consisting of a pair of emission and technology norms (E_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 if equations (13) and (15) are fulfilled.*

c) Double negligence with uniform subsidies may lead to higher welfare than either 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 from Example 1, i.e, $B(E_i,T_i) = aE_i - b\left(\sqrt{T_i}+1\right)E_i^2 + \frac{1}{4}\frac{a^2}{b}\left(\sqrt{T_i}+1\right)$, $D(E_i) = dE_i^2$, $\alpha = 0.01, a = 10000, b = 100,$ $d = 500, L = 100000$, and $H = 200000$.

In Section IV.3, it was shown that for these parameter values in the case of the double negligence rule with a uniform subsidy, both firms choose their socially optimal activity levels. For the type-specific negligence rules with compliance-contingent subsidies, the following results can be found:

a) *Simple negligence*: Under simple negligence, the firms have a choice between the emission norm $E_L^{FB} = 6.895$ combined with the subsidy $s_L^{FB} = 1990.2$ (*L*-contract) and the emission norm $E_H^{FB} = 7.560$ combined with the subsidy $s_H^{FB} = 980.1$ (*H*-contract).

Given that firm *L* chooses its socially optimal activity levels, firm *H* would prefer to comply with the *H*-contract, with corresponding profits given by $B(E_H^{FB}, T_H^{FB}) - (H - s_H^{FB})r_H^{FB} = 397954.1$.

(If firm *H* instead chooses the *L*-contract, its optimal investment level would be given by $r_H = 0.368$ (instead of $r_H^{FB} = 0.3610$ under the *H*-contract). The resulting profits would be given by $\max_{r_H}\left\{B(E_L^{FB}, r_H + \alpha r_L^{FB}) - (H - s_L^{FB})(r_H)\right\} = 393229.6$.)

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* chooses the *L*-contract, its profits would be given by $B(E_L^{FB}, T_L^{FB}) - (L - s_L^{FB})r_L^{FB} = 467970.2$. Under the *H*-contract and given that firm *H* would choose the socially optimal activity levels, firm *L* would choose $r_L = 1.518$ with corresponding profits $\max_{r_L}\left\{B(E_H^{FB}, r_L + \alpha r_H^{FB}) - (L - s_H^{FB})(r_L)\right\} = 470906.6$. Thus, it is more attractive for firm *L* to choose the *H*-contract. This implies that in our example, the type-specific simple negligence rule with compliance-contingent subsidies is unable to induce both firms to choose their socially optimal activity levels and is therefore inferior to the double negligence rule with a uniform subsidy. In fact, in equilibrium, neither of the firms chooses their socially optimal investment level, since firm *H* would take into account the fact that the investment level of firm *L* under the *H*-contract is lower than r_L^{FB}. Thus, in equilibrium, firm *H* receives lower technology spillovers and reacts with an investment higher than r_H^{FB}. If both firms make their investment decisions simultaneously, firm *L* chooses $r_L = 1.549$ and firm *H* chooses $r_H = 0.3611$. The corresponding equilibrium profits are $B(E_H^{FB}, r_H + \alpha r_L) - (H - s_H^{FB})r_H = 397929.7$ for firm *H* and $B(E_H^{FB}, r_L + \alpha r_H) - (L - s_H^{FB})r_L = 472455.8$ for firm *L*.

b) *Double negligence*:

With double negligence, the firms have a choice between the pair of norms (E_L^{FB}, T_L^{FB}) combined with the subsidy s_L^{FB} (*L*-contract) and the pair of norms (E_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* under double negligence than it was under simple negligence, due to the higher investment requirement. (Firm *H*'s profit under compliance with the *L*-contract would be given by $B(E_L^{FB}, T_L^{FB}) - (H - s_L^{FB})(T_L^{FB} - \alpha r_L^{FB}) = 314177.1$.)

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* chooses the *L*-contract, its profit would (as under simple negligence) be given by $B(E_L^{FB}, T_L^{FB}) - (L - s_L^{FB}) r_L^{FB} = 467970.2$. Hence, the *H*-contract would be more attractive for firm *L*. Under the *H*-contract and given that firm *H* would choose the socially optimal activity levels, firm *L* would have to invest only $T_H^{FB} - \alpha r_H^{FB} = 0.373$. The corresponding profit would be 432868.6. However, firm *L* could further increase its profits by over-fulfilling the technology norm. Given $r_H = r_H^{FB}$, its optimal investment level would be given by $r_L = 1.518$ with corresponding profit 470906.6. (Note that similar to the argumentation for the simple negligence rule, the equilibrium investment levels of both firms would have to be determined simultaneously.)

In summary, unlike 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 in comparison to the type-specific negligence rules may be explained as follows: In the case of double negligence with a uniform subsidy, firm *L* has to "pay" for a deviation from its socially optimal activity levels by bearing the costs of environmental harm. In the case of the type-specific negligence rules with compliance-contingent subsidies, the firm only loses the benefit of the higher subsidy, while the requirements with respect to emissions are reduced. In the case of the type-specific negligence rule, firm *L* (as well as firm *H*) has three options instead of two, and this widening of its scope of actions may lead to a destabilization of the social optimum.

VI. Extensions

In this section, we consider two variations of the framework analyzed in depth in the main part of our paper. First, we turn to a setting with a general number *N* of firm types (in contrast to the scenario of *N=2* analyzed in Sections II-V). Subsequently, we explore whether assumptions regarding how technical change influences the firms' benefit function critically affect our results. To this end, we consider the possibility that the marginal benefits of greater emissions are increased by more highly advanced abatement technology, which mirrors the scenario in which technical change increases marginal abatement costs.

VI.1 Extension 1: *N* firm types

In the following analysis, we assume that there are $N > 2$ types that differ with respect to their R&D investment costs. The investment costs of firm $i \in \{1,...,N\}$ are assumed to be given by $I(i)$, with $I(1) = L$, $I(N) = H$, and $I(i) < I(i+1)\ \forall i \in \{1,...,N-1\}$. Moreover, the technology level of firm i is given by $\mathrm{T_i} = \mathrm{r_i} + \alpha \sum_{\mathrm{j \neq i}} \mathrm{r_i}$.

First, note that the results of Sections II and III can directly be transferred to a setting with $N > 2$ firms. In particular, the optimization problem faced by the social planner is given by

$$(16) \qquad \max_{E_i, r_i} W = \sum_{i \in \{1,...,N\}} \left(B(E_i, r_i + \alpha \sum_{j \neq i} r_j) - D(E_i) - ir_i \right),$$

with the corresponding first-order conditions

$$(16.a) \quad \partial W / \partial r_i = B_T(E_i, T_i) + \alpha \sum_{j \neq i} B_T(E_j, T_j) - i = 0 \text{ and}$$

$$(16.b) \quad \partial W / \partial E_i = B_E(E_i, T_i) - D'(E_i) = 0.$$

This enables us to determine the ranking $E_i^{FB} < E_j^{FB}$ and $r_i^{FB} > r_j^{FB}$ for the socially optimal emission and investment levels of two firms *i* and *j* with $i < j$, as well as $s_i^{FB} = \alpha \sum_{j \neq i} B_T(E_j, T_j)$ in the case of complete information (under either strict liability or a negligence rule).

VI.1.1 Uniform double negligence and R&D subsidies

For the more relevant scenario of incomplete information, in the following analysis we restrict our attention to the equilibrium outcomes of a double negligence rule with uniform norms combined with a uniform subsidy that is paid irrespective of a firm's compliance with the double norms (see Section IV.3) and the double negligence rule with compliance-contingent subsidies (see Section V), since the uniform double negligence rule performed slightly better than the uniform simple negligence rule. Additionally, the simple negligence rules can be interpreted as a special case of the double negligence rule with a non-binding technology norm.

