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On the costs of reducing GHG emissions and its underlying uncertainties

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1. Introduction

1.1. Background

Aimed at hampering the anthropogenic climate change the Kyoto Protocol obligates the Parties (developed countries or group of countries) to reduce or to limit GHG emissions from their base year levels. The agreement was drawn up in 1997 under the UN Framework Convention on Climate Change (UNFCCC). The emission targets, specified for each Party, need to be achieved within the commitment period of 2008-2012.
Implementing the Protocol requires accurate and verifiable inventories of emission by sources and removals by sinks conducted at a national scale (Article 5). Guidelines for such national systems have been already specified by the International Panel on Climate Change (IPCC 1996). However, uncertainty is unavoidable in preparing such large scale inventories, especially given the fact that GHG emissions are not directly measurable. They are assessed on the basis of (1) emission factor from test data or scientific calculation, and (2) activity data reflecting GHG-related activities. Both the quantities are uncertainty loaded. Reducing uncertainty level may thus be aimed at both more accurate estimation of emission factors as well as improvement in data collecting systems [7].
The uncertainty inherent in emission inventories becomes crucial in the context of emission trading scheme. Article 17 of the Protocol introduces emission trading in order to facilitate achieving the agreed reduction targets. The Parties listed in Annex B to the Protocol are allowed to buy or sell their domestic emission reduction permits. Environmental markets are regarded as an attractive policy instrument since they provide potential for cost-efficiency.

1.2. Accounting Costs of Uncertainty Reduction – Where is the Problem

When accounting costs of uncertainty reduction one should thoroughly examine dependencies between emission and uncertainty reduction. The quality of monitoring system is reflected by relative uncertainty. Thus investing in the quality of monitoring system aims at reducing relative uncertainty. Also improved estimation of emission factors will be measured in terms of relative uncertainty. On the other hand let us analyse the opposite case of financing projects that reduce just emission level while keeping the quality of monitoring system unchanged. This kind of activity will influence not only the emission level, but it also induces reduction of absolute uncertainty magnitude.
An alternative for this approach is the following: to regard uncertainty and emissions reduction as two independent processes. Then, two functions depicting cost of each of the abatement activity are believed to depend on uncorrelated variables: uncertainty level (expressed in absolute terms) and emissions level, respectively. This approach has been already applied in the literature.

1.3. Overview of the Study

Our main objective is to grasp the differences between two inverse approaches to calculating costs of uncertainty reduction. Therefore, the focus of the paper is to incorporate the idea of dependencies between emission and uncertainty reductions into existing models of economic framework under the Kyoto Protocol. We do not tend to compare the models themselves. Section 2 provides an overview of the models that will be of use in the sequel. According to our knowledge there are two publications considering analytically the problem of uncertainty in the Kyoto agreement i.e. [3] (see also [2]) and [8]. In Section 3 we present the modification of the scheme introduced in [8]. It allows to assess general differences between the former notion of uncertainty cost function and the new one. Section 4 scrutinizes [3] in order to analyse cost efficiency of the carbon market. Concluding remarks are given in Section 5.

2. Review of the Literature

Montgomery [6] proved that emission trading creates opportunity to achieve the aggregate reduction of pollution at the least total cost to all the Parties. The mechanism can be feasible under the assumption that all the transactions are made at the same point in time and at equilibrium prices known to all the Parties. That would require the full knowledge of cost functions by the central environmental agency and this fact places the countries in an unfavourable position.

Starting from this point Ermoliev *et al.* [1] developed a dynamic scheme of tradeable permit market, where permit prices are adjusted to equilibrium levels in consecutive steps. A scheme of sequential bilateral trade was analysed. Two parties with differing cost functions meet at random and exchange their permits. A new pair is picked and the procedure is repeated. The process goes on as long as there are two or more sources with differing costs. It has been demonstrated that this scheme will lead the Parties to the least cost solution, while the information about each Party's emission reduction cost function remains unrevealed.

The issue of uncertainties related to carbon reporting has been introduced into the Kyoto framework in [8]. It has been considered the case in which apart from managing its emission level a party can also actively reduce its uncertainty level. The general aim of the model is to optimise on a country's choice between emission and uncertainty reduction to meet the agreed Kyoto reduction target. The authors seek for an optimal rate of emission ΔF and uncertainty reduction $\Delta\varepsilon$. In other words, two choice variables represent exhibited reduction from the fixed initial value of emission F_0 or uncertainty ε_0, respectively.

