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Auteurs

J. Jacob, S. Spaeter

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Faculté des sciences économiques et de gestion
Pôle européen de gestion et d'économie (PEGE)
61 avenue de la Forêt Noire
F-67085 Strasbourg Cedex

Secrétariat du BETA
Géraldine Del Fabbro
Tél. : (33) 03 68 85 20 69
Fax : (33) 03 68 85 20 70
g.delfabbro @unistra.fr
www.beta-umr7522.fr

UNIVERSITÉ DE LORRAINE

UNIVERSITÉ DE STRASBOURG

Large-scale risks and technological change: What about limited liability?[1]

Julien JACOB[2] Sandrine SPAETER[3]

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[2]BETA, CNRS and University of Lorraine (julien.jacob@univ-lorraine.fr)

[3]BETA, CNRS and University of Strasbourg (spaeter@unistra.fr)

Technological change and limited liability
Sandrine Spaeter (spaeter@unistra.fr)

Abstract

We consider a firm under strict liability that must choose between two risky technologies, one being safer but costlier than the other one. The total potential level of damage increases with the level of activity. We show that, under limited liability, technological change is welfare improving and leads to full risk internalization when the firms are sufficiently capitalized. Nevertheless, the percentage of firms adopting the safer technology and full risk internalization is higher under unlimited liability than under limited liability. We show how an adequate tax policy increases this percentage. We also determine the characteristics of a second-best tax policy.

Keywords: Technological risk; limited liability; incentives; technical choice; taxes.
JEL Classification: D81, H23, K39, Q55.

1 Introduction

Limiting the firm's liabilities to her net value helps her to innovate and to levy funds for research and development (R&D) by fostering a reassuring legal and economic environment. Nevertheless, it is common knowledge, since Shavell (1986), that a limited liability regime may also induce either partial risk internalization by firms or over-investment in risky activities. Indeed and contrary to an unlimited liability regime, limited liability creates an *ex post* payment ceiling for the firm: she will have to pay for the damage only up to her net present value and the firm's shareholders do not have to compensate the victims through their own funds in the case of a huge accident. Thus some firms and their shareholders may carry out projects driving excessive risk, some part being transferred to Society.

In order to countervail these negative effects some works have focused on a regime that extends the financial liability to the operators of a liable firm. An operator (a bank for instance) will have to pay for extra damage if the firm goes bankrupt[1]. Such a regime should increase the available funds for compensation. But it may also lessen the incentives of firms to invest in prevention, for their financial liability is transferred to the other operators (Beard (1990), Pitchford (1995), Boyd & Ingberman (1997), Boyer & Laffont (1997), Dionne & Spaeter (2003), Martimort & Hiriart (2006)).

Some other economists and some jurists advocate for unlimited liability from a normative point of view (Faure (1995), Hansmann & Kraakman (1991), Halpern *et al.* (1980)): the potential injurer must always pay for all the damage caused by her activity, so that risk is fully internalized. However it can be complex to implement it in practice. Indeed Alexander (1992) p. 389, writes: "To the extent that the proposal could constitutionally be implemented, enforcement would raise substantial procedural obstacles". For some practical reasons, the law could even be unenforceable (think about out-of-state shareholders who must be identified) and implementation costs could be higher than the net benefit for Society[2]. In the particular case of large-scale (or catastrophic) risks, the efficiency of unlimited liability in terms of risk internalization can still be put in doubt: the shareholders' assets are not always sufficient to compensate the whole damage. Besides, it can take a very long time until a legal court obtains all the information and takes a decision about who should pay and how much. Hence limited liability may not be welfare inferior if all costs are taken into account.

The questions of technological change incentives can be split into two issues: the incentives to *design* a new technology through the process of R&D, and the incentives to *adopt* a new technology, once developed (process of diffusion). A large number of papers focuses on the R&D process (and firms' imitation abilities for Parry (1995) and Fischer *et al.* (2003); or pollutant technologies as in Magat (1978, 1979)). Diffusion is also widely investigated. Downing & White (1986) and Milliman & Prince (1989) are often referred as being the first papers having formally analysed the issue of the diffusion process of a green technology in the framework of pollution control.[3] All of these analyses take the liability context as given, although the liability rule

[1] See Klimek (1990) for some US practical cases.

[2] See also Easterbrook & Fischel (1985) and Grundfest (1992).

[3] See Requate (1998), Requate & Unold (2003), Coria (2009) and Sanin & Zanaj (2011) for an adoption

at stake does play a significant role in the decision process as showed earlier by Shavell (1980, 1986).[4]

To our knowledge, the first studies that analyze the incentives induced by some liability rules to adopt safer technologies are provided by Endres *et al.* (Endres & Bertram (2006), Endres *et al.* (2007), Endres *et al.* (2008), Endres & Friehe (2011b)). Nevertheless they consider that the firm is always able to fully compensate the damage: the issue of partial risk internalization due to "judgment-proofness" is put aside.

In this paper, we compare two liability regimes in terms of incentives to *adopt* a safer (already designed) technology. We show that strict but limited liability does not always lead to less risk internalization or poorer incentives for technological change compared to strict and unlimited liability. We consider that the risk driven by the activity of the firm is simultaneously affected by her technological choice *and* her level of production. Many risk management models assume that the risk of accident only depends on prevention and not on production. Here, technological change induces both a decrease in the probability of accident and an increase in the marginal cost of production. The latter reflects the past R&D process, adoption costs or imperfect training of the staff. Finally the level of production impacts the severity of the damage whenever an accident occurs.[5]

As a direct consequence of the correlation between the level of activity and the level of the potential damage, insolvency is endogenous in our model: by choosing *ex ante* her level of activity, a limited liability firm also chooses to benefit, or not, from what we call in the paper the "*ex post* financial protection". A high level of activity implies a high level of potential damage, which pushes the firm into bankruptcy in the accident state. On the contrary, if she adopts a level of activity lower than a bankruptcy threshold defined by the model, the firm remains solvent even if facing an accident: all the risk is internalized by the firm and *ex post* financial protection does not hold.
Other papers consider endogenous insolvency. Friehe (2007) extends Shavell (1986)'s framework to monetary precaution care, which worsens the firm's solvency. He shows that some agents act strategically with the possibility to be insolvent: they choose to over-invest in care to become insolvent in the accident state. Boyd & Ingberman (1994) consider situations in which care first decreases the probability of accident, and second reduces the severity of the damage. In our analysis a technological change affects simultaneously the probability, the level of damage, *and* the marginal cost of production. This is rather different from assuming that an investment in prevention impacts either the probability of accident, or the level of damage, or even both such as in the "separate-probability-magnitude model" developed by Dari-Mattiacci & De Geest (2005, 2006).

