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Abstract

This paper analyzes the output, abatement, and investment decisions made by a monopolistic polluter under environmental liability law. The model applied considers both integrated and end-of-pipe abatement technologies. We find that in the case of fixed technology, in many instances negligence produces more favorable results than strict liability in terms of social welfare. The reason is that output under strict liability is always less than first-best output, whereas output under negligence is not similarly limited. However, this ranking of liability rules may be reversed when technology is endogenous. Under such conditions investment in both integrated and end-of-pipe abatement technologies under negligence is guided by motives foreign to the social planner, whereas the polluter's calculus under strict liability is similar to that of the social planner.

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1 Introduction

In most discussions about market failure, the various possible causes are dealt with separately. The distortion under consideration in a particular analysis - externalities or imperfect competition, for example - is modeled in a setting that is otherwise perfect. Policy recommendations derived from this kind of analysis aim at a first-best solution. However, an important branch of the literature follows a different direction. Here, the focus is on the interactions between the various causes of market failure. The relevant question is to what extent the results of first-best analyses and the policy recommendations thus derived carry over to more realistic second-best settings with multiple causes of market failure. For this paper, the simultaneous existence of market power and externalities is of particular concern.

In the relevant literature, the *monopolistic polluter* is an archetypical figure. In his seminal 1969 paper, J.M. Buchanan argued that this economic actor simultaneously causes two kinds of market failure that tend to balance each other out. In his role as a monopolist, this agent produces less than the socially optimal output, exploiting the divergence between price and marginal revenue. In his role as a polluter, he produces too much, ignoring the external side of his production costs. In the knife-edge case, the two distortions may exactly offset each other in terms of economic welfare.[1] In another important paper, Barnett (1980) established that under most circumstances the optimal environmental tax is less than the marginal harm when the polluter is a monopolist. Thus, the traditional Pigouvian policy advice must be adjusted in the case of a monopolistic polluter.

Since the publication of these two papers, the implications for environmental policy of pollution generated by firms with market power have been thoroughly analyzed in the literature. The focus of these analyses has been on emission taxes, transferable discharge permits, and command and control policy.[2] An important environmental policy instrument that has been overlooked by this literature is environmental liability law. The present paper is an attempt to

[1] This scenario relies on the assumption that output reduction is the only available means of pollution control. In the presence of other abatement strategies, the situation becomes more complicated (see Endres 1978, 2011).

[2] See Requate (2006) for a review of this literature. Other recent contributions in this field include Boom and Dijkstra (2009), Kurtyka and Mahenc (2011), Malueg and Yates (2009), Perino (2010), Sanin and Zanaj (2011), and Schoonbeek and de Vries (2009). A public choice analysis of the monopolistic polluter is provided by Heijnen and Schoonbeek (2008).

fill this gap.

We analyze environmental liability law in terms of two alternative liability rules: strict liability and negligence. Under strict liability, the polluter is required to compensate harm, irrespective of behavior. Under negligence, the polluter's liability is contingent on a breach of a behavioral standard. The application of strict liability or negligence in real-world legislation often depends on the activity in question. For instance, the Environmental Liability Directive of the European Union lists activities that are subject to strict liability; other activities are subject to negligence.

Most of the literature on environmental policy uses a static framework. Pollution abatement technology and thus abatement cost functions are assumed to be given. However, the regulator's choice of environmental policy instruments affects the polluter's choice of environmental abatement technologies a well as the incentives to develop these technologies in the first place. This issue is of particular policy relevance. As has been argued by Acemoglu et al. (forthcoming), among others, it is unlikely that fundamental environmental problems such as global warming can be solved with the present state of technology. The ability of environmental policy instruments to induce environmentally friendly technical progress has been considered in various settings (see, e.g., Endres 2011, Parry 2003, Requate 2005a, Requate and Unold 2003, Ulph and Ulph 2007). However, most of these analyses have also been confined to the consideration of transferable discharge permits, emission taxes, and command and control regulations. Recently, the range of environmental policy instruments considered in the context of induced technical change has been extended to environmental liability law (see Endres and Bertram 2006, Endres et al. 2007, 2008, Endres and Friehe 2011a,b).[3]

In this paper, we evaluate the performance of environmental liability law in the presence of a monopolistic polluter according to two criteria. First, we compare the equilibrium pollution abatement level of a monopolistic polluter with the socially optimal abatement level using the traditional framework with predetermined technology. Our model allows for two types of pollution abatement technology: end-of-pipe and integrated technology. Abatement equilibria are differentiated according to whether they are attained under the rule of strict liability or under the rule of negligence. Second, we examine the more sophisticated case involving endogenous

[3]However, these papers are strictly limited to the consideration of perfectly competitive polluters. The present paper examines policy maker's options in a monopolistic market structure.

technology. Here, equilibrium investment in technological change by a monopolistic polluter is compared with socially optimal investment.[4] Again, equilibria are derived for the case of negligence and for the case of strict liability. We establish that negligence will in many instances outperform strict liability from a social welfare maximization standpoint, given a defined state of integrated and end-of-pipe technology. This observation follows from the fact that under negligence firms that abide by the abatement standard no longer bear liability for environmental harm and therefore choose higher output than under strict liability, whereas the output under strict liability is clearly excessively constrained. In other words, attainment of the first-best outcome is possible only under negligence. However, this ranking of outcomes under the two rules assumes an exogenous state of integrated and end-of-pipe technology, and may be reversed once induced technical change of integrated and end-of-pipe technology is taken into account. This potential reversal follows from the fact that under negligence the standard-obedient firm is primarily concerned with the effect innovation might have on the behavioral standard and may thus lack the incentive to invest in integrated abatement technology. In contrast, under strict liability, the monopolistic polluter's calculus with respect to technical change follows the same arguments as the policy maker's calculus, albeit evaluated with different weights.

In most of the literature, liability law is exclusively investigated in the context of accidents. Liability in our framework may also be interpreted as an instrument to internalize externalities from continuous pollution due to production. This is in line with existing legislation, in which liability is in fact not confined to accidents. Examples include the Environmental Liability Directive of the EU cited above, which applies to harm irrespective of whether it is caused by accidents or by continuous pollution, and the German Environmental Liability Act (GELA) of 1991.[5] Under the GELA, firms are generally strictly liable for any harm caused by operating equipment specified in the GELA-Annex. Liability applies to harm from continuous emissions just as it applies to harm resulting from accidents. Liability under GELA cannot be avoided when causality is certain. However, importantly, in the case of uncertain causality, the following procedure comes into play: It is presumed that the firm under consideration caused the harm

[4]In this paper we assume technical progress to be produced by investment in R&D. An alternative assumption would be that technical progress is achieved via learning by doing. See Clark et al. (2008) on the economic theory of these two assumptions and on their practical applications.

[5]See Endres (2011: 75-80) and Feess (2007: 154-157) for an economic assessment. Both authors examine the roles of strict liability and negligence for continuous pollution in the context of this law.

when the firm is (according to the facts of the case) capable of causing the harm in question. However, the firm can refute this *presumption of causality* by showing that its facility was operating in accordance with regulations. Specifically, this refers to compliance with the environmental requirements imposed by the German Clean Air Act (*Bundesemissionsschutzgesetz*) and other regulations derived from this act, such as the Technical Instructions for Clean Air (*TA Luft*). Essentially, in the case of uncertain causation, firms are exempt from liability when they stay within the confines of the environmental standards prescribed by policy makers.[6] Our modeling of the negligence rule is a stylization of this kind of legislation. The environmental standards defined in command and control regulations are analogous to the due care standard in the application of liability in accident cases: When a firm violates the norm, it is considered negligent and is therefore held liable for the harm. When a firm respects the norm, it is exempt from liability.

Above, we briefly alluded to some existing legislation in which liability law is applied to harm from pollution not generated by accidents. Such circumstances might also have consequences for future legislation. Consider recent developments in US air pollution control policy:[7] Until quite recently, greenhouse gases (and in particular CO_2) were not considered "pollutants" subject to restriction under the Clean Air Act. However, in December 2009, the US Environmental Protection Agency (EPA) determined that greenhouse gases are dangerous to human health and the environment. Subsequently, and with the backing of the Supreme Court's decision in Mass. v. EPA (2007), the EPA began to regulate greenhouse gases (in particular CO_2 emissions) under the Clean Air Act, using the traditional command and control approach. Currently, the process of regulating stationary sources such as power plants and industrial facilities via the Clean Air Act is in progress. Now that CO_2 and other greenhouse gas emissions have been determined to generate harm, the question of how to design liability will have to be answered. As soon as command and control regulations for these emissions are included in the Clean Air Act, it must be decided whether compliance with these standards will be sufficient to absolve

[6]The idea that the violation of norms imposed by command and control policies is similar to not exercising due care can be found in many liability laws regarding harm generated by accidents. For example, the US Oil Pollution Act of 1990 (OPA 90) generally protects the defendant in liability cases by capping compensation payments. However, caps are waived in cases of gross negligence or of violations of applicable regulations, according to OPA 90, 33 U.S.C. §2704 (c).

[7]See Burtraw et al. (2011) for a more detailed discussion of these developments.

CO_2-emitting firms from liability. The choice between strict liability and negligence for harm due to CO_2 emissions will thus be on the scholarly and political agenda. Since CO_2 emissions are a by-product of economic activity (and are not only the result of accidents), the interpretation of liability analyzed in the present paper may also be applied to this forthcoming regulatory debate.[8]

The structure of the paper is as follows: Section 2 presents the model. In Section 3, we consider - given exogenous integrated and end-of-pipe abatement technology - the social optimum and the private optimum under strict liability and negligence, respectively. Similarly, in Section 4, we consider - given endogenous integrated and end-of-pipe abatement technology - the social optimum and private optimum under strict liability and negligence, respectively. Section 5 concludes.

2 The Model

In laying out the framework, we first examine the model given a fixed state of end-of-pipe and integrated technology. Next, we introduce aspects of the model related to the possibility to determine the state of the respective technologies.