Reduction of emission and uncertainty requires bearing some costs specified by two separate cost functions. The idea of uncertainty reduction cost function c_ε^{av} has been introduced and according to the model set-up the function c_ε^{av} depends on the level of absolute uncertainty ε. The cost of emission reduction c_F^{av} is associated with emission level F. Both functions refer to average costs.

The problem has been formulated as the maximization of the profit function π:

$$\max_{\Delta F,\Delta\varepsilon} \pi = \{[\Delta F - (\varepsilon_0 - \Delta\varepsilon)]p - c_F^{av}\cdot\Delta F - c_\varepsilon^{av}\cdot\Delta\varepsilon\} \quad (1)$$

$$\text{s.t. } KRT \leq \Delta F - (\varepsilon_0 - \Delta\varepsilon) \quad (2)$$

where p stands for the price of carbon permit, established on a competitive market. The profit function π reflects balancing costs incurred on reduction of emission and/or reduction of uncertainty with the market value of achieved emission reduction undershot by uncertainty level. The optimisation constraint specifies that at the commitment period the achieved emission reduction ΔF corrected by its uncertainty level (ε_0 - $\Delta\varepsilon$) has to be compared with the Kyoto reduction target KRT. The approach is based on the linear Verification Time concept introduced in [5].

Reduction in emission ΔF and reduction in uncertainty level $\Delta\varepsilon$ are regarded as independent of each other. Additionally, assuming that both cost functions c_ε^{av} and c_F^{av} are convex and at least twice differentiable, the concavity of the optimisation problem is assured. Setting up the Lagrangian and deriving the first order conditions allows to determine the optimal decision rule at a level of a single Party:

$$\Delta F^* = \frac{(c_\varepsilon^{av})'}{(c_\varepsilon^{av})' + (c_F^{av})'}[KRT + \varepsilon_0] + \frac{c_\varepsilon^{av} - c_F^{av}}{(c_\varepsilon^{av})' + (c_F^{av})'} \quad (3)$$

$$\Delta\varepsilon^* = \frac{\left(c_F^{av}\right)'}{\left(c_F^{av}\right)' + \left(c_F^{av}\right)'}\left[KRT + \varepsilon_0\right] + \frac{c_F^{av} - c_\varepsilon^{av}}{\left(c_\varepsilon^{av}\right)' + \left(c_F^{av}\right)'} \tag{4}$$

where $(c_F^{av})'$ and $(c_\varepsilon^{av})'$ denote the first derivatives of the corresponding cost functions.

The simulation of carbon permit market regarding uncertain reporting of carbon fluxes was provided in [3]. The equilibrium on the market is approached with the methodology of the sequential bilateral trade. Reduction of uncertainty is regarded in absolute terms and the uncertainty reduction cost function was employed to model costs of reducing 'unreported' emissions.

Consider a set of the Kyoto Parties numbered with i ($i = 1,\ldots,N$) and acting on a permit market. Each of them face a two-step optimisation problem. First, they choose between emissions and uncertainty abatement for a given amount of permits. Similarly to [8] two separate cost functions have been considered:

- $c_{F,i}(F_i)$ - the total cost for the Party i of keeping emission on the level F_i;
- $c_{\varepsilon,i}(\varepsilon_i)$ - the total cost for the Party i of keeping uncertainty on the level ε_i.

Additionally, let us denote:

- K_i – the Kyoto emissions target for the Party i;
- y_i – the number of emission permits handled by the Party i. The value may be positive (a purchaser of the permits) or negative (a supplier of the permits).

The optimisation task for an individual Party is formulated:

$$f_i(y_i) = \min_{F_i,\varepsilon_i}\left[c_{F,i}(F_i) + c_{\varepsilon,i}(\varepsilon_i)\right] \tag{5}$$

$$\text{s.t. } F_i + \varepsilon_i \le K_i + y_i \tag{6}$$

Both cost functions $c_{F,i}(F_i)$ and $c_{\varepsilon,i}(\varepsilon_i)$ are assumed to be positive, decreasing and convex in F_i and ε_i, respectively. The convexity of the function $f_i(y_i)$ is assured as it is the minimum of sum of two convex functions subject to a linear constraint. There is one solution to the task (5), (6). Setting up the Lagrangian it can be found that in the cost minimum solution the marginal costs of reducing uncertainty and emissions will be equal.