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process analysis when firms interact.

[4]Actually, liability and incentives to design/adopt a new technology were first studied in the context of product-liability (Viscusi & Moore (1993), Daughety & Reinganum (1995), Baumann *et al.* (2011)). Endres & Friehe (2011a) consider non-point source pollution and analyze the impact of liability rules on technological change. Product liability and non-point source pollution go beyond the scope of this paper.

[5]Shavell (1980, 2004) also considers the relationship between the level of damage and the level of production, but he compares the strict liability rule with the negligence rule.

Finally, in our model the firm maximizes her expected net value by choosing between two technologies that have different marginal productivities regarding both output and frequence of accident (both elements impacting the level of risk). We are able to show that some firms decide to fully internalize the risk driven by her activity despite limited liability. This result shall increase the attractiveness of limited liability among economists and jurists who have contested it so far. However, the percentage of firms that adopt the new technology with full risk internalization is always lower under limited liability than under unlimited liability. Then by introducing a unit tax that depends on the chosen technology, we show that there exist some tax policies which permit us to increase the number of firms that adopt the new technology AND full risk internalization. Moreover, we determine the characteristics of a second-best tax policy.

An important assumption of our model with taxation deals with the fact that the regulator is informed about the technology chosen by the firms. This is in line with what is observed in the large-scale risk management field. Indeed in the US as well as in Europe, the legislator has made specific provisions to supervise industrial activities that may be dangerous for Society, including on-site inspections and different standards that firms have to meet. In the US, firms from the chemical sector must obtain a RMP (Risk Management Plan) agreement, the requirements of which strongly depend on their technological process. Besides, under the "Toxic Release Inventory (TRI) Program" firms must also declare each year the amount of toxic substances they manipulate.

In the Canadian province of British-Columbia, the firms of the pulp and paper industry face different effluents standards depending on their technology (kraft process *versus* mechanical process) (see Foulon *et al.* (2002)). In Europe, the *Seveso* Directive has been implemented in order to compell firms to provide a complete risk assessment program.

Notice that, although taxation is a common practice, the combination of civil liability with taxation has received almost no attention in the economic literature in the past. To our knowledge, the two only exceptions are the studies by Gravelle (1987) and Endres (1991).[6]

The paper is organized as follows. Section 2 starts with the computation of the social optimum with regard to technological choice and output level. Then it presents the technological choice and the production decision made by a given firm alternatively under unlimited and limited liability. In particular we compute the percentage of firms that adopt the new technology with full risk internalization in different situations. It is always lower with limited liability than with unlimited liability. In Section 3 we introduce taxation in order to increase it. A second-best-tax policy is determined. Section 4 concludes the paper. All proofs are given in the appendix.

2 Optimal output and technological choices

Consider a competitive economy with risk-neutral firms selling an homogeneous product at a price p. The demand displays an infinite elasticity. Each firm finances her activity out of

[6]While Gravelle (1987) wants to better internalize the full cost of activity of each party involved in a (potential) bilateral accident, Endres (1991) considers the issue of non compliance with an optimal standard of negligence.

her equity E, with E taking values in the interval $\left[0, \overline{E}\right]$ and with $\overline{E}$ the equity of the highest capitalized firm. Firms are uniformly distributed over $\left[0, \overline{E}\right]$.

The activity of a given firm gives rise to a large-scale risk of accident, which occurrence probability depends on the type of the production technology she adopts. The firm must choose between two technologies indexed by $i = 1, 2$. The first one is the technology that is initially adopted by the firm (default technology). It drives a higher probability of accident than the second one. We denote it φ_i, with $\varphi_i \in [0, 1]$ and $\varphi_2 < \varphi_1$. We denote y_i the level of production chosen by the firm when she uses technology i ($i = 1, 2$). The total production cost for technology i equals $Z_i y_i^2$ with $Z_1 < Z_2$.[7] For a given level y, the higher marginal cost of production of technology 2 captures the past R&D process, the adoption costs of a new technology, and/or may be the consequence of a low level of experience[8] associated with the use of the new technology 2.

Let d be the damage rate, that is the potential level of damage per unit of production. The total amount of damage dy_i depends on the level of activity y_i and, as a direct consequence, on the technological choice.[9] Thus the random variable that defines the risk of accident for technology i is $\widetilde{D_i} \equiv (1 - \varphi_i, \varphi_i; 0, dy_i)$.

Assumption 1 *We assume that* $\varphi_i d < p < d$.

We are dealing with large-scale risks, so that $p < d$ is fair. Besides, if we had also $p < \varphi_i d$, this would mean that the marginal revenue of production p would even be insufficient to cover the expected marginal loss $\varphi_i d$, without any consideration of the marginal costs of production. This is a kind of strong closing condition of the firm and, for any unit price p lower than $\varphi_i d$, the optimum would be $y_i = 0$. In what follows we assume that production is always valuable so that $p > \varphi_i d$.

Perfect information about the decisions of the firm applies in this paper. The firm chooses the technology that she decides to keep (if $i = 1$) or to adopt (if $i = 2$), and the level of her activity. Thus the level of activity y_i that maximizes her expected net value is a best response to technology i.

In what follows, we consider first the social optima, second strict and unlimited liability of firms, and third strict but limited liability.

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[7] In our simple setting, quadratic production costs allow for interior solutions concerning the optimal level of production. Moreover, they match decreasing returns, which is in line with the assumption of perfect competition between the firms.

[8] In line with the experience curve hypothesis (Abell & Hammond (1979), Neij (1997, 2008), Isoard & Soria (2001), Kobos *et al.* (2006)), processes cost reductions are in proportion to accumulated production in many industries. In this case, in the short term the implementation of a new technology can be more costly.

[9] This assumption is close to the one considered by Shavell (1980), Boyd and Ingbermann (1994) and by Dari-Mattiacci and De Geest (2005). In insurance economics, it can be made close to the issue of self-insurance, which consists of assuming that firms can control their level of damage (Ehrlich & Becker (1972); Briys & Schlesinger (1990); Lee (1998)).

2.1 Social optima

The social welfare W^S is the sum of all firms' values and the expected damage borne by Society:

$$W^S =_0^{\overline{E}} \left(py_i - Z_i y_i^2 + E - \varphi_i d y_i\right) f(E)dE, \tag{1}$$

With $f(E) = \frac{1}{\overline{E}}$, a regulator in charge of the social welfare would have to compute the following program:

$$\max_{i,y_i} W^S = py_i - Z_i y_i^2 + \frac{\overline{E}}{2} - \varphi_i d y_i \tag{2}$$

The social optima are given by Lemma 1 hereafter.

