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Halvor Briseid Storrøsten

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Abstract

Authorities often lack information for efficient regulation of the commons. This paper derives a criterion comparing prices versus tradable quantities in terms of expected welfare, given uncertainty, optimal policy and endogenous cost structure. I show that one cannot determine which regulatory instrument that induces the highest expected welfare based on the relative curvatures of the cost and benefit functions alone. Furthermore, optimal policy involves different production (or price) targets across the regulatory instruments, and does not equalize marginal costs and expected marginal benefits under prices. The reason is that firms choose a cost structure which induces exaggerate fluctuations in consumption of the public good under prices, and the regulator has to compensate for this when determining optimal policy. Because no such negative externality arises under quantities, the relative performance of prices is deteriorated. A numerical illustration suggests significant impact. Finally, either regulatory instrument may induce the highest technology investment levels.

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Halvor Briseid Storrøsten
Statistics Norway
Research Department
Oslo / Norway
hbs@ssb.no

1 Introduction

Authorities often lack the information they need for efficient regulation of the commons. Protection or regulation of access to public goods like clean air, water, biodiversity, fisheries and recreational areas are all important examples.

In his seminal paper on price- versus quantity-based regulatory instruments, Weitzman (1974) addressed the question about how to regulate public goods under uncertainty. Price-based regulatory instruments fix the price of licenses, but leave the issued quantity uncertain. In contrast, quantity-based instruments fix the quantity of licenses issued, but leave the price uncertain. This trade-off raises an essential question for policy design: which type of regulation best help mitigate the cost of uncertainty so as to maximize social benefits of the public good? Weitzman (1974) found that price-based instruments are advantageous when the marginal benefit schedule is relatively flat as compared to the marginal cost schedule, and vice versa. This has since been the consensus among most economists (e.g., Kolstad, 2000; Hoel and Karp, 2001; Pizer, 2002; Nordhaus, 2007).

It is also widely recognized that firms' cost structures are endogenous in the longer run, and that regulatory instruments have the ability to induce investment and technological progress. Indeed, a large body of literature argues that long run effects on R&D and firms' implementation of technology may be at least as important as short-run cost effects for evaluating public policy.[1] Particularly relevant for the present paper, this literature finds that different policy instruments tend to induce disparate investment levels (e.g., Montero, 2002; Requate and Unold, 2003; Zhao, 2003) and technology choices (Krysiak, 2008; Storrøsten, 2013).[2]

[1]See Kneese and Schultze (1975) and Orr (1976) for early presentations of this view. Jaffe and Stavins (1995) offer an empirical approach. See Jaffe et al. (2002), Löschel (2002) and Requate (2005) for surveys of the literature.

[2]So far, there has been little empirical analysis on the effects of different policy instruments on environmental R&D, mainly because of little available data (Jaffe et al.,

There are several reasons why firms may invest in new equipment; e.g., equipment breakdown or poor performance, R&D and new available technologies, and new information on market conditions or the de facto strictness of regulation. Of course, such factors may induce investment also after regulation is introduced. Furthermore, it is often the case that the equipment necessary to produce some public good is not installed (or even developed) before the public policy is announced. A good example is pollution abatement equipment, which tends to be installed after regulation has been announced.[3]

Firms that invest in production equipment usually face a menu of possible technologies. For example, emissions of greenhouse gases may be reduced by, e.g., a switch from coal to gas, renewable energy, or carbon capture and storage. It is reasonable to expect the choice of technology to affect the firm's cost structure. But if so, the slope of the marginal production cost schedule, which is a central exogenous parameter in Weitzman (1974), is endogenous and may depend on the regulatory instrument.[4] This is relevant even in the short run if the firms' investment decisions take place after regulation is announced.

The central question addressed by this paper: what is the best regulatory instrument under uncertainty when the firms' cost structures are endogenous? I derive an analytical criterion for ex-ante evaluation of the relative performances of prices versus tradable quantities under optimal policy with endogenous technology choice. Following Weitzman (1974), the comparative results are based on expected welfare across the two regulatory instruments,

2002). Still, there are some empirics on the effects of alternative policy instruments on the innovation of energy-efficiency technologies. These studies generally suggest that there is a significant relationship between environmental regulation and R&D, see, e.g., Lanjouw and Mody (1996), Newel et al. (1999), and Popp (2002).

[3]See Fowlie (2010) for an empirical analysis of technology implementation induced by the US NO_x Budget Program.

[4]How the choice of technology is affected by the regulatory instrument is arguably an important consideration in evaluation of public policy in itself (Krysiak, 2008). Furthermore, firms' technology choice will affect the demand for technology and, thereby, the direction of R&D effort (Griliches, 1957; Ruttan, 2001).

and derived under the assumptions of quadratic cost and benefit functions. I assume reciprocal technology investment costs. The (non-comparative) results about social optimal policy under the two instruments are also first derived under these assumptions, but later generalized to less restrictive functional forms.[5]

I show that one cannot determine which regulatory instrument that induces the highest expected welfare based on the relative curvatures of the cost and benefit functions alone; i.e. the well-known criterion derived in Weitzman (1974) does not apply when the firms cost structures are endogenous. For example, the relative performance of tradable quantities decreases in the cost of investment and increases in the intercept parameter of the marginal benefit function. Furthermore, optimal policy involves different production (or price) targets across the regulatory instruments, and does not equalize marginal costs and expected marginal benefits under prices. The reason is that firms choose a cost structure which induces exaggerate fluctuations in consumption of the public good under prices, and the regulator has to compensate for this when determining optimal policy. A numerical illustration, calibrated for the European Union Emissions Trading Scheme, suggests that the impact of the negative externality induced by endogenous technology choice under prices significantly favors quantity-based regulation. Finally, I derive an analytical condition that evaluates whether price- or quantity-based regulation induces the most capital intensive technology, with associated higher firm investment levels. Because of the different analytical framework employed in the present paper, in particular the modelling of technology choice and uncertainty, this criterion differs substantially from the results in the literature on regulation and induced investment referred above. For example, tradable quantities induce more technology investment than prices if the cost of investment is sufficiently low.

Stigler (1939) and Marschak and Nelson (1962) early examined firms'

[5] The generalization is done in Subsection 2.5.

choice of cost structure, and referred to the firms' ability to change production levels in response to new information as their "flexibility". This terminology is carried on by Mills (1984), who shows that an unregulated competitive firm will invest more in production flexibility if demand uncertainty increases. Mendelsohn (1984) examines investment under price- and quantity-based regulation. He finds that quantity-based instruments have an advantage, because price-based regulation induces excessive variation in output. Krysiak (2008) shows that price-based regulation induces a more flexible technology than tradable quantities, and that technology choice is socially suboptimal under prices.[6]

In the next section, I set up the analytical model and derive and discuss theoretical results. Section 3 presents simple numerical illustrations. Section 4 concludes.

2 Theoretical analysis

The model is organized in three periods. In period 1, the regulator sets the socially optimal fixed price or total quantity of the public good to produce. Then, the firms invest in production technology in period 2. Last, the firms choose their production levels in period 3.

Consider the regulation problem where any firm $i \in N = \{1, 2, ..., n\}$ can choose the technology parameter $\beta_i > 0$ in the following cost function:

$$C_i(q_i, \beta_i) = (\alpha + \theta_i)\, q_i + \frac{\beta_i}{2} q_i^2 + \frac{k}{2\beta_i}. \tag{1}$$

Here q_i is firm i's production of the public good, $\alpha \geq 0$ and $k > 0$ are constants, and $\theta_i \sim (0, \sigma^2)$ is a firm-specific random variable with expected value 0 and variance σ^2.[7] Production costs are convex in q_i, and the chosen

[6] See also Morton and Schwartz (1968), Magat (1978), Kon (1983), Lund (1994) Kaboski (2005) and Storrøsten (2013).

[7] In the case of pollution abatement, q_i may be interpreted as the difference between

technology parameter incurs investment costs $k/(2\beta_i)$. The latter implies that reducing operating costs always increases capital costs, and that the marginal costs of reducing β_i increases for lower values of the technology parameter (i.e., more advanced technology). This is in accordance with the standard assumption of decreasing marginal productivity of capital. The cost function (1) is similar to Weitzman (1974), except for the endogeneity of β_i and the associated investment cost.[8]

I add $\theta_i \sim (0, \sigma^2)$ to firm i's production costs. For example, this reflects fluctuations in factor prices or factor productivity, or a breakdown of production equipment. As argued by Weitzman (1974), the determination of θ_i could involve elements of genuine randomness, but might as well stem from lack of information. The cost shock θ_i enters the functional form (1) linearly, which is similar to, e.g., Weitzman (1974), Hoel and Karp (2002), and Krysiak (2008). I assume that the outcomes of the stochastic variables are determined between periods 2 and 3. That is, regulation and investment decisions in periods 1 and 2 are made under uncertainty, whereas firms have full information when they chose production in period 3. Note that all firms share the same uncertainty and menu of possible production cost structures. Therefore, they choose equal production technologies (because they are identical when they invest in technology in period 2). I henceforth suppress the firm-specific subscript i except where necessary (i.e., on variables that differ across firms) to streamline notation.[9] I assume that the θ's are symmetrically correlated across firms; i.e. that $\rho = E(\theta_i \theta_j) / \sigma^2$ $(\forall i \neq j)$. We must then have $\rho \in [-1/(n-1), 1]$ in order to obtain a valid covariance matrix

exogenous business as usual emissions and actual emissions (after abatement).