The second optimisation problem involves finding permit distribution among the Parties that would assure the least cost solution for all the sources. The aggregate cost of reaching the agreement is defined as the sum of all the individual costs:

$$\min_{y_i} \sum_{i=1}^{N} f_i(y_i) \tag{7}$$

$$\text{s.t. } \sum_{i=1}^{N} y_i = 0 \tag{8}$$

Convexity of individual cost functions $f_i(y_i)$ assures also convexity of aggregate optimisation function, thus achieving the global least cost solution. The applied sequential bilateral trading scheme is proved to converge to this equilibrium.

3. Introducing Relative Uncertainty to the 'Obersteiner *et al.*' Set-up

3.1. Necessary Conditions for the Party's Optimal Strategy

To derive conditions for the country's optimal choice we will closely follow the authors' original concept. Let c_F^{av} describe the average cost of emission reduction being dependent on ΔF and F. However, instead of the function c_ε^{av}, which corresponded with absolute uncertainty, we introduce the function of *relative* uncertainty reduction cost c_R^{av}. The function describes average costs and it depends on ΔR, and therefore on both ΔF and $\Delta\varepsilon$ correlated in the following way:

$$\Delta R = \frac{\Delta\varepsilon \cdot F_0 - \varepsilon_0 \cdot \Delta F}{F_0^{\,2}} \tag{9}$$

The new cost function c_R^{av} is introduced into the formula (1) instead of the former c_ε^{av} and consequently ΔR applied instead of $\Delta\varepsilon$:

$$\max_{\Delta F, \Delta\varepsilon}\left[(\Delta F - \varepsilon_0 + \Delta\varepsilon)p - c_F^{av} \cdot \Delta F - c_R^{av} \cdot \Delta R\right] \tag{10}$$

$$\text{s.t.} \qquad KRT \le \Delta F - \varepsilon_0 + \Delta\varepsilon \tag{11}$$

We set up the first order conditions for the maximum of the goal function (L – the Langrange function):

$$\begin{aligned}
&\frac{\partial L}{\partial \Delta F} = p - \left[(c_F^{av})' \cdot \Delta F + c_F^{av}\right] - \left[-(c_R^{av})' \cdot \frac{\varepsilon_0}{F_0^{\,2}} \cdot \Delta R + c_R^{av} \cdot \left(-\frac{\varepsilon_0}{F_0^{\,2}}\right)\right] + \lambda = 0\\
&\frac{\partial L}{\partial \Delta\varepsilon} = p - \left((c_R^{av})' \cdot \frac{1}{F_0} \cdot \Delta R + c_R^{av} \cdot \frac{1}{F_0}\right) + \lambda = 0\\
&\frac{\partial L}{\partial \lambda} = -KRT + \Delta F - \varepsilon_0 + \Delta\varepsilon = 0
\end{aligned} \tag{12}$$

Finally, we obtain the formula for the optimal ΔF:

$$\begin{aligned}
\Delta F^* = {} & \frac{\frac{1}{F_0^{\,2}}(1+R_0)(c_R^{av})'}{\left[(c_F^{av})' + \frac{\varepsilon_0}{F_0^{\,3}}(1+R_0)(c_R^{av})'\right] + (c_R^{av})'(1+R_0)\frac{1}{F_0^{\,2}}}\left[KRT + \varepsilon_0\right] + \\
& \frac{\frac{1}{F_0} c_R^{av}(1+R_0) - c_F^{av}}{\left[(c_F^{av})' + \frac{\varepsilon_0}{F_0^{\,3}}(1+R_0)(c_R^{av})'\right] + (c_R^{av})'(1+R_0)\frac{1}{F_0^{\,2}}}
\end{aligned} \tag{13}$$

as well as for the optimal $\Delta\varepsilon$:

$$\begin{aligned}
\Delta\varepsilon^* = {} & \frac{(c_F^{av})' + \frac{\varepsilon_0}{F_0^{\,3}}(1+R_0)(c_R^{av})'}{\left[(c_F^{av})' + \frac{\varepsilon_0}{F_0^{\,3}}(1+R_0)(c_R^{av})'\right] + (c_R^{av})'(1+R_0)\frac{1}{F_0^{\,2}}}\left[KRT + \varepsilon_0\right] + \\
& \frac{c_F^{av} - \frac{1}{F_0}(1+R_0)c_R^{av}}{\left[(c_F^{av})' + \frac{\varepsilon_0}{F_0^{\,3}}(1+R_0)(c_R^{av})'\right] + (c_R^{av})'(1+R_0)\frac{1}{F^2}}
\end{aligned} \tag{14}$$

where R_0 stands for the initial level of relative uncertainty $\left(R_0 = \frac{\varepsilon_0}{F_0}\right)$.