Lemma 1

(i) The optimal social level of output y_i^S that must be produced by a given risk-neutral firm with technology i satisfies:

$$y_i^S = \frac{p - \varphi_i d}{2Z_i}, \quad i = 1, 2 \tag{3}$$

(ii) Technology 2 is the socially optimal technology if and only if

$$\frac{(p - \varphi_1 d)^2}{Z_1} < \frac{(p - \varphi_2 d)^2}{Z_2} \tag{4}$$

Notice that the social optima do not depend on the level of equity E of the firm. This is a consequence of full risk internalization. We will come back to this property when dealing with the private program of the firm.

Inequality (4) comes from the difference of net expected welfares evaluated at optimum. Technological change occurs if doing so is profitable for Society. In what follows, we are interested in the technological change only if it is welfare improving. Thus the following assumption will hold in the course of the paper.

Assumption 2 *Let us assume that* $\frac{(p-\varphi_1 d)^2}{Z_1} < \frac{(p-\varphi_2 d)^2}{Z_2}$.

2.2 Private choices under unlimited liability

Under a *strict liability rule*, the firm is always financially liable when an accident occurs. If the regime in place under this strict liability rule is an *unlimited liability regime*, then the firm will have to pay *ex post* for all the damage caused by her activity whatever its level. In such a setting of strict and unlimited liability, *ex post* profits can be negative and all the risk of accident is internalized. If the amount of damage is higher than the net value of the firm at the time of the accident, owners will have to pay out of their pocket[10]. Formally with $E\left(\widetilde{\pi}(y_i)\right)$ the expected profit with technology i, the firm's maximization program is:

$$\max_{i,y_i} E\left(\widetilde{\pi}(y_i)\right) = py_i - Z_i y_i^2 - \varphi_i d y_i + E \tag{5}$$

[10] We assume that they always can pay for the remaining damage beyond the net value of the firm.

It is immediate to check that the expected profit (net of the equity) is equivalent to the expected social welfare (net of equity) given by (2). Hence the private optimal choices of output and of technology are those that maximize the expected social welfare. Conditions (3) and (4) given by Lemma 1 can be used here in the private decision process. These properties are summarized in the following Proposition 1.

Proposition 1 *Under strict and unlimited liability:*

(i) The private choices of output and technology made by a risk-neutral firm fit with the social optima. Hence when technological change is decided by the firm, it is always welfare improving.

(ii) Either all firms initially endowed with technology 1 or no firm turn to technology 2. This fits with the social optimum.

Under unlimited liability, technological change privately decided by the firm is always welfare improving for Society. Thus, even though technological change can induce an increase in the level of production that increases the severity of injuries in the case of an accident, risk mitigation occurs. This is because unlimited liability requires that the firm and her shareholders pay for all the damage in case of an accident whatever its severity and whatever the level of the firm's equity: profits may become strictly negative. This also explains why the level of equity does not enter into the optimal values: whatever the firm's level of capitalization, she will always have to pay for all the consequences of a technological damage.

Furthermore, firms being differentiated exclusively with respect to their level of equity, result (ii) is rather immediate. Expression (4) does not depend on E. Hence, if the condition for technological change is met for one firm, it is met for all firms[11].These results do no longer hold if liability is limited *ex post* to the net value of the firm, as shown in the following subsection.

2.3 Strict but limited liability and optimal risk internalization

Now let us consider the case in which the firm faces strict but limited liability. *Ex ante*, she is still liable for all the damage caused by her activity but, *ex post*, she will not have to pay more than her net present value. Hence, if the damage is higher than the firm's net value, Society will have to bear the difference.

In opposition to Beard (1990), Pitchford (1995) and to Dionne and Spaeter (2003), who also consider limited liability, our approach endogenizes the level of potential damage. Thus, the firm can decide to benefit, or not, from the *ex post* financial protection. To clarify this point, we need to define the level of activity that pushes the firm into bankruptcy following an accident.

Lemma 2 *Let $\widehat{y_i}$ be the minimum production level that leads to an ex post firm's net value equal to zero when technology i $(i = 1, 2)$ is chosen and an accident occurs. We have:*

$$\widehat{y_i} = \frac{(p-d) + \sqrt{(p-d)^2 + 4Z_iE}}{2Z_i} \geq 0 \tag{6}$$

[11]This result differs from the one obtained by Requate (2005), who assumes that firms are differentiated with respect to their ability to efficiently abate pollution with a, given, new technology. Such an hypothesis adapted to our model would mean that, for a given and unique new technology, firms would not face the same probability of accident φ_2. But Requate (2005) also notices that without this assumption, either all firms or no firm would adopt the new technology.

We obtain the intuitive property that a higher capitalized firm is pushed less often into bankruptcy: $\widehat{y_i}$ is increasing in E. In this framework, a firm facing limited liability and that adopts a level of activity y_i higher than $\widehat{y_i}$ will benefit from the financial protection beyond her net value in the case of an accident: she will be declared bankrupt and all her assets will be confiscated for compensation, but not more. Her net value after accident will be zero whatever her activity level y_i with $y_i > \widehat{y_i}$. If the firm chooses y_i such that $y_i \leq \widehat{y_i}$, her *ex post* net value will always be positive: The firm will always be able to pay for all the damage and she will never need any financial protection. In this last situation, by choosing a level of activity lower than the bankruptcy threshold $\widehat{y_i}$, the firm decides to internalize all the risk driven by her activity.

As a direct consequence, the decision of taking or not taking advantage of the *ex post* legal protection under the limited liability regime becomes endogenous to the model. For a given technology $i = 1, 2$, and a level of production y_i, the firm's expected value is now:

$$E\left[\widetilde{\pi}(y_i)\right] = \begin{cases} py_i - Z_i y_i^2 - \varphi_i d y_i + E \text{ if } y_i \leq \widehat{y_i} & a) \\ (1-\varphi_i)\left(py_i - Z_i y_i^2 + E\right) \text{ if } y_i > \widehat{y_i} & b) \end{cases} \tag{7}$$

In case (7.a), the level of production y_i yields a level of potential damage $d.y_i$ that never pushes the firm into bankruptcy: The expression of the firm's expected value is identical to (5), but this value is always positive. In case (7.b), the value of the firm goes to zero as a result of an accident. And it is positive and equal to $py_i - Z_i y_i^2 + E$ in the no accident state, which occurs with probability $(1-\varphi_i)$. Hence the private optimal level of production differs whether the firm chooses to fully (case a) or partially (case b) internalize the risk for a given technology.

