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Price versus tradable quantity regulation
Uncertainty and endogenous technology choice

Abstract:
This paper shows that tradable emissions permits and an emissions tax have a risk-related technology choice effect. We first examine the first- and second-order moments in the probability distributions of optimal abatement and production under the two instruments. The two instruments will, in general, lead to different expected aggregate production levels when technology choice is endogenous, given that regulation is designed to induce equal expected aggregate emissions. Moreover, either regulatory approach may induce larger variance in optimal production and optimal abatement levels, depending on the specification of the stochastic variables. Finally, because firms' valuation of a flexible technology increases if the variance in abatement is inflated and vice versa, either of the two instruments may induce the most flexible technology. Specifically, a tax encourages the most flexibility if and only if abatement costs and the equilibrium permit price have sufficiently strong positive covariance compared with the variance in the price on the good produced.

Keywords: Regulation; Technology choice; Uncertainty; Investment.

JEL classification: H23; Q55; Q58.

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1 Introduction

Regulation of economic externalities may induce significant technological innovations. In the longer run, the cumulative effect of such research and development (R&D) may dwarf the short-run gains from cost-effective regulation. Furthermore, it may expand the opportunity set of the regulatory policy itself.[1] As such, it is not surprising that the literature on R&D and firms' incentives to invest in advanced technology is vast.[2]

However, as pointed out by Krysiak (2008), one aspect of this literature is somewhat surprising: these studies tend to analyze how much is invested, but do not consider the kind of technology that is implemented. This constitutes a shortcoming of the literature. For example, emissions reductions of SO_x and NO_x may be achieved either by installing scrubbers[3] or by relying on fuel substitution to, e.g., low-sulfur coal. Similarly, emissions of CO_2 may be reduced by, e.g., a switch from coal to gas or carbon capture and storage (CCS). How this choice is affected by the environmental policy regime is arguably an important consideration in evaluation of public policy. Furthermore, firms' technology choice will affect the demand for technology and, thereby, the direction of R&D effort (see, e.g., Griliches, 1957 or Ruttan, 2001).

This paper inquires whether environmental regulation has a risk-related technology choice effect in addition to the well-known effects on cost efficiency and investment levels.[4] We consider two types of regulation: tradable emissions permits and an emissions tax. These are presently by far the most important occurrences where both price- and quantity-based regulatory approaches are suitable. Under tradable emissions permits, the government sets a cap on aggregate emissions, and the issued licenses to emit (permits) are tradable among firms. Prominent examples of such schemes are found in the EU emissions trading scheme (EU ETS), the US SO_2 trading program and various regulatory schemes for NO_x emissions in the US.[5] Price-based approaches like harmonized prices, fees, or taxes as a method of coordinating environmental policies among countries currently have no international

[1] See for instance Kneese and Schultze (1975) or Orr (1976) for an early presentation of this view. Jaffe and Stavins (1995) offer an empirical approach.

[2] For a thorough discussion on the literature on environmental policy and R&D we refer to Jaffe et al. (2002), Löschel (2002), or Requate (2005a).

[3] That is, e.g., post-combustion flue-gas desulfurization and selective catalytic reduction, respectively.

[4] For the latter, see for instance Denicolo (1999) and Requate and Unold (2003).

[5] See EU (2003, 2005, 2009) or Convery and Redmond (2007) for more on the EU ETS. Joskow et al. (1998) offer a brief but informative account of the US SO_2 trading program. The NO_x program features the Regional Clean Air Incentives Market (RECLAIM), the Ozone Transport Commission (OTC), NO_x Budget Program, and the NO_x State Implementation Plan (SIP). For details, see Burtraw et al. (2005).

experience (Nordhaus, 2007). However, emissions taxes have considerable national experience. Two examples are the US tax on ozone-depleting chemicals and the Norwegian NO_x tax.

We utilize that firms' choices of abatement technology depends on the extent of anticipated fluctuations in the abatement level. This relationship was recognized early by Stigler (1939) and Hart (1940) (applied to the production of a good). Following Stigler (1939), and later extended by Marschak and Nelson (1962), we refer to the firms' ability to change abatement levels in response to new information as their "flexibility". That is, the better equipped a firm is to respond to new information, the more flexible is its abatement technology. As argued by Stigler (1939), flexibility is not a free good: a plant specially designed to work at a given production level q will produce this quantum cheaper than a plant built to be passably efficient between $q/2$ and $2q$. Accepting this argument, we get a trade-off between efficient output at minimum average cost and flexibility. This paper models this trade-off by assuming that minimum average abatement costs and the slope of the marginal abatement cost curve vary inversely with flexibility (see Figure 1). This is in agreement with Stigler (1939), Marschak and Nelson (1962) and Mills (1984).[6]

This paper introduces two sources of uncertainty: an exogenously given stochastic product price (e.g., because of demand uncertainty) and uncertain firm-specific abatement costs. In the first part of this paper (Subsection 2.1), we examine the first- and second-order moments in the probability distributions of optimal abatement and optimal production under tradable emissions permits and an emissions tax. Our results indicate that the above-mentioned uncertainties affect the firms differently under the two environmental policy regimes. In particular, the two regulatory instruments will, in general, lead to different expected aggregate production levels, given that regulation is designed to induce equal expected aggregate emissions, and abatement technology choice is endogenous. Furthermore, the variances in firms' optimal production and abatement levels may be larger under either regulatory regime. The key determinants of this ambiguity are the covariance between the permit price and the firm-specific stochastic abatement costs, and the variance in the product price. As such, the ranking of the variances depends on the specification of the stochastic elements.

[6] The discussion of flexibility in Stigler (1939) is not formal, but Marschak and Nelson (1962) argue persuasively that Stigler's notion of flexibility satisfies this criterion.

In the second part of the paper (Subsection 2.2), we use the derived first- and second-order moments to examine the technology choice of the forward-looking firms. We find that tradable emissions permits and an emissions tax in general lead to implementation of different technologies. A tax encourages the most flexibility if and only if abatement costs and the equilibrium permit price have sufficiently strong positive covariance compared with the variance in the price of the good produced. Otherwise, tradable emissions permits induce the most flexible technology. The argument behind our result is straightforward. Firstly, we establish in Subsection 2.1 that both types of regulation may induce a larger variance in each firm's abatement levels, depending on the above-mentioned stochastic variables. Secondly, we show in Subsection 2.2 that firms implement a more flexible abatement technology if the variance in abatement is inflated and vice versa. Therefore, the firms may choose the most flexible abatement technology under either regulatory regime. Subsection 2.3 provides a brief extension, allowing for heterogeneous risk across firms. Section 3 concludes.

Technology choice is examined by the literature on price-induced innovation. Among these, Morton and Schwartz (1968) show that optimal technology choice depends on the initial technology, the relative factor prices and the relative costs of acquiring different types of innovations. Magat (1978) introduces regulation and finds that effluent taxes and effluent standards lead to a distinctively different allocation of R&D funds between improvements in abatement technology and production technology. Kon (1983) looks at the role of output price uncertainty and shows that it can lead to investment in more labor-intensive technologies. Mills (1984) shows that an unregulated competitive firm will invest more in flexibility if demand uncertainty increases. Lund (1994) allows R&D growth to take more than one direction, and shows that this may create the need for interplay between R&D subsidies and a carbon tax. Zhao (2003) finds that abatement cost uncertainties reduce firms' investment incentive under both tradable emissions permits and emission taxes if the investment is irreversible, and more so under taxes. Kaboski (2005) shows that relative input price uncertainty can cause investment inaction as the firms wait to get more information about what type of technology is most profitable to implement. Fowlie (2010) examines the US NO_x Budget Program and finds that deregulated plants were less likely to implement more capital intensive environmental compliance options compared with regulated or publicly owned plants. Furthermore, the literature on implications of uncertainty on optimal choice of policy instruments (without technology investment) is extensive. In a seminal article, Weitzman (1974) shows that a higher ratio of the slope of marginal damages relative to the slope of marginal abatement costs favors quotas. Hoel and Karp (2002) and Newell and Pizer (2003) extend this result to stock pollutants with additive uncertainty.[7] They also find that an increase in the discount rate or the stock decay rate favors tax usage, and obtain numerical results that suggest that taxes dominate quotas for the control of greenhouse gases. Hoel and Karp (2001) examine the case with stock pollutants and multiplicative uncertainty. Their analytical results are ambiguous, but, using a numerical model, they find that taxes dominate quotas for a wide range of parameter values under both additive and multiplicative uncertainty in the case of climate change mitigation policies. Stavins (1996) shows that positive correlation between marginal costs and marginal benefits works in favor of quantity-based instruments with flow pollutants. Hybrid policies that combine price- and quantity-based policies have been examined by, e.g., Roberts and Spence (1976), Weitzman (1978), Pizer (2002) and Jacoby and Ellerman (2004). These studies suggest that hybrid policies generally dominate a single instrument approach.