3.2. Differences Between Cost Curves of Absolute and Relative Uncertainty Reduction

We can find an analogy between the above expressions for ΔF^*, $\Delta\varepsilon^*$ (equations (13) and (14)) and the solutions of the original model in [8] (equations (3) and (4)). Particular costs and their derivatives from the original and modified version may be compared, as specified in Table 1.

Table 1. Comparison between cost functions and their derivatives – equations (3) and (4) vs. equations (13) and (14).

Obersteiner *et al.* (2000)	Modified version
c_F^{av}	c_F^{av}
$(c_F^{av})'$	$(c_F^{av})' + \frac{\varepsilon_0}{F_0^3}(1+R_0)(c_R^{av})'$
c_ε^{av}	$\frac{1}{F_0}(1+R_0)c_R^{av}$
$(c_\varepsilon^{av})'$	$\frac{1}{F_0^2}(1+R_0)(c_R^{av})'$

To carry out the comparison we require that c_F^{av} for both approaches are equal and additionally $c_\varepsilon^{av} = \frac{1}{F_0}(1+R_0)c_R^{av}$. Then, the optimal ΔF and $\Delta\varepsilon$ are calculated for the particular cases of $c_F^{av} = 0$, $c_F^{av} = c_\varepsilon^{av}$ and $c_\varepsilon^{av} = 0$, as showed in Table 2.

Table 2. Comparison between the optimal solutions for three cases.

Case	Obersteiner *et al.* (2000)	Modified version
$c_F^{av} = 0$	$\Delta F = (KRT+\varepsilon_0) + \frac{c_\varepsilon^{av}}{(c_\varepsilon^{av})'}$ $\Delta\varepsilon = -\frac{c_\varepsilon^{av}}{(c_\varepsilon^{av})'}$	$\Delta F = \frac{F_0}{F_0+\varepsilon_0}(KRT+\varepsilon_0) + \frac{F_0}{F_0+\varepsilon_0}\cdot\frac{c_\varepsilon^{av}}{(c_\varepsilon^{av})'}$ $\Delta\varepsilon = \frac{\varepsilon_0}{\varepsilon_0+F_0}(KRT+\varepsilon_0) + \frac{\varepsilon_0}{\varepsilon_0+F_0}\cdot\frac{c_\varepsilon^{av}}{(c_\varepsilon^{av})'}$
$c_F^{av} = c_\varepsilon^{av}$	$\Delta F = \frac{1}{2}(KRT+\varepsilon_0)$ $\Delta\varepsilon = \frac{1}{2}(KRT+\varepsilon_0)$	$\Delta F = KRT+\varepsilon_0$ $\Delta\varepsilon = 0$
$c_\varepsilon^{av} = 0$	$\Delta F = -\frac{c_F^{av}}{(c_F^{av})'}$ $\Delta\varepsilon = (KRT+\varepsilon_0) + \frac{c_F^{av}}{(c_F^{av})'}$	$\Delta F = -\frac{c_F^{av}}{(c_F^{av})'}$ $\Delta\varepsilon = (KRT+\varepsilon_0) + \frac{c_F^{av}}{(c_F^{av})'}$

4. Introducing Relative Uncertainty to the Emission Trading Scheme

Below we show the consequences for the carbon market resulting from introducing the concept of dependencies between the reduction of emission and its underlying uncertainties. Namely, the carbon market may be restrained from the convergence to its least cost solution among all the Parties. First, the analytical description is given and then an illustrative example follows.

4.1. The Model

Following the methodology from [3], the first step is to find the optimal level of emission and uncertainty for a single Party given a certain amount of permits y.

Reshaping the task from its original form we introduce two scales of uncertainty at the same time. In terms of minimized costs we consider relative uncertainty function $c_R(R)$. We assume that costs incurred in order to reduce uncertainty are associated with decreasing its relative level R. However, in order to comply with the Kyoto obligations it is inevitable to switch to the absolute terms. Emission level F corrected by its underlying absolute uncertainty $\varepsilon = F \cdot R$ cannot exceed the agreed Kyoto target K increased/decreased by a specific amount of permits y.