In the course of the paper, we denote by y_i^{LL+} (LL for *Limited Liability*) the private optimal level of activity when the firm chooses to benefit from *ex post* financial protection with technology i (i.e. $y_i^{LL+} > \widehat{y_i}$) and by y_i^{LL-} the optimal level of activity when the firm fully internalizes the risk under limited liability (i.e. $y_i^{LL-} \leq \widehat{y_i}$).

Proposition 2 *Consider a risk-neutral firm that chooses technology i under strict but limited liability.*

(i) If the firm chooses a level of production higher than the bankruptcy threshold $\widehat{y_i}$*, then partial risk internalization holds and the private optimal level of output satisfies:*

$$y_i^{LL+} = \frac{p}{2Z_i} \tag{8}$$

(ii) If the firm chooses a level of production lower than the bankruptcy threshold $\widehat{y_i}$*, then full risk internalization holds and the private optimal level of output satisfies:*

$$y_i^{LL-} = \frac{p - \varphi_i d}{2Z_i} \tag{9}$$

Now, we must determine the conditions that lead the firm to either adopt or give up *ex post* financial protection.

Proposition 3 *Let us consider a risk-neutral firm under strict but limited liability. We define* $\underline{E_i} = \frac{p(2d-p)-\varphi_i d^2}{4Z_i}$, $i = 1, 2$.

(i) We have $\underline{E_i} > 0$*.*

(ii) The firm adopts full (respectively partial) risk internalization with technology i if and only if her equity satisfies $E \geq \underline{E_i}$ *(respectively* $E < \underline{E_i}$*).*

Technological change induces a change in the production level. Thus the firm can decide to benefit from the *ex post* financial protection even though she was internalizing all the risk before the technological change. Precisely, from Proposition 3, low-capitalized firms have higher incentives to choose *ex post* financial protection than high-capitalized ones. This is explained by the fact that the threshold of activity $\hat{y}_i$, given by (6), is increasing in E. Proposition 3 can be illustrated by Figure 1 hereafter.

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Figure 1 about here

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It represents the firm's expected net value when choosing either partial of full risk internalization, for a given technology and with respect to her level of equity. With technology i and for $E < \underline{E_i}$, the firm has a higher expected profit when internalizing partially the risk. On the contrary, her expected profit is higher with full risk internalization if her level of equity is $E \geq \underline{E_i}$.

Now we have to analyze the conditions under which technological change occurs under limited liability. To do so, we assume that the number of firms uniformly distributed on $\left[0, \overline{E}\right]$ is sufficiently high in order to consider some firms with partial risk internalization and some others with full internalization: $\overline{E} > \max\left\{\underline{E_1}, \underline{E_2}\right\}$. Full risk internalization being welfare improving, we focus exclusively on the conditions that lead a given firm to associate full risk internalization with a technological change. Hence Assumption 3 hereafter permits us to restrict the number of cases.

Assumption 3 *Assume that* $\frac{1-\varphi_2}{Z_2} > \frac{1-\varphi_1}{Z_1}$*.*

This condition compares the ratios of the probability of no accident over the unit cost parameter for each technology. It implies that technology 2 is more efficient than technology 1 in relative terms.

Proposition 4 *Assume that a limited liability regime holds.*

(i) Firms having adopted full risk internalization while endowed with technology 1 always turn to technology 2. Those, over the firms in $\left[0, \overline{E}\right]$*, which also decide to continue to fully internalize the risk represent the percentage:*

$$N_{1-,2-} = \frac{\overline{E} - \max\left\{\underline{E_1}, \underline{E_2}\right\}}{\overline{E}} > 0 \tag{10}$$

(ii) Consider the firms that have adopted partial risk internalization while endowed with technology 1.

a) If $\underline{E_1} \leq \underline{E_2}$*, none of them turn to technology 2 and to full risk internalization.*

b) If $\underline{E_1} > \underline{E_2}$*, the percentage of firms that turn to technology 2 and to full risk internalization is* $N_{1+,2-} = \frac{\underline{E_1}-\underline{E_2}}{\overline{E}} > 0$.

(iii) The percentage of firms that adopt technology 2 and full risk internalization, whatever the sign of the difference $\underline{E_1} - \underline{E_2}$*, is* $0 < N_{2-} = \frac{\overline{E}-\underline{E_2}}{\overline{E}} < 1$.

In such a setting, a firm that has chosen full risk internalization with the default technology 1 will always turn to technology 2 knowing that her initial private program fits with the social one: technology 2 being welfare improving, it yields an expected profit higher than technology 1. Nevertheless, not all these firms will keep continuing to fully internalize the risk: $N_{1-,2-} < 1$. Indeed, it may be possible that partial risk internalization with technology 2 becomes more profitable than full risk internalization.

Now, among the firms that partially internalized the risk with technology 1, it is possible that none of them turn to full risk internalization following a technological change. In the following section, we introduce taxation in order to encourage more firms to adopt technology 2 and full risk internalization.

3 Taxation as a mean to increase risk internalization and technical change under limited liability

From the preceding results, limited liability regains some appeal. Indeed, risk mitigation and limited liability do not always conflict, contrary to what is often argued in the literature. Knowing that it can be much more costly to manage a legal system with unlimited than with limited liability (e.g. Grundfest, 1992), this is a promising result. Unfortunately, we have also shown that the percentage of firms under limited liability that adopt the new technology and full risk internalization is no longer equal to the socially optimal one (recall that it equals one when technology 2 is welfare improving). Moreover, firms that were only partially internalizing the risk with technology 1 may never give up the *ex post* financial protection following a technological change.

Hereafter we check whether an adequate taxation policy could improve the situation. Our aim is to find some tax parameters that increase the previous percentage N_{2-} without imposing unlimited liability.

Let us assume that the production is taxed. The technology chosen by the firm is observable[12] by the regulator so that the unit tax can be differentiated with respect to the technology. We denote it t_i, $i = 1, 2$.

[12] As explained in the introduction, this is a fair assumption in the large-scale risk management context. For instance, in the US the firms that use chemical substances in their production process have to design "Risk Management Plans" and to submit them to the Environment Protection Agency (EPA) for agreement. The EPA can proceed to on-site inspections to audit the safety of plans and installations (see EPA, 2011, Clean Air Act section 112(r)EPA-2011). Such on-site inspections also exist in Europe. Firms with activities presenting some large-scale risks must disclose detailed informations about their production process in order to obtain a label of "classified installations" (*Seveso* directive).

Such a kind of taxation is adapted to our setting[13] knowing that the level of activity y_i chosen by the firm affects the level of risk borne by Society. The important point will be the ability of the regulator to determine the level of the unit taxes that makes full risk internalization more attractive to the firm, but without mitigating her incentives to adopt the safer technology.

Similarly to the threshold defined in Lemma 2, the minimum level of production $\widehat{y_i^t}$ that induces an *ex post* firm's net value equal to zero following an accident satisfies $(p - t_i)\widehat{y_i^t} - Z_i(\widehat{y_i^t})^2 - d\widehat{y_i^t} + E = 0$, $i = 1, 2$. Here also, the firm can decide to benefit, or not, from the *ex post* financial protection by choosing *ex ante* an adequate level of activity y_i^t. Assume that the firm chooses $y_i^t > \widehat{y_i^t}$. Her program is:

$$\max_{y_i^t, i} \quad E\left[\widetilde{\pi}(y_i^t)\right] = (1 - \varphi_i)\left((p - t_i)y_i^t - Z_i(y_i^t)^2 + E\right)$$

Introducing a unit tax is similar to differentiating prices with respect to the chosen technology. Nevertheless, in this setting goods continue to be sold at unit price p: We do not consider any factor that influences the consumers' willingness to pay for safer products. This goes beyond the scope of this paper. The firm's private optimal level of activity under partial risk internalization and taxation is denoted y_i^{tLL+}. It satisfies:

$$y_i^{tLL+} = \frac{p - t_i}{2Z_i} \tag{11}$$

On the contrary, if the firm chooses to produce a level y_i^{tLL-} lower than $\widehat{y_i^t}$, her optimization program is: $\max_{y_i^t, i} \quad E\left[\widetilde{\pi}(y_i^t)\right] = (p - t_i)y_i^t - Z_i(y_i^t)^2 - \varphi_i d y_i^t + E$.

And we have :

$$y_i^{tLL-} = \frac{p - t_i - \varphi_i d}{2Z_i}, \quad i = 1, 2 \tag{12}$$

The introduction of taxes does not change the rationale followed by the firm when she decides to benefit, or not, from *ex post* financial protection.

Proposition 5 *Let us consider a risk-neutral firm under strict but limited liability, and a unit tax t_i that is applied to each unit of good produced with technology i. We use the notation $p_i = p - t_i$.*

The firm chooses to fully internalize the risk with technology i if and only if her equity satisfies

$$E \geq \underline{E_i^t} = \frac{p_i(2d - p_i) - \varphi_i d^2}{4Z_i}, \tag{13}$$

At first glance, it seems counterintuitive to tax a technology that is welfare improving. But recall that a higher production y_i increases the level of potential damage dy_i, whatever the chosen technology. On the contrary, a unit taxation lessens the level of production, and thus the level of potential damage. Proposition 6 hereafter displays a taxation policy that gives firms additional incentives to adopt technology 2 and full risk internalization.

[13] It is also used for environmental regulation, in order to reduce pollutant emissions and to foster technological change. Concerning heating gases for instance, several countries (Switzerland, Sweden, Norway, Denmark, Finland, Germany, England; while France tried, but failed, in 2009 to implement a "carbon tax") have already adopted taxes based on the production of some specific sectors or on the consumption of some specific goods.

Proposition 6 *Assume that a limited liability regime holds and that a unit tax t_i is applied to each unit of good produced with technology i.*

A taxation policy (t_1, t_2) that satisfies $0 \leq t_2 \leq ct_1 + f$ with $c = \frac{\sqrt{Z_2}}{\sqrt{Z_1}} > 1$ and $f = (p - \varphi_2 d) - c(p - \varphi_1 d) > 0$, ensures that

(i) Technology 2 remains welfare improving compared to technology 1;

(ii) The percentage of firms that adopt technology 2 and full risk internalization is

$$N_{2-}^t = \frac{\overline{E} - \underline{\underline{E_2^t}}}{\overline{E}}, \tag{14}$$

and it satisfies $N_{2-} \leq N_{2-}^t$.

An adequate taxation policy does not decrease the incentives to adopt the safer technology, and it also leads to a higher percentage of firms that keep or adopt full risk internalization.

In our setting the social welfare can never be higher with limited liability compared to unlimited liability. To go further in the analysis, it would be useful to take into account the costs of implementing the different regimes: unlimited liability, or limited liability and taxation. Incentives to invest in R&D, which are often considered as stronger under limited liability, could also be considered and, finally, limited liability could even be better than unlimited liability in terms of expected social welfare. We do not consider these sophisticated cases in this paper. Nevertheless, we want that taxation brings limited liability closer to unlimited liability in terms of expected social welfare. Thus we must discuss further the characteristics of a second-best tax policy in our simple setting.

It is not so obvious that the tax policy presented in Proposition 6 is a second-best tax policy. Indeed with such a policy, all firms are taxed even those that comply with the social optimum y_2^{LL-}. Actually, there are two opposite effects of taxation. First, the social welfare is improved because some firms with partial risk internalization move to full risk internalization. Second, it is deteriorated because of a decrease in the private profits of firms that were internalizing all the risk before taxation.

Instead of taxing all firms, consider a situation in which only firms that decide to partially internalize the risk are taxed. Now, a firm compares the expected untaxed profit that she would obtain with full risk internalization to the expected taxed profit obtained with partial risk internalization. In Proposition 7 hereafter, we define the characteristics of a taxation policy that induces full risk internalization by all firms, whatever their level of equity. This policy is self-enforcing and, at equilibrium, no firm is taxed.

Proposition 7 *The taxation policy (t_1^*, t_2^*) that satisfies $t_2^* = p - \frac{(p-\varphi_2 d)}{\sqrt{(1-\varphi_2)}}$ and $\frac{1}{c}.(t_2^* - f) \leq t_1^*$, c and f being defined in Proposition 6, is self-enforcing and a first-best policy in terms of optimal expected social welfare.*

The condition $\frac{1}{c}.(t_2^* - f) \leq t_1^*$ ensures that Point i) of Proposition 6 remains satisfied. The level of tax $t_2^* = p - \frac{(p-\varphi_2 d)}{\sqrt{(1-\varphi_2)}}$ leads to a higher expected profit with full risk internalization and without taxation than with partial risk internalization and taxation at level t_2^*.

Finally, all firms choose the social optimum under such a policy: technology 2 AND full risk internalization. Moreover, at equilibrium, there is no tax distortion since no firm is taxed. And this tax policy is self-enforcing. Indeed, if some firms decide to partially internalize the risk despite the threat of being taxed, the regulator taxes them at the level t_2^*: their expected profits decrease below the value of the expected profits that they would obtain with full risk internalization. Finally they decide to adopt this last strategy. Although the social welfare can decrease compared to the first-best if the regulator carries out its threat, the threat of being taxed remains credible since the firms only look at their private profits: they act rationnally and adopt full risk internalization in order to escape from taxation. At equilibrium, nobody is taxed. The expected social welfare increases to its first-best level.[14] Figure 2 illustrates this mechanism.