2.1 The Model with Given Abatement Technology

A monopolistic firm produces output q at marginal production costs normalized to zero. Demand for the firm's output can be represented by the inverse demand function $P(q)$, with $P'(q) < 0 \leq P''(q)$. Production causes emissions at level $E(q, \beta) = (1 - \beta)q$, with $1 > \beta \geq 0$. The parameter β represents the state of the integrated abatement technology. The integrated abatement technology thus directly impacts the emission coefficient of output. The monopolistic polluter can lower the level of emissions resulting from production at an output level q by using a level x of end-of-pipe abatement at cost $g(x, \alpha)$, $\partial g/\partial x$, $\partial^2 g/\partial x^2 > 0$, where α represents the state of the end-of-pipe abatement technology. The end-of-pipe technology takes the emissions created by the firm's activity as given (an example of such technology would be a

[8]The economic and legal aspects of using liability law to curb CO_2 emissions have been analyzed by Faure and Peeters (2011), who discuss general issues of economic incentives and legal feasibility as well as specific European and US perspectives on climate change liability.

scrubber). For simplicity, we assume that the end-of-pipe abatement costs are independent of output. Industry-specific (or local) net emissions $E - x$ cause environmental harm $D(E - x)$, where D', $D'' > 0$.

2.2 The Model with Endogenous Abatement Technology

We allow for the case in which the state of both types of abatement technology (integrated and end-of-pipe) can be improved upon. An increase in α decreases end-of-pipe abatement costs $g(x, \alpha)$ with regard to their level at a diminishing rate and at the margin ($\partial g/\partial\alpha < 0$, $\partial^2 g/\partial\alpha^2 > 0$, and $\partial^2 g/\partial x \partial\alpha < 0$), and will be referred to as an improvement in end-of-pipe abatement technology. Investment costs associated with state α of end-of-pipe abatement technology are $A(\alpha)$; a marginal improvement comes at cost $A'(\alpha) > 0$, which is weakly increasing, $A''(\alpha) \geq 0$. An increase in β denotes an improvement in the emission coefficient of the production process and will be referred to as an improvement in integrated abatement technology. Investment costs associated with state β of integrated abatement technology are represented by $B(\beta)$; a marginal improvement comes at cost $B'(\beta) > 0$, which is weakly increasing, $B''(\beta) \geq 0$.

3 Exogenous Abatement Technology

In this section, we assume that the states of both integrated and end-of-pipe technologies are given exogenously, and we derive the social and the private optimum under strict liability and negligence, respectively. The next section will detail the socially and privately optimal levels of investment in integrated and end-of-pipe technology.

3.1 Social Optimum with Given Abatement Technology

We assume that the policy maker maximizes social welfare, defined as the difference between consumer surplus and the sum of both end-of-pipe abatement costs and environmental harm.

$$SW = \int_0^q P(c)dc - g(x, \alpha) - D(E - x) \tag{1}$$

The socially optimal level of end-of-pipe abatement for a given level of emissions solves

$$\frac{\partial SW}{\partial x} = -\frac{\partial g(x^*, \alpha)}{\partial x} + D'(E - x^*) = 0. \tag{2}$$

Thus, this first-best level is obtained when marginal end-of-pipe abatement costs are equal to marginal environmental harm. Socially optimal end-of-pipe abatement increases with the level of emissions and the state of the end-of-pipe abatement technology, corresponding to

$$\frac{\partial x^*}{\partial E} = \frac{D''}{\frac{\partial^2 g}{\partial x^2} + D''} > 0 \tag{3}$$

$$\frac{\partial x^*}{\partial \alpha} = -\frac{\frac{\partial^2 g}{\partial x \partial \alpha}}{\frac{\partial^2 g}{\partial x^2} + D''} > 0, \tag{4}$$

which may be used to define the following optimal value function:

$$C(E, \alpha) = g(x^*(E, \alpha), \alpha) + D(E - x^*(E, \alpha)) \tag{5}$$

this represents minimized social costs of pollution. Naturally, a higher level of emissions implies a higher level of social pollution costs, as

$$\frac{\partial C}{\partial E} = D' > 0 \tag{6}$$

$$\frac{\partial^2 C}{\partial E^2} = D'' \left(1 - \frac{\partial x^*}{\partial E}\right) > 0. \tag{7}$$

Denoting the abatement costs at optimal abatement as $c(E, \alpha)$, we find that

$$\frac{\partial c}{\partial E} = \frac{\partial g(x^*, \alpha)}{\partial x} \frac{\partial x^*}{\partial E} = D' \frac{\partial x^*}{\partial E} > 0, \tag{8}$$

where the second equality uses the first-order condition for end-of-pipe abatement.[9] Since $\partial x^*/\partial E < 1$, this establishes that the increase in minimized abatement costs is only a portion of the increase in minimized social pollution costs (i.e., $\partial c/\partial E < \partial C/\partial E$).

The above analysis allows us to restate social welfare as a function of output only:

$$SW = \int_0^q P(c)dc - C((1 - \beta)q, \alpha). \tag{9}$$

The first-order condition is given by

$$\frac{dSW}{dq} = P(q^*) - (1 - \beta)\frac{\partial C((1 - \beta)q^*, \alpha)}{\partial E} = 0. \tag{10}$$

The second-order condition is fulfilled, as $P' - (1 - \beta)^2 \partial^2 C/\partial E^2 < 0$. Given that we have normalized marginal production costs to zero, the first-best output level leads to the equalization

[9] We assume that $\partial^2 c/\partial E^2 = D'' \frac{\partial x^*}{\partial E} + D' \frac{\partial^2 x^*}{\partial E^2} \geq 0$ in order to avoid detailed explanation of the required assumptions for the third-order derivatives of D and g.

of the marginal willingness to pay and the marginal increase in the total social pollution costs due to the increase in output.

Turning to a comparative-statics analysis, it can be established that first-best output increases with the state of the end-of-pipe abatement technology α:

$$\frac{\partial q^*}{\partial \alpha} = \frac{(1-\beta)\frac{\partial^2 C}{\partial E \partial \alpha}}{P' - (1-\beta)^2 \frac{\partial^2 C}{\partial E^2}} > 0, \tag{11}$$

since

$$\frac{\partial^2 C}{\partial E \partial \alpha} = -D'' \frac{\partial x^*}{\partial \alpha} < 0. \tag{12}$$

The influence that the state of the integrated abatement technology has on output is

$$\frac{\partial q^*}{\partial \beta} = -\frac{\frac{\partial C}{\partial E} + (1-\beta)\frac{\partial^2 C}{\partial E^2} q^*}{P' - (1-\beta)^2 \frac{\partial^2 C}{\partial E^2}} > 0. \tag{13}$$

How the state of the integrated abatement technology β influences the socially optimal level of end-of-pipe abatement is ambiguous when taking the change of output in (13) into account. This impact will be determined by how emissions $E^* = (1-\beta)q^*$ are influenced, and the effect on the level of emissions is decided by two opposing factors. The direct effect of an increase in β is negative and given by $-q^*$, whereas the indirect effect is positive, given by $(1-\beta)\partial q^*/\partial \beta$. From (3), it is clear that abatement increases (decreases) when the direct effect is absolutely smaller (larger) than the indirect effect. From the above, it follows that:

Lemma 1 *In the social optimum:*
(i) Output q^* increases with α. (ii) Output q^* increases with β. (iii) End-of-pipe abatement x^* increases with α. (iv) End-of-pipe abatement x^* increases (decreases) with β if $q^* < (>)\, (1-\beta)\partial q^*/\partial \beta$.

The level of social welfare attainable by selecting the socially optimal levels of output and abatement can be stated as

$$SW^* = \int_0^{q^*} P(c)dc - C((1-\beta)q^*, \alpha) \tag{14}$$

and is a function of the exogenous technology parameters (α, β).

3.2 Equilibrium with Given Technology

In this section, we describe privately optimal decisions under strict liability and under negligence, given the state of both types of technology.

3.2.1 Strict Liability

The monopolistic firm under strict liability maximizes profits with respect to output and the abatement level, where profits take into account both end-of-pipe abatement costs and environmental harm D. Here, we explicitly assume that the monopolistic polluter will definitely be held responsible for the exact level of harm caused. Using C as defined above, profits may be stated as a function of output:

$$\pi^{SL} = P(q)q - C((1-\beta)q, \alpha). \tag{15}$$

The corresponding first-order condition is given by

$$\frac{d\pi^{SL}}{dq} = P'(\bar{q})\bar{q} + P(\bar{q}) - (1-\beta)\frac{\partial C((1-\beta)\bar{q}, \alpha)}{\partial E} = 0. \tag{16}$$

We assume that the second-order condition is fulfilled, so that $P''q+2P'-(1-\beta)^2\partial^2 C/\partial E^2 < 0$. The output level maximizing profits under strict liability leads to the equalization of marginal revenue and the marginal increase in social pollution costs due to the increase in output. The condition demonstrates that privately optimal output will be less than socially optimal output q^*. Since this implies lower emissions, this in turn implies that the level of privately optimal abatement will be less than the level of socially optimal abatement. These considerations allow us to explicate the following finding:

Proposition 1 *Under strict liability:*
(i) Monopolistic firms choose a socially suboptimal output level, $\bar{q} < q^*$. (ii) Monopolistic firms choose end-of-pipe abatement below the socially optimal level, $\bar{x} < x^*$. (iii) Monopolistic firms' abatement mix is distorted towards output reduction.

Proof. Claims (i) and (ii) follow from the arguments in the previous paragraph. Claim (iii) follows because the monopolistic polluter underestimates the costs from reducing emissions by reducing the level of output, $P'(q)q + P(q) < P(q)$. ■

Regarding Claim (ii), we would like to note that the level x^* is first-best from a social welfare-maximizing standpoint only if output is set equal to q^*. Consequently, given that the monopolist's output choice is different from q^*, the abatement level x^* is no longer first-best for the output level selected. More concretely, if $\bar{q} < q^*$, the policy maker bound by this output choice would like to induce end-of-pipe abatement below the level x^* - specifically, $\bar{x}$.

For Claim (iii) in Proposition 1, note that the monopolistic firm's cost for avoiding emissions via output reduction are equal to the marginal revenue and are thus smaller than the costs from a social perspective. As we have established that $\bar{x} < x^*$, we can also argue using (2) that $D'((1-\beta)\bar{q} - \bar{x}) < D'((1-\beta)q^* - x^*)$ must hold, a finding that will later be of relevance.

Lemma 2 *Under strict liability:*
(i) The privately optimal output $\bar{q}$ increases with α. (ii) The privately optimal output $\bar{q}$ increases with β. (iii) The privately optimal abatement $\bar{x}$ increases with α. (iv) The privately optimal abatement $\bar{x}$ increases (decreases) with β if $\bar{q} < (>) \, (1-\beta)\partial\bar{q}/\partial\beta$.

Proof. When we carry out the comparative-statics analysis regarding the privately optimal level of output, we obtain

$$\frac{\partial \bar{q}}{\partial \alpha} = \frac{(1-\beta)\frac{\partial^2 C}{\partial E \partial \alpha}}{P''q + 2P' - (1-\beta)^2 \frac{\partial^2 C}{\partial E^2}} > 0 \tag{17}$$

$$\frac{\partial \bar{q}}{\partial \beta} = -\frac{\frac{\partial C}{\partial E} + (1-\beta)\frac{\partial^2 C}{\partial E^2}\bar{q}}{P''q + 2P' - (1-\beta)^2 \frac{\partial^2 C}{\partial E^2}} > 0. \tag{18}$$

Claim (iii) follows, as privately optimal end-of-pipe abatement is also socially optimal end-of-pipe abatement when evaluated at $\bar{E} = (1-\beta)\bar{q}$. Accordingly, as was true for the social welfare-maximizing level of abatement, the sign of the derivative of privately optimal end-of-pipe abatement with respect to an improvement in integrated technology is not clear. Again, it is critical whether an improvement in the integrated abatement technology implies an increase or a decrease in the optimized level of emissions, $(1-\beta)\bar{q}$. ■

By behaving in the privately optimal fashion, a firm will attain a profit of $\Pi^{SL} = P(\bar{q})\bar{q} - C((1-\beta)\bar{q}, \alpha)$, which is a function of the exogenous technology parameters (α, β).

3.2.2 Negligence

Under negligence, liability is contingent on the breach of a behavioral duty. In this context, the behavioral duty is the implementation of a minimum level of end-of-pipe abatement x. Consequently, we make the realistic assumption that the policy maker will prescribe the use of some type of filtering, for example, but will refrain from defining a maximum output level.

A legal principle that is frequently invoked when determining such due behavioral standards is the so-called 'Learned Hand rule,' which can be interpreted in our context to require that the standard be set to minimize the sum of environmental harm and abatement costs (see, e.g., Brown 1973, Cooter 1991). We therefore presume that the policy maker will implement a standard for end-of-pipe abatement set at the abatement level that solves

$$\min_x SC = g(x,\alpha) + D((1-\beta)q - x) \tag{19}$$

for a given level of output. Our approach is thereby in line with Polinsky and Rogerson (1983), among others.[10] The resulting abatement level is first-best given the output level and the state of both the integrated and the end-of-pipe abatement technologies, $x^s((1-\beta)q,\alpha)$, thus solving

$$\frac{\partial g(x^s,\alpha)}{\partial x} = D'((1-\beta)q - x^s). \tag{20}$$

This level changes with the parameters that are exogenous from the policy maker's viewpoint as follows:

$$\frac{\partial x^s}{\partial q} = \frac{(1-\beta)D''}{\frac{\partial^2 g}{\partial x^2} + D''} > 0 \tag{21}$$

$$\frac{\partial x^s}{\partial \alpha} = -\frac{\frac{\partial^2 g}{\partial x \partial \alpha}}{\frac{\partial^2 g}{\partial x^2} + D''} > 0 \tag{22}$$

$$\frac{\partial x^s}{\partial \beta} = -\frac{qD''}{\frac{\partial^2 g}{\partial x^2} + D''} < 0, \tag{23}$$

where $\partial x^s/\partial E = \frac{\partial x^s/\partial q}{(1-\beta)} = -\frac{\partial x^s/\partial \beta}{q}$. Note that this may be interpreted as the policy maker responding to a given q, α, and β instead of prescribing abatement levels in advance of the polluter's output decision. Such a structure is realistic, particularly if the policy maker's commitment ability or information regarding technological opportunities is limited. The literature commonly either assumes ex-post policy design or ex-ante commitment to a certain policy level (see, e.g., Requate 2005a, b). The sequence of moves tends to codetermine equilibrium behavior. Indeed, it is of central importance for our argument that the abatement standard responds to variations in the state of both integrated and end-of-pipe abatement technologies, which applies only in the case of ex-post regulation.

The firm seeks to maximize profits, here represented by a step-wise function:

$$\pi^N = \begin{cases} P(q)q - g(x,\alpha) - D((1-\beta)q - x) & \text{if } x < x^s \\ P(q)q - g(x,\alpha) & \text{if } x \geq x^s. \end{cases} \tag{24}$$

[10] Polinsky and Rogerson (1983) compare alternative liability rules in the product-liability context in which consumers underestimate harm and producers have market power. In their analysis of negligence, it is assumed that the standard of care minimizes the sum of care costs and expected accident losses.

For a given level of output, the choice of x^s is clearly cost-minimizing for the firm, given that x^s fulfills (20). We may thus write profits under negligence as

$$\pi^N|_{x=x^s} = P(q)q - c((1-\beta)q, \alpha). \tag{25}$$

where $c((1-\beta)q, \alpha)$ was defined in Section 3.1. The profit-maximizing output level $\tilde{q}$ follows from

$$\frac{d\pi^N}{dq}|_{x=x^s} = P'(\tilde{q})\tilde{q} + P(\tilde{q}) - (1-\beta)\frac{\partial c}{\partial E} = 0. \tag{26}$$

The profit-maximizing output is found where marginal revenue is equal to the increase in the level of minimized abatement costs due to the increase in output. Using $\partial c/\partial E < \partial C/\partial E$, it follows that $\tilde{q} > \bar{q}$. The comparison of $\tilde{q}$ and the first-best output level q^* hinges on whether or not the impact on the marginal benefit of output, $P'(\tilde{q})\tilde{q}$, is absolutely greater than the impact on the marginal costs of output, $(1-\beta)\partial C/\partial E\ (1-\partial x/\partial E)$, where $\partial x/\partial E < 1$. The following proposition employs the difference in marginal incentives,

$$\xi = P'(q)q + (1-\beta)\frac{\partial C}{\partial E}\left(1 - \frac{\partial x}{\partial E}\right). \tag{27}$$

Proposition 2 *Under negligence:*
(i) The firm chooses socially suboptimal (excessive) output if $\xi <\ (>)0$. *(ii) The firm's abatement mix is distorted towards (away from) output reduction if* $\xi <\ (>)0$.

Proof. Follows from the above. ■

With regard to a comparative-statics analysis, we find that the signs of $\frac{\partial \tilde{q}}{\partial \alpha} = -\frac{\partial^2 \pi^N}{\partial q \partial \alpha} / \frac{\partial^2 \pi^N}{\partial q^2}$ and $\frac{\partial \tilde{q}}{\partial \beta} = -\frac{\partial^2 \pi^N}{\partial q \partial \beta} / \frac{\partial^2 \pi^N}{\partial q^2}$ are the same as the signs of $\frac{\partial(-\frac{\partial g}{\partial x}\frac{\partial x^s}{\partial q})}{\partial \alpha}$ and $\frac{\partial(-\frac{\partial g}{\partial x}\frac{\partial x^s}{\partial q})}{\partial \beta}$, respectively. Choosing activity levels $(x^s, \tilde{q})$ allows a profit level of $\Pi^N = P(\tilde{q})\tilde{q} - c((1-\beta)\tilde{q}, \alpha)$, which is a function of the exogenous technology parameters (α, β).

3.2.3 Comparing Strict Liability and Negligence

By contrasting the private outcome under strict liability with that under negligence, we find that negligence may be superior for the following reason: The monopolistic polluter chooses more end-of-pipe abatement and a higher output level under negligence compared to the levels chosen under strict liability.

Corollary 1 *(i) The firm chooses an output level* $\tilde{q}$*, which is higher under negligence than under strict liability,* $\tilde{q} > \bar{q}$*. (ii) The firm chooses the end-of-pipe abatement level* $x^s(\tilde{q})$*, which is higher under negligence than under strict liability,* $x^s(\tilde{q}) > x^s(\bar{q})$*.*

Proof. Claim (i) follows from using $\partial c/\partial E < \partial C/\partial E$. Claim (ii) uses the fact that the level of abatement is socially optimal given the level of the other variables in the two scenarios, but also the fact that the level of emissions is higher under negligence due to Claim (i). ■

The levels of output and end-of-pipe abatement under strict liability are certainly too small (i.e., $\bar{q} < q^*$). The firm's output under strict liability is too small due to the fact that the monopolistic firm is concerned about marginal pollution costs and marginal revenue, which in this case is distinct from willingness to pay. Negligence removes the burden of environmental harm and thereby encourages a higher level of output than strict liability (i.e., $\tilde{q} > \bar{q}$). This level of privately optimal output under negligence may thus be closer to the first-best level. Negligence therefore may allow for the attainment of the first-best outcome, an impossibility under strict liability. When $\bar{q} < \tilde{q} \leq q^*$, negligence will certainly induce higher welfare levels than strict liability. However, negligence may induce lower welfare levels than strict liability when $\bar{q} < q^* < \tilde{q}$, implying that there may be instances in which negligence is inferior to strict liability in terms of social welfare, should the increased output under negligence be excessively distorted. The smaller the distortion under strict liability relative to the benchmark and the smaller the marginal costs that the monopolistic polluter internalizes under negligence, the more likely the possibility of an adverse impact on social welfare becomes. The smaller the value of D'', the smaller the marginal costs (as this implies that $\partial x^s/\partial E$ is smaller).

4 Endogenous Abatement Technology

In this section, we will describe the socially and privately optimal levels of investment in both integrated and end-of-pipe technology. Here, we interpret decision-making as a sequence of decisions, in which technology is determined first, before output and end-of-pipe abatement are decided upon. The previous section presented decision-making at the second stage; we turn now to the first stage.

