Does uncertainty justify intensity emission caps?

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Abstract

Environmental policies often set "relative" or "intensity" emission caps, i.e., emission limits proportional to the polluting firm’s output. One of the arguments put forth in favour of relative caps is based on the uncertainty on business-as-usual output: if the firm's production level is higher than expected, so will be business-as-usual emissions, hence reaching a given level of emissions will be more costly than expected. As a consequence, it is argued, a higher emission level should be allowed if the production level is more important than expected. We assess this argument with a stochastic analytical model featuring two random variables: the business-as-usual emission level, proportional to output, and the slope of the marginal abatement cost curve. We compare the relative cap to an absolute cap and to a price instrument, in terms of welfare impact. It turns out that in most plausible cases, either a price instrument or an absolute cap yields a higher expected welfare than a relative cap. Quantitatively, the difference in expected welfare is typically very small between the absolute and the relative cap but may be significant between the relative cap and the price instrument.

Keywords: Uncertainty, Policy choice, Environmental taxes, Tradable permits, Intensity target

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1. Introduction[*]

Many environmental policies set "relative", "intensity", "specific", "rate-based" or "output-based" emission caps, i.e., they do not limit the absolute level of polluting emissions but the emissions per unit of a firm's output[1]. Indeed, most command-and-control regulations are closer to relative than to absolute caps and numerous voluntary agreements and emission trading schemes around the world set relative emission limits. Furthermore a number of researchers have considered greenhouse gas emission caps for developed and/or developing countries to replace or complement the absolute caps defined by the Kyoto Protocol. Since 2002 the unilateral announcement by the U.S. of a relative national CO_2 target has further stirred the debate on these instruments. One of the main arguments put forward for relative caps is that since a higher output entails more emissions, more allowances should be distributed to high-output firms, to prevent too high a compliance cost.

However to our knowledge this argument has never been studied in an elaborate formal model. Although some recent papers have compared relative and absolute caps, these analyses have been conducted in a deterministic framework. Koutstaal et al. (2002, section 3.3) assert, but do not prove, that "the Weitzman theorem, which states that under uncertainty the preference for either price control through taxes or quantity control with tradable emission permits depends on the relative steepness of the marginal cost and benefit curves, is not affected directly if instead of absolute caps, trading with relative caps is analysed", but as we demonstrate in the present paper, this statement is not correct.

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[1] As exemplified by these various wordings, the vocabulary is not completely set. Terms like "performance standard" are also utilised. Throughout the present text, we utilise "relative caps" and we do not enter into any distinction between these instruments; for such a distinction, see Fisher (2001). Since we assume that the output level is not affected by environmental policies, what is important for us is whether the *overall* cap is fixed (absolute cap) or proportional to output (relative cap).

Our model builds on the Weitzman (1974) prices vs. quantities model. We enhance it by distinguishing two sources of uncertainty on costs: business-as-usual emissions, assumed proportional to output, and the slope of the marginal abatement cost curve. The use of such uncertainty factors allows us to compare relative emission caps not only to absolute caps but also to price instruments (taxes or subsidies). We thus compare three instruments: an absolute cap, a relative cap and a price instrument, as regards expected welfare.

The present article is organised as follows. We first describe existing policy programs based on relative caps (section 2), the relevant literature (section 3), our model and main assumptions (section 4) and the policy instruments we assess (section 5). We then compare these instruments in terms of welfare impact (section 6), and section 7 concludes.

2. Relative emission caps in practice

Defined widely enough, a relative cap is by no means a new policy instrument: such caps are parts of many command-and-control regulations, voluntary agreements and emission trading schemes.

Many command-and-control regulations worldwide are set in units of pollutants per square meter of exhaust fumes or effluent water. Since, for a given installation, the volume of exhaust fumes or effluent water is closely linked to output, this kind of cap is closer to a "relative" cap than to an "absolute" one. The argument holds also for technology prescriptions.