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Figure 2 about here

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The expected profits increase linearly with the firm's level of equity. By decreasing the value of the Y-intercept of the straight line $E\left[\widetilde{\pi}(y_2^{tLL+})\right]$, it is possible to decrease the expected profits $E\left[\widetilde{\pi}(y_2^{tLL+})\right]$ obtained with partial risk internalization and taxation below the expected untaxed profits $E\left[\widetilde{\pi}(y_2^{LL-})\right]$ obtained with full risk internalization. As a direct consequence, the latter are always higher than the former whatever the firm's level of equity if $\frac{(p-\varphi_2 d)^2}{4Z_2} = \frac{(1-\varphi_2)(p-t_2)^2}{4Z_2}$ (both Y-intercepts are equal). And this is obtained for $t_2 = t_2^*$.

4 Conclusion

In this paper, we have considered a firm whose activity drives a technological risk of accident. We analyzed the impact of unlimited liability, then limited liability, on technological change.

The potential damage increases with the level of production. Two technologies are available: the default technology displays a higher probability of accident than the new one, but a lower marginal cost of production. One originality of our contribution is to allow the firm to choose to partially or fully internalize the risk of accident under a limited liability regime: the firm can choose a level of activity such that she will or will not go bankrupt in the case of a damage. We have shown that limited liability can induce simultaneously full risk internalization and risk mitigation through technical change, especially from a firm with a high level of equity. This result should increase the attractiveness of limited liability to economists and jurists who have contested it so far.

Nevertheless, we have also shown that the percentage of firms adopting the safer technology and full risk internalization is lower under limited liability than under unlimited liability. Knowing that it can be costly to manage unlimited liability, we have introduced unit taxation in Section 3, in order to increase the incentives under limited liability. The unit tax was applied to

[14] We forget the cost of building and announcing such a policy. With those costs, the first best social welfare is no longer reached, but the private optimal levels of production remain first-best ones.

production (recall that it affects the level of damage), and it was differentiated with respect to the chosen technology. In this setting, we have defined the characteristics of a second-best tax policy. In particular, we found an optimal level of tax applied to the safer technology whenever the firm refuses to adopt full risk internalization. This policy acts as a threat: at equilibrium all firms choose the safer technology and full risk internalization, no firm is taxed and the policy is self-enforcing.

From these results, civil liability combined with taxation adds several interesting and powerful dimensions to the regulator's policy. In particular, it can be adapted to the type of sector that is considered (with high-, medium-, or low-capitalized firms).

Our model is based on simple assumptions and its scope could (and should) be extended. The first extension could be to study the impact of the existence of a technology under development, that calls for additional R&D in order to properly assess the related technological risks. Another interesting extension of this work could be to consider an endogenous level of capital by allowing firms to borrow external funds.

Lastly, we have chosen to consider taxation only in the limited liability case. This should not preclude to work with taxed/subsidized technologies in the unlimited liability context.

Appendix

Proof of Lemma 1.

Differentiation of W^S in (2) with respect to y_i leads to $\frac{dW^S}{dy_i} = p - 2Z_i y_i - \varphi_i d$. It equals zero at $y_i^S = \frac{p-\varphi_i d}{2Z_i}$. This is Point (i). Technology 2 is an optimal social choice if W^S evaluated with technology 2 is higher than W^S evaluated with technology 1:

$$py_1^S - Z_1(y_1^S)^2 + \frac{\overline{E}}{2} - \varphi_1 d y_1^S < py_2^S - Z_2(y_2^S)^2 + \frac{\overline{E}}{2} - \varphi_2 d y_2^S$$

Using (3), we obtain $\frac{(p-\varphi_1 d)^2}{Z_1} < \frac{(p-\varphi_2 d)^2}{Z_2}$. This is Point (ii). ♦

Proof of Lemma 2.

The after accident firm's net value at $y_i = \widehat{y_i}$ writes $-Z_i\widehat{y_i}^2 + (p-d)\widehat{y_i} + E = 0$. The roots are $\widehat{y_i} = \frac{(p-d)+\sqrt{(p-d)^2+4Z_iE}}{2Z_i}$ and $\widehat{y_i} = \frac{(p-d)-\sqrt{(p-d)^2+4Z_iE}}{2Z_i}$. From Assumption 1, the second root is always negative. ♦

Proof of Proposition 2

Condition (8) (respectively (9)) is obtained from a differentiation of (7.b) (respectively (7.a)) with respect to y_i. ♦

Proof of Proposition 3

Assumption 1 is equivalent to $pd - \varphi_i d^2 > 0$. Knowing that $p < d$, this implies $p(2d-p) - \varphi_i d^2 > 0$. Thus $\underline{E_i} = \frac{p(2d-p)-\varphi_i d^2}{4Z_i} > 0$. This is Point (i). For a given technology i, a firm adopts full risk internalization if and only if her expected net value is higher than the one she could obtain under financial protection:

$$py_i^{LL-} - Z_i(y_i^{LL-})^2 - \varphi_i d y_i^{LL-} + E \geq (1-\varphi_i)(py_i^{LL+} - Z_i(y_i^{LL+})^2 + E)$$

With (8) and (9), this leads to $E \geq \frac{p(2d-p)-\varphi_i d^2}{4Z_i} = \underline{E_i}$. This is Point (ii). ♦

Proof of Proposition 4

The expected profit of firms that internalize all the risk is equivalent to the social one. From Assumption 2, technology 2 is always welfare improving, so that technology 2 yields a higher expected profit than technology 1 with full risk internalization. Hence all the firms that have chosen full risk internalization while endowed with technology 1 will move to technology 2: for them we have $E\left(\widetilde{\pi}_1^{LL+}\right) < E\left(\widetilde{\pi}_1^{LL-}\right) < E\left(\widetilde{\pi}_2^{LL-}\right)$. This is the first part of Point (i).

Now, from Proposition 3, firms that decide to continue to fully internalize the risk with technology 2 (those for which $E\left(\widetilde{\pi}_2^{LL+}\right) < E\left(\widetilde{\pi}_2^{LL-}\right)$) have equity that satisfies $E \geq \underline{E_2}$. And, because they were already internalizing all the risk with technology 1, their equity satisfies also $E \geq \underline{E_1}$. Thus these firms represent a percentage $N_{1-,2-} = \frac{\overline{E}-\max\left\{\underline{E_1},\underline{E_2}\right\}}{\overline{E}}$ of the firms distributed on $\left[0, \overline{E}\right]$. It is strictly positive and strictly lower than 1 knowing that $\underline{E_i} > 0$ (Proposition 3.i)) and $\overline{E} > \max\left\{\underline{E_1}, \underline{E_2}\right\}$ by assumption. This is the second part of Point (i).

Firms having adopted partial risk internalization with technology 1 have equity that satisfies $E < \underline{E_1}$. And they adopt full risk internalization following a technological change if and only if $E \geq \underline{E_2}$. Thus we must have $\underline{E_2} \leq E < \underline{E_1}$, which is not possible if $\underline{E_1} \leq \underline{E_2}$. Point (ii.a) is immediate. If $\underline{E_1} > \underline{E_2}$, we need to identify the firms within $\left[\underline{E_2}, \underline{E_1}\right]$ that move to technology 2. For these firms we must have $E\left(\widetilde{\pi}_1^{LL+}\right) < E\left(\widetilde{\pi}_2^{LL-}\right)$, that is:

$$\begin{aligned}
(p-\varphi_2 d)y_2^{LL-} - Z_2(y_2^{LL-})^2 + E - (1-\varphi_1)\left(py_1^{LL+} - Z_1(y_1^{LL+})^2 + E\right) > 0 \\
\Leftrightarrow \frac{(p-\varphi_2 d)^2}{4Z_2} - \frac{(1-\varphi_1)p^2}{4Z_1} + \varphi_1 E > 0 \\
\Leftrightarrow E > \frac{1}{4\varphi_1}\left[(1-\varphi_1)\frac{p^2}{Z_1} - \frac{(p-\varphi_2 d)^2}{Z_2}\right] = \widehat{E} \qquad (15)
\end{aligned}$$

Now, consider the following writing of $\underline{E_2}$:

$$\begin{aligned}
\underline{E_2} &= \frac{p(2d-p)-\varphi_2 d^2}{4Z_2} \\
&= \frac{1}{\varphi_2}\frac{\varphi_2\left(p(2d-p)-\varphi_2 d^2\right) - p^2 + p^2}{4Z_2} \\
&= \frac{1}{4\varphi_2}\left[(1-\varphi_2)\frac{p^2}{Z_2} - \frac{(p-\varphi_2 d)^2}{Z_2}\right] \qquad (16)
\end{aligned}$$

A comparison of (16) with (15) shows that a necessary condition for $\widehat{E} \geq \underline{E_2}$ is $\frac{(1-\varphi_1)}{Z_1} > \frac{(1-\varphi_2)}{Z_2}$, which is not considered in this setting (see Assumption 3). Thus, we have $\widehat{E} < \underline{E_2}$ and $E \geq \underline{E_2}$ ensures that (15) is satisfied: The firms in $\left[\underline{E_2}, \underline{E_1}\right]$ move to technology 2 and adopt full risk internalization. Their percentage over the entire interval $\left[0, \overline{E}\right]$ is finally $N_{1+,2-} = \frac{\underline{E_1}-\underline{E_2}}{\overline{E}}$. This is Point ii.b).

At last, when $\underline{E_1} \leq \underline{E_2}$ (case ii.a)), we know that only firms having adopted full risk internalization with technology 1 adopt technology 2 AND full risk internalization. Thus the total percentage of firms moving to technology 2 and to full risk internalization whatever their initial choice is $N_{2-} = N_{1-,2-} = \frac{\overline{E}-\underline{E_2}}{\overline{E}}$. If $\underline{E_1} > \underline{E_2}$ (case ii.b), the total percentage is $N_{2-} = N_{1-,2-} + N_{1+,2-} = \frac{\overline{E}-\underline{E_2}}{\overline{E}}$. This is Point iii). ♦

Proof of Proposition 5

Replacing p by $p_i = p - t_i$ in the proof of Proposition 3, Point ii), yields the result. ♦

Proof of Proposition 6.

Technology 2 remains welfare improving if $\frac{(p_1-\varphi_1 d)^2}{Z_1} < \frac{(p_2-\varphi_2 d)^2}{Z_2}$ (this is obtained by adapting the proof of Lemma 1 to the case with taxation). We have:

$$\begin{aligned} & \frac{(p_1-\varphi_1 d)^2}{Z_1} < \frac{(p_2-\varphi_2 d)^2}{Z_2} \\ \Leftrightarrow\ & \frac{(p-\varphi_1 d)}{\sqrt{Z_1}} - \frac{t_1}{\sqrt{Z_1}} < \frac{(p-\varphi_2 d)}{\sqrt{Z_2}} - \frac{t_2}{\sqrt{Z_2}} \\ \Leftrightarrow\ & \frac{t_2}{\sqrt{Z_2}} - \frac{t_1}{\sqrt{Z_1}} < \frac{(p-\varphi_2 d)}{\sqrt{Z_2}} - \frac{(p-\varphi_1 d)}{\sqrt{Z_1}} \\ \Leftrightarrow\ & t_2 \leq c.t_1 + f \end{aligned} \tag{17}$$

with $c = \frac{\sqrt{Z_2}}{\sqrt{Z_1}} > 1$ and $f = (p - \varphi_2 d) - c(p - \varphi_1 d) > 0$ from Assumption 2. This is Point (i). Under the conditions of Point (i), now we can adapt the proof of Proposition 4 in order to obtain that the percentage of firms moving to technology 2 and to full risk internalization under taxation, whatever the sign of $\underline{E_2^t} - \underline{E_1^t}$, is $N_{2-}^t = \frac{\overline{E}-\underline{E_2^t}}{\overline{E}}$. Furthermore, we have:

$$\frac{\partial \underline{E_2^t}}{\partial t_2} = \frac{-(2d-(p-t_2))+(p-t_2)}{4Z_2} = \frac{-2(d-(p-t_2))}{4Z_2} < 0. \tag{18}$$

Hence $t_2 \geq 0$ implies that $\underline{E_2^t} \leq \underline{E_2}$ so that $N_{2-} \leq N_{2-}^t$. This is Point (ii). ♦

Proof of Proposition 7.