[8]Weitzman (1974) approximates cost with $f(\theta) + (\alpha + f(\theta))(q - \widehat{q}) + \beta (q - \widehat{q})^2 / 2$, where q varies around the constant $\widehat{q}$ and $f(\theta)$ is a stochastic function. Equation (1) simplifies by omitting the random lump sum cost term, setting the constant $\widehat{q} = 0$, and using the stochastic variable θ directly.

[9]As a notational convention, "x" may refer to variable/parameter x under either regulatory regime. If confusion is possible, I use "x_Q" and "x_P" to refer to x under tradable quantitites and prices, respectively.

(Storrøsten, 2013).

The endogenous cost parameter β reflects the scale of production the firm has adapted to, and lower values on β reduces the operating costs. We observe that the model setup relates to the literature on regulatory induced investment referred in the introduction in the sense that a lower value on β may be interpreted as a higher technology investment level. Further, a lower β may also be interpreted as indicating a more flexible technology, because a lower value on β reduces the slope of the marginal abatement cost function and increases the firms' ability to respond to new information (see, e.g., Krysiak, 2008).

For example, abatement of NO_x from electricity production is possible through, e.g., installation of Selective Catalytic Reduction (SCR), which incur high capital costs and can reduce emissions by up to 90 percent, or Selective Non-Catalytic reduction (SNCR), which have lower investment costs but only reduces emissions rates with up to 35 percent. In terms of our stylized functional form (1), SCR technology will be characterized by a lower value on β than that of the SNCR technology. Similarly, emissions reduction of CO_2 is possible by use of, e.g., CCS or by fuel substitution. While CCS is capital intensive and allows for large emissions reductions with relatively small increases in marginal abatement costs (low β), fuel substitution is less capital intensive but cannot achieve high emissions reductions without increasing marginal costs substantially (high β).

Utility from consumption of the public good is approximated by $a\sum_{i\in N} q_i - b\left(\sum_{i\in N} q_i\right)^2/2$, where the constants satisfy $a, b > 0$. Welfare can then be expressed as:

$$W = a\sum_{i\in N} q_i - \frac{b}{2}\left(\sum_{i\in N} q_i\right)^2 - \sum_{i\in N}\left(\left(\alpha+\theta_i\right)q_i + \frac{\beta}{2}q_i^2 + \frac{k}{2\beta}\right). \tag{2}$$

Because firms' choice of cost structures differ across the regulatory instruments (this is shown formally below) we have $\beta \in \{\beta_Q, \beta_P\}$, and the welfare function (2) is not equal under prices and tradable quantities. Therefore, optimal policy prescribes different aggregate production targets (or expected marginal costs) across the instruments. In this paper I consider optimal policy; i.e., I assume that the regulator maximizes the expected value of equation (2), subject to the regulatory instrument and the associated firm behavior.

The model is solved by backwards induction and the equilibrium concept is that of a subgame perfect Nash equilibrium.[10]

2.1 The firms' production of the public good

Let p_Q and p_P refer to the market clearing price and the fixed price on the public good, respectively. The profit function in period 3 of any firm $i \in N$ is given by:

$$\pi_i(q_i; \beta_i) = \max_{q_i} \left(pq_i - (\alpha + \theta_i)\, q_i - \frac{\beta}{2} q_i^2 \right), \tag{3}$$

where $p \in \{p_Q, p_P\}$ remains to be determined. Assuming an interior solution, we have the following first-order conditions for any firm $i \in N$:

$$q_i = \frac{1}{\beta} \left(p - \alpha - \theta_i \right). \tag{4}$$

Note that each firm's production level is a random variable before the outcomes of the stochastic events are known (i.e., in periods 1 and 2).

Under quantity-based regulation, the firms supply a fixed aggregate amount $\overline{Q}_Q$ of the public good, with $\overline{Q}_Q$ previously determined by the regulator in period 1. The market clearing condition is:

$$\overline{Q}_Q = \sum_{i \in N} q_i = \frac{1}{\beta_Q} \sum_{i \in N} \left(p_Q - \alpha - \theta_i \right), \tag{5}$$

[10] The derived subgame perfect Nash equilibrium is in Markov strategies. It is therefore also a Markov perfect equilibrium.

where I used the first order condition (4). The market clearing price that solves equation (5) is:

$$p_Q = \alpha + \frac{1}{n}\left(\beta_Q \overline{Q}_Q + \sum_{i \in N} \theta_i\right), \tag{6}$$

with expectation $E(p_Q) = \alpha + \overline{Q}_Q \beta_Q / n$. Inserting the equilibrium price (6) in the first order condition (4), we get the production of firm $i \in N$ under tradable quantities:

$$q_{iQ} = \frac{\overline{Q}_Q}{n} + \frac{1}{\beta_Q}\left(\frac{1}{n}\sum_{j \in N} \theta_j - \theta_i\right). \tag{7}$$

We observe that firm i's production increases in the stochastic shocks to the cost functions of the $j \in N \backslash \{i\}$ other firms. The reason is simply that the equilibrium price of the public good (6) increases in production costs.

In order to simplify comparison of the regulatory instruments, I let the fixed price under price-based regulation p_P be determined implicitly as the price that realizes the expected production level $\overline{Q}_P$ (which may of course differ from $\overline{Q}_Q$ under optimal policy). That is, p_P solves:

$$\overline{Q}_P = E\left[\frac{1}{\beta_P}\sum_{i \in N}(p_P - \alpha - \theta_i)\right], \tag{8}$$

where $E[\cdot]$ is the expectations operator.[11] Because the expectations operator is present in equation (8), but not in equation (5), the two regulatory instruments differ with respect to the risk imposed upon the regulated firms. It follows from equation (8) that the fixed price is $p_P = \alpha + \beta_P \overline{Q}_P / n$ and,

[11] It does not affect our results whether the regulator chooses p_P directly or via (8), because the regulator correctly foresee the firm's actions (contingent on θ_i). The explicit reduced form solution for p_P is given in the text in Subsection 2.2.

using equation (4), that the production of firm $i \in N$ under prices is:

$$q_{iP} = \frac{\overline{Q}_P}{n} - \frac{\theta_i}{\beta_P}. \tag{9}$$

Comparison of equations (7) and (9) shows that the variance in production is larger under price-based regulation than under tradable quantities if $\beta_Q = \beta_P$.[12] The reason is that the covariance between the equilibrium product price p_Q and production cost shocks θ_i is non-negative. That is, a high (low) price tends to occur together with high (low) realized production costs. This reduces the firms' responses to the cost shocks. Of course, this mechanism is absent under price-based regulation where the price is fixed.

2.2 The firms' investment decisions

In period 2, any firm $i \in N$ maximizes expected profits with respect to cost structure as determined by the technology parameter β:

$$\max_{\beta} \left(E\left[\pi_i\left(\cdot\right)\right] - \frac{k}{2\beta} \right),$$

where $\pi_i\left(\cdot\right)$ is given by equation (3). Using the envelope theorem, the firms' first order condition yields:

$$\frac{k}{\beta^2} = Var\left[q\right] + \left(E\left[q\right]\right)^2, \tag{10}$$

where $Var\left[\cdot\right]$ is the variance operator. This first order condition implies that a higher expected production level increases the firms' investments in capital (decreases the optimal β). Moreover, for a given expected production level, it can be shown that the firms choose a higher capital intensity (low β) if the variance in the production level is large. This is consistent with

[12] We have $var\left[q_Q\right] = \left(1-\rho\right)\left(n-1\right)\sigma^2/n\beta_Q^2$, $var\left[q_P\right] = \sigma^2/\beta_P^2$, and $cov(p_Q, \theta_i) = \left(1+\left(n-1\right)\rho\right)\sigma^2/n \geq 0$.

interpreting a lower β as indicating a more flexible production technology. In the particular case with equal production targets $\overline{Q}_Q = \overline{Q}_P$ and technology $\beta_Q = \beta_P$, we have $E[q_Q] = E[q_P]$ and $Var[q_Q] < Var[q_P]$ (cf. equations 7 and 9). Together with equation (10) and the firms' second order conditions, this imply that firms will choose a more capital intensive technology (lower β) under price-based regulation if $\overline{Q}_Q = \overline{Q}_P$.