4.1 Social Optimum with Endogenous Technology

The policy maker maximizes social welfare (i.e., the difference between consumer surplus and the sum of end-of-pipe abatement costs and environmental harm), taking into account that end-of-pipe and integrated abatement technologies can be influenced at costs A and B, respectively. The policy maker thus chooses to

$$\max_{\alpha,\beta} W = SW^*(\alpha,\beta) - A(\alpha) - B(\beta)$$
$$= \int_0^{q^*} P(c)dc - C((1-\beta)q^*, \alpha) - A(\alpha) - B(\beta), \tag{28}$$

where $SW^*(\alpha,\beta)$ gives the maximal level of social welfare without dynamic considerations, as derived in Section 3 (see (14)). The function W represents the objective function of the policy maker, including considerations relating to the endogeneity of the state of technology. An increase in either of the technology parameters impacts the levels of socially optimal output and abatement. However, in differentiating, corresponding terms cancel out by application of the envelope theorem. After simplification, we arrive at the following set of first-order conditions:

$$\frac{\partial W}{\partial \alpha} = -\frac{\partial C((1-\beta)q^*, \alpha)}{\partial \alpha} - A'(\alpha^*) = 0 \tag{29}$$
$$\frac{\partial W}{\partial \beta} = \frac{\partial C((1-\beta)q^*, \alpha)}{\partial E} q^* - B'(\beta^*) = 0, \tag{30}$$

where $\partial C/\partial \alpha = \partial g/\partial \alpha < 0$ and $\partial C/\partial E = D' > 0$. The direct effect of an improvement in end-of-pipe technology on SW^* is the decrease in end-of-pipe abatement costs at optimal abatement. The direct effect of a change in β on SW^* is given by the decrease in environmental harm at optimal output and end-of-pipe abatement, weighted by first-best output, $D'((1-\beta)q^* - x^*)q^*$.

4.2 Equilibrium with Endogenous Technology

In this section, we describe privately optimal decisions regarding integrated and end-of-pipe technology under strict liability and under negligence.

4.2.1 Strict Liability

The firm maximizes the level of profits, accounting for the fact that end-of-pipe and integrated abatement technologies can be influenced at costs A and B, respectively.

$$\begin{aligned} Y =& \Pi^{SL}(\alpha,\beta) - A(\alpha) - B(\beta) \\ =& P(\bar{q})\bar{q} - C((1-\beta)\bar{q},\alpha) - A(\alpha) - B(\beta) \end{aligned} \tag{31}$$

The following conditions are solved by the levels that are privately optimal under strict liability

$$\frac{\partial Y}{\partial \alpha} = -\frac{\partial C((1-\beta)\bar{q},\alpha)}{\partial \alpha} - A'(\bar{\alpha}) = 0 \tag{32}$$

$$\frac{\partial Y}{\partial \beta} = \frac{\partial C((1-\beta)\bar{q},\alpha)}{\partial E}\bar{q} - B'(\bar{\beta}) = 0. \tag{33}$$

The direct effect of a change in α on Π^{SL} is given by the decrease in end-of-pipe abatement costs at privately optimal abatement. The direct effect of a change in β on Π^{SL} is the decrease in environmental harm at privately optimal output and end-of-pipe abatement, weighted by the privately optimal level of output. Consequently, the monopolistic firm makes the same calculations in weighing the trade-offs between the marginal benefits and marginal costs of a marginal improvement in technology as the policy maker does. However, we obtain profit-maximizing levels of investment deviating from socially optimal investment because the firm evaluates the functions at different variable levels. This explains the following observations:

Proposition 3 *Under strict liability:*
(i) Monopolistic firms choose a socially suboptimal level of investment in end-of-pipe technology, $\bar{\alpha} < \alpha^*$. (ii) Monopolistic firms choose a socially suboptimal level of investment in integrated technology, $\bar{\beta} < \beta^*$.

Proof. The first claim follows from the fact that $|\partial C((1-\beta)\bar{q},\alpha)/\partial\alpha| = |\partial g(\bar{x},\alpha)/\partial\alpha| < |\partial g(x^*,\alpha)/\partial\alpha| = |\partial C((1-\beta)q^*,\alpha)/\partial\alpha|$, since $\bar{x} < x^*$ and $\partial^2 g/\partial x \partial\alpha < 0$. The second claim follows from the observation emphasized in Section 3.2.1 that $D'((1-\bar{\beta})q^* - x^*) > D'((1-\bar{\beta})\bar{q} - \bar{x})$, a relationship which is only pronounced by $\bar{q} < q^*$ in the first-order conditions determining privately and socially optimal integrated technology. ■

The findings with regard to investment in technology under strict liability are intuitive, given the profit-maximizing behavior $(\bar{q},\bar{x})$ at the next stage. The monopolistic firm intends to produce less output and implement less abatement than the policy maker does and therefore perceives marginal benefits from investing to be lower.

4.2.2 Negligence

In the following analysis, we assume that the firm anticipates that the standard regarding end-of-pipe abatement, $x^s((1-\beta)q, \alpha)$, which was discussed in some detail in Section 3.2.2, will adapt as a consequence of changes in the technology parameters.