Let us now turn to voluntary and negotiated agreements. In the Netherlands, long-term agreements on energy efficiency, which have been made with industry and other sectors since 1992, are expressed in energy consumption per physical unit of product. In the U.K., France and Germany, voluntary agreements on CO_2 include more relative than absolute targets (Boemare et al., 2003). In the U.S., in February 2003, the Bush administration announced a series of voluntary global warming agreements with the industry, most of which are expressed in greenhouse gas intensity (electric utilities, wood/paper industry, chemical industry, and cement industry) or energy intensity (oil and gas industry, iron and steel industry, railroad). Only one new pledge of reducing absolute emissions was presented, for auto manufacturing plants. Although it is unclear whether or not all these targets are below business as usual expected emissions, their existence confirms the prevalence of relative targets in environmental regulation.

Relative emission caps are also used in some emission trading schemes (Boemare and Quirion, 2002). The first such scheme has probably been the U.S. phase out of lead in gasoline: petroleum refining companies had a target expressed in mass of lead per gallon of gasoline sold and could exchange allowances with one another. Since the cap did not define the total mass of lead released but the lead/output ratio, this was a relative cap. In the U.K., most firms covered by the greenhouse gas emission trading scheme, based on the above-mentioned voluntary agreements, are covered by relative caps. Lastly, a NO_X trading scheme based on relative caps will soon be implemented in the Netherlands (Jansen, 2004).

3. Lessons from existing literature

Relative caps have been analysed by two strands of literature: one is about intensity emission caps for countries (i.e., emissions per unit of GDP) in international agreements, and the second deals with relative emission caps on firms or sectors, as exemplified in the above section.

Intensity country caps applied to greenhouse gas emissions have prompted a lively debate, generally based on non-formalised analyses. In particular, stochastic modelling has not been utilised, although uncertainty is recognised as a key issue by most authors. Since we do not focus on greenhouse gas emissions but aim to provide general results, we do not present this discussion further. For a survey of the literature, see Philibert and Pershing (2002: 132-142), and for more recent references Ellerman and Sue Wing (2003), Kolstad (2005) and Pizer (2003).

Turning to domestic instruments, the only existing models are deterministic and focus on relative targets for individual firms; cf. e.g. Ebert (1998), Fischer (2001) or Koutstaal et al. (2002). Our motivation is different: we do not focus on different incentives for individual firms but on the welfare impact of various aggregate caps. To keep our analytical model tractable, we do not concern ourselves with the mechanisms highlighted by these authors. This is not to understate their importance but to disentangle these well-known, deterministic, mechanisms from the stochastic mechanisms we identify in the present paper.

4. Key assumptions and model description

The key difference between relative and absolute caps when it comes to uncertainty is that with the former, regulated entities receive more (less) allowances if their output or GDP is higher (lower) than expected. The rationale for this instrument is that a higher output entails more emissions, other things being equal, "so that" more allowances should be distributed to prevent too high a compliance cost. Industry lobbyists have consistently put this argument forward, in particular during the negotiation of the European greenhouse gas allowance-trading directive.

To compare in a formal framework relative and absolute caps, we depart from Weitzman's model in three ways. First we have to model the uncertainty on business as usual (BaU) emissions that we assume linked to output, hence to the quantity of allowances distributed under the relative cap. Therefore we distinguish two kinds of cost uncertainty: the level of BaU emissions and the marginal cost of abatement for a given rate of abatement. Second, because BaU emissions vary, it is more convenient to reason in term of emissions instead of abatement. Third, for the same reason, we cannot rely on local approximations of marginal cost and benefit curves around an optimum. We thus end up with the following total abatement cost:

$$TAC = \frac{f(\alpha - e)^2}{2\alpha} \quad (1)$$

Hence the marginal abatement cost:

$$MAC = -\frac{\partial TAC}{\partial e} = f - \frac{f}{\alpha} e. \quad (2)$$

Where

- $e \in [0, \alpha]$ is the emission level,
- $\alpha > 0$ is a stochastic variable representing both the production level (assumed not affected by environmental policies) and the ex post BaU emissions, normalised so that $E[\alpha] = 1$[2],
- $f > 0$ is a stochastic variable representing uncertainty on the slope of the MAC curve, normalised so that $E[f] = 1$. We assume that *f* and α are not correlated.