I now compare the firms' technology choice in equation (10) with the technology that is socially optimal, conditional on the firms' actions under the two regulatory instruments. Maximization of expected social welfare (2) with respect to the technology parameter β, subject to equation (7) under tradable quantities and (9) under prices, yields the following first order conditions (see Appendix A):

$$\frac{k}{\beta^2} = Var[q] + (E[q])^2 + X, \tag{11}$$

with $X = 0$ under tradable quantities and $X = -2b(1 + (n-1)\rho)\sigma^2/\beta_P^3 \leq 0$ under prices. Comparison with equation (10) yields the following result:

Lemma 1 *Assume competitive firms and welfare as given by equation (2). Then, the firms implement the socially optimal technology under tradable quantities. The firms choose a technology that is more capital intensive (lower β) than socially optimal under prices, given $\sigma^2 > 0$ and $\rho > -1/(1-n)$.*

Proof. The lemma follows from equations (10) and (11), and the firms' second order condition under prices. ■

Intuitively, the firms cannot adjust aggregate production after the shocks to production costs have been realized under tradable quantities. Therefore, utility of consumption is constant and maximization of welfare in periods 2 and 3 reduces to minimizing the expected cost of producing $\overline{Q}_Q$, cf. equation (2). This cost-minimization problem is internalized by the firms. Thus, the profit maximization problem of the firms coincides with maximization of expected welfare, and their technology choice is socially optimal.

Under prices, aggregate production fluctuates while marginal production costs remain constant and equal to the fixed price.[13] This reduces welfare from consumption of the public good by concavity of utility and Jensen's inequality. The associated loss of expected welfare is not internalized by the firms, which face a given price per unit of production under price-based regulation and have no incentive to internalize the concavity of utility in their technology investment decisions. Therefore, the profit maximization problem of the firms do not coincide with maximization of expected welfare, and the firms' technology choice is socially suboptimal.

Finally, the firms' technology choice under the two regulatory schemes are (cf. equations 7, 9 and 10):

$$\beta_Q = \frac{\sqrt{n\left(kn - \sigma^2\left(1-\rho\right)\left(n-1\right)\right)}}{\overline{Q}_Q} \equiv \frac{\gamma_Q}{\overline{Q}_Q}, \tag{12}$$

$$\beta_P = \frac{n\sqrt{k-\sigma^2}}{\overline{Q}_P} \equiv \frac{\gamma_P}{\overline{Q}_P}. \tag{13}$$

Note that $\gamma_Q \geq \gamma_P$, with strict inequality unless $\sigma^2 = 0$ or $\rho = -1/(n-1)$.

2.3 The social planner's optimal policy

In this section I examine the social planner's optimal policy ($\overline{Q}_Q$ and $\overline{Q}_P$), given the choice of regulatory instrument and the firms' associated behavior. In period 1, the social planner maximizes expected welfare as given by equation (2):

[13] The covariance between the marginal utility of consumption of the public good and aggregate production under prices is $cov\left[a - b\sum_{i\in N} q_i, \sum_{i\in N} q_i\right] = -nb\left(\rho\left(1-n\right)+1\right)\sigma^2/\beta_P^2 \leq 0$.

$$\max_{\overline{Q}} E[W],$$

subject to equations (7) and (12) under quantity-based regulation, and (9) and (13) under price-based regulation. The first order conditions yield the following reduced form solutions for the socially optimal production targets under the two regulatory instruments (see Appendix A):

$$\overline{Q}_Q = \frac{1}{b}\left(a - \alpha - \frac{\gamma_Q}{n}\right), \tag{14}$$

$$\overline{Q}_P = \frac{1}{b}\frac{\gamma_P^2}{\gamma_Q^2}\left(a - \alpha - \frac{\gamma_P}{n}\right). \tag{15}$$

It can be shown that the reduced form solution for the fixed price under price-based regulation that induces expected aggregate production equal to $\overline{Q}_P$ is $p_P = \alpha + \sqrt{k - \sigma^2}$.[14]

Equations (14) and (15) imply that optimal policy involves different production targets under prices and tradable quantities, because the firms' implemented cost structures differ due disparate risk environments across the regulatory instruments. This entails that comparison of instruments under the assumption of equal aggregate quantity targets (or equal expected marginal production costs) is badly founded when the firms' cost structures are endogenous. For example, tradable quantities would have an unreasonable advantage if comparison is done given an aggregate production target that happens to be relatively close to $\overline{Q}_Q$ (and far away from $\overline{Q}_P$).

A well known result by Denicolo (1999) states that prices and tradable quantities are fully equivalent under optimal policy and ex-post regulation.

[14] The omission of the parameters a, b and ρ in p_P may appear puzzling. The explanation is that the cost of producing the public good under prices decreases in a, and increases in b and ρ, because of the endogenous cost structure (cf. equation 17). Therefore, for a given p_P, expected aggregate production increases in a and decreases in b and ρ. The simplest derivation for p_P is $p_P = \alpha + \beta_P \overline{Q}_P / n = \alpha + \sqrt{k - \sigma^2}$ (cf. equations 8 and 13).

Equations (14) and (15) demonstrates that this does result not generalize to the case with endogenous cost structure.[15] The explanation is that the firms' production technology and the associated optimal policy targets differ across the regulatory instruments.

We have the following result on the regulator's optimal choice of aggregate production targets:[16]

Proposition 1 *Assume competitive firms, welfare as given by equation (2), $\sigma^2 > 0$ and $\rho > -1/(1-n)$. We then have:*

(i) Optimal policy involves different production (or price) targets across the regulatory instruments.

(ii) Under tradable quantities, the regulator chooses $\overline{Q}_Q$ such that marginal utility from consumption of the public good equals expected marginal production costs of the public good.

(iii) Under price-based regulation, the regulator sets $\overline{Q}_P$ such that expected marginal utility from consumption of the public good is larger than marginal production costs.

Proof. Different production targets follows from equations (14) and (15). Under tradable quantities the expected equilibrium price is $E(p_Q) = \alpha + \gamma_Q/n$, and marginal utility from consumption is $a - b\overline{Q}_Q = \alpha + \gamma_Q/n$, cf. equations (2), (6), (12) and (14). Under prices, the fixed price is $E(p_Q) = \alpha + \gamma_P/n$, but expected marginal utility from consumption is $a - b\overline{Q}_P = a - \left(\gamma_P^2/\gamma_Q^2\right)\left(a - \alpha - \frac{\gamma_P}{n}\right)$, cf. equations (2), (8), (13) and (15). We have $a - \left(\gamma_P^2/\gamma_Q^2\right)\left(a - \alpha - \frac{\gamma_P}{n}\right) - (\alpha + \gamma_P/n) = \left(1 - \gamma_P^2/\gamma_Q^2\right)\left(n(a-\alpha) - \gamma_P\right)/n > 0$, cf. equations (12), (13) and (15). The proposition follows because the price equals marginal production costs under both regulatory schemes. ■

[15] The subgame perfect Nash equilibrium derived in the present paper is ex-post socially optimal in terms of expected values.

[16] Corollary 1 in Subsection 2.5 provides a generalization of Proposition 1 to less rigid functional forms.

The mechanism detected in Proposition 1 pulls in the direction of a more ambitious policy target under tradable quantities than under price-based regulation when cost structure is endogenous.[17]

Intuitively, the regulator knows that the firms implement the socially optimal technology under tradable quantities. Therefore, he may use his single instrument $\overline{Q}_Q$ to obtain equalization of marginal benefits and expected marginal costs. Under prices, however, the regulator also has to consider the negative externality caused by endogenously determined cost structure. That is, the regulator faces a trade-off between using his single instrument p_P (implicitly defined by $\overline{Q}_P$ in equation 15) to equalize marginal costs and expected marginal benefits on the one hand, and to correct for the negative externality from endogenous technology choice on the other. Because the firms invest in a too low β_P and $\partial\beta_P/\partial\overline{Q}_P < 0$, this trade-off induces lower expected aggregate production than otherwise optimal under prices. The wedge between marginal costs and benefits under prices is illustrated in Figures 2 and 3 (in Section 3 and Appendix B).

Equations (12) to (15) can be used to solve for the reduced form solutions for firms' technology choices under optimal policy:

$$\beta_Q = \frac{bn\gamma_Q}{n(a-\alpha)-\gamma_Q} \quad (16)$$

$$\beta_P = \frac{bn\gamma_Q^2}{n\gamma_P(a-\alpha)-\gamma_P^2} \quad (17)$$

Inserting equations (7), (9), and (14) to (17) into the welfare function (2), rearranging and taking expectations, we get the following reduced form

[17] It is possible, however, to construct examples with $\overline{Q}_P > \overline{Q}_Q$ (see Figure 3.a in Appendix B).

expressions for expected welfare under the two regulatory instruments:

$$E[W_Q] = \frac{1}{2bn^2}\left(n(a-\alpha)-\gamma_Q\right)^2 \tag{18}$$

$$E[W_P] = \frac{1}{2bn^2}\frac{\gamma_P^2}{\gamma_Q^2}\left(n(a-\alpha)-\gamma_P\right)^2 \tag{19}$$

Remember that we have $\gamma_Q = \gamma_P$ without uncertainty ($\sigma^2 = 0$), or of the correlation coefficient approaches its lower bound ($\rho = -1/(n-1)$), so that expected welfare is then equal across the regulatory schemes.