Finally, this paper is related closely to Krysiak (2008), who finds that price-based regulation leads to implementation of a more flexible technology than tradable emissions permits.[8] This differs from our finding that either regulatory regime may induce most flexibility. The difference stems from different underlying assumptions, as will be clear in the subsequent analysis. Most importantly, this paper departs from Krysiak (2008) by introducing a product market with a fluctuating price for the good whose production causes emissions subject to regulation as a byproduct.

2 Theoretical analysis

Consider a sector featuring *n* risk-neutral firms that supply a homogeneous good *q* to the world market. One unit of production causes one unit of emissions that is subject to either an emissions tax or tradable emissions permits regulation. This could, for example, be a country (or group of countries like the EU) that mitigates carbon emissions in order to meet its Kyoto requirements. We assume that the area covered by regulation constitutes a sufficiently small part of the world market to leave the price of the good produced

[7] Additive and multiplicative uncertainty applies to the intercept and the slope of marginal abatement costs, respectively.

[8] The focus in Krysiak (2008) is not flexibility per se. Rather, he finds that the most flexible technology (interpreted as a smaller slope of the marginal cost function that does not necessarily entail a higher minimum average cost) is socially suboptimal because it increases the variation in production of the public good. This reduces utility as evaluated by a concave welfare function, by Jensen's inequality. The reasons for the more modest conclusions in this paper are given in the conclusions. Moreover, the use of a concave utility function may be questionable because of this paper's relevance for a stock pollutant such as CO_2.

exogenous.[9] Moreover, we assume divisibility between the costs of abatement and other production costs. This is reasonable in the case of end-of-pipe abatement technology like, e.g., carbon capture and storage. In order to focus on the abatement technology choice, we let the cost of producing the good (without abatement) be given by $q_i^2/2$ for all firms $i \in N = \{1,2,...,n\}$. Finally, perfect competition is assumed in all markets.[10]

Let all firms share the same menu of possible abatement cost structures. Except for the extension of Subsection 2.3, they also face the same uncertainty. Thus, firms choose equal abatement technologies (because they are identical). We omit the firm-specific subscript *i* except where necessary (i.e., on variables that differ across firms) to streamline notation. The firms' choice of technology is governed by the flexibility parameter $\gamma \in [\Gamma_L, \Gamma_H]$, with flexibility increasing in γ. Any firm $i \in N$ may choose its technology (γ) from the following continuum of cost curves:

$$c_i(a_i, \gamma) = F(\gamma) + (\gamma + \eta_i)a_i + \frac{a_i^2}{2\gamma}, \qquad (1)$$

where a_i is firm *i*'s abatement and the fixed-cost component satisfies $F_\gamma, F_{\gamma\gamma} > 0$ for all γ. The loss of generality incurred by assuming a quadratic cost function is modest, because our main result states that either regulatory regime may induce the most flexible technology. As stated in the introduction, our choice of modeling involves the slope of the marginal abatement cost curve decreasing with the degree of flexibility, and minimum average abatement cost increasing with the degree of flexibility. In this respect, we observe that marginal expected abatement cost decreases in $\gamma \le \Gamma_H < \sqrt{a_i}$.[11] Moreover, it can be shown that expected minimum average cost increases in γ (see the Appendix). We add $\eta_i a_i$ to firm *i*'s abatement cost, with $\eta_i \sim (0, \sigma_\eta^2)$ being a firm-specific stochastic variable.[12] For example, this reflects fluctuations in factor prices or factor productivity, or a breakdown of abatement equipment.

[9] An alternate simplifying assumption is a perfectly inelastic demand for the good produced. This assumption is made by, e.g., Mills (1984) and Sheshinski and Drèze (1976) in their study of competitive equilibrium with fluctuating demand. Krysiak (2008) points out that interpretation of the public good as emissions abatement in his analysis requires that the demand for the private good produced is highly inelastic. Excepting part (*i*) of Proposition 1, it can be shown that the qualitative results stated in Propositions 1 to 3 in the present paper remain valid under this alternate assumption.

[10] Results by Joskow et al. (1998) and Convery and Redmond (2007) indicate, respectively, that the US market for sulfur dioxide emissions and the EU emissions trading scheme are competitive.

[11] Even though *a* is stochastic, it is simple to define the model parameters such that this inequality holds.

[12] As usual, $\eta_i \sim (0, \sigma_\eta^2)$ means that η_i is randomly distributed with expected value 0 and variance σ_η^2.

As argued by Weitzman (1974), the determination of η_i could involve elements of genuine randomness, but might also stem from lack of information. The abatement cost shock η_i enters our functional form linearly, which is similar to, e.g., Hoel and Karp (2002), Karp and Zhang (2006), and Krysiak (2008).

The model is organized in three periods. First, in period 1, the regulator sets the emissions tax or a binding cap on aggregate emissions. This is done in such a way that expected aggregate emissions are equal under the two regulatory instruments. Our assumption on timing and regulation is sometimes referred to as interim regulation in the literature (see, e.g., Requate (2005b)). The firms react to the regulation and invest in abatement technology in period 2. Finally, the firms choose their abatement and production levels in period 3. We assume that the outcomes of the stochastic variables are determined between periods 2 and 3. That is, decisions in periods 1 and 2 are made under uncertainty, while firms have full information in period 3. The firms' production and abatement decisions in period 3 are made contingent on the firms' abatement technology decisions in period 2. As such, the firms' investment decisions are formulated as a two-stage game: the payoffs in period 3 determine the technology investment decisions in period 2. The model is solved backwards and our equilibrium concept is that of a subgame perfect equilibrium.

2.1 Period 3: The production and abatement decisions

Let the exogenously given price on good q be given by $D+\varepsilon$, where $\varepsilon \sim (0,\sigma_\varepsilon^2)$ and D is an exogenous constant. It is natural to interpret ε as driven by stochastic fluctuations in demand, or supply shocks to firms that produce q but are not covered by the emissions trading scheme.[13] We assume that the product price shock ε and the abatement cost shock η_i are independently distributed random variables, i.e., the expected value $E(\varepsilon\eta_i)=0$ for all $i \in N$. Let p refer to the price of permits and τ denote the emissions tax. The profit function in period 3 of any firm $i \in N$ is given by:

$$\pi_i = \max_{q_i,a_i}\left[(D+\varepsilon)q_i - \frac{1}{2}q_i^2 - (q_i - a_i)w - F(\gamma) - (\gamma+\eta_i)a_i - \frac{1}{2\gamma}a_i^2\right], \qquad (2)$$

[13] Baldursson and von der Fehr (2004) examine emissions permits and assume that risk may originate from two sources: the number of firms and production of the pollutant prior to abatement.

with $w \in \{p, \tau\}$ and $a_i \in [0, q_i]$.[14] Both the permit price p and the emissions tax τ remain to be determined. Remember that firms have full information in period 3 (i.e., the outcomes of the random variables η_i and ε are known) and that the shape on the firms' abatement cost functions was determined by the firms' technology choice γ in period 2. Because technology may differ across the regulatory regimes, we have $\gamma \in \{\gamma_{tax}, \gamma_{trad}\}$.[15] We get the following first-order conditions for any firm $i \in N$:

$$q_i = q = D + \varepsilon - w\,, \tag{3}$$

$$a_i = (w - \gamma - \eta_i)\gamma\,, \tag{4}$$

under the assumptions of interior solutions for production q_i and abatement a_i. We also observe that the second-order condition of the maximization problem (2) is fulfilled. Note that each firm's production and abatement levels are random variables before the outcomes of the stochastic events are known (i.e., in periods 1 and 2). We now examine tradable emissions permits in Subsection 2.1.1, while Subsection 2.1.2 focuses on the emissions tax. Finally, we compare the regimes in Subsection 2.1.3.

2.1.1 Tradable emissions permits

The regulator sets a binding cap on aggregate emissions denoted S under tradable quantity regulation. The emissions trading market-clearing condition then becomes (remember that one unit of production causes one unit of emissions):

$$S = nq_{trad} - \sum_{i \in N} a_{i,trad}\,, \tag{5}$$

where q_{trad} and $a_{i,trad}$ refer to the optimal levels of production and abatement under tradable emissions permits, respectively. We see that aggregate abatement depends on aggregate production and, therefore, by equation (3), on the product price shock ε. This is no surprise. Fluctuations in emissions, e.g., because of stochastic demand for the good produced, must be mirrored in a one-to-one relationship by aggregate abatement when there is a binding cap on aggregate emissions. From equations (3), (4) and (5) we get the following market-clearing permit price:

[14] The fixed cost $F(\gamma)$ may alternatively be paid in period 2. This has no consequence for our results.

[15] As a notational convention we let the subscripts "trad" and "tax" refer to tradable emissions permits and an emissions tax, respectively.

$$p = \frac{1}{1+\gamma_{trad}}\left(D + \varepsilon - \frac{S}{n} + \gamma_{trad}\left(\frac{1}{n}\sum_{i\in N}\eta_i + \gamma_{trad}\right)\right). \tag{6}$$

The equation shows that the equilibrium permit price increases in the stochastic shocks to abatement costs η_i and the stochastic shocks to the product price ε. Inserting the above solution for the permit price p into the first-order conditions (3) and (4), we get the following solutions for the production and abatement of any firm $i \in N$:

$$q_{trad} = \frac{\gamma_{trad}}{1+\gamma_{trad}}\left(D + \varepsilon + \frac{S}{n\gamma_{trad}} - \gamma_{trad} - \frac{1}{n}\sum_{i\in N}\eta_i\right), \tag{7}$$

$$a_{i,trad} = \frac{\gamma_{trad}}{1+\gamma_{trad}}\left(D + \varepsilon - \frac{S}{n} - \gamma_{trad} + \frac{\gamma_{trad}}{n}\sum_{j\in N}\eta_j\right) - \eta_i\gamma_{trad}\ . \tag{8}$$

Not surprisingly, equation (7) shows that production increases in the stochastic shock to the product price ε. Moreover, the production of any firm $i \in N$ decreases in the stochastic shocks to the abatement cost η_i of all the $i = 1,2,...,n$ firms. This occurs because the total cost of production depends on the permit price, which is strictly increasing in abatement costs (cf. equation 6).[16] Regarding abatement, we see from equation (8) that firm *i*'s abatement decreases in the stochastic shock to firm *i*'s abatement costs η_i. Furthermore, a positive shock to the product price ε increases the abatement of the firms. The reason is that there is a binding cap on aggregate emissions and $\varepsilon > 0$ increases production (cf. equation 7). Finally, we note that firm *i*'s abatement increases in the stochastic shocks to the abatement costs of any other firm $\eta_{j'}$ with $j' \in N \setminus \{i\}$, because of a higher equilibrium permit price (cf. equation 6).

Equations (7) and (8) yield the equilibrium emissions $q_{trad} - a_{i,trad} = \frac{S}{n} + \gamma_{trad}(\eta_i - \frac{1}{n}\sum_{j\in N}\eta_j)$ for any firm $i \in N$. Naturally, aggregate emissions are equal to the binding emissions cap S under tradable emissions permits.

From equations (7) and (8) we get the following expected values of the firms' optimal production and abatement levels under tradable emissions permits:

$$E(q_{trad}) = \frac{\gamma_{trad}}{1+\gamma_{trad}}\left(D + \frac{S}{n\gamma_{trad}} - \gamma_{trad}\right), \tag{9}$$

[16] The term "total cost of production" refers to the negative of the last five terms in equation (2).

$$E(a_{trad}) = \frac{\gamma_{trad}}{1+\gamma_{trad}}\left(D - \frac{S}{n} - \gamma_{trad}\right), \tag{10}$$

which are equal across all firms $i \in N$. We also observe that each firm's expected emissions are given by S/n, which is simply total emissions (as given by the emissions cap *S*) divided by the number of firms *n*.

Following Krysiak (2008), we define the correlation coefficient $\rho = E(\eta_i \eta_j)/\sigma_\eta^2$ for all firms $i, j \in N$ $(i \neq j)$. Do such symmetrically correlated variables imply any restrictions on the correlation coefficient ρ?[17] We state the following lemma:

Lemma 1. *Let the correlation coefficient be given by* $\rho = E(\eta_i \eta_j)/\sigma_\eta^2$ *for all firms* $i, j \in N$ $(i \neq j)$*. Then we have* $\rho \in [-1/(n-1), 1]$.
Proof. See the Appendix.

Note in particular that the lower bound on the correlation coefficient ρ become arbitrarily close to zero as the number of firms (*n*) increases.

Lemma 1 implies that the simplifying assumption of symmetrically correlated stochastic shocks to the abatement costs precludes a negative covariance between the firms' abatement costs η_i and the permit price *p*. This is seen easily from the covariance between η_i and *p*, which is derived from equation (6) and given by $\text{cov}(\eta_i, p) = \frac{1}{n}\frac{\gamma_{trad}}{1+\gamma_{trad}}(1+(n-1)\rho)\sigma_\eta^2$. It is strictly increasing in the correlation coefficient ρ, and equal to 0 and $\frac{\gamma_{trad}}{1+\gamma_{trad}}\sigma_\eta^2$ when $\rho = -1/(n-1)$ and $\rho = 1$, respectively. In particular, we have $\text{cov}(\eta_i, p) = 0$ if $\rho = 0$ and $n \to \infty$, i.e., if the abatement cost shocks are independently distributed across firms and we have a continuum of firms.[18] The assumption of homogeneous risk environments across firms is relaxed in Subsection 2.3. Finally, we note from equation (6) that $\text{cov}(\varepsilon, p) = \frac{\gamma_{trad}}{1+\gamma_{trad}}\sigma_\varepsilon^2 > 0$, because a positive shock to the product price ε increases production and, thereby, the abatement needed to satisfy the emissions cap. The associated higher marginal abatement costs increases the permit price *p*.

[17] Krysiak (2008) assumes $\rho \in [0,1]$.

[18] We need $n \to \infty$ when $\rho = 0$ to achieve $\text{cov}(\eta_i, p) = 0$ because each firm's own shock to abatement costs η_i affects the permit price, cf. equation (6). This influence becomes infinitesimal as $n \to \infty$.

The variances of the firms' optimal production and abatement levels under tradable emissions permits are derived from equations (7) and (8) (see the Appendix):

$$\mathrm{var}(q_{trad}) = \left(\frac{\gamma_{trad}}{1+\gamma_{trad}}\right)^2 \left(\sigma_\varepsilon^2 + \frac{\sigma_\eta^2}{n}(1+(n-1)\rho)\right), \tag{11}$$

$$\mathrm{var}(a_{trad}) = \left(\gamma_{trad}^2 - \frac{K_1}{n}(1+(n-1)\rho)\right)\sigma_\eta^2 + K_2\sigma_\varepsilon^2 , \tag{12}$$

with $K_1 \equiv \frac{2\gamma_{trad}^3+\gamma_{trad}^4}{(1+\gamma_{trad})^2} > 0$ and $K_2 \equiv \left(\frac{\gamma_{trad}}{1+\gamma_{trad}}\right)^2 > 0$. The variances are equal across all firms $i \in N$. Moreover, the variance in the optimal abatement under tradable emissions permits is strictly decreasing in ρ and satisfies $\mathrm{var}(a_{trad}) \in \left[K_2(\sigma_\varepsilon^2 + \sigma_\eta^2), K_2\sigma_\varepsilon^2 + \gamma_{trad}^2\sigma_\eta^2\right]$, because the correlation coefficient between the firms' abatement costs satisfies $\rho \in [-1/(n-1), 1]$. In particular, $\mathrm{var}(a_{trad}) > 0$ even if $\rho = 1$ and $\sigma_\varepsilon^2 = 0$. This is true because abatement costs affect production, and thereby the level of aggregate abatement needed to satisfy the emissions cap.

2.1.2 Emissions tax

The government sets a tax on emissions that we denote τ under price-based regulation. This is set to induce equal expected aggregate emissions under the two regulatory regimes. Thus, the tax solves $S = E(nq_{tax} - \sum_{i\in N} a_{i,tax})$. Using the first-order conditions (3) and (4), this implies:

$$\tau = \frac{1}{1+\gamma_{tax}}\left(D - \frac{S}{n} + \gamma_{tax}^2\right). \tag{13}$$

Note that the tax is equal to the expected value of the permit price (6) if the technology parameters (γ) are equal under the two regulatory regimes. The fixed tax contrasts with the stochastic permit price. This simply reflects that price-based regulation features a fixed price and endogenous quantities, while the opposite applies to tradable quantity regulation.

The first-order conditions (3) and (4) and the tax given by equation (13) yields:

$$q_{tax} = \varepsilon + \frac{\gamma_{tax}}{1+\gamma_{tax}}\left(D + \frac{S}{n\gamma_{tax}} - \gamma_{tax}\right), \tag{14}$$

$$a_{i,tax} = \frac{\gamma_{tax}}{1+\gamma_{tax}}\left(D - \frac{S}{n} - \gamma_{tax}\right) - \eta_i \gamma_{tax} \ , \tag{15}$$

for all firms $i \in N$. We first observe from equation (14) that the firm's production level is independent of the stochastic element to abatement costs η_i under an emissions tax. This reflects our assumption of separability between abatement costs and other production costs, and that the marginal cost of emissions is constant and equal to the tax in equilibrium. This leaves the total costs of production independent of the abatement cost shock η_i. Furthermore, the two elements that constitute the stochastic exogenous price for the good produced, $D+\varepsilon$, affect optimal production in different ways, because the regulator sets the tax based on expected values, and $E(\varepsilon)=0$, while D is an exogenous constant. Proceeding to abatement, we note from equation (15) that the firm's optimal abatement level is independent of the product price shock ε under price-based regulation. The reason is that firms simply abate until marginal abatement costs are equal to the tax, leaving aggregate emissions endogenous under price-based regulation.

Equations (14) and (15) yield the equilibrium emissions $q_{tax} - a_{i,tax} = \frac{S}{n} + \varepsilon + \gamma_{tax}\eta_i$ for any firm $i \in N$. Note that aggregate emissions are equal to $S + n\varepsilon + \gamma_{tax}\sum_{i\in N}\eta_i$, with an expected value equal to the emissions cap under tradable emissions permits S.

Finally, we derive the expectations and variances in optimal production and abatement from equations (14) and (15):

$$E(q_{tax}) = \frac{\gamma_{tax}}{1+\gamma_{tax}}\left(D + \frac{S}{n\gamma_{tax}} - \gamma_{tax}\right), \tag{16}$$

$$E(a_{tax}) = \frac{\gamma_{tax}}{1+\gamma_{tax}}\left(D - \frac{S}{n} - \gamma_{tax}\right), \tag{17}$$

$$\text{var}(q_{tax}) = \sigma_\varepsilon^2 \ , \tag{18}$$

$$Var(a_{tax}) = \sigma_\eta^2 \gamma_{tax}^2 \ , \tag{19}$$

which are equal across all firms $i \in N$.

2.1.3 Comparison of the regimes

Based on the previous analysis, we state the following result regarding the first- and second-order moments in the probability distributions of optimal abatement and production under the two regulatory regimes:

Proposition 1. *Assume that the two regulatory instruments are designed to induce equal expected aggregate emissions and let the firms' profit maximization problem be given by equation (*2*). Then we have the following:*

i. $E(q_{trad}) = E(q_{tax})$ *if and only if* $\gamma_{tax} = \gamma_{trad}$. *We have* $E(q_{trad}) \neq E(q_{tax})$ *otherwise.*

ii. $\mathrm{var}(q_{trad}) \geq (\leq) \mathrm{var}(q_{tax})$ *if and only if* $\sigma_\varepsilon^2 \leq (\geq) \frac{K_3}{n}(1+(n-1)\rho)\sigma_\eta^2$, *with* $K_3 \equiv \frac{\gamma_{trad}^2}{1+2\gamma_{trad}} > 0$.

iii. $\mathrm{var}(a_{trad}) \geq (\leq) \mathrm{var}(a_{tax})$ *if and only if* $\sigma_\varepsilon^2 \geq (\leq) \frac{K_4}{n}(1+(n-1)\rho)\sigma_\eta^2 + K_5\sigma_\eta^2$, *with* $K_4 \equiv 2\gamma_{trad} + \gamma_{trad}^2 > 0$ *and* $K_5 \equiv \frac{(1+\gamma_{trad})^2}{\gamma_{trad}^2}(\gamma_{tax}^2 - \gamma_{trad}^2)$.

Proof. The Proposition is obtained from equations (9) to (12) and (16) to (19).

Interpreting part (*i*), each firm has equal expected emissions across the regimes, i.e., $E(q_{tax} - a_{tax}) = E(q_{trad} - a_{trad})$. This is not surprising, as we have assumed equal aggregate expected emissions across the regulatory instruments. However, the expected values of optimal production (and thereby abatement) are equal across the regimes if and only if the firms technology choices satisfy $\gamma_{tax} = \gamma_{trad}$. This happens because the regulator has only one instrument available for each regulatory regime (i.e., the emissions cap *S* or the tax τ), while the firms have three decision variables. That is, if the regulatory instruments are used to impose equal expected aggregate emissions across the regimes, the regulator cannot ensure equal expected production levels. Therefore, although tradable emissions permits and a tax may be equivalent with respect to expected aggregate emissions, the regulatory regimes will in general have different effects on the product market when the abatement cost structure is endogenous. Note that the regulator could alternatively calibrate its instruments in order to induce equal expected aggregate production across the regulatory regimes.

Interpreting part (*ii*), we emphasize two opposing mechanisms that are present under tradable emissions permits, but not under an emissions tax. On the one hand, a positive shock to the price of the good produced ε increases production and thereby aggregate emissions.

Because there is a cap on aggregate emissions under tradable emissions permits, this implies more aggregate abatement and, hence, a higher permit price (cf. equation 6). This increases total production costs and thereby reduces the firms' response to the product price shock ε. The mechanism is absent under price-based regulation, because the emissions tax is constant. This explains why a higher variance in the price of the good produced σ_ε^2 tends to decrease the variance in production under tradable emissions permits $\text{var}(q_{trad})$ as compared with the variance in production under a tax $\text{var}(q_{tax})$. On the other hand, $\text{var}(q_{trad})$ tends to increase in ρ, i.e., in the correlation coefficient across the shocks to the firms' abatement costs η_i, and in the variance in the abatement cost shocks σ_η^2. The reason is that the variance in the permit price (6), and thereby total production costs, increases in these two variables. In particular, $\text{var}(q_{trad})$ remains positive even if we impose the extra restrictions that $\eta_i \equiv 0$ and $\varepsilon \equiv 0$, given that $\eta_j \sim (0, \sigma_\eta^2 > 0)$ for any other firm $j \in N \setminus \{i\}$ and $\rho > -1/(n-1)$ (cf. equation 11). Again, this does not happen under an emissions tax, where the price on emissions is constant.

Interpreting part (*iii*) of Proposition 1, we again emphasize two opposing mechanisms. Firstly, a larger σ_ε^2 tends to increase the variance in abatement under tradable emissions permits $\text{var}(a_{trad})$, but does not affect the variance under a tax $\text{var}(a_{tax})$ (cf. equations 12 and 19). The reason is that fluctuations in aggregate emissions (caused by fluctuations in production) must be mirrored by aggregate abatement in order to satisfy the emissions cap under tradable emissions permits. Naturally, this does not occur in a tax regime where aggregate emissions are endogenous. Secondly, a high (low) equilibrium permit price tends to occur together with high (low) realized abatement costs, given $\rho > -1/(n-1)$. This reduces the effect σ_η^2 has on $\text{var}(a_{trad})$. Finally, we observe that $K_5 = 0$ if and only if $\gamma_{trad} = \gamma_{tax}$.

The effects discussed in the two preceding paragraphs are summarized in Table 1 for convenience. On the one hand, both ε and η_i affect the optimal levels of production and abatement under tradable emissions permits. In contrast, optimal production and abatement under price-based regulation are only affected by one shock each, i.e., ε and η_i, respectively. On the other hand, the equilibrium permit price tends to reduce the effect of η_i on abatement and ε on production. Whether the variances are larger under price- or quantity-based regulation depends on the relative strengths of these mechanisms, as captured by the conditions on technology and the stochastic elements in Proposition 1.

Finally, we note that there is no reason to expect the firms to increase their profits if the variances in production or abatement decrease, even though larger variances in production and abatement tend to increase production and abatement costs.[19] Why is this? Note that the firm could always choose to keep abatement and production constant, even though prices or costs differ from their expected values. This strategy would yield the firm's profits as a linear and increasing function of $D+\varepsilon-(w+\eta)$. However, we know that the profit-maximizing firm does not follow this strategy (cf. equations 3 and 4). This is because it can do better by changing its production and abatement levels, which implies that profits (2) are convex in $D+\varepsilon-(w+\eta)$.[20] We also observe from the first-order condition (4) that a higher γ induces a stronger response in optimal abatement for any given change in $D+\varepsilon-(w+\eta)$. This simply reflects the value of flexibility discussed in the Introduction.

2.2 Period 2: The investment decision

The impetus of our analysis of the firms' investment decisions in period 2 is that their abatement technology choice depends on the extent of anticipated future fluctuations in abatement. More specifically, the firms' choices between abatement cost structures represent a trade-off between static efficiency and flexibility (as illustrated in Figure 1). Intuition suggests that the relative weight on flexibility in this trade-off increases if uncertainty regarding the future abatement level is large. For example, if the equilibrium permit price turns out to be unexpectedly high in period 3, a firm may reduce its costs with a higher level of abatement. The firm can increase its adaptability to such future events in period 3 by investing in a more flexible technology in period 2.

In period 2, any firm $i \in N$ maximizes expected profits with respect to abatement cost structure as determined by γ:

$$\max_{\gamma\in[\Gamma_L,\Gamma_H]} E[\pi_i], \tag{20}$$

[19] On the other hand, a smoother consumption path over time increases the consumers' utility, given that the utility function is concave in consumption of the good *q*.

[20] The increase in profits because of higher price variability was first noted by Oi (1961). In particular, this implies that minimum average abatement costs are higher than the permit price in competitive equilibrium with zero profits, free entry/exit and a fluctuating permit price.

with π_i given by equation (2). The competitive firm's influence on the market-clearing permit price *p* is infinitesimal and ignored under tradable emissions permits. The emissions tax τ is a constant fixed by the regulator. Hence, $w \in \{p, \tau\}$ is a constant in the maximization problem above.

The interior solution to the maximization problem (20) is characterized by the following first-order condition (see the Appendix):

$$F_\gamma + E(a) - \frac{1}{2\gamma^2}(E(a))^2 = \frac{1}{2\gamma^2}\operatorname{var}(a), \tag{21}$$

with expectations $E(a)$ and variances $\operatorname{var}(a)$ as given by equations (10) and (12) under tradable emissions permits and (17) and (19) under an emissions tax. Note that all elements in equation (21) are equal across the regulatory regimes, except the decision variable γ and $\operatorname{var}(a)$. We show in the proof of Proposition 2 below that the first- and second-order conditions of the maximization problem (20) imply that $\partial\gamma / \partial \operatorname{var}(a) > 0$ in the interior solution. This implies that a larger $\operatorname{var}(a)$ increases the expected gain from flexibility. Flexibility is not a free good, however. The expected unit cost of abatement increases in flexibility at the abatement level that induces minimum average abatement costs. As such, equation (21) gives the solution to the firm's trade-off between static efficiency and flexibility. The firm is willing to increase abatement costs at an abatement level a_i close to minimum average cost in order to reduce its costs when a_i is further away from this level. The greater the variance in a_i, the greater is the cost the firm is willing to accept to increase its ability to accommodate such future events.[21]

For values of our exogenous variables where the maximization problem (20) has no interior solution, the following rule applies:

$$\gamma = \Gamma_L \quad if \quad F_\gamma + E(a) - \frac{1}{2\gamma^2}(E(a))^2 > \frac{1}{2\gamma^2}\operatorname{var}(a), \forall\gamma, \tag{22}$$

$$\gamma = \Gamma_H \quad if \quad F_\gamma + E(a) - \frac{1}{2\gamma^2}(E(a))^2 < \frac{1}{2\gamma^2}\operatorname{var}(a), \forall\gamma. \tag{23}$$

Therefore, the firm will choose the lowest possible level of flexibility if the cost of flexibility is very high, or, alternatively, if the gain from flexibility represented by $\operatorname{var}(a)$ is low (cf. equation 22). In particular, we get this border solution if the variance in abatement, as

[21] Note the analogy to the lower expected utility a risk-averse agent is willing to accept in order to increase utility if the outcome of the risk is bad.

given by equations (12) or (19), is zero, in which case the firm would choose the technology that yields the lowest possible minimum average abatement costs. In contrast, if the cost of flexibility is low, the firm may choose the highest possible level of flexibility (cf. equation 23).

In the introduction to this paper, we outlined the following research question: does environmental regulation have a risk-related technology choice effect in addition to the effects on cost efficiency and investment levels? We state the following result:

Proposition 2. *Assume that the two regulatory instruments are designed to induce equal expected aggregate emissions and let the firms' profit maximization problem be given by equation (*20*). Then we have* $\gamma_{trad} \geq (\leq) \gamma_{trad}$ *if and only if* $\mathrm{var}(a_{trad}) \geq (\leq) \mathrm{var}(a_{tax})$.

Proof. See the Appendix.

Strict inequalities in the condition on the variances yield strict inequalities between the flexibility parameters γ in the two regimes (with at least one interior solution for γ). Note that the condition for $\mathrm{var}(a_{trad}) \geq (\leq) \mathrm{var}(a_{tax})$ is given in part (*iii*) of Proposition 1.

Proposition 2 establishes that the intuition stated in the beginning of this section is indeed correct: the firms' choice between abatement cost functions represents a trade-off between static efficiency and flexibility. In this trade-off, firms are willing to sacrifice more static efficiency in order to gain a flexible technology if the variance in abatement is inflated and vice versa.

Proposition 2 has two important consequences. First, the two regulatory instruments lead to implementation of different technologies unless the variances satisfy $\mathrm{var}(a_{trad}) = \mathrm{var}(a_{tax})$. The unequal choices of technology follow from the different economic environments with regard to risk caused by the two regulatory regimes (the regimes are equal when $\sigma_\varepsilon^2 = \sigma_\eta^2 = 0$).[22] This implication corroborates a point emphasized by Krysiak (2008): the choice of environmental policy instrument can have a lock-in effect. That is, a switch between price- and quantity-based regulations could render existing technology suboptimal and, therefore, devalue the installed equipment and the acquired technological knowledge. If

---

[22] Krysiak (2008) states that different technology choices must occur because the regulator has only one instrument, while the firms have two technology choice variables (in his model). However, Proposition 2 shows that this is not a necessary condition to achieve this result. Indeed, what matters is that the regulator has already used its instrument to achieve equal expected aggregate emissions (or, as in Krysiak (2008), equal expected marginal production costs).

the resultant loss of sunk technology investment costs is substantial, it may deter a change of regulatory instrument once it has been implemented. Second, Proposition 2 states that both types of regulation may induce stronger incentives to choose the most flexible technology (remember the ambiguity stated in Proposition 1, point *iii*).

Propositions 1 and 2 have the following corollary:

Corollary 1. *Assume that the two regulatory instruments are designed to induce equal expected aggregate emissions and let the firms' profit maximization problem be given by equation (20). Then we have the following:*

i. $E(q_{trad}) = E(q_{tax}) \Leftrightarrow \sigma_\varepsilon^2 = \frac{K_4}{n}(1+(n-1)\rho)\sigma_\eta^2 + K_5\sigma_\eta^2$. *Otherwise,* $E(q_{trad}) \neq E(q_{tax})$.

ii. $\gamma_{trad} \geq (\leq)\gamma_{tax} \Leftrightarrow \sigma_\varepsilon^2 \geq (\leq) \frac{K_4}{n}(1+(n-1)\rho)\sigma_\eta^2 + K_5\sigma_\eta^2$.

iii. If $\sigma_\varepsilon^2 = 0 \cap \sigma_\eta^2 > 0$, then $\gamma_{trad} < (=)\gamma_{tax}$ if and only if $\rho > (=) -1/(n-1)$. The technology choices become arbitrarily close to identical as n increases if $\rho = 0$.

iv. *If* $\sigma_\varepsilon^2 > 0 \cap \sigma_\eta^2 = 0$, *then* $\gamma_{trad} > \gamma_{tax}$.

Proof. The corollary follows directly from Propositions 1 and 2.

Parts (*i*) and (*ii*) in the corollary simply merge the results obtained previously in Propositions 1 and 2 (remember that K_4 and K_5 are defined in Proposition 1, part *iii*). Their interpretations are not repeated here.

Interpreting part (*iii*) in Corollary 1, the variance in abatement is less under tradable emissions permits as long as the correlation coefficient between the shocks to the firms' abatement cost functions satisfies $\rho > -1/(n-1)$ and the product price is deterministic (i.e., $\sigma_\varepsilon^2 = 0$). The regimes become equal if ρ reaches its lower bound $\rho = -1/(n-1)$. Note that we require negative correlation in order to induce equal technology across the regulatory regimes (for a bounded number of firms *n*). This is because the realized abatement cost of any firm $i \in N$ itself influences the permit price under tradable emissions permits. The reader may have observed that part (*iii*) of Corollary 1 omits that Propositions 1 and 2 imply $\gamma_{trad} > \gamma_{tax}$ if $\rho < -1/(n-1)$ when $\sigma_\eta^2 > \sigma_\varepsilon^2 = 0$. This is because Lemma 1 states that $\rho \geq -1/(n-1)$ when $E(\eta_i \eta_j)$ is equal for all $i, j \in N$ ($i \neq j$). Hence, it is impossible to have values of ρ that induce $\gamma_{trad} > \gamma_{tax}$ in this case. The assumption of homogeneous risk environments across firms is relaxed in Subsection 2.3.

We last observe that the regimes yield the same technology if $\rho = 0$, $n \to \infty$ and $\sigma_\varepsilon^2 = 0$. This is true because the probability distribution of the market-clearing permit price (6) then collapses around its expected value (by the law of large numbers), which becomes equal to the emissions tax. That is, the characteristics of tradable emissions permits converge toward those of price-based regulation as n increases when the ηs are independent across firms $(\rho = 0)$ and $\sigma_\varepsilon^2 = 0$. Part (*iii*) of Corollary 1 is related closely to Krysiak (2008), which assumes that unexpected shocks may only occur to the firms' supply costs. This translates to $\varepsilon \equiv 0$ in our model. In this particular case, our model reproduces the result on technology choice in Krysiak (2008).

Part (*iv*) of Corollary 1 is true because $Var(a_{tax}) = 0$ while $Var(a_{trad}) > 0$ under the given assumptions (cf. equations 12 and 19). Intuitively, there is no source of uncertainty in optimal abatement under an emissions tax: both abatement costs and the tax (τ) are known with certainty. The same is not true under tradable emissions permits, where the equilibrium permit price is stochastic. Therefore, the corollary implies that firms' abatement decisions under an emissions tax are unaffected by a change in the price of the good of which emissions are a by-product. As such, tax-based regulation transfers risk from the firms to the regulator, who supposedly cares about the overall level of emissions (given the regulation).[23] This latter result relies on our assumption that abatement costs are separable from other costs of production.

2.3 Two types of firms

In this extension we relax the assumption of homogeneous risk environments across firms. Let there be two types of firms: the "*i*-firms" consisting of $i = 1,2,...,\alpha$, and the "*j*-firms" consisting of $j = \alpha + 1, \alpha + 2,...,n$. The abatement costs of these firms are hit by the stochastic shocks $\eta_i \equiv \eta_1 = \eta_2 = ... = \eta_\alpha$ and $\eta_j \equiv \eta_{\alpha+1} = \eta_{\alpha+2} = ... = \eta_n$. Otherwise, the firms are identical in all respects. Both η_i and η_j are random variables with expectation and variance equal to zero and σ_η^2, respectively. We have $\rho \equiv E(\eta_i \eta_j) / \sigma_\eta^2 \in [-1,1]$. We further

[23] Of course, the firms still have to pay the tax for their higher emissions.

limit the analysis to the case where n is a very large number and set $\alpha / n \approx 0$. The focus is on the i-firms, which have an infinitesimal effect on the equilibrium permit price under tradable emissions permits. One possible interpretation of this scenario is that we analyze the investment decisions in a sector that only constitutes a small part of an emissions trading scheme covering several other sectors. We set $\varepsilon \equiv 0$ for simplicity (we already know from the previous analysis that $\sigma_\varepsilon^2 > 0$ increases the relative flexibility under tradable emissions permits).

The analysis of an emissions tax remains unaltered. Under tradable emissions permits, the first-order conditions (3) and (4) remain valid, while the emissions trading market equilibrium condition (5) is replaced with $S = \alpha(q_i - a_i) + (n-\alpha)(q_j - a_j)$. This leaves us with $2n+1$ equations and $2n+1$ unknowns in period 3. The solution of this linear system of equations and the firms' technology investment decisions are left to the proof of Proposition 3 in the Appendix. We note, however, that the j-firms' actions under tradable quantities are identical to the previous analysis, setting $\rho = 1$ and $\sigma_\varepsilon^2 = 0$. We state the following result regarding the i-firms' investment decision:

Proposition 3. *Assume that the equilibrium permit price is a stochastic variable of which the firms in question have infinitesimal influence. Moreover, let the two regulatory instruments be designed to induce equal expected aggregate emissions and let the firms' profit maximization problem be given by equation (20). Then we have:*

$$\gamma_{i,trad} \geq (\leq) \gamma_{tax} \cap \mathrm{var}(a_{i,trad}) \geq (\leq) \mathrm{var}(a_{tax}) \Leftrightarrow \rho \leq (\geq) \frac{1}{2} \frac{\left(\gamma_j^2 + 2\gamma_j + 1\right)\left(\gamma_i^2 - \gamma_{tax}^2\right) + \gamma_i \gamma_j^3}{\gamma_i \gamma_j^2 \left(1 + \gamma_j\right)}.$$

Proof. See the Appendix.

Note that the condition would simplify to $\rho \leq (\geq) \frac{1}{2} \frac{\gamma_j}{1+\gamma_j}$ if we imposed $\gamma_i = \gamma_{tax}$ (applied to the variances only). This is equivalent to the requirement that the correlation coefficient between p and η_i satisfies $corr(p, \eta_i) \leq (\geq) \frac{1}{2}$.[24] Thus, if the equilibrium permit price is a stochastic variable over which the firms in question have infinitesimal influence, the variance in the firms abatement level will be larger (smaller) under emissions trading if and

[24] The correlation coefficient is derived from the expression for the permit price in the proof of Proposition 3.

only if the correlation coefficient between the shocks to the firms abatement costs and the permit price is smaller (larger) than 1/2 (for a given technology $\gamma_i = \gamma_{tax}$).

Proposition 3 shows that *some* firms may invest in the most flexible technology under tradable emissions permits, even though the correlation between the shocks that occur to the firms' abatement costs is positive and $\varepsilon \equiv 0$. The variance in the *j*-firms' abatement is less than that of the *i*-firms and, indeed, less than it would be under an emissions tax. Therefore, they choose a less flexible technology than they would under a tax (cf. part (*iii*) of Corollary 1, with $\rho = 1$ and $\sigma_\varepsilon^2 = 0$).

Therefore, the firms' choices of technology may differ under tradable emissions permits when we relax the assumption of homogeneous risk across firms. This is not surprising, as firms no longer have the same variance in abatement. It contrasts with an emissions tax, where all firms still invest in the same technology. Independent (or weakly correlated) ηs may be reasonable if much of the noise in abatement costs stems from random events such as breakdown of infrastructure or abatement equipment.[25]

3 Conclusion

This paper examined whether environmental regulation has a risk-related technology choice effect in addition to the well-known effects on cost efficiency and investment levels. In order to answer this question, we first examined the first- and second-order moments in the probability distributions of optimal abatement and optimal production under price- and quantity-based regulation. Then, we used the regulatory regime-dependent (random) payoffs to derive the technology choice of the forward-looking firms. Besides determining which of the existing technologies is implemented, we emphasize that the firms' technology choice may also influence the direction of R&D efforts. This occurs through the demand for advanced abatement technology (e.g., see Griliches, 1957 or Ruttan, 2001).

Regarding the first-order moments, we found that the two regulatory instruments in general lead to different expected aggregate production levels when technology choice is endogenous, given that regulation is designed to induce equal expected aggregate emissions.

[25] Parson et al. (2009) states that a disruption in delivery of low-sulfur coal because of track failures in October 2005 created a bottleneck that reduced deliveries significantly. In addition, a pair of coal mines had extended outages. The price of low-sulfur coal trading in the Midwest peaked in December 2005 at a level triple the price a year earlier. The shortage in low-sulfur coal forced 11 power companies to shift to higher-sulfur coal with attendant higher SO_2 emissions.

The result, although not surprising, as the regulator only has one instrument (i.e., a tax or an emissions cap), emphasizes that price- and quantity-based regulation will have different effects on the product market. Regarding the second-order moments, we found that either regulatory regime may induce the larger variance in optimal production and optimal abatement levels. This is true because the regimes induce different economic environments with regard to risk. In short, both uncertainty regarding the price for the good produced (production of which causes emissions as a byproduct) and uncertainty about the abatement costs affect the optimal levels of production and abatement under tradable emissions permits. In contrast, optimal production and abatement under an emissions tax are only affected by one shock, i.e., product price uncertainty and abatement cost uncertainty, respectively. On the other hand, the equilibrium permit price tends to reduce the effect of abatement cost uncertainty on abatement, and of product price uncertainty on production. Whether the variances are larger under price- or quantity-based regulation depends on the relative strengths of these mechanisms.

We then showed that firms accommodate the different risk environments by implementing different types of technology. The intuition behind our result on technology choice is straightforward. First, both regulatory regimes may cause the highest variance in abatement. Second, the firms' valuation of a flexible technology increases if the variance in optimal abatement is inflated. Therefore, the firms may choose the most flexible abatement technology under either regulatory regime, depending on the characteristics of the stochastic elements. Finally, we showed that tradable emissions permits induce heterogeneous technology investments if we allow the risk environment to differ across firms. This result stems from the attendant dissimilar variances in the firms' abatement levels. The firms always implement the same technology under an emissions tax, given the assumptions of this paper.