For $N = 2$ firm types, we have established that the double norm with a uniform subsidy may result in higher welfare than the double (and the simple) negligence rule with compliance-contingent subsidies. The intuition for this result is that the combination of standards tailored to the low-cost type and a subsidy tailored to the high-cost type can successfully induce a separation. Under this system, both types choose their socially optimal activity levels, even in cases in which this is not possible using compliance-contingent subsidies. However, when $N > 2$, it follows straightforwardly that an undifferentiated negligence rule combined with a uniform subsidy will be unable to induce a perfect screening with each firm choosing its socially optimal activity levels.

Proposition 7: ***Uniform double negligence with incomplete information and more than two firms***

For $N > 2$, a uniform double negligence rule combined with a uniform subsidy is unable to induce the social optimum.

Proof:

If, on the one hand, at least two firms (i, j) comply with the norms, they will choose $E_i = E_j = \overline{E}$. Since $E_i^{FB} \neq E_j^{FB}$, such an allocation cannot be socially optimal. If, on the other hand, at least two firms do not comply with the double norm, they will receive the same subsidy, which differs for at least one firm (i) from the socially optimal subsidy. Thus, the allocation cannot be optimal, since either a firm $j \neq i$ will choose a suboptimal activity level or (given that firms $j \neq i$ choose the socially optimal activity levels) firm i will deviate from the socially optimal choice. **(q.e.d.)**

This raises the following question: Does Proposition 7 imply that the counterintuitive result (i.e., that a double negligence rule with a uniform subsidy may outperform negligence with compliance-contingent subsidies) does not hold in a model with $N > 2$ firm types? To answer this question, we more closely examine firm behavior in the scenario of compliance-contingent subsidies.

VI.1.2 Double negligence with compliance-contingent subsidies

Analogous to Section V, we assume that the regulator offers N "contracts", i.e., each of the N firms are offered subsidy levels s_i^{FB} combined with emission and technology norms E_i^{FB} and T_i^{FB}.

We analyze the firm behavior as a two-stage game, in which the firms choose the contracts in the first stage and choose their equilibrium investment and emission levels in the second. Note that each firm complies at least with the weakest norms E_H^{FB} and T_H^{FB}, i.e., non-compliance does not occur in equilibrium.

Let $v_i \in \{1,...,N\}$ denote the chosen contract of firm *I*, with $v_i = j$ denoting the contract $(\overline{E} = E_j^{FB}, \overline{T} = T_j^{FB}, \overline{s} = s_j^{FB})$ – i.e., the higher the v_i, the less ambitious the firm *i*'s chosen contract. Moreover, let $v = (v_1,...,v_N)$ denote the vector of contracts chosen by firms.

To simplify the equilibrium analysis, we may make use of the following facts:

- At the second stage, we only have to consider vectors *v* with $v_i \le v_j \ \forall i < j$; i.e., for a firm *i* with lower investment costs, it cannot be optimal to choose a less ambitious contract than a firm *j* with higher investment costs.
- A firm that chooses contract *j* chooses the corresponding emission level $\overline{E} = E_j^{FB}$.
- A firm that chooses a contract $v_i = j > i$ over-fulfills the technology norm. This follows from its first-order condition:
  $$\frac{\partial \pi}{\partial r_i} = B_T(E_j^{FB}, T_i) - (i - s_j^{FB}) = 0$$
  $$B_T(E_j^{FB}, T_i) = i - s_j^{FB} < j - s_j^{FB} = B_T(E_j^{FB}, T_i) \underset{B_{TT}<0}{\Rightarrow} T_i^* > T_j^{FB}.$$
- For a firm that chooses a contract $\mathrm{v_i = j \le i}$, the restriction $T \ge T_j^{FB}$ is binding due to $B_T(E_j^{FB}, T_j^{fB}) = j - s_j^{FB} \le i - s_j^{FB}$, i.e., the marginal costs of over-fulfilling the technology norm will exceed the marginal benefits.

In sum, the equilibrium investment levels in the second stage can be determined by the set of N equations $e_i = 0, i \in \{1,...,N\}$, with

(17)
$$e_i = \begin{cases} B_T(E_j^{FB}, r_i + \alpha \sum_{j \ne i} r_j) - (i - s_j^{FB}) & \text{if} \quad v_i > i \\ r_i + \alpha \sum_{j \ne i} r_j - T_{v_i}^{FB} & \text{if} \quad v_i \le i. \end{cases}$$

Inserting the equilibrium investment (and emission) levels into the private cost functions gives us the private cost vector $\pi(v)$ for each contract vector. Hence, we may solve the first stage of the game as follows: *v* is a (Nash) equilibrium contract vector if there does not exist a firm $i \in N$ and a contract vector *w* such that $\pi_i(w) > \pi_i(v)$ and $w_j = v_j \ \forall j \ne i$.

VI.1.3 Welfare comparison

The implementation of the type-specific double negligence rule with compliance-contingent subsidies requires more information on firm behavior and characteristics than the implementation of a uniform negligence rule combined with a uniform subsidy. Nevertheless, also for $N > 2$ (just as in the case of $N = 2$), the type-specific rule does not necessarily outperform the (in the case of $N > 2$, not socially optimal) uniform double negligence rule with respect to total welfare.[21]

This assertion is proven by the following example, which demonstrates that also for $N > 2$, the uniform double negligence rule with $\bar{E} = E_1^{FB}$, $\bar{T} = T_1^{FB}$ combined with a uniform subsidy s_N^{FB} may lead to higher welfare than the double negligence rule with type-specific norms and compliance-contingent subsidies.[22]

Example 3:

a) As in the previous examples, let the benefit function be represented by $B(E_i, T_i) = aE_i - b\left(\sqrt{T_i} + 1\right)E_i^2 + \frac{1}{4}\frac{a^2}{b}\left(\sqrt{T_i} + 1\right)$, and environmental harm by $D(E_i) = dE_i^2$. Further assume that there are $N = 4$ firms. For the parameter values $\alpha = 0.003, a = 10000, b = 100, d = 500, I(1) = L = 100000, I(2) = 105000, I(3) = 150000$, and $I(4) = H = 200000$, we obtain the following results.

The vectors of first-best emission and R&D levels are given by $E^{FB} = (6.903, 6.961, 7.329, 7.560)$ and $r^{FB} = (1.538, 1.391, 0.666, 0.366)$. The corresponding first-best levels for the R&D subsidy are given by $s^{FB} = (1354, 1339, 1204, 1053)$.

If, under the differentiated double negligence rule with compliance-contingent subsidies, each firm chooses its type-specific contract, i.e., $v^{FB} = (1, 2, 3, 4)$, the vector of firm profits would be given by $\pi^{FB} = (467398, 460512, 419936, 397017)$ and the corresponding aggregate welfare by $W^{FB} = \sum_i (\pi_i^{FB} - d(E_i^{FB})^2 - r_i^{FB} s_i^{FB}) = 1636239$. However, the unique equilibrium contract vector is given by $v^C = (4, 4, 4, 4)$, with corresponding firm profits of $\pi^C = (471372, 464200, 421500, 396992)$; i.e., only the high-cost firm 4 prefers $v^{FB} = (1, 2, 3, 4)$ over $v^C = (4, 4, 4, 4)$. The corresponding investment levels are given by $r^C = (1.517, 1.373, 0.663, 0.366)$, which implies that firms 1 to 3 over-fulfill the technology norm of contract 4. Note that although aggregate firm profits are higher in the case of $v^C = (4, 4, 4, 4)$ than in the case of $v^{FB} = (1, 2, 3, 4)$, aggregate welfare $W^C = 1635635$ is lower than in the case of v^{FB} due to higher environmental damages.

Under the uniform double negligence rule with $\bar{E} = E_1^{FB} = 6.903$, $\bar{T} = T_1^{FB} = 1.545$ combined with a uniform subsidy $s_4^{FB} = 1053$, only firms 1 and 2 comply with the norms. The corresponding emission and investment vectors are given by $E^U = (6.903, 6.903, 7.330, 7.560)$ and $r^U = (1.537, 1.537, 0.674, 0.377)$. Firm profits equal

[21] Note that double negligence with compliance-contingent subsidies requires the knowledge of each type-specific socially optimal combination of emission, technology, and subsidy levels.

[22] Note that in the extensions in Section VI, we only emphasize results as "propositions" when they differ from the results of our main model; here, this is not the case.

$\pi^U = (466978, 459291, 393043, 368528)$. Thus, each firm would prefer the negligence rule with compliance-contingent subsidies over the uniform negligence rule, since the emission and technology norms under the preferred contract 4 are weaker and the subsidy is identical to the uniform subsidy. However, aggregate welfare under the uniform negligence rule is given by $W^U = 1635862$ and is thus higher than aggregate welfare under double negligence with compliance-contingent subsidies.

b) As the following variant of Example 3 demonstrates, for the screening under the uniform double negligence rule to successfully outperform compliance-contingent subsidies, there must be a sufficiently large gap between the costs of the types that comply with the norms and those that do not comply. Therefore, assume $I(2) = 125000$ as a single modification to Example 3.a.

As in Example 3.a, the equilibrium coalition structure under compliance-contingent subsidies is given by $v^C = (4,4,4,4)$, whereas in the case of the uniform double negligence rule, firms 1 and 2 comply with the double norm. However, now aggregate welfare is higher in the case of compliance-contingent subsidies ($W^C = 1612513 > W^U = 1605068$).

VI.2 Extension 2: An alternative stylization of technical change

Until recently, the literature has maintained that a more advanced abatement technology should be conceptualized as a decrease in marginal abatement costs. This scenario is addressed in the main part of our paper, in which $B_{ET} < 0$ is assumed, and produces the outcome that firms with more advanced technologies have lower emissions in the social optimum. The increasing strictness of both emission and technology norms was supposedly useful when trying to separate different firm types by the use of negligence-based liability rules. For example, double negligence with compliance-contingent subsidies removes the liability burden and pays low subsidies as soon as firms comply (as is optimal for firms of type *H*), but transfers the high level of the subsidy to the firm only when both emissions are reduced and technology is further improved. Thus, it is interesting to explore whether or not the assumption regarding the applicable kind of technical change is critical for the finding that liability rules combined with R&D subsidies are capable of inducing the social optimum in a setting with two externalities and asymmetric information.

In this section, we test the robustness of our central findings under an alternative specification of technical change (taking up the issues raised in the literature referred to in Footnote 11). More concretely, we consider the possibility that the influence of a more advanced technology on marginal abatement costs may be positive, such that $B_{ET} > 0$ in the relevant range, while maintaining that the other assumptions detailed in Section II hold (including $B_T > 0 > B_{TT}$).

Indeed, the scenario in which the impact of technical advancement on marginal costs depends on the extent of abatement is often discussed in the literature (see, e.g., Perino and Requate 2012). Turning first to the issue of socially optimal emission and investment levels (i.e., the results derived in Section II), we find that the ranking of first-best investment levels is still given by $r_L^{FB} > r_H^{FB}$. This is intuitive, given that firm *L* bears lower R&D costs. However, when we examine the socially optimal level of emissions, the ranking of the technology investments and the assumption regarding the cross-partial derivative of the benefit function, $B_{ET} > 0$, signify that the emission level that is first-best for firm *L* exceeds the level that is efficient for firm *H,* i.e., $E_L^{FB} > E_H^{FB}$. In other words, the firm asymmetry makes it desirable for firm *L* to invest more in R&D. For a given spillover, this entails that firm *L* will use better technology. In circumstances in which marginal abatement costs increase with the state of the abatement technology, it is efficient for firm *L* to abate less than firm *H* in the social optimum. This result stands in a sharp contrast to the ranking obtained in Section II and can be established by the steps detailed in the proof for Proposition 1.

The change in the assumption about the sign of the cross-partial derivative for the benefit function in the relevant range does not affect the results attained for the benchmark scenario in which the policy maker has information about both firm type and firm behavior (i.e., the results derived in Section III). However, one might expect that the variation in the ranking of first-best activity levels could have an impact on the ability to induce first-best activity levels when the policy maker can only rely on information about firm behavior. This will be addressed in the following section.

VI.2.1 Uniform double negligence and R&D subsidies

In Section IV, it was established that a double negligence rule that makes use of two behavioral norms (one governing technological investment and the other, the emission level) can in some cases implement first-best activity levels even when used in combination with a uniform subsidy. In contrast, strict liability and simple negligence cannot induce the social optimum when used with a uniform subsidy.

In order to be compliant when the traditional assumption $B_{ET} < 0$ applies, firms must invest to a large extent and considerably restrict their emissions, since the norms are set at socially optimal levels for firm *L* and both $E_L^{FB} < E_H^{FB}$ and $T_L^{FB} > T_H^{FB}$ apply. In contrast, when the assumption $B_{ET} > 0$ is used, firms that seek to comply with the norms must still invest in technology to a large extent but are also allowed to emit extensively, since both $E_L^{FB} > E_H^{FB}$ and $T_L^{FB} > T_H^{FB}$ hold. Adherance to the standards of behavior frees firms from expected liability. It should be noted that this is relatively less important for firm *H* under the present assumptions, as $B_{ET} > 0$ connotes that the firm with inferior technology will seek to emit less (implying a relatively lower level of damages that can be avoided by choosing compliant behavior). For the same reason, obeying the norms is relatively more important for firm *L*. Even though the relatively less restrictive emissions norm (in comparison to the standard case from Sections II-V) may make adherence to the norms set at the first-best activity levels of firm *L* appealing to both firms, we still find that there are circumstances in which it is only firm *L* that complies, while firm *H* prefers to be negligent (and, as a result, chooses activity levels that are socially optimal for firm *H*). When firm *L* deviates from the norm and anticipates expected liability as a result, it chooses a lower level of technology investment (given that the uniform subsidy is set at the first-best level for firm *H*). The resulting state of technology falls below T_L^{FB}, which means that the privately optimal level of emissions will fall short of E_L^{FB}. Given that firm L complies with the norms, firm *H* compares the payoff consequences of choosing norm compliance, $(E_H, r_H) = (E_L^{FB}, T_L^{FB} - \alpha r_L^{FB})$, to the alternative, which is first-best behavior for the given type, $(E_H, r_H) = (E_H^{FB}, r_H^{FB})$. Given that $E_L^{FB} > E_H^{FB}$, the incentives for firm *H* to behave true to its type (by choosing to be negligent) are stronger when the respective levels of technological investments in the social optimum are very disparate, as $T_L^{FB} - \alpha r_L^{FB} = (1-\alpha) r_L^{FB} + \alpha r_H^{FB}$.

In summary, the finding that the double negligence rule with a uniform subsidy level may induce first-best activity levels is not affected by our consideration of alternative technical change.

Example 4:

Let the benefit function be represented by $B(E_i, T_i) = a\left(1 - b\left(1 + \sqrt{T_i}\right)\right)E_i - cE_i^2\left(1 - f\left(1 + \sqrt{T_i}\right)\right) + g\left(1 + \sqrt{T_i}\right)$. This is an adaptation of the benefit function used in the preceding example. For this function, we obtain $B_E(E_i, T_i) = a\left(1 - b\left(1 + \sqrt{T_i}\right)\right) - 2cE_i\left(1 - f\left(1 + \sqrt{T_i}\right)\right) + g\left(1 + \sqrt{T_i}\right)$,

$B_T(E_i, T_i) = \frac{1}{2}(cfE_i^2 - abE_i + g)T_i^{-\frac{1}{2}}$, and $B_{ET}(E_i, T_i) = \left(cfE_i - \frac{1}{2}ab\right)T_i^{-\frac{1}{2}}$ such that the cross-partial will change its sign once, being positive for sufficiently high emission levels. The level of environmental harm continues to be denoted by $D(E_i) = dE_i^2$. We use $\alpha = 0.15, a = 25000, b = 0.05, c = 2000, \quad d = 800, f = 0.2, g = 200000, L = 100000, H = 175000$. In this case, we find that $B_T > 0 > B_{TT}$, $B_{ET} < 0$ for $E_i < 1.5625$ and $B_{ET} > 0$ for $E_i > 1.5625$, and $dE_{\max} / dT > 0$ for $0 < T < 4$.

The first-best emission and R&D levels for the low-cost and high-cost firms are given by $(E_L^{FB}, r_L^{FB}) = (5.95, 1.86)$ and $(E_H^{FB}, r_H^{FB}) = (5.34, 0.11)$, respectively. The asymmetry in the firms' efficiency with regard to R&D is thus clearly evident in the magnitude of the difference in first-best technology levels. The corresponding first-best levels for the R&D subsidy are given by $s_L^{FB} = 24552.4$ and $s_H^{FB} = 11317.1$.

Under the double negligence rule, with $\bar{E} = E_L^{FB}$, $\bar{T} = T_L^{FB}$, and $s = s_H^{FB}$, the profits of firm *L* (assuming that $r_H = r_H^{FB}$ holds) are given by $\pi_L^{compliance} = 402920$ if it complies with the standards. Under non-compliance, the optimal activity levels of firm *L* would be given by

$(E_L, r_L) = (5.76, 1.33)$. This illustrates the claim made above that the non-compliant firm *L* would choose a lower technology investment and emit less than in the first-best scenario. Given that $\pi_L^{non-compliance} = 378376$, firm *L* prefers to abide by the norms. In contrast, firm *H* is better off being negligent, as we obtain $\pi_H^{compliance} = 306334$ and $\pi_H^{non-compliance} = 368074$, with compliance requiring a technology investment of $T_L^{FB} - \alpha r_L^{FB} = 1.598$.

In summary, the double negligence rule with the uniform subsidy can effectively induce first-best activity levels.

VI.2.2 Negligence with compliance-contingent subsidies

In Section V, it was established that the use of compliance-contingent subsidies can allow the implementation of the social optimum when used either with simple or with double negligence. The simple negligence rule ensured freedom from expected liability and a high (low) subsidy when the chosen level of emissions remained slightly below the first-best level of emissions for a firm of type *L* (*H*). It is straightforward to see that this no longer applies when $B_{ET} > 0$ is assumed to hold in the relevant range, since $E_L^{FB} > E_H^{FB}$.

Proposition 8: ***Differentiated simple negligence rules with compliance-contingent subsidies***

Assume that $B_{ET} > 0$ in the relevant range and that firm type is private information. Then, simple negligence with two type-specific negligence contracts, each consisting of the emission norm E_i^{FB} and a compliance-contingent subsidy $s_i^{FB}, i \in \{L, H\}$, is unable to induce the socially optimal activity levels.

The effectiveness of the simple negligence rule in Section V relies on the ranking of first-best emission levels that results when technical change necessarily lowers marginal abatement costs. Under such circumstances, firm *H* may prefer to emit more even though this implies a lower level of the subsidy. In contrast, in the present framework, firm *H* can actually emit more and receive the higher subsidy, meaning that the simple negligence rule loses its screening potential (i.e., that the weak inequality (14) can never hold). In other words, the fact that the emission norm is more lenient towards firm *L* under the present assumptions rules out the possibility that simple negligence can implement the first-best outcome.