2.4 Comparison of the regulatory instruments

I posed the following main research question in the introduction: what is the best choice between prices and tradable quantities under uncertainty when the firms' cost structures are endogenous? Comparing equations (18) and (19), we get the following criterion for evaluating the regulatory instruments' relative performances in terms of expected values (see Appendix A):[18]

$$E[W_Q] \geq (\leq) E[W_P] \Leftrightarrow \left(\gamma_Q - \gamma_P\right)(a-\alpha) - (1+(n-1)\rho)\sigma^2 \geq (\leq) 0. \tag{20}$$

We then have the following result:

Proposition 2 *Assume optimal policy, (positive) welfare given by equation (2), competitive firms, $\rho > -1/(n-1)$ and $\sigma^2 > 0$. Then we have:*

(i) The relative performance of tradable quantities decreases in investment costs (k) and the intercept parameter of the marginal production cost

[18] We may have $W_Q < W_P$ ex-post even tough $E[W_Q - W_P] \geq 0$, and vice versa (the same caveat applies to Weitzman, 1974). However, if we assume that the model features period 1 and 2 as before, but let period 3 be divided into a sequence of T subperiods $[3.t]_{t=1}^{t=T}$, we have $\text{plim}_{T\to\infty}(W_{QT} - W_{PT}) = E[W_Q - W_P]$ by the law of large numbers.

function (α), whereas it increases in the intercept parameter of the marginal utility function (a).

(ii) The effects of increased uncertainty (σ^2) and correlation (ρ) are ambiguous.

(iii) The curvature on the utility function (b) does not affect the relative performances of the regulatory instruments.

Proof. Use equation (20) to define $\kappa = E[W_Q - W_P] = (\gamma_Q - \gamma_P)(a - \alpha) - (1 + (n-1)\rho)\sigma^2$. Then we have:

$$\begin{aligned}
\frac{\partial \kappa}{\partial k} &= \frac{n^2}{2\gamma_P \gamma_Q}(\alpha - a)(\gamma_Q - \gamma_P) \leq 0, \\
\frac{\partial \kappa}{\partial a} &= \frac{-\partial \kappa}{\partial \alpha} = \gamma_Q - \gamma_P \geq 0, \\
\frac{\partial \kappa}{\partial (\sigma^2)} &= \frac{n}{2}(a - \alpha)\left(\frac{n}{\gamma_P} - (1-\rho)\frac{n-1}{\gamma_Q}\right) - \rho(n-1) - 1 \lesseqgtr 0, \\
\frac{\partial \kappa}{\partial \rho} &= \sigma^2 (n-1)\left(\frac{(a-\alpha)n}{2\gamma_Q} - 1\right) \lesseqgtr 0, \\
\frac{\partial \kappa}{\partial b} &= 0,
\end{aligned}$$

with strict inequalities if $\rho > -1/(n-1)$ and $\sigma^2 > 0$. The proposition follows. ■

Note that we have $E[W_Q] = E[W_P]$ if $\rho = -1/(n-1)$ or $\sigma^2 = 0$. I now interpret the parts of Proposition 2. The results discussed below are illustrated in Figures 2 and 3 in Section 3 and Appendix B.

The proposition first states that an increase in the investment cost parameter k decreases the relative performance of tradable quantities (Figure 2.a). The reason is that firms implement a socially suboptimal cost structure under prices, and that the regulator chooses a lower aggregate production target ($\overline{Q}_P$) than otherwise optimal to correct for this negative externality (cf. Proposition 1). The strength of this negative externality decreases in investment costs k. Moreover, the slope of the marginal production cost curve increases in investment cost k (cf. equations 16 and 17). We know from Weitzman (1974) that the relative performance of prices increases in this slope. Regarding the intercept of the marginal benefit function (a), a higher a increases the relative performance of tradable quantities (Figure 3.b). The explanation is that the social planner determines $\overline{Q}_P$ under prices such that expected marginal utility from consumption of the public good is larger than marginal production cost (cf. Proposition 1), and the associated loss due lower consumption increases in a.[19] By a similar argument, the relative performance of tradable quantities decreases in the production cost component α.

Part (ii) in Proposition 1 arises from three opposing mechanisms. Firstly, uncertainty (σ^2) and correlation (ρ) incur a welfare loss due to fluctuation in consumption of the public good under price-based regulation. Secondly, the wedge between marginal costs and expected marginal benefits under prices increases in σ^2 and ρ (because the social cost of a too flexible technology increases in σ^2 and ρ).[20] Thirdly, uncertainty allows firms to increase profits by producing more when cost is low and vice versa.[21] This mechanism increases firms' expected profits, and is stronger under prices because aggregate production is constant under tradable quantities. Finally, we observe that the firms' ability to take advantage of cost fluctuations decreases in ρ under tradable quantities, because the (non-negative) covariance between the

[19] The proof of Proposition 1 can be used to show that the wedge between marginal cost and expected marginal benefits under prices increases in a. See also Figure 3.a in Appendix B.

[20] The difference between marginal cost and marginal expected benefit is $\left(1-\gamma_P^2/\gamma_Q^2\right)\left(n\left(a-\alpha\right)-\gamma_P\right)/n$ under prices, see the proof of Proposition 1. This expression can be shown to increase in σ^2 and ρ. See also Figure 2.b.

[21] Expected profits increases in uncertainty because the profit function is convex in θ_i. That profits increases in (demand) uncertainty was first shown by Oi (1961). Note that equations (18) and (19) imply that $\partial E\left[W_Q\right]/\partial\sigma^2 \geq 0$ and $\partial E\left[W_P\right]/\partial\sigma^2 \lesseqgtr 0$, respectively.

equilibrium price and a firm's realized production cost increases in ρ.[22]

Part (*iii*) of Proposition 1 reflects that the benefit curvature parameter b affects welfare equally adverse across the regulatory instruments when technology is endogenous (cf. equations 18 and 19) (Figure 3.a). Note that optimal policy ensures that the relative slopes of the marginal cost and benefit curves are independent of b; i.e., the ratio b/β is constant in b (cf. equations 16 and 17).

It is also interesting to examine what kind of technology the regulatory instruments encourage. For example, it is important whether a regulatory instrument tends to induce greenhouse gas abatement by fuel substitution, or a larger share of renewable energy. Within our stylized analytical framework, technology choice is best interpreted as a choice about the capital intensity of the technology; i.e. the firms face a trade-off between low capital costs and high operating cost (high β, e.g., abatement by fuel substitution), or higher capital costs with associated lower operating costs (low β, e.g., hydro power and CCS). We have the following result on the firms' technology choice under optimal policy:

Proposition 3 *Assume optimal policy with welfare given by equation (2) and competitive firms. Then we have:*

$$\beta_P \geq (\leq)\beta_Q \Leftrightarrow E\left[W_Q\right] \geq (\leq) E\left[W_P\right].$$

Proof. The proposition follows directly from equations (16), (17), and (20), see Appendix A. ■

The proposition states that the highest expected welfare is associated with the most capital intensive technology (low β).

Proposition 3 relates to the literature on regulatory induced investment (low β implies high investment) and technology choice referred in Section 1.

[22] We have $cov(p_Q, \theta_i) = (1 + (n-1)\,\rho)\,\sigma^2/n$.

In particular, the result differs from Krysiak (2008), whose results imply that technology investment is higher under prices (i.e., $\beta_Q \geq \beta_P$).[23] The reason for this difference is that Krysiak (2008) examines policy with equal expected marginal costs of production. This is equivalent to assuming equal production targets for the public good $\overline{Q}_Q = \overline{Q}_P$ in our analysis. We remember that this yielded $\beta_Q \geq \beta_P$ in Subsection 2.2. Under optimal policy, however, the optimal production target tends to be be larger under quantity-based regulation (cf. Proposition 1). Therefore, because β decreases in the expected production level (cf. equation 10 and the firms' second order conditions), we may have $\beta_Q < \beta_P$.

2.5 Generalization

So far, the analysis has been limited to quadratic functions and reciprocal investment costs. This allowed clear and transparent results. However, the intuition behind Proposition 1 suggests that it may be valid under less strict assumptions. In this subsection, I briefly generalize the results about the qualitative characteristics of the regulatory instruments given in Subsection 2.3 to less restrictive functional forms.

Let production costs, investment costs and utility of consumption be given by $c_i\left(q_i, \beta_i, \theta_i\right)$, $k_i\left(\beta_i\right)$ and $u\left(\sum_i q_i\right)$, respectively. Further assume that $c_i(\cdot)$ is increasing in θ_i, and convex and increasing in q_i and β_i. Investment costs $k_i(\cdot)$ are convex and decreasing in β_i, while utility $u(\cdot)$ is increasing and (weakly) concave in q_i.[24] We then have the following:

Corollary 1 *Assume optimal policy, (positive) welfare, competitive firms and $\sigma^2 > 0$. Then we have:*

(i) Optimal policy does not in general involve equal production (or price) targets across the regulatory instruments.