It may be tempting to argue that, because flexibility comes at the cost of static efficiency, one type of regulation is better than the other. There are, however, at least two reasons for not doing this. Firstly, we found that an emissions tax may move the risk caused by product price uncertainty from the firms to the regulator.[26] That is, a less risky environment for the firms does not necessarily imply less overall risk in a welfare analysis. Secondly, a flexible technology is very likely to reduce the costs of altered policy targets (e.g., because of new information on damages from greenhouse gas emissions). This is

[26] Given that the regulator cares about the emissions level and not the firms' cost of abatement (or tax revenue). See, e.g., Weitzman (1974) for a discussion of the short-run properties of price- and quantity-based regulation under uncertainty.

relevant, as we have examined the long-run cost functions of the firms (allowing for technology investments).

The analysis features some assumptions that should be commented on. First, we have examined the case where the regulator faces a given target for aggregate emissions. This could, for example, reflect a country that must fulfill its part of some international climate change treaty. Alternatively, it could depict a case with insufficient knowledge on environmental costs or industry benefits of emissions, rendering classical optimal policy such as a Pigovian tax infeasible. Note that optimal policy (that equalizes marginal expected environmental damage and marginal expected abatement costs) would typically involve different expected aggregate emissions levels under tradable emissions permits and a tax, given that the regimes in general induce different technologies. Second, our representation of technology is very stylized and adopted to get tractable analytical results. However, as our analysis indicates ambiguity in the case with quadratic cost functions, this obviously implies that there is ambiguity in the general case too. Regarding our assumption of one probability distribution for η_i, equal for all γs, we note that a primary motivation for technology investment could be to reduce uncertainty related to future costs. To alleviate this we would have to let σ_η^2 be a function of γ, which would complicate the analysis. Furthermore, we assumed divisibility between abatement costs and other production costs. Without this assumption, we would have additional spillover effects under both regulatory approaches (featuring cross derivatives between the elements a and q in the cost function). Third, we have assumed an exogenous number of firms, but the exit and entry of firms are known to influence the ranking of regulatory instruments (see Spulber (1985)). Moreover, Mills (1984) shows that competitive equilibrium with free entry and exit may sustain a higher number of firms if demand fluctuates than if demand is stationary at its expected value. Although the analysis of Mills (1984) does not feature regulation, similar mechanisms may have emerged if we relaxed the assumption of a given number of firms. This would affect the conditions on the stochastic elements in our results.

Related to the previous literature, our results have much in common with Mills (1984), who shows that an unregulated competitive firm will invest more in a flexible production technology if demand uncertainty related to the good produced increases. Moreover, as our theoretic framework differs from that of Krysiak (2008), our results corroborate Krysiak's result that regulation has a technology choice effect in addition to the well-known effects on cost efficiency and investment levels. However, our findings indicate that this effect is not as clear-cut as stated by Krysiak (2008). That is, both price- and quantity-based regulation may induce the most flexible technology, and the ranking depends on the nature of the uncertainty faced by the firms.

Appendix

Because there is no danger of misinterpretation we omit the regime specific subscripts "trad" and "tax" in this appendix (to simplify notation).

The expected minimum average abatement cost of (1) increases in γ: The expected marginal cost is given by $\gamma_i + a\gamma^{-1}$, while average cost is $F(\gamma)/a + \gamma_i + a/2\gamma$. Hence, minimum expected average cost is given by $\gamma + a\gamma^{-1} = F(\gamma)/a + \gamma + a/2\gamma \Leftrightarrow a = \sqrt{2\gamma F(\gamma)}$. Inserting in equation (1) we get $c(a = \sqrt{2\gamma F(\gamma)}, \gamma) = 2F(\gamma) + \gamma\sqrt{2\gamma F(\gamma)}$, which increases in γ.

Proof that a valid covariance matrix is achieved if and only if $\rho \in [-1/(n-1), 1]$: A matrix is a valid covariance matrix if and only if it is positive semi-definite. With m identical firms the covariance matrix takes the form of the following $m \times m$ matrix:

$$\sigma_\eta^2 \begin{pmatrix} 1 & \rho & \dots & \rho \\ \rho & 1 & \dots & \rho \\ \vdots & \vdots & \ddots & \vdots \\ \rho & \rho & \dots & 1 \end{pmatrix}.$$

The determinant of this matrix is given by $(1-\rho)^{m-1}(1+\rho(m-1))$. It can be shown that the principal minors of our $n \times n$ covariance matrix satisfy the criteria necessary for positive semi-definiteness if and only if $\rho \in [-1/(n-1), 1]$ (use the determinant criteria for positive semi-definiteness with the given formula for $m = 1, m = 2, ..., m = n$).

Derivation of equation (11): Equation (7) yields:

$$
\begin{aligned}
Var(q_{trad}) &= \left(\frac{\gamma}{1+\gamma}\right)^2 Var\left(\varepsilon - \frac{1}{n}\sum_{j\in N}\eta_j\right),\\
&= \left(\frac{\gamma}{1+\gamma}\right)^2 \left(\sigma_\varepsilon^2 + E\left(\frac{1}{n}\sum_{j\in N}\eta_j\right)^2 - \left(E\left(\frac{1}{n}\sum_{j\in N}\eta_j\right)\right)^2\right),\\
&= \left(\frac{\gamma}{1+\gamma}\right)^2 \left(\sigma_\varepsilon^2 + E\left(\frac{1}{n}\sum_{j\in N}\eta_j\right)^2 - 0\right),\\
&= \left(\frac{\gamma}{1+\gamma}\right)^2 \left(\sigma_\varepsilon^2 + \frac{\sigma_\eta^2}{n}(1+(n-1)\rho)\right),
\end{aligned}
$$

which is equation (11). We use $E(\varepsilon\eta_i)=0$ and $\rho\sigma_\eta^2 \equiv E(\eta_i\eta_j)$.

Derivation of equation (12**):** Equation (8) yields:

$$
Var(a_{trad}) = \left(\frac{\gamma}{1+\gamma}\right)^2 Var\left(\frac{\gamma}{n}\sum_{j\in N}\eta_j - \eta_i(1+\gamma)\right) + \left(\frac{\gamma}{1+\gamma}\right)^2 Var(\varepsilon), \tag{24}
$$

where we use $E(\varepsilon\eta_i)=0$. We have:

$$
\begin{aligned}
&Var\left(\frac{\gamma}{n}\sum_{j\in N}\eta_j - \eta_i(1+\gamma)\right),\\
&= E\left(\frac{\gamma}{n}\sum_{j\in N}\eta_j - \eta_i(1+\gamma)\right)^2 - \left(E\left(\frac{\gamma}{n}\sum_{j\in N}\eta_j - \eta_i(1+\gamma)\right)\right)^2,\\
&= E\left(\frac{\gamma}{n}\sum_{j\in N}\eta_j - \eta_i(1+\gamma)\right)^2 - 0,\\
&= E\left(\left(\frac{\gamma}{n}\right)^2\left(\sum_{j\in N}\eta_j\right)^2 - \frac{2\gamma(1+\gamma)}{n}\left(\eta_i\sum_{j\in N}\eta_j\right) + (\eta_i(1+\gamma))^2\right).
\end{aligned}
$$

Note that $E\left(\sum_{j\in N}\eta_j\right)^2 = n(1+(n-1)\rho)\sigma_\eta^2 = nE\left(\eta_i\sum_{j\in N}\eta_j\right)$, with $\rho\sigma_\eta^2 \equiv E(\eta_i\eta_j)$. Therefore, we have:

$$
Var\left(\frac{\gamma}{n}\sum_{j\in N}\eta_j - \eta_i(1+\gamma)\right) = \left((1+\gamma)^2 - \frac{\gamma}{n}(2+\gamma)(1+(n-1)\rho)\right)\sigma_\eta^2 .
$$

Inserting into equation (24) yields equation (12).

Derivation of equation (21**) and proof of Proposition 2:** The maximization problem (20) is given by:

$$\max_{\gamma\in[\Gamma_L,\Gamma_H]} E\left[\max_{q_i\geq 0, a_i\in[o,q]}\left[(D+\varepsilon)q_i-\frac{1}{2}q_i^2-(q_i-a_i)w-F(\gamma)-(\gamma+\eta)a_i-\frac{1}{2\gamma}a_i^2\right]\right],$$

where the solution to the inner problem is given by equations (7) and (8) under tradable emissions permits, and (14) and (15) under an emissions tax. We henceforth denote the optimal levels of production and abatement q^* and a_i^* ($\forall i\in N$) under both regulatory regimes. Inserting, we get:

$$\max_{\gamma\in[\Gamma_L,\Gamma_H]} E\left[(D+\varepsilon)q^*-\frac{1}{2}(q^*)^2-(q^*-a_i^*)w-F(\gamma)-(\gamma+\eta)a_i^*-\frac{1}{2\gamma}(a_i^*)^2\right],$$

with the following $i=1,2,...n$ first-order conditions:

$$E\left[(D+\varepsilon-w-q^*)\frac{dq^*}{d\gamma}+\left(w-\gamma-\eta_i-\tfrac{a_i^*}{\gamma}\right)\frac{da_i^*}{d\gamma}-F_\gamma-a_i^*+\frac{1}{2\gamma}(a_i^*)^2\right]=0,$$

$$E\left[-F_\gamma-a_i^*+\frac{1}{2\gamma^2}(a_i^*)^2\right]=0,$$

$$-F_\gamma-E(a^*)+\frac{\mathrm{var}(a^*)+(E(a^*))^2}{2\gamma^2}=0,$$

which is equivalent to equation (21). We use the envelope theorem to derive the second equality (i.e., the two sets of inner parentheses on the left are equal to zero by the first-order conditions 3 and 4). Furthermore, we utilize that $E(\frac{1}{2\gamma^2}(a^*)^2)=\frac{1}{2\gamma^2}\mathrm{var}(a^*)+\frac{1}{2\gamma^2}(E(a^*))^2$ in the derivation of the third equality.