Note that at BaU ($e = \alpha$), we have $MAC = TAC = 0$.

Equations (1) and (2) imply a normalisation (without loss of generality) of marginal cost and emissions: the marginal cost for a complete abatement is normalised to *f* and BaU emissions are normalised to α.

Total environmental (or external) cost (*TEC*) is closed to Weitzman's formulation, but once again formulated in emissions, not abatement:

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[2] This corresponds to "multiplicative" uncertainty as studied, in a Weitzman-like model, by Hoel and Karp (2001). However these authors do not provide analytical results (because their dynamic model does not allow for them) and do not study a relative quota. Furthermore, their model features only one stochastic variable.

$$TEC = b_1 e + b_2 \frac{e^2}{2} \tag{3}$$

We set b_1<1 to avoid a zero-pollution solution and $b_2 \geq 0$ as in Weitzman's model. We do not model the uncertainty on the benefit side since it is well known that this uncertainty matters only when correlated with abatement cost (Weitzman, 1974, Stavins, 1996). In our model, as in these two papers, adding (uncorrelated) uncertainty on benefits does not influence the ranking of instruments.

For each policy instrument, we then look for the level that minimises the expected total social cost (*TSC*), defined as below:

$$TSC = TAC + TEC = \frac{\alpha f}{2} + (b_1 - f)e + \left(\frac{b_2}{2} + \frac{f}{2\alpha}\right)e^2 \tag{4}$$

5. Three policy instruments

We compare three policy instruments:

- *Q*, an absolute emission cap, as in the U.S. SO_2 program;
- *P*, a price instrument which may be a tax, a subsidy or a combination of both;
- *R*, a "relative" emission cap, i.e., an emission cap proportional to the firm's output. This is equivalent to a performance standard limiting the emissions to output ratio.

As stressed by Weitzman, without uncertainty on the reaction function of the firms (the *MAC* curve) all instruments would yield the same outcome, which would be an optimal solution[3]. If, however, the ex post *MAC* curve differs from what the regulator expects, the outcome will differ among instruments and from the ex post optimum.

5.1. Absolute quota (Q)

[3] Weitzman only studies *Q* and *P*, but his argument applies to *R* as well.

With the absolute quota (Q), the authorities set the maximum emission level $\hat{e}$ which minimises the expected total social cost. We then maximise the expected value of *TSC* (4) with respect to e, taking the first order condition, leading to[4]:

$$\hat{e} = \frac{1 - b_1}{b_2 + E[1/\alpha]} \tag{5}$$

Note that $\hat{e}$ differs from the emission level which would be allowed without uncertainty. As stressed by Hoel and Karp (2001), this is because α features "multiplicative" uncertainty. Conversely, under an additive uncertainty as in Weitzman (1974), the “certainty equivalence” principle applies. Here, in particular, $\hat{e}$ is lower than without uncertainty. Indeed we know, by Jensen’s inequality and the convexity of $1/\alpha$ for α >0, that $E[1/\alpha] > 1/E[\alpha] = 1$.

The allowance price is, by (2) and (5):

$$p(\hat{e}) = f - \frac{(1 - b_1) f}{\alpha(b_2 + E[1/\alpha])}\,. \tag{6}$$

5.2. Price instrument (P)

With the price instrument (P), the authority sets the tax or subsidy level which minimises the expected total social cost, knowing that firms will abate emissions so that their *MAC* will equal this price. We then introduce in *TSC* (4), the emission level $e(p)$ which solves p=*MAC*, we take the expected value of this expression and we maximise with respect to p, taking the first-order condition, leading to the optimal emission price:

$$\tilde{p} = \frac{\left(b_1 + b_2\left(1+\sigma^2\right)\right) E[1/f]}{b_2\left(1+\sigma^2\right) E\left[1/f^2\right] + E[1/f]} \tag{7}$$

[4] All demonstrations are available from the author as a Wolfram Mathematica notebook. Hence all results are easily replicable.

In the above equation, σ^2 is the variance of α . Firms abate emissions until their *MAC* equals $\tilde{p}$, hence, using (2):

$$e(\tilde{p}) = \frac{\alpha}{f}\left(f - \frac{\left(b_1 + b_2\left(1+\sigma^2\right)\right)E\left[1/f\right]}{b_2\left(1+\sigma^2\right)E\left[1/f^2\right] + E\left[1/f\right]}\right) \quad (8)$$

5.3. Relative cap (R)

To model the relative cap (*R*), we have to re-write the model as a function of the emission-output ratio *r*:

$$r \equiv \frac{e}{\alpha} \quad (9)$$

We thus substitute $e = r\alpha$ in (4), take the expected value in the resulting expression and maximise with respect to *r* taking the first-order condition, leading to the optimal ratio $\hat{r}$:

$$\hat{r} = \frac{1-b_1}{1+b_2\left(1+\sigma^2\right)} \quad (10)$$

The resulting emission level is, by (9) and (10):

$$e(\hat{r}) = \alpha \frac{1-b_1}{1+b_2\left(1+\sigma^2\right)} \quad (11)$$

Proposition 1. Without uncertainty on BaU emissions, relative and absolute caps are equivalent.

Proof. Without uncertainty on α , we have $\alpha = 1$, $\sigma^2 = 0$ and $E\left[1/\alpha\right] = 1$. By (5) and (11), we then have $\hat{e} = e(\hat{r})$.

This result is not surprising since the quantity of allowances allocated under *R* is not modified by *f* but only by α . Without uncertainty on this latter variable the authority will set the same emission cap for these two instruments.

Proposition 2. Without uncertainty on *f* the relative cap is equivalent to the price instrument.

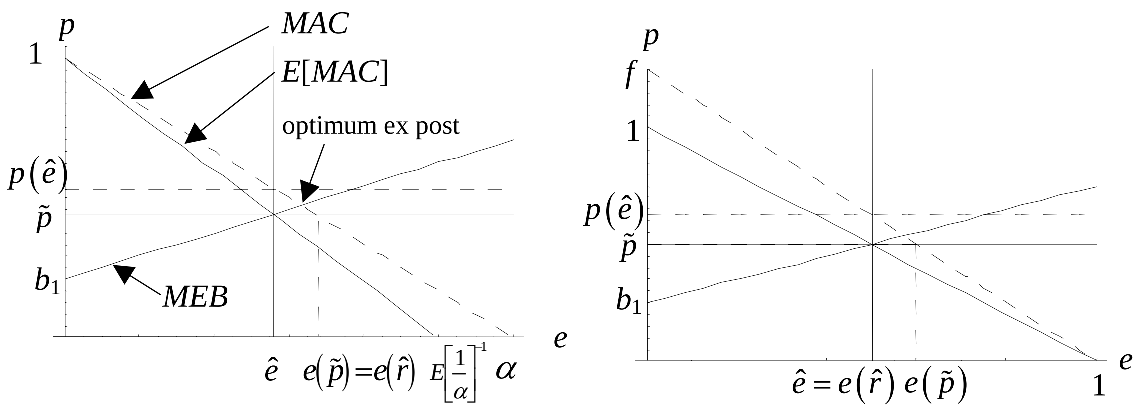
Proof. Without uncertainty on *f*, we have $f = E\left[1/f^2\right] = E\left[1/f\right] = 1$, hence, by (8) and (11), $e(\tilde{p}) = e(\hat{r})$.

An intuitive explanation of proposition 2 is that the BaU emission level is a multiplicative parameter of the emission level stemming from the optimal application of *P* and *R*. For example, a doubling of BaU emissions and production leads to a doubling of the allowed emission level for a given $\hat{r}$. Because the *MAC* curve is linear, the same is true for a given $\tilde{p}$.

Figure 1 below provides a graphical representation of the three instruments under each of the two sources of uncertainty. On the left panel, the BaU emission level is higher than expected; on the right panel, the slope of the *MAC* curve is higher than expected. As a result, in both cases the ex post *MAC* curve (dashed line) is above the ex ante one (plain line). As a consequence, as indicated by the horizontal and vertical dashed lines, the absolute cap yields too low an emission level and the tax too high an emission level, as compared to the ex post optimum, defined by the intersection of the ex post *MAC* curve and the *MEB* curve. In accordance with propositions 1 and 2, the relative cap behaves like the tax on the left panel and like the absolute cap on the right panel.

Figure 1. Outcome of the three instruments under each source of cost uncertainty

Left panel: higher than expected BaU emissions ($\alpha > 1$); right panel: higher than expected *MAC* curve slope ($f > 1$)



6. Is there a room for relative caps?

We may now look for the instrument which leads to the lowest expected social cost. Let c_2 be the expected slope of the *MAC* curve. From (2):

$$c_2 \equiv -\frac{\partial E[MAC]}{\partial e} = E\left[\frac{1}{\alpha}\right] \tag{12}$$

Note that c_2 is higher if BaU emissions are uncertain than if they are not, since, as we have seen, $E[1/\alpha] > 1$.

From equations (4), (5), (11) et (12), the expected welfare from *R* is higher than that from *Q* if and only if:

$$R \succ Q \Leftrightarrow b_2 < \frac{E[1/\alpha]-1}{\sigma^2} = \frac{c_2 - 1}{\sigma^2} \tag{13}$$

Where σ^2 is the variance of α. *R* thus tends to be preferred to *Q* if b_2 is lower than c_2, i.e., if the marginal benefit curve is flatter than the expected marginal cost curve. However, both the numerator and the denominator of the right-side of the (13) are affected by the uncertainty on

α. To go further, we have to specify the probability law of α by assuming than α may take, with an equal probability, two values, $1+\sigma$ et $1-\sigma$, where $\sigma \in (0,1)$ is the standard deviation.

Proposition 3. If the uncertainty on BaU emissions follows a discrete probability law with an equal likelihood for its two realisations, the relative cap should be preferred over the absolute cap if and only if the expected *MAC* curve is steeper than the *MEB* curve.

Proof. With such a probability law, we have $c_2 = E\left[1/\alpha\right] = 1/\left(1-\sigma^2\right)$, hence (13) becomes:

$$R \succ Q \Leftrightarrow b_2 < \frac{1}{1-\sigma^2} = c_2 \tag{13'}$$

We are back to the criterion established by Weitzman (1974) to choose between *P* and *Q* under additive uncertainty, except that c_2 is an uncertain parameter here. Since, without uncertainty on *f*, *P* and *R* are equivalent (proposition 2), a corollary of propositions 2 and 3 is that Weitzman's criterion is still valid to choose between *P* and *Q* under multiplicative uncertainty as we have modelised it for α.

Let us turn to the choice between relative caps and price instruments. From (4), (5) and (8), the relative cap *R* should be preferred to the price instrument *P* if and only if:

$$R \succ P \Leftrightarrow b_2 > \frac{1}{1+\sigma^2}\left(\frac{E\left[1/f\right]^2 - E\left[1/f\right]}{E\left[1/f^2\right] - E\left[1/f\right]^2}\right) \tag{14}$$

From Jensen's inequality, combined with the convexity of 1/*f* and of f^2 for $f > 0$, we know that the right-hand term of (14) is positive. Neglecting for the moment the quotient in brackets, we see that *R* should be preferred to *P* if b_2 is high enough, and that a higher uncertainty on α makes *R* more interesting when compared to *P*.

To go further, we have to specify the probability law of *f*. As for α above, we assumed that *f* may take with an equal probability two values, $1+\delta$ and $1-\delta$, where $\delta \in (0,1)$ is the standard deviation. With such an assumption:

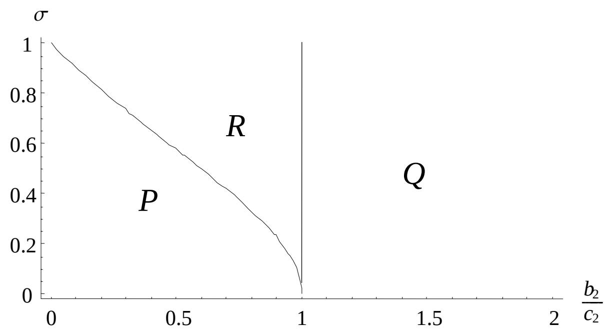
Proposition 4. If the uncertainty on *f* follows a discrete probability law with two possible realisations of an equal probability, the relative cap tends to be preferred to the price instrument if the *MEB* curve is steeper than the expected *MAC* curve. If the variance of BaU emissions rises, the relative cap becomes more interesting when compared to the price instrument.

Proof. With the probability law we assume, we have $E\left[1/f\right] = 1/\left(1-\delta^2\right)$ and $E\left[1/f^2\right] = \left(1+\delta^2\right)/\left(1-\delta^2\right)^2$, hence equation (14) can be re-written, using (12):

$$R \succ P \Leftrightarrow \frac{b_2}{c_2} > \frac{1-\sigma^2}{1+\sigma^2} \qquad (14')$$

Figure 2 below displays, in the (b_2/c_2, σ) space, the preferred instrument which yields the lowest expected total social cost, by tracing the frontiers of (12') and (13'). *R* should be preferred between the two curves, *P* to the left of the decreasing curve and *Q* to the right of the vertical line.

Figure 2. Preferred instrument in the parameters space



It turns out that for plausible values of the standard deviation, the range of values of b_2/c_2 for which *R* is the preferred instrument is extremely narrow[5]. Indeed, with the probability law we have assumed, it stems from (12') and (13') that even with a standard deviation of one third, implying a factor of two between the high and the low scenarios, b_2/c_2 should be between 0.8 and 1 for *R* to be preferred. An even higher gap between the two scenarios seems extremely unlikely, except for the very long term, but in the latter case it is possible to change the policy instruments and targets across time. For example, if we take the six greenhouse gas "marker scenarios" elaborated for the Special report on emission scenarios (SRES) of the IPCC (2000), the gap between the highest (A1FI) and the lowest (B2) emission scenarios reaches two only in 2050.

Furthermore, in concrete situations, one can expect either a very steep benefit curve in case of an ecological or health-related threshold (water eutrophication for example) or a rather flat

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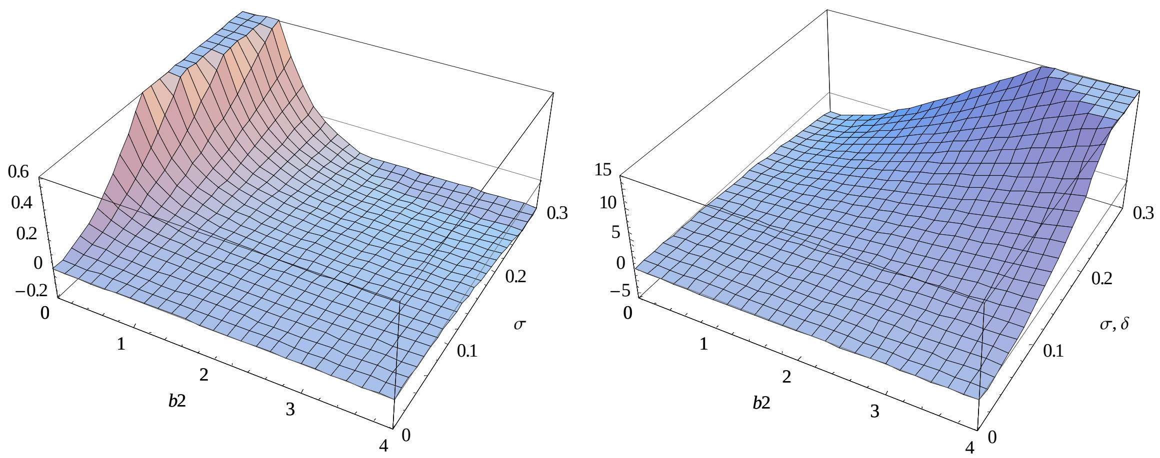
[5] Note that the frontier between *R* and *Q* is vertical, i.e., the level of uncertainty on BaU emissions does not influence the ranking of these two instruments, as soon as there is *some* uncertainty (otherwise these instruments provide an identical output, see proposition 1 above). However the level of uncertainty on BaU emissions increases the difference in expected welfare between these instruments (but does not change the sign of this difference), see Figure 3 below.