[23] To be precise, Krysiak (2008) also assumes $\sigma^2, \rho > 0$. This yields $\beta_Q > \beta_P$.

[24] The derivatives satisfy $u_q, c_q, c_{qq}, c_\beta, c_{\beta\beta}, c_\theta, -k_\beta, k_{\beta\beta} > 0$ and $u_{qq} \leq 0$.

(ii) *Tradable quantities equalizes marginal utility from consumption of the public good with expected marginal production costs of the public good.*

(iii) *Price-based regulation does not in general equalize expected marginal utility from consumption of the public good with marginal production costs (unless marginal utility is constant).*

Proof. See Appendix A. ■

The intuition behind the corollary is similar to that of Proposition 1 in Subsection 2.3. It is not repeated here. Note that the regulator does not fail to equalize marginal utility with marginal production costs under prices when marginal utility is constant. The explanation is that the regulator's incentive to dampen fluctuations in aggregate output when determining optimal policy arises from concavity of utility.

3 Numerical illustration

In this section I briefly illustrate two issues within a simple numerical model: the difference in the basis of comparison of policy instruments between the present paper and Weitzman (1974), and how the results in Propositions 1 to 3 are affected by changes in the exogenous parameters of the model. The numerical illustration use equations (14) to (19) above and is calibrated to reflect a 20% cut in emissions of greenhouse gases (GHG) in the European Union (EU) in the year 2020, relative to 1990 levels (see Appendix B for details). This is part of the EU's so-called "20-20-20" target.[25] The simulated cost of achieving the "20-20-20" GHG emissions target is 0.7 percent of EU GDP in 2020.[26] Interpretation of production (q) as pollution abatement

[25] http://ec.europa.eu/clima/policies/package/index_en.htm.

[26] See Hoel et al. (2009) for a survey of numerical studies on climate policy costs.

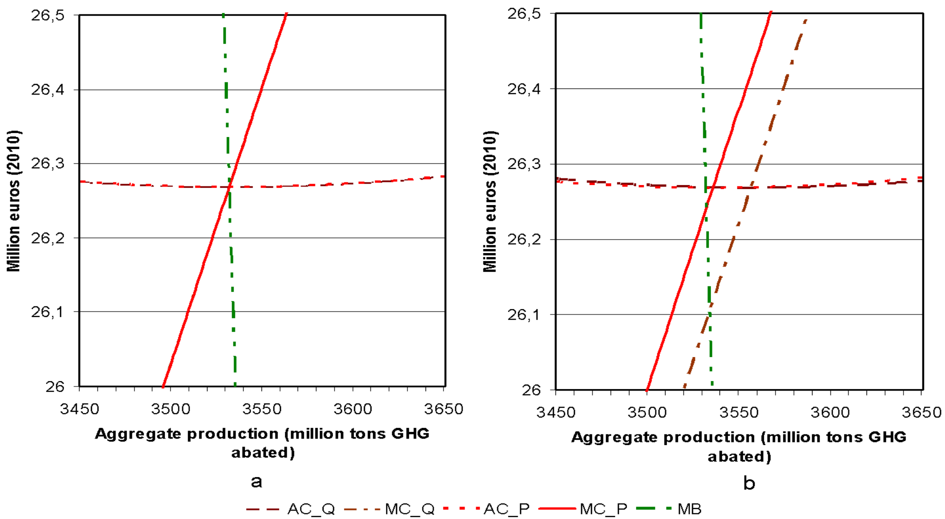

Figure 1: Production cost structures in benchmark scenario without uncertainty (a) and with uncertainty (b).

is perhaps most appropriate under the assumption that business as usual emissions are exogenously given.[27]

Figure 1 illustrates how comparison of regulatory instruments with endogenous cost structure differs from the analysis in Weitzman (1974). Here AC, MC and MB refers to average cost, marginal cost and marginal benefits, respectively. Figure 1.a shows the benchmark scenario in the special case without uncertainty (the curves for tradable quantities (subscript Q) and prices (subscript P) are on top of each other). This yields the familiar case with curves depicting marginal cost, marginal benefit and average cost all intersecting at minimal efficient scale. The aggregate production target is given by $Q_Q = Q_P = 3532$ million tons of GHG abatement at the intersection of the three curves. As is well known, the instruments are equivalent

[27]Emissions is then equal to BaU emissions minus abatement (q_i). It is possible to interpret the cost shocks θ_i to also reflect uncertainty regarding BaU emissions. In this case the assumption of equal variances σ^2 across the instruments may be disputed (Storrøsten, 2013).

in this case.[28] The comparison of instruments in Weitzman (1974) may be illustrated with a figure similar to Figure 1.a, where the slopes of the curves are known and exogenous and the aggregate production targets are equal across the instruments. Weitzman (1974) then compares expected welfare under uncertainty about the vertical placement of the curves.[29]

In the present paper, with firms' choosing their cost structure by investing in technology, uncertainty does not only affect the vertical placement of the cost curves, but also their slopes. Furthermore, optimal policy then prescribes different aggregate production targets because of the disparate cost structures. This is illustrated in Figure 1.b, which shows the cost structures in the benchmark scenario (with uncertainty). The analysis in the present paper compares expected welfare across the instruments with uncertainty about the vertical placement of the cost curves in Figure 1.b, given endogenous technology and ex-ante socially optimal aggregate production targets.

Figure 1.b also illustrates Proposition 1 quite clearly. In the benchmark scenario, aggregate production (abatement) is equal to $Q_Q = 3534$ and $Q_P = 3491$ million tons under tradable quantities and prices, respectively.[30] It is then clear from Figure 1.b that marginal benefit equals expected marginal cost under tradable quantities while, in contrast, expected marginal utility from consumption of the public good is larger than marginal cost under prices. This wedge reduces the relative performance of prices, and expected welfare is 1.2 percent higher under tradable quantities than under prices in the benchmark scenario.

Figure 2 illustrates how the results in Propositions 1 to 3 are affected

[28] Baldursson and von der Fehr (2008) show that this equivalence holds only if quotas are short lived when the government is motivated by public-finance concerns.

[29] Weitzman (1974) includes uncertainty about cost and benefits, but only cost uncertainty affects the relative performance of the instruments.

[30] Cost at minimal efficient scale is 26.3 and the expected price is 26.1 under quantities, which might seem to suggest that the firms earn negative profits. This is not true, however, because the firms produce more when production costs are low and vice versa, see, e.g., Oi (1961) and Mills (1984).

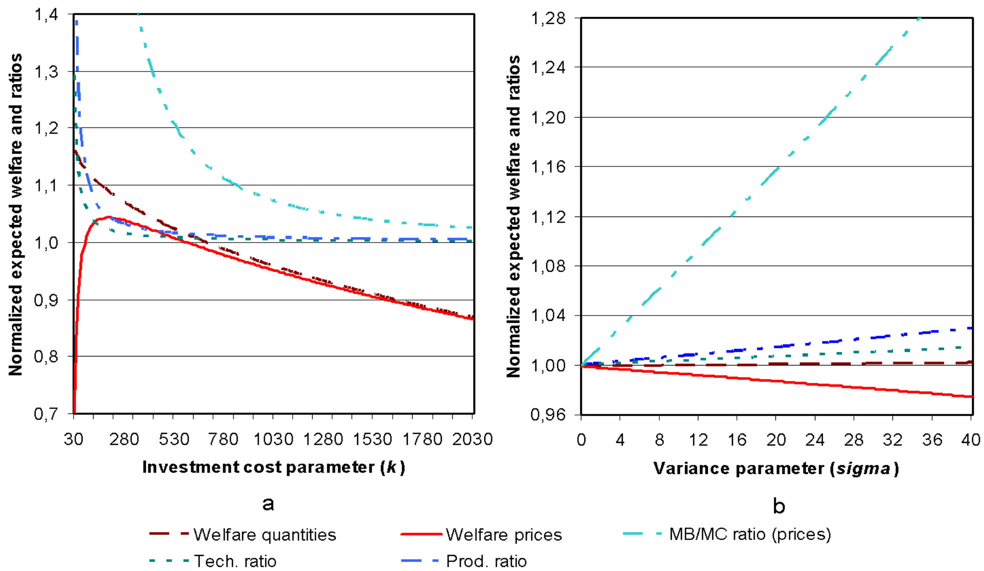

Figure 2: Effects of changes in investment cost parameter k and uncertainty parameter σ^2.

by two central parameters in the model: investment cost k and uncertainty σ^2. The figure illustrates how expected welfare evolves as the two exogenous parameters change.[31] Benchmark parameter values are 690 and 17.4 for k and σ^2, respectively. The figure also graph the ratios Q_Q/Q_P, β_P/β_Q and $E\left[MB_P\right]/MC_P$. Note that expected welfare is larger under tradable quantities everywhere, except for the case without uncertainty at $\sigma^2 = 0$. We also observe that technology investment and expected aggregate production are larger under tradable quantities, unless $\sigma^2 = 0$.