The firm thus maximizes

$$\begin{aligned} Z =& \Pi^N(\alpha, \beta) - A(\alpha) - B(\beta) \\ =& P(\tilde{q})\tilde{q} - c((1-\beta)\tilde{q}, \alpha) - A(\alpha) - B(\beta). \end{aligned} \tag{34}$$

The following first-order conditions, which have been simplified by the application of the envelope theorem, determine the privately optimal investment levels under negligence:

$$\frac{\partial Z}{\partial \alpha} = -\frac{\partial c((1-\beta)\tilde{q}, \alpha)}{\partial \alpha} - A' \leq 0 \tag{35}$$

$$\frac{\partial Z}{\partial \beta} = \frac{\partial c((1-\beta)\tilde{q}, \alpha)}{\partial E}\tilde{q} - B' \leq 0 \tag{36}$$

$$\frac{\partial Z}{\partial \alpha} \times \alpha = 0 \tag{37}$$

$$\frac{\partial Z}{\partial \beta} \times \beta = 0, \tag{38}$$

where $\partial c/\partial \alpha = \partial g/\partial x \; \partial x^s/\partial \alpha + \partial g/\partial \alpha$, and $\partial c/\partial E = D' \partial x^s/\partial \beta$ follows from using the first-order condition for x^s, equation (20).

The condition (35) shows that the polluter will weigh marginal benefits (the decrease in minimized abatement costs) against marginal costs, which include not only the marginal investment costs but also the fact that the standard will become stricter as a consequence of a higher α, which obviously implies additional abatement costs. In contrast, an increase in β will lower the abatement standard x^s. This fact is the sole incentive for investing in development of integrated abatement technology at all. When comparing the private incentives under negligence to the incentives of the social planner, it is once again important to remember that $\partial c/\partial E < \partial C/\partial E$.

Optimization of the firm's decisions with regard to technology parameters under negligence allows the following observations:

Proposition 4 *Under negligence:*

(i) Monopolistic firms choose socially suboptimal investment in end-of-pipe technology for given

levels of output and abatement, $0 < \tilde{\alpha} < \alpha^*$. *(ii) The monopolistic firm's choice of investment in end-of-pipe technology is the closer to the first-best level, the less important the strategic effect* $\partial g/\partial x \; \partial x^s/\partial\alpha$ *is. (iii) Monopolistic firms choose socially suboptimal investment in integrated technology for given levels of output and abatement,* $\tilde{\beta} < \beta^*$. *(iv) Monopolistic firms that invest in integrated technology do so only to decrease the abatement standard.*

Proof. Follows from the above. ■

4.2.3 Comparing Strict Liability and Negligence

If we first turn to a direct comparison of emergent investment levels under strict liability and under negligence, we obtain

Corollary 2 *Monopolistic firms choose lower levels of investment in end-of-pipe and integrated abatement technology under negligence than under strict liability for given levels of output and abatement.*

Proof. Follows from the above. ■

When we compare the profit-maximizing levels of investment under strict liability and negligence to the first-best levels of integrated and end-of-pipe technology, we find that under strict liability the monopolistic polluter assesses marginal benefits and marginal costs according to criteria similar to the policy maker's. In contrast, under negligence technology incentives are dramatically distorted. Under negligence, the polluter is concerned about the impact that investment could have on the regulatory standard; with this rule, a profit-maximizing firm may have no incentive at all to invest in integrated technology. Consequently, although the equilibria under both strict liability and under negligence turn out to be suboptimal compared to the first-best pattern and level of investment, the relative distortions created by the two liability rules differ considerably.

5 Conclusion

The monopolistic polluter has attracted a great deal of attention in the literature on the economics of environmental policy. This interest is due to the fact that to some extent the imperfect competition distortion nullifies the externality distortion. This interaction could affect traditional policy recommendations.

This paper contributes by considering the monopolistic polluter under environmental liability both when technology is exogenous and when it is endogenous. We find that negligence will in many instances be preferable to strict liability in terms of social welfare, given exogenous integrated and end-of-pipe technology. This follows from the fact that under negligence, firms that abide by the abatement standard no longer bear liability for environmental harm and therefore choose higher output than under strict liability. Indeed, negligence may allow the first-best outcome to be attained. However, the welfare ranking of outcomes under the two liability rules obtained for exogenous integrated and end-of-pipe technology may reverse once induced development of integrated and end-of-pipe technology is accounted for. This potential reversal is due to a particular distortion of the incentives to invest in technological change under negligence. In this case, the private incentive to invest is strongly affected by the influence that the polluter's technology choice could exert on the behavioral standard. This may have the extreme implication that the firm would have no incentive at all to invest in end-of-pipe abatement technology, as this would only increase the level of abatement required in the standard of negligence. Under strict liability, the monopolistic polluter uses the same logical calculations as the policy maker, albeit evaluated with different priorities.

Our analysis contributes to the economic assessment of the relative performance of strict liability and negligence as strategies to internalize externalities and to induce socially optimal technical change. Our findings also bear important implications with respect to R&D stimulating policies. Under strict liability, incentives for technical change are too little but act in the right direction; under negligence, polluters may avoid investing in abatement technology altogether. Consequently, the performance of environmental liability law with respect to inducing advances in abatement technology is inadequate under negligence. This suggests that to encourage technological progress, it would be necessary to complement liability law with other policy instruments, particularly when the negligence rule is applied.

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