In contrast, the double negligence rule used in combination with compliance-contingent subsidies continues to be an instrument capable of inducing socially optimal decisions when the weak inequalities (13) and (15) are fulfilled. In contrast to simple negligence, double negligence continues to have (at least) one standard that is stricter for firms of type *L*: the norm governing technological investment.

Example 4 (continued):

The double negligence rule with compliance-contingent subsidies promises freedom from expected liability and a per-unit subsidy of s_L^{FB} when $E_i \leq E_L^{FB}$ and $T_i \geq T_L^{FB}$ applies. When one of these two conditions is violated but at least $E_i \leq E_H^{FB}$ and $T_i \geq T_H^{FB}$ holds, the firm will still be considered non-negligent but will receive only s_H^{FB}. The first-best activity levels for the low-cost firm and the high-cost firm are given by $(E_L^{FB}, r_L^{FB}) = (5.95, 1.86)$ and $(E_H^{FB}, r_H^{FB}) = (5.34, 0.11)$, respectively, with resulting subsidies of $s_L^{FB} = 24552.4$ and $s_H^{FB} = 11317.1$.

The argument that firms will never choose negligence but instead select one of the two contracts (as explained in detail in Section V) remains valid under the present assumptions. When firm *L* opts for the *H*-contract, its profit is $B(E_H^{FB}, T_H^{FB}) - (L - s_H^{FB})(T_H^{FB} - \alpha r_H^{FB}) = 376061$. When firm *L* chooses the norm combination actually designed for its type (i.e., the *L*-contract), then its profit is $B(E_L^{FB}, T_L^{FB}) - (L - s_L^{FB}) r_L^{FB} = 427538$. As a result, firm *L* prefers to behave true to type. For firm *H*, when it opts for the *H*-contract, its profit is $B(E_H^{FB}, T_H^{FB}) - (H - s_H^{FB}) r_H^{FB} = 390902$. When instead firm *H* mimics firm *L* by choosing the *L*-contract, its profit is $B(E_L^{FB}, T_L^{FB}) - (H - s_L^{FB})(T_L^{FB} - \alpha r_L^{FB}) = 327482$. As a result, firm *H* prefers to obey the norm set at the socially optimal activity levels for firm *H*.

In summary, the double negligence rule with compliance-contingent subsidies is effective in inducing first-best activity levels.

VI.2.3 Summary for alternative technical change

The conclusion reached in the main part of the paper – namely, that the combination of two instruments (a negligence-based liability rule and R&D subsidies) can allow a policy maker who is informed only about firm behavior but not firm type to induce first-best levels of emissions and investment – is not called into question by the consideration of alternative technical change. Although the assumption regarding how technical change influences marginal abatement costs is critical for the ranking of first-best emission levels, this has no bearing on the activity that is directly related to the type variable, that is, technology investment. The difference in the level of R&D costs implies that the isoprofit curves of firm *L* and firm *H* have different slopes in the emission and technology investment space, which makes firm *L* relatively more willing to comply with demanding technology investment norms. Different valuations for an additional unit of emissions are only indirectly affected via the state of technology reached by investment, while the benefit functions are not type-specific.

VII. Conclusion

This paper analyzes emission and technology choices by two (or more) 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 this case, the two liability rules considered can both induce first-best decisions by private actors. This symmetry no longer holds when incomplete information about firms' costs is assumed.

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 (featuring emission and investment norms tailored to the firm with low investment costs and a subsidy tailored to the firm with high investment costs), but it is not possible for the policy maker to induce the social optimum via strict liability. In cases in which the double negligence rule is unable to induce the social optimum, it performs at least as well as strict liability and the simple negligence rule. In addition, it has been shown that the double negligence rule with a uniform subsidy may even outperform simple and double negligence rules with compliance-contingent subsidies. As a result, screening via compliance and non-compliance with a simple negligence rule combined with a uniform subsidy may be more efficient than screening using type-specific negligence norms and subsidies.

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