The numerical results indicate that tradable quantities performs better than prices for regulating greenhouse gas emissions in the European Union for a broad range of parameter values (see the appendix for sensitivity to changes in exogenous parameters other than k and σ^2). This is interesting

[31]Figures for expected welfare is normalized by dividing with expected welfare under quantities in the benchmark scenario.

because most studies conclude that prices are preferable in the case of GHG abatement, see e.g., Pizer (2002), Hoel and Karp (2001, 2002) and Karp and Zhang (2006). Two important reasons for the different results are the social planner's failure to equalize marginal costs and benefits under prices (cf. Proposition 1), and the endogenously determined relative slope of the marginal cost and benefit functions in the present paper.[32]

4 Conclusion

It is well known that authorities generally lack information needed for efficient regulation of the commons. In this paper, I have expanded the model in Weitzman (1974) by deriving an analytical criterion for ex-ante evaluation of the relative performances of prices and tradable quantities under uncertainty, given optimal policy and endogenous cost structure.

The results suggest that the relative performance of tradable quantities is improved when the implemented technology is endogenous. The reason is that optimal policy does not equalize marginal costs and expected marginal benefits under price-based regulation. Intuitively, a negative externality caused by the firms' technology choice is present under price-based regulation, but not under tradable quantities. This negative externality is (partly) compensated for by the regulator when determining optimal policy. This compensation, however, comes at the cost of failure to equalize marginal costs and marginal expected benefits from the public good. Consequently, the relative performance of prices is deteriorated. The numerical illustration indicates that the impact is significant.

The criteria derived in this paper may be helpful when evaluating the expected performances of price- and quantity-based regulatory instruments.

[32] The numerical model offers a highly simplified modelling of costs, benefits and agent behaviour. Hence, this result should not be attached too great importance. Nevertheless, it reflects that the relative performance of tradable quantities is significantly improved when technology choice is accounted for.

For example, the relative performance of tradable quantities decreases in the investment and production cost parameters (k and α), and increases in the intercept parameter of the marginal benefit function (a). Furthermore, the analysis suggests that the importance of the curvature on the consumption benefit function (b) is exaggerated in the literature. In particular, it is not justifiable to conclude that one type of regulation has a comparative advantage in terms of induced expected welfare merely on the basis of the relative curvatures of the cost and benefit functions (as suggested by Weitzman, 1974).[33]

The analysis relies upon four important assumptions. Firstly, excepting Subsection 2.5, it is limited to quadratic cost and benefit functions and reciprocal investment costs. As pointed out by Weitzman (1974), second order approximations of the true functional forms are justified only if the amount of uncertainty in marginal cost is taken as sufficiently small. Secondly, firms may only choose the slope parameter of marginal production costs β. It is not straightforward to derive interpretable analytical results if both a and β are endogenous, however. Thirdly, the analysis only considers optimal policy. In reality, political considerations outside the scope of the present paper (e.g., lobbying, fairness and distributive effects) tend to play an important role in determining both the stringency of regulation and the choice of regulatory instrument. An important reason for considering optimal policy in this paper is that the socially optimal production (or price) target depends upon the firms' cost structure, which differs across the instruments. Therefore, the relative performance of the instruments would otherwise depend on how close the chosen production target (or fixed price) is to the target that is socially optimal, rendering the comparative results at random. Fourth and last, the model does not feature potentially important elements like, e.g., knowledge spillovers, endogenous R&D, distorting taxes and gradually

[33] For example, an emissions tax does not necessarily perform better than emissions trading for regulating greenhouse gas emissions even if the marginal environmental damage function facing the relevant jurisdictional area is nearly horizontal.

disclosed information.

Appendix A: proofs and derivations

Here I derive equations (11), (14), (15) and (20), and present the proofs of Proposition 3 and Corollary 1. In order to simplify notation I define $V = 1 + (n-1)\rho$, and omit subscripts indicating regulatory instrument when no confusion is possible. The definitions $\gamma_P = n\sqrt{k - \sigma^2}$ and $\gamma_Q = \sqrt{n\left(kn - \sigma^2\left(n - V\right)\right)}$ are used extensively.

Derivation of equation (11). I first derive equation (11) under tradable quantities. Expected welfare for arbitrary $\overline{Q}$ under tradable quantities is (cf. equations 2 and 7):

$$
\begin{aligned}
E\left[W_Q\right] &= E\left[a\overline{Q} - \frac{b}{2}\overline{Q}^2\right] \\
&- E\left[\sum_i \left((\alpha+\theta)\left(\frac{\overline{Q}}{n} + \frac{1}{\beta}\left(\frac{1}{n}\sum_i \theta_i - \theta_i\right)\right) + \frac{\beta}{2}\left(\frac{\overline{Q}}{n} + \frac{1}{\beta}\left(\frac{1}{n}\sum_i \theta_i - \theta_i\right)\right)^2 + \frac{k}{2\beta}\right)\right] \\
&= E\left[aQ - \frac{b}{2}\overline{Q}^2\right] \\
&- E\left[-\sum_i \left(\frac{\beta\overline{Q}^2}{2n^2} - \frac{\alpha\theta}{\beta} - \frac{\theta^2}{2\beta} + \frac{\overline{Q}}{n^2}\sum_i \theta_i + \frac{1}{2n^2\beta}\left(\sum_i \theta_i\right)^2 + \frac{\overline{Q}}{n}\alpha + \frac{\alpha}{n\beta}\sum_i \theta_i + \frac{k}{2\beta}\right)\right] \\
&= a\overline{Q} - \frac{b}{2}\overline{Q}^2 - n\left(\frac{1}{2}\frac{\overline{Q}^2}{n^2}\beta - \frac{1}{2\beta}\sigma^2 + \frac{1}{2}\frac{nV\sigma^2}{n^2\beta} + \frac{\overline{Q}}{n}\alpha + \frac{k}{2\beta}\right) \\
&= \overline{Q}\left(a - \alpha\right) - \frac{1}{2}\overline{Q}^2\left(b + \frac{\beta}{n}\right) + \frac{1}{2\beta}\left(n\sigma^2 - V\sigma^2 - kn\right) \\
&= \overline{Q}\left(a - \alpha\right) - \frac{1}{2}\overline{Q}^2\left(b + \frac{\beta}{n}\right) - \frac{1}{2\beta}\frac{\gamma^2}{n}.
\end{aligned} \tag{21}
$$

Differentiating (21) with respect to technology choice β we get $\partial E(W_Q)/\partial\beta = -\left(\overline{Q}^2\beta^2 - \gamma^2\right)/2n\beta^2 = 0$. Hence, the first order condition is $Q^2\beta^2 - \gamma^2 = 0$, with solution $\beta = \gamma/\overline{Q}$ (for $\beta \geq 0$). It follows by comparison with (12) that the technology technology investment induced by equation (10), and for given arbitrary $\overline{Q}$, is optimal under tradable quantities. Hence, $X = 0$ in equation (11).

I now derive equation (11) under prices. Expected welfare for arbitrary $\overline{Q}$ under prices is (cf. equations 2 and 9):

$$\begin{aligned}
E\left[W_P\right] &= E\left[a\sum_i\left(\frac{\overline{Q}}{n}-\frac{\theta_i}{\beta}\right)-\frac{b}{2}\left(\sum_i\left(\frac{\overline{Q}}{n}-\frac{\theta_i}{\beta}\right)\right)^2\right] \\
&\quad - E\left[\sum_i\left((\alpha+\theta)\left(\frac{\overline{Q}}{n}-\frac{\theta_i}{\beta}\right)+\frac{\beta}{2}\left(\frac{\overline{Q}}{n}-\frac{\theta_i}{\beta}\right)^2+\frac{k}{2\beta}\right)\right] \\
&= E\left[a\left(\overline{Q}-\frac{1}{\beta}\sum_i\theta_i\right)-\frac{b}{2}\left(\left(\overline{Q}-\frac{1}{\beta}\sum_i\theta_i\right)\right)^2\right] \\
&\quad - E\left[\sum_i\left(\frac{k}{2\beta}-\frac{\theta^2}{2\beta}-\frac{\alpha\theta}{\beta}+\frac{\beta\overline{Q}^2}{2n^2}+\frac{\alpha\overline{Q}}{n}\right)\right] \\
&= \overline{Q}a-\frac{\overline{Q}^2 b}{2}-\frac{bnV\sigma^2}{2\beta^2}-n\left(\frac{k}{2\beta}-\frac{\sigma^2}{2\beta}+\frac{\beta\overline{Q}^2}{2n^2}+\frac{\alpha\overline{Q}}{n}\right). \qquad (22)
\end{aligned}$$

Differentiating (22) wrt. the technology parameter β we get the first order condition:

$$\begin{aligned}
\frac{\partial E(W_P)}{\partial\beta} &= -\frac{\overline{Q}^2\beta^3+n^2\sigma^2\beta-2Vbn^2\sigma^2-kn^2\beta}{2n\beta^3}=0 \\
&\Leftrightarrow\ 0=\overline{Q}^2\beta^3+n^2\sigma^2\beta-2Vbn^2\sigma^2-kn^2\beta \\
&\Leftrightarrow\ \frac{k}{\beta^2}=\frac{\overline{Q}^2}{n^2}+\frac{\sigma^2}{\beta^2}-2Vb\frac{\sigma^2}{\beta^3},
\end{aligned}$$

which is equation (11) (we have $(E[q])^2 = \overline{Q}^2/n^2$, $var[q_P] = \sigma^2/\beta^2$ and $X = -2Vb\sigma^2/\beta^3$). It can be shown that the firms' second order condition in period 2 implies that β_P decreases in the absolute value of X and, hence, that firms overinvest in technology under prices.