The second-order condition is given by:

$$\frac{d}{d\gamma}\left(-F_\gamma-E(a^*)+\frac{\mathrm{var}(a^*)+(E(a^*))^2}{2\gamma^2}\right)<0.$$

Note that this implies $\frac{d}{d\gamma}\left(F_\gamma+E(a^*)-\frac{1}{2\gamma^2}(E(a^*))^2\right)>\frac{d}{d\gamma}\left(\frac{1}{2\gamma^2}\mathrm{var}(a^*)\right)$, which establishes that γ increases in var(a). Proposition 2 follows directly.

Proof of Proposition 3: The first-order conditions (3) and (4) remain valid, while the emissions trading market equilibrium condition (5) is replaced with:

$$S = \alpha(q_i - a_i) + (n-\alpha)(q_j - a_j)$$
$$\Leftrightarrow \frac{S}{n} = q_j - a_j\,,$$

where we used $\alpha / n \approx 0$. Inserting for *a* and *q* from equations (3) and (4) with $\varepsilon = 0$ we get:

$$\frac{S}{n} = D - p - \left(p - \gamma_j - \eta_j\right)\gamma_j$$
$$\Leftrightarrow p = \frac{1}{1+\gamma_j}\left(D - \frac{S}{n} + \gamma_j\left(\eta_j + \gamma_j\right)\right).$$

Therefore, the *j*-firms' actions under tradable quantities are identical to the previous analysis, setting $\rho = 1$ and $\sigma_\varepsilon^2 = 0$. Concerning the *i*-firms, we have:

$$a_i = \frac{\gamma_i}{1+\gamma_j}\left(D - \frac{S}{n} - \gamma_i + \gamma_j^2 - \gamma_i\gamma_j + \gamma_j\eta_j\right) - \gamma_i\eta_i\,.$$

Therefore, we have:

$$\mathrm{var}(a_i) = \left(\frac{\gamma_i}{1+\gamma_j}\right)^2 \mathrm{var}\left(\gamma_j\eta_j - \eta_i\left(1+\gamma_j\right)\right),$$
$$= \left(\frac{\gamma_i}{1+\gamma_j}\right)^2 \mathrm{var}\left(\gamma_j^2\,\mathrm{var}\left(\eta_j\right) + \left(1+\gamma_j\right)^2\mathrm{var}\left(\eta_i\right) - 2\gamma_j\left(1+\gamma_j\right)\mathrm{cov}\left(\eta_i.\eta_j\right)\right),$$
$$= \left(\frac{\gamma_i}{1+\gamma_j}\right)^2 \left(\gamma_j^2 + \left(1+\gamma_j\right)^2 - 2\gamma_j\left(1+\gamma_j\right)\rho\right)\sigma_\eta^2\,,$$
$$= \left(\gamma_i^2 - \frac{\gamma_j^2\gamma_i}{\left(1+\gamma_j\right)^2}\left(2\left(\gamma_j+1\right)\rho - \gamma_j\right)\right)\sigma_\eta^2\,.$$

Comparison with equation (19) yields that:

$$\mathrm{var}(a_i) \geq (\leq)\,\mathrm{var}(a_{tax}) \Leftrightarrow \rho \leq (\geq)\frac{1}{2}\frac{\left(\gamma_j^2 + 2\gamma_j + 1\right)\left(\gamma_i^2 - \gamma_{tax}^2\right) + \gamma_i\gamma_j^3}{\gamma_i\gamma_j^2\left(1+\gamma_j\right)}.$$

The proposition then follows from equation (21) and the second-order condition to the maximization problem (20).

Figures and tables

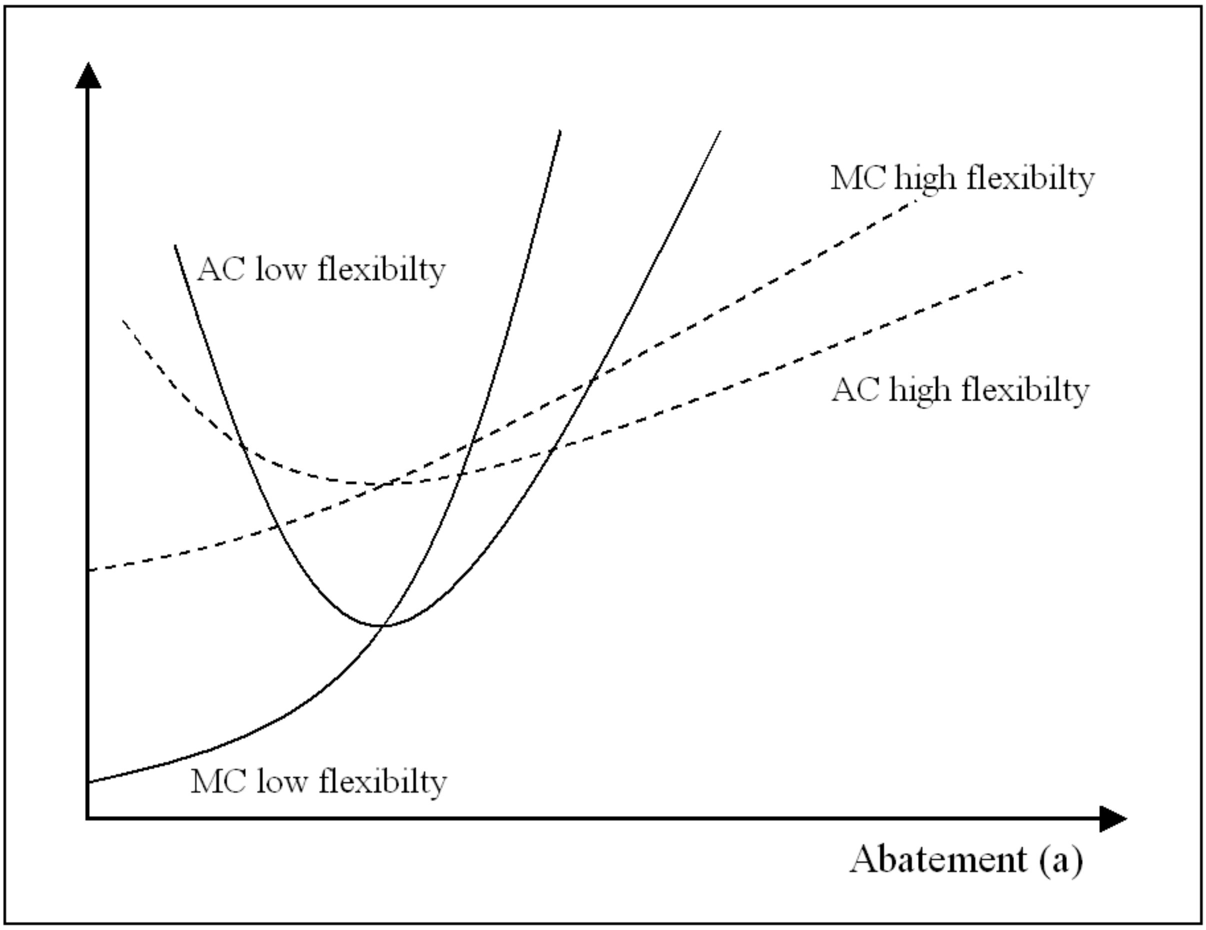

Figure 1. Minimum average cost and the slope of the marginal abatement cost function vary inversely with flexibility (AC and MC denote average cost and marginal cost, respectively). Note that the assumption in the present analysis of quadratic abatement costs yields linear MC curves.

	q_{tax}	a_{tax}	q_{trad}	a_{trad}
ε	++	0	+	+
η	0	--	-	-

Table 1. Effects of stochastic variables on optimal production and abatement (two signs denote a stronger effect than one sign).

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