A Party's optimisation problem is restated as[1]:

$$f(y) = \min_{F,R} z(F,R) \tag{15}$$

$$\text{s.t.} \quad F + F \cdot R \le K + y \tag{16}$$

where $z(F,R) = c_F(F) + c_R(R)$

It is assumed that both cost functions $c_F(F)$ and $c_R(R)$ exhibit the same properties as in the original version. They are positive, decreasing, convex and continuously differentiable. We consider the level of emission F and the level of relative uncertainty R as being positive, which reflects reality. We also assume that $K + y > 0$ as countries are not allowed to sell more permits y than they are given their Kyoto endowments K. Furthermore, in the realistic case the constraint (16) will hold with equality since countries have no incentive to 'over-reduce' their emission below the Kyoto target and to keep their excess reduction y unsold. Hence the Lagrange function of the problem is:

$$L(F,R,\lambda) = c_F + c_R + \lambda \cdot (F + F \cdot R - K - y) \tag{17}$$

and the first order conditions become:

$$\begin{aligned} \frac{\partial L}{\partial F} &= c_F' + \lambda + \lambda \cdot R = 0 \\ \frac{\partial L}{\partial R} &= c_R' + \lambda \cdot F = 0 \\ \frac{\partial L}{\partial \lambda} &= F + F \cdot R - K - y = 0 \end{aligned} \tag{18}$$

We obtain the necessary condition for the minimization of the total costs for complying with the Protocol given a particular amount of permits y:

$$\frac{c_F'}{c_R'} = \frac{1+R}{F} = \frac{(1+R)^2}{K+y} = \frac{K+y}{F^2} \tag{19a,b,c}$$

In the cost-minimum solution the ratio between the marginal costs is dependent on both the emissions and the relative uncertainty level. In the original case of independent emission and uncertainty reduction the ratio was equal to 1.

However, according to this setting $f(y)$ is a minimum of two convex functions but subject to a constraint which is a non linear one with respect to decision variables. The sufficient condition for the solution to be a minimum requires checking the second derivative of the function $z(F, R)$ in regard to both the variables.

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[1] Starting from this point the problem may be formulated either with respect to F and R as model variables or with respect to F and ε. The conclusions would be the same.

Regarding the fact that the constraint (16) typically becomes the equality we may express the goal function as dependent on F by substituting (16) in (15):

$$z(F) = c_F(F) + c_R\left(\frac{K+y-F}{F}\right) \tag{20}$$

Then the second derivative become:

$$\left.\frac{\partial^2 z}{\partial F^2}\right|_{\frac{\partial z}{\partial F}=0} = c_F'' + \left(\frac{c_F'}{c_R'}\right)^2 \cdot c_R'' + 2\sqrt{\frac{c_F'}{c_R'}} \cdot \frac{c_F'}{\sqrt{K+y}} \tag{21}$$

The first two components of the equation (21) are positive due to convexity of the cost functions c_F and c_R. The third component is negative as the function c_F is assumed to be decreasing. Thus, depending on the values of the three components, the second derivative may become negative for the arguments for which $\frac{\partial z}{\partial F} = 0$.

Similarly we derive the goal function $z(R)$ and the corresponding second derivative:

$$z(R) = c_F\left(\frac{K+y}{1+R}\right) + c_R(R) \tag{22}$$

$$\left.\frac{\partial^2 z}{\partial R^2}\right|_{\frac{\partial z}{\partial R}=0} = c_R'' + \left(\frac{c_R'}{c_F'}\right)^2 \cdot c_F'' + 2\sqrt{\frac{c_R'}{c_F'}} \cdot \frac{c_R'}{\sqrt{K+y}} \tag{23}$$

Parallel calculations indicate that also in this case the second derivative may be negative. In general, the optimisation problem (15), (16) may appear to be non convex and there may exist few local minima.

For the permit market it would mean that the achieved solution may not be the least cost one. The market may be locked in a local solution. Reaching the global solution would then require a central agency that knew cost functions for all the countries. Feasibility of the sequential bilateral trade to reach the market equilibrium becomes questionable.

4.2. Example

To illustrate the non convexity problem in the carbon permit trade we present below the goal function simulations for the case of the USA.

The data on costs of emission reduction were estimated from the MERGE model. Provided with linear marginal cost functions of emission reduction c_F' we consider a quadratic function of emission reduction total costs $c_F(F) = b \cdot (F-a)^2$ for $F \in [0;a]$. Emission level $F = a$ reflects the baseline emission (also called a 'business-as-usual' level) performed in the absence of emission regulations.