Derivation of equation (14). Inserting $\beta = \gamma/\overline{Q}$ (cf. equation 12) in equation (21) we get $E\left[W_Q\right] = \overline{Q}\left((a-\alpha) - \gamma/n - \overline{Q}b/2\right)$. Differentiating wrt. $\overline{Q}$ yields the first order condition $\left(n\left(a-\alpha\right) - \gamma - \overline{Q}bn\right)/n = 0$, with solution given by equation (14).

Derivation of equation (15). Inserting $\beta = \gamma/\overline{Q}$ (cf. equation 13) in equation (22) yields $E\left[W_P\right] = \overline{Q}\left(2n\gamma^2\left(a-\alpha\right) - 2\gamma^3 - \overline{Q}bn\left(\gamma^2 + Vn\sigma^2\right)\right)/\left(2n\gamma^2\right)$. Differentiating wrt. $\overline{Q}$ we obtain the first order condition:

$$\begin{aligned}
0 &= \frac{1}{n\gamma_P^2}\left(n\gamma_P^2\left(a-\alpha\right) - \gamma_P^3 - \overline{Q}_P bn\left(\gamma_P^2 + Vn\sigma^2\right)\right) \\
&\Leftrightarrow \; \overline{Q}_P = \frac{\gamma_P^2}{Vbn^2\sigma^2 + bn\gamma_P^2}\left(an - n\alpha - \gamma_P\right) \\
&\Leftrightarrow \; \overline{Q}_P = \frac{1}{b}\frac{\gamma_P^2}{\gamma_Q^2}\left(a - \alpha - \frac{\gamma_P}{n}\right),
\end{aligned}$$

which is equation (15).

Derivation of equation (20). From equations (18) and (19) we have $E(W_Q) > E(W_P)$ iff:

$$\begin{aligned}
0 &< \frac{1}{2bn^2}\left(n\left(a-\alpha\right) - \gamma_Q\right)^2 - \frac{1}{2bn^2}\frac{\gamma_P^2}{\gamma_Q^2}\left(n\left(a-\alpha\right) - \gamma_P\right)^2 \\
&\Leftrightarrow \; 0 < n\left(a-\alpha\right) - \gamma_Q - \frac{\gamma_P}{\gamma_Q}\left(n\left(a-\alpha\right) - \gamma_P\right) \\
&\Leftrightarrow \; 0 < \frac{\gamma_P^2}{\gamma_Q} - \gamma_Q + n\left(1 - \frac{\gamma_P}{\gamma_Q}\right)\left(a-\alpha\right) \\
&\Leftrightarrow \; 0 < \gamma_P^2 - \gamma_Q^2 + n\left(\gamma_Q - \gamma_P\right)\left(a-\alpha\right) \\
&\Leftrightarrow \; 0 < n^2\left(k - \sigma^2\right) - n\left(kn - \sigma^2\left(n - V\right)\right) + n\left(\gamma_Q - \gamma_P\right)\left(a-\alpha\right) \\
&\Leftrightarrow \; 0 < -Vn\sigma^2 + n\left(\gamma_Q - \gamma_P\right)\left(a-\alpha\right) \\
&\Leftrightarrow \; 0 < \left(\gamma_Q - \gamma_P\right)\left(a-\alpha\right) - V\sigma^2,
\end{aligned}$$

which is equation (20). To prove that $E(W_Q) \lesseqgtr E(W_P)$ is possible, I evaluate the criterion with parameter values $a = 3$, $b = \alpha = 1$, $n = 100$, $k = 2$ and $\sigma^2 = \rho = 1/2$. This yields $E(W_Q) < E(W_P)$. Substituting $a = 3$ with $a = 4$ we have $E(W_Q) > E(W_P)$. The numerical model has been checked to solve with these values.

Proof of Proposition 3. From equations (16) and (17) we have $\beta_P > \beta_Q$ iff:

$$\begin{aligned} 0 &< bn\frac{\gamma_Q^2}{n\gamma_P(a-\alpha)-\gamma_P^2} - bn\frac{\gamma_Q}{n(a-\alpha)-\gamma_Q} \\ &\Leftrightarrow \ 0 < \frac{\gamma_Q}{n\gamma_P(a-\alpha)-\gamma_P^2} - \frac{1}{n(a-\alpha)-\gamma_Q} \\ &\Leftrightarrow \ 0 < \frac{1}{\gamma_P}\frac{\gamma_P-\gamma_Q}{(\gamma_P+n\alpha-an)\left(\gamma_Q+n\alpha-an\right)}\left(\gamma_P+\gamma_Q+n\alpha-an\right). \end{aligned}$$

We have $(\gamma_P + n\alpha - an)\left(\gamma_Q + n\alpha - an\right) > 0$ for positive production, cf. equations (14) and (15). Hence, the above equation is equivalent with:

$$\begin{aligned} 0 &< \left(\gamma_P-\gamma_Q\right)\left(\gamma_P+\gamma_Q+n\alpha-an\right) \\ &\Leftrightarrow \ 0 < \gamma_P^2-\gamma_Q^2+n\left(\gamma_Q-\gamma_P\right)(a-\alpha) \\ &\Leftrightarrow \ 0 < \left(\gamma_Q-\gamma_P\right)(a-\alpha)-V\sigma^2, \end{aligned}$$

which is equation (20). See the derivation of equation (20) above for the derivation of the third line. Proposition 3 follows.

Proof of Corollary 1. Parts (i) and (iii) of Corollary 1 follows directly from Proposition 1 (except the parenthesis in (iii) which is proved below). To prove part (ii), I solve the model with backwards induction. In the third period, any firm $i \in N$ solves $\max_{q_i}\left(pq_i - c_i\left(q_i, \beta_i, \theta_i\right)\right)$ with first order condition:

$$p - \frac{\partial c_i\left(q_i^*, \beta_i, \theta_i\right)}{\partial q_i} = 0. \tag{23}$$

This condition implicitly yields the profit maximizing quantum q_i^* as a function of p, β_i and θ_i:

$$q_i^* = q_i(p, \beta_i, \theta_i) . \tag{24}$$

In the second period, any firm $i \in N$ maximizes expected profits wrt. technology β_i:

$$\max_{\beta_i} \left(E\left[p q_i^* - c_i\left(q_i^*, \beta_i, \theta_i\right)\right] - k_i\left(\beta_i\right)\right),$$

with first order condition:

$$\begin{aligned} 0 &= E\left[\left(p - \frac{\partial c_i(\cdot)}{\partial q_i}\right)\frac{\partial q_i^*}{\partial \beta_i} - \frac{\partial c_i(\cdot)}{\partial \beta_i}\right] - \frac{\partial k_i(\cdot)}{\partial \beta_i} \\ &= -E\left[\frac{\partial c_i(\cdot)}{\partial \beta_i}\right] - \frac{\partial k_i(\cdot)}{\partial \beta_i}, \end{aligned} \tag{25}$$

where I used equation (23). The interpretation is that the expected decrease in marginal production cost induced by investment equals marginal investment cost. It implicitly yields the profit maximizing β_i^* as a function of the price p and the stochastic element θ_i:

$$\beta_i^* = \beta_i(p, \theta_i) . \tag{26}$$

In the first period, the regulator knows that p depends on the policy variable $\overline{Q}$, along with the β_i^*'s and the θ_i's, i.e., we have $p = p\left(\overline{Q}, \beta_{i\in N}^*, \theta_{i\in N}\right)$ in equations (24) and (26). The regulator maximizes expected welfare wrt. policy instrument $\overline{Q}$:

$$\max_{\overline{Q}} \left(E\left[u\left(\sum_{i\in N} q_i^*\right) - \sum_{i\in N} c_i\left(q_i^*, \beta_i^*, \theta_i\right)\right] - \sum_{i\in N} k_i\left(\beta_i^*\right)\right).$$