With Assumption 3, all firms choose technology 2. Now, a firm chooses to fully internalize the risk with technology 2 if and only if:

$$\begin{aligned} & p y_2^{LL-} - Z_2 (y_2^{LL-})^2 - \varphi_2 d y_2^{LL-} + E \geq (1-\varphi_2)(p_2 y_2^{tLL+} - Z_2 (y_2^{tLL+})^2 + E) \\ \Leftrightarrow\ & \frac{(p-\varphi_2 d)^2}{4Z_2} \geq \frac{(1-\varphi_2)(p-t_2)^2}{4Z_2} - \varphi_2 E \end{aligned}$$

The last expression is always satisfied, whatever the value of E, if it is satisfied for $E = 0$, that is $t_2 \geq p - \frac{(p-\varphi_2 d)}{\sqrt{(1-\varphi_2)}}$. Thus $t_2^* = p - \frac{(p-\varphi_2 d)}{\sqrt{(1-\varphi_2)}}$ is the minimum level of tax that leads the firm to choose full risk internalization whatever her level of equity. Besides, one must also tax technology 1 so that it never dominates technology 2 after taxation: It is sufficient to impose a tax level t_1 on technology 1 that satisfies Point i) of Proposition 6. ♦

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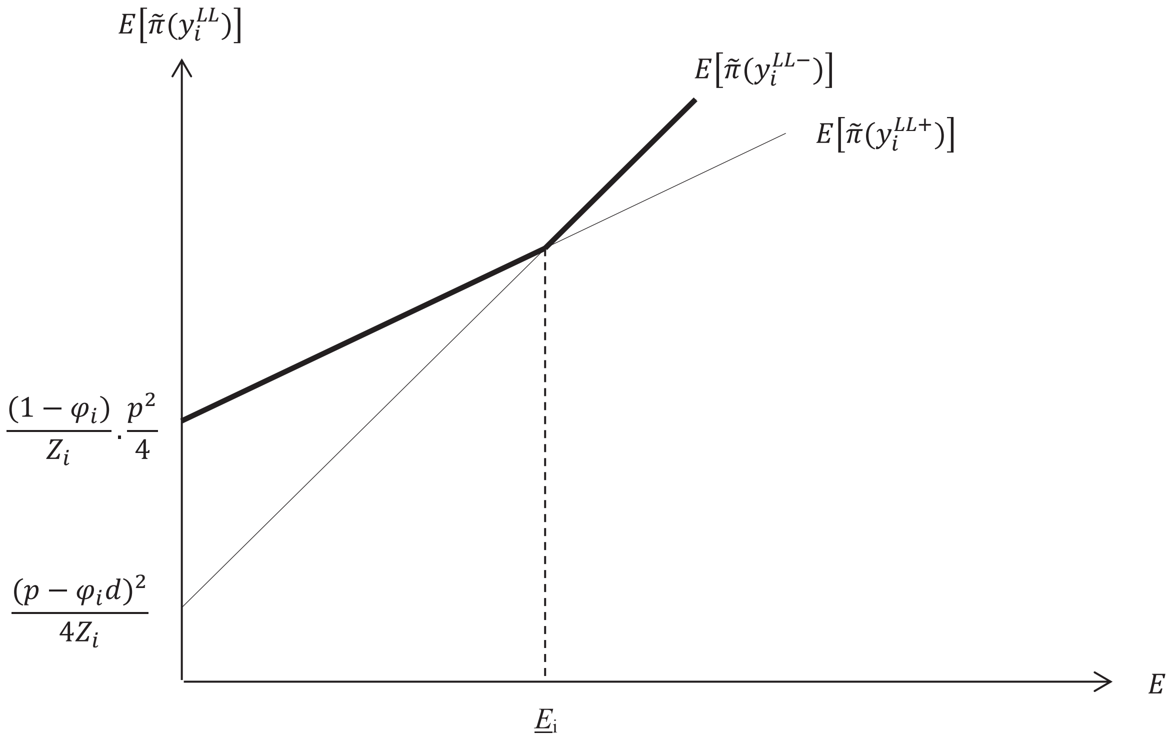

Figure 1. Level of equity and (private) optimal risk internalization under limited liability[1]

[1] The proof relative to the ranking of the Y-intercepts is available upon request to the authors.

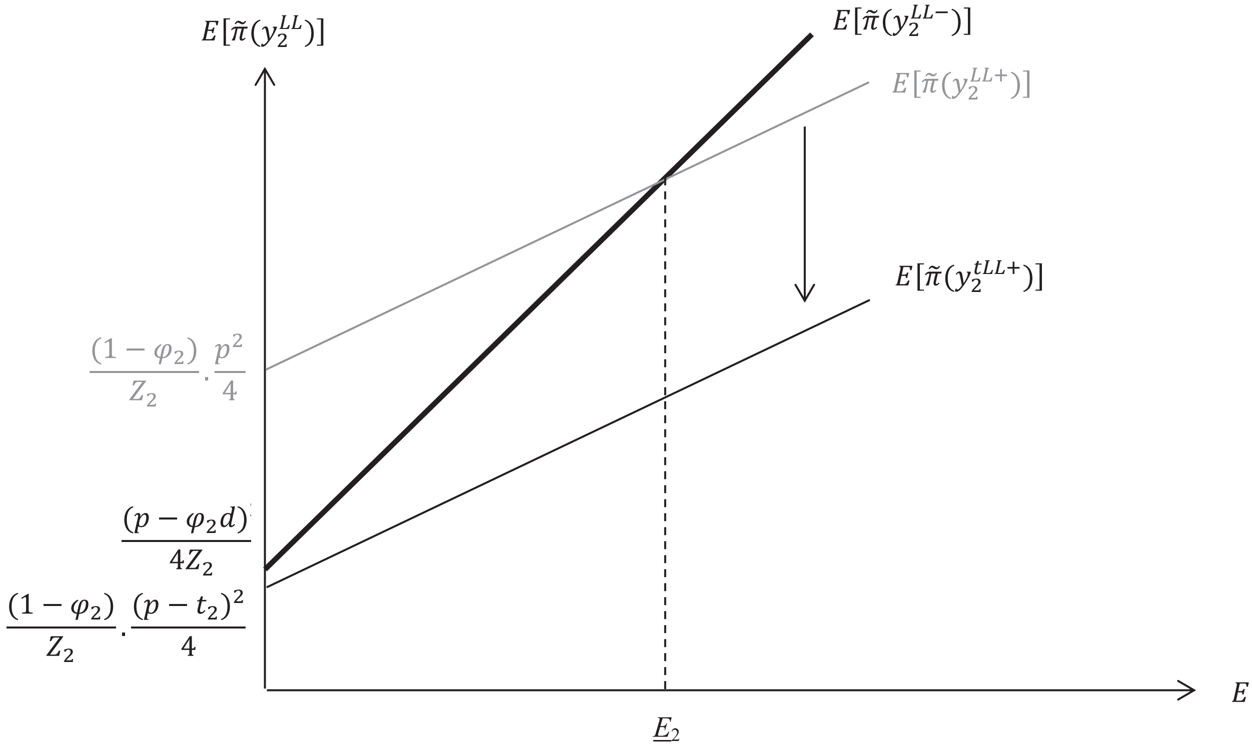

Figure 2. Equity and risk internalization when only partial risk internalization is taxed