Costs of uncertainty reduction have been much less explored in the literature. Let us model the uncertainty reduction cost function as $c_R(R) = d \cdot (R - R_0)^2$ for $R \in [0;R_0]$. R_0 indicates the 'baseline' relative uncertainty level without incurring any costs for its reduction.

The following data have been applied: $a = 1820$ MtC/year, $b = 0.2755$, $K = 1251$ MtC/year ([4] page 28), and $R_0 = 10\%$ ([2] page 9). Parameter d has been chosen arbitrarily ($d = 750\,000$). We analyse the case before trade ($y = 0$).

Consider the function $z(F)$ according to equation (20). The minimum solution holds for $F = 1440.14$ MtC/year as illustrated on Figure 1.

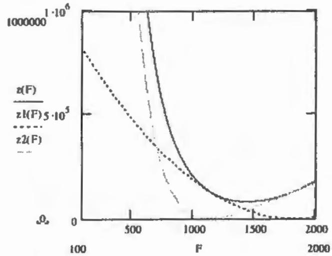

Figure 1. An example of the goal function z(F), where $z1(F) = b(F-a)^2$ and $z2(F) = d(\frac{K+y-F}{F} - R_0)^2$ (the case of the real Kyoto target K = 1251 MtC/year).

There is one global solution in this case, however, let us analyse the first order conditions. We require the first derivative of $z(F)$ to be equal to zero:

$$2b(F-a)^2 - 2d(\frac{K+y}{F} - 1 - R_0)\cdot\frac{K+y}{F^2} = 0 \tag{24}$$

which may be reshaped into:

$$F^3(F-a) + \frac{d}{b}(K+y)(1+R_0)(F - \frac{K+y}{1+R_0}) = 0 \tag{25}$$

It can be noticed that for $\frac{K+y}{1+R_0} = a$ equation (25) takes form:

$$(F-a)\left[F^3 + \frac{b}{d}(K+y)(1+R_0)\right] = 0 \tag{26}$$

and it has only one positive solution $F = a$ which is also a root of equations $z1(F) = 0$ and $z2(F) = 0$. This feature holds also in some neighbourhood of the point a. Therefore, if the roots of $z1(F) = 0$ and $z2(F) = 0$ are sufficiently remote, there may exist more than one minimum (see the Figure 2).

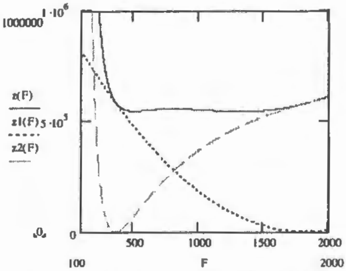

Figure 2. An example of two minima goal function (the case of a hypothetical Kyoto target K = 400MtC).

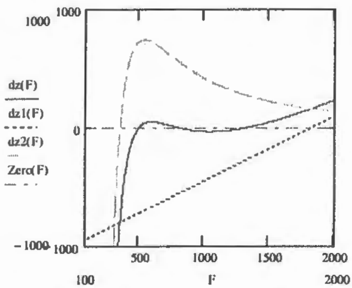

Figure 3. The first derivative dz(F) of the two minima goal function z(F) and its two components z1(F) and z2(F).

5. Concluding Remarks

The presented work puts under discussion the methodology of cost calculations related to uncertainty abatement in reporting GHG emissions. Two approaches have been contrasted. The first one, developed so far in the literature, reflects emissions and uncertainty reduction as two independent processes. The suggested approach captures a 'real-life' cross-correlation between the mentioned activities since costs of uncertainty reduction are measured in terms of relative uncertainty. The concept has been applied into two economic schemes that consider the uncertainty problem under the Kyoto framework.

Basing on the set-up introduced in [8] we are in the position to outline a general comparison between two approaches.

Potential performance of the carbon permit market has been also examined following [5]. It shows that there exist danger of non-effective solutions when introducing the idea of cost function for relative uncertainty reduction. The sequential bilateral trading scheme is no longer valid to converge to the least cost solution. A central agency with perfect knowledge about cost curves among all the Parties would be required in such a case.

Calculations are general enough to enable drawing conclusions beyond the Kyoto case. It can be stated that there exist trade-off between the extent of reflecting reality in the design of permit market and its efficiency as an environmental policy instrument. Therefore, perhaps a kind of combined approach to cost calculations of uncertainty reduction should be considered in the future.

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