Under quantities $u\left(\sum_{i\in N} q_i^*\right) = u\left(\overline{Q}\right)$ is a non-stochastic constant determined directly by the regulator. The problem then reduces to:

$$\max_{\overline{Q}} \left(u\left(\overline{Q}\right) - E\left[\sum_{i \in N} c_i\left(q_i^*, \beta_i^*, \theta_i\right)\right] - \sum_{i \in N} k_i\left(\beta_i^*\right)\right),$$

subject to equations (24) and (26). The first order condition is:

$$\begin{aligned} \frac{du\left(\overline{Q}\right)}{d\overline{Q}} &= E\left[\sum_{i \in N}\left(\frac{\partial c_i(\cdot)}{dq_i^*}\frac{\partial q_i^*}{\partial \overline{Q}} + \left(\frac{\partial c_i(\cdot)}{\partial \beta_i^*} + \frac{\partial k_i}{\partial \beta_i^*}\right)\frac{\partial \beta_i^*}{\partial \overline{Q}}\right)\right] \\ &= E\left[\sum_{i \in N}\left(\frac{\partial c_i(\cdot)}{dq_i^*}\frac{\partial q_i^*}{\partial \overline{Q}}\right)\right], \qquad (27) \end{aligned}$$

with (above I used equation 25):

$$\sum_{i \in N} \frac{dq_i^*}{d\overline{Q}} = \sum_{i \in N}\left(\frac{dq_i^*}{dp}\left(\frac{dp}{d\overline{Q}} + \frac{dp}{d\beta_i^*}\frac{d\beta_i^*}{d\overline{Q}}\right) + \frac{dq_i^*}{d\beta_i^*}\frac{d\beta_i^*}{d\overline{Q}}\right).$$

Equation (27) states that marginal utility of the public good equals expected marginal cost of production under quantity-based regulation. This proves part (*ii*) of Corollary 1.

Under prices the first order condition is (with $\sum_{i \in N}\left(\partial q_i^*/\partial \overline{Q}\right)$ as above):

$$E\left[\left(\frac{du\left(\sum_{i \in N} q_i^*\right)}{d\sum_{i \in N} q_i^*} - \sum_{i \in N}\frac{\partial c_i(\cdot)}{dq_i^*}\right)\frac{\partial q_i^*}{\partial \overline{Q}}\right] = 0, \qquad (28)$$

which does not imply equalization of marginal cost and expected marginal benefit from the public good. The reason is that an increase in $\overline{Q}$ not only reduces production costs, but also increases fluctuations in utility from consumption via technology investment (remember from the quadratic model that a lower β entailed two costs under prices: (*i*) higher investment cost and (*ii*) reduced expected utility due increased fluctuations around the expected value of the concave utility function). The exception is the case with constant marginal costs $du\left(\sum_{i\in N} q_i^*\right)/d\left(\sum_{i\in N} q_i^*\right) \equiv u'$, in which case (28) reduces to:

$$u' = \sum_{i\in N}\left(\frac{\partial c_i(\cdot)}{dq_i^*}\frac{\partial q_i^*}{\partial \overline{Q}}\right).$$

Appendix B: Calibration of the numerical illustration

The model is calibrated to reflect a 20% cut in emissions of greenhouse gases (GHG) relative to 1990 levels in the European Union (EU) in the year 2020. The IMF World Economic Outlook Database October 2012 (IMF WOE) projects GDP until the year 2017, and I use the IMF WOE figures for the average growth rate in the EU from 1980 to 2017 to derive an estimate for the period 2018 to 2020.[34] This yields a GDP of 14289 billion €(2010) in 2020. Further, GDP figures from IMF WOE and GHG emission figures from EEA imply an average emissions intensity of 0.56 kilo GHG per €(2010) GDP in the period 2000 to 2004.[35] I use this intensity and the above GDP estimate to derive business as usual (BaU) emissions in EU in the year 2020.[36] The derived figure imply that EU must abate 44% of BaU emissions in 2020 in order to reach its 20-20-20 target.

Nordhaus (1994b) relates fractional reductions in greenhouse gases to fractional reductions in world output by the following power rule (based on a survey in Nordhaus, 1993): $fractional\ reduction\ in\ global\ output = b_1(fractional\ reduction\ in\ GHG\ emissions)^{2.887}$. Nordhaus (1994b) considers a range of values for b_1: 0.027, 0.034, 0.069, 0.080 and 0.133, with the best guess being 0.069.[37] The value 0.069 implies that the above 44% reduction

[34] http://www.imf.org/external/pubs/ft/weo/2011/02/weodata/index.aspx. I use GDP (and emission) figures for the 27 countries that are EU members in 2012 for the whole time period. All figures are converted to €(2010).

[35] http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/main_tables.

[36] There is no clear trend in the EU (27countries) emissions intensity in the period 1990 to 2002. In 2003 the emissions intensity starts to decline. I do not use years after 2004 to approximate BaU emissions, because the EU ETS was initiated in 2005.

[37] These figures are also used by Pizer (2002).

in global emissions cost 0.65% of GDP in EU 2020. I set $\alpha = 0$ and calibrate the investment cost parameter k such that the expected cost of producing the public good under tradable quantities is equal to 0.65% of the estimate of EU GDP in 2020, which implies $k = 690$.[38] Note that a lower α, everything else equal, favours tradable quantities (cf. Proposition 2). However, a lower α also involves a higher investment cost parameter k in order to retain the assumed abatement cost, which favours prices (cf. Proposition 2). Experimentation with the numerical model shows that a low value on α (and the associated larger k) favours the relative performance of prices. Finally, I set the correlation coefficient $\rho = 1/2$ and the variance parameter $\sigma^2 = 17.35$. Then the variance in the allowance price is 1/3 of the expected allowance price, which turns out to be 26 €(2010) per ton GHG. Figure 2 illustrates the sensitivity of the results with respect to changes in investment cost k and uncertainty σ^2.

Benefits of GHG abatement, being determined by long term climate changes and the associated impact on welfare, are perhaps the most uncertain and subjective area of climate modelling. Indeed, Nordhaus (1994a) found that scientist' opinions on the possible damages from climate change range from 0% to 50% loss of global output. Carbone et al. (2009) assume an initial marginal value of abatement of 300 \$(1998) per ton carbon for Western Europe. In the present paper I use this guesstimate, which translates to $a = 303$ €(2010). The results are not sensitive to this value. I calibrate $b = 0.0785$ such that the optimal production target $(\overline{Q}_Q)$ is equal to the 20-20-20 target. The value of b is irrelevant for the relative performances of the regulatory instruments (cf. Proposition 2). Finally, the number of firms is set to $n = 1000$. The number of firms has no influence on the results.

Figure 3 illustrates how the results in Propositions 1 to 3 are affected by changes in the welfare parameters a and b. The figure is similar to Figure 2

[38] The global cost curve for GHG abatement published by McKinsey (Enkvist et al., 2007) has negative marginal abatement cost for low abatement levels.

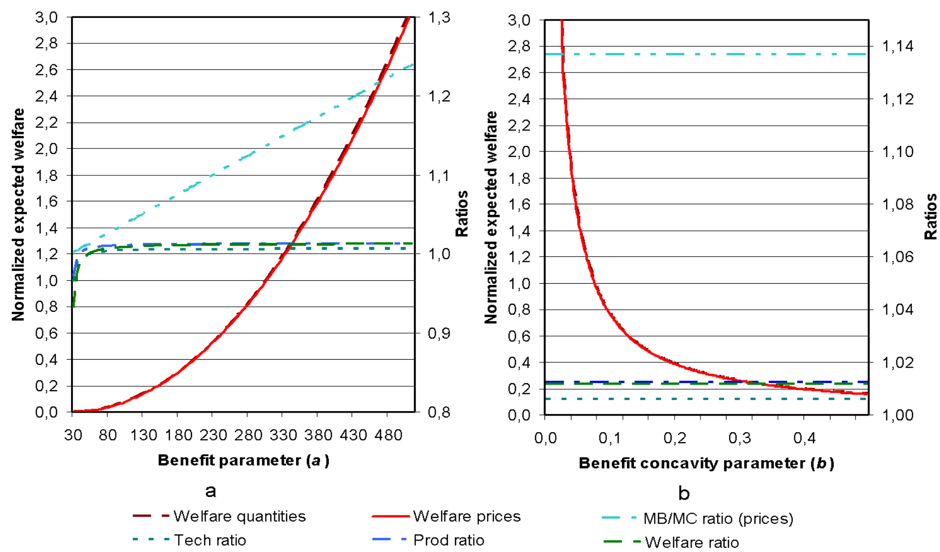

Figure 3: Effects of changes in consumption benefit function parameters a and b.

explained in Section 3, except that it also features the welfare ratio defined as $E[W_Q]/E[W_P]$. Figure 3 suggests that the numerical results are not sensitive to the above calibration of a and b. Note that prices performs best only if $30 \leq a \leq 50$ (optimal production is zero for $a < 28$). A figure depicting changes in the correlation coefficient ρ is not included, but looks very similar to Figure 2.b in the text (welfare and production targets decline in ρ under both instruments, and fastest under prices).

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