On the opposite, the level of uncertainty on BaU emissions influences both the ranking and the quantitative difference in expected welfare between *P* and *Q*.

one, if no threshold is identified. An absolute cap would be more appropriate in the former case, a price instrument in the latter one.

Quantitatively, is the difference in expected welfare significant among the instruments? Figure 3 below displays the difference in expected welfare between *R* and *Q* (left panel) and between *R* and *P* (right panel), as a percentage of total social cost *TSC*. In both cases, we took b_1=0.5, but taking other values for this parameter does not change the results much. The horizontal lines display the zero level.

Figure 3. Difference in expected welfare between *R* and *Q* (left) and between *R* and *P* (right), with b_1=0.5, in percentage of total social cost



7. Conclusions

We built an analytical stochastic model inspired by Weitzman's (1974) prices-vs.-quantities paper but featuring uncertainty both on *business-as-usual* emissions and on the slope of the marginal abatement cost curve. We compared the expected welfare from three policy instruments to reduce polluting emissions: a relative cap, by which the public authority limits the emissions/production ratio, a cap on absolute emissions and a price instrument (a tax, a subsidy or a combination of both).

The ranking of the three instruments depends on two parameters: the relative slope of marginal benefit and cost curves, and the level of uncertainty on business-as-usual emissions. As in Weitzman's original model, the absolute cap is the preferred instrument if and only if the marginal benefit curve is steeper than the marginal cost curve. If not, the price instrument is preferred in most cases, being dominated by the relative cap only if the slope of the marginal benefit and cost curves is almost equal, or if the uncertainty level of business-as-usual emissions is extremely high. For example, with the probability law we assumed (two equally likely scenarios), even if the gap between the high and low scenario reaches a factor of two, implying an very high uncertainty level, the relative cap is the best instrument only if the ratio of the marginal benefit and cost curves is between 0.8 and 1.

Such a condition seems highly unlikely. In concrete cases, one can expect the marginal benefit curve to be either very steep, in case of an ecological or health-related threshold (water eutrophication for example), or rather flat, if no threshold is identified. An absolute cap should be preferred in the former case, a price instrument in the latter one.

In most plausible cases, the relative cap is thus dominated either by the absolute cap or by the price instrument. To choose between these two instruments, Weitzman's (1974) criterion, i.e., the relative slope of the expected marginal cost and benefit curves, is still relevant.

Admittedly, if either the price instrument or the absolute cap is not available, implementing a relative cap instead of the remaining available instrument may very well enhance expected welfare. For example, a number of authors (e.g., Pizer, 1999, or Hoel and Karp, 2001) argue that a price instrument is better suited than a quantity one to tackle climate change. However, negotiating an international tax may prove even more difficult than negotiating national (absolute or relative) targets. In such a situation, uncertainty does provide a rationale for relative caps over absolute ones. This is in line with conclusions reached by several authors in a less formal framework (cf. Philibert and Pershing, 2002, and references therein). However a better compromise between price and quantity instruments does exist: an absolute cap combined with properly defined price cap and price floor yields a higher expected welfare than either the price instrument or the absolute cap with neither price cap nor price floor, as demonstrated by Robert and Spence (1976).

Finally, quantitatively, the gap in expected welfare (in percentage of total social cost) between relative and absolute caps is very low whatever the parameters. The choice between these instruments should thus be driven by other differences than the one we studied here, i.e., the way they react to uncertainty: distributional effects, incentives to inter-sectoral substitutions, monitoring costs, etc.

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