Pricing externalities

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Abstract:

The efficiency of mechanisms to control activities with negative externalities is limited by uncertainty about the social costs of these activities. Existing regulatory mechanisms require negotiated compromise about either the prices of activities or the levels to be tolerated. We offer a mechanism in which today's price of an activity is a market-based estimate of future informed beliefs about the social cost of today's activity. This can be expected to increase the precision and accuracy of estimates of the right price and to make it likely that agents will base their decisions on better estimates of the harm they cause.

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1. Introduction

Efficiency requires that every person bear the full social cost and receive the full social benefit of his actions. When a person would otherwise bear less than the full social cost of his actions, a Pigouvian tax equal to the difference between the social cost and the private cost of his actions provides him with an incentive to reduce his activity to the efficient amount. If the social cost is not directly observable, then it must be estimated. A common objection to Pigouvian taxes is that it is often difficult to establish the social cost of negative externalities with sufficient accuracy. In this paper we describe a pricing mechanism that reduces the severity of this objection.

While it is relatively straightforward to assess the social costs of activities that affect marketable goods directly—for example, the social cost of a factory whose smoke emissions harm the business of a nearby laundry—it is much more difficult to determine social costs if there is uncertainty about the physical extent of the externality and the amount of harm that a specified extent of the externality causes. For example, while there is considerable agreement that today's emissions of CO_2 have social costs that deserve attention, there is much less agreement about the magnitude of these costs, partly because of uncertainty about the impact of emissions of CO_2 on climate and partly because of uncertainty about the economic costs of climate change. How should the level of a Pigouvian tax on CO_2 emissions be determined under these circumstances?

We propose a pricing mechanism that is based on two simple ideas. First, the degree of uncertainty regarding the social cost of many activities can be expected to decrease over time as society learns more about the physical, social, and economic effects of these activities. For example, while the social costs of using the insecticide DDT were not well known in the 1940s and 1950s, peoples' understanding of these costs increased as they learned about the persistence of DDT and its danger to human and animal health. By the 1970s, the social cost of any usage of DDT during the 1940s and 1950s could be estimated with much less uncertainty than before. Similarly, while there is still considerable uncertainty about the social costs of CO_2 emissions, the range of estimates of these costs has decreased during the past decade. For example, the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 1995 reported estimates of social costs between \$5 and \$125/tCO_2, while the IPCC's Fourth Assessment Report in 2007 reported a 20 percent smaller range (-\$3 to \$95/tCO_2, from 100 estimates) with an average of \$12/tCO_2.[3] The fact that the range of estimates has decreased considerably during the relatively short span of 12 years suggests that future scientific and economic research may reduce the uncertainty of the social cost of CO_2 emissions even further, making the best estimates of the harm from today's CO_2 emissions much more precise and accurate, say, 30 years from now than they are today.[4]

Whenever such increases in understanding reduce the uncertainty about the social cost of today's activities, future estimates of the social costs of today's activities will be more accurate than today's estimates. Thus if it were possible to levy today's Pigouvian taxes on the

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[3] The ranges are reported in IPCC (1996, p.51) and IPCC (2007, p.69). The 1996 report does not list an average value.

[4] For example, the 1995 IPCC report emphasized that "[t]his range of estimates does not represent the full range of uncertainty. The estimates are also based on models that remain simplistic and are limited representations of the actual climate processes in being and are based on earlier IPCC scientific reports. The wide range of damage estimates reflects variations in model scenarios, discount rates and other assumptions. It must be emphasized that the social cost estimates have a wide range of uncertainty because of limited knowledge of impacts, uncertain future technological and socio-economic developments, and the possibility of catastrophic events or surprises." (IPCC, 1996, p.51). The 2007 report states that "[i]t is very likely that globally aggregated figures underestimate the damage costs because they cannot include many non-quantifiable impacts" (IPCC, 2007, p.69).

basis of future—rather than today's—estimates of the social cost of today's externalities, then it would be possible to allocate resources more efficiently today.

The second idea on which our mechanism is based is that futures and prediction markets provide the best known way of predicting a future statistic. For example, Hamilton (2009) shows that near-term futures contracts of the federal funds rate are very accurate predictors of the federal funds rate. Dohlman *et al*. (2000) suggests that the futures market for soybeans provides a better estimate of the future price of soybeans than predictions obtained by compiling information from a number of statistical reports produced by the USDA and other governmental agencies.[5] Similarly, the Iowa Electronic Markets regularly predict the outcome of elections more accurately than the average poll and, arguably, even the best poll.[6] Thus a market in future externality costs can be expected to provide a better estimate of the future perceived costs of externalities than an average of the surveyed opinions of those who generate, experience, or regulate those externalities.

We show in this paper how, for harmful activities whose quantities can be measured with sufficient accuracy at a non-prohibitive cost, it is possible to charge for their negative externalities according to market-based estimates of future assessments of their costs. This is accomplished with a combination of (1) government bonds that those who cause the negative externality in question are required to purchase and whose redemption value is what is left after paying the external cost of a given quantity of a harmful activity today (as estimated on a specified future date), and (2) a market in which these bonds can be traded. The mandatory

[5] They find that predictions based on soybean futures have a smaller mean square error than the predictions made by the US Department of Agriculture in their *World Agricultural Supply and Demand Estimates*,

[6] See Berg *et al*. (2008a) for an analysis of the accuracy of the Iowa Electronic Markets in the 1988 – 2004 United States presidential elections.

purchase of such government bonds, in conjunction with the opportunity to sell the bonds in a market, is equivalent to the mandatory payment of a Pigouvian tax that reflects the best available estimate of the social cost of the externality. The higher current informed estimates of the future estimate of the social cost of today's activity are, the lower the bond's market value will be. The bond's market price implies a guess by the bond's buyers and sellers of what the regulatory estimate of the social cost of today's activity will be at the specified future date.

Pricing externalities in this way is likely to lead to more accurate estimates of their social costs than what a regulatory agency in charge of determining the appropriate Pigouvian taxes can achieve. In addition to this direct efficiency gain, the marketable bonds make it more difficult than it is with conventional methods to base regulation on goals other than improving economic efficiency. Because the total value of the obligations to pay for today's externalities will be determined at a time that is many years in the future, it is less feasible to use such regulation for short-term political gain. The bond market would make willful underassessment of the costs of today's externalities visible because the bonds would be valued at zero immediately. By providing an opportunity to sell the bonds, the market also permits those who generate negative externalities to escape willful overestimation of social costs.

The idea of relating today's Pigouvian taxes to anticipated changes in society's understanding about costs is not new. Karp and Zhang (2006) describe a dynamic model in which a regulator bases current regulation on what he expects to know in future years about the social cost of today's externalities. The models by Kolstad (1996), Kelly and Kolstad (1999), and Leach (2007) that incorporate learning and are solved numerically for their respective dynamic equilibrium growth paths incorporate anticipated learning implicitly. Our contribution differs from that of previous work in two ways. First, we develop a market mechanism that incorporates today's expectations about future information regarding the costs of today's externalities into today's corrective tax, rather than assuming that regulators are able to choose the most accurate tax on the basis of their own expectations. Second, our mechanism ensures that, as long as society's future understanding of the cost of today's emissions does not exceed the maximum cost considered possible today, somebody will ultimately pay the social cost of today's externalities.

In this paper we focus exclusively on the comparison of our market mechanism with traditional Pigouvian taxes and tradable allowances, and we do not model how society's knowledge of the costs of externalities changes over time. Kelly and Kolstad (1999) and Leach (2007) have developed models of climate change in which a social planner uses Bayesian updating to incorporate observed realizations of the stochastic relationship between temperature and greenhouse gas concentrations into his belief structure about costs. While it would be straightforward to include a similar system of learning here, we believe that doing so would distract from conveying understanding of our mechanism. For our mechanism to work, it is irrelevant how and at what rate society accumulates knowledge about costs—what matters is only that there is an improvement over time in society's understanding of what tax would have been optimal for externalities that were generated earlier. We therefore investigate the circumstances under which our pricing mechanism provides different incentives than traditional mechanisms for the generation of externalities.

The remainder of this paper is organized as follows: We describe the efficient Pigouvian tax on externalities with uncertain social cost in Section 2, and our alternative pricing mechanism in Section 3. In Section 4, we compare our mechanism with conventional emission taxes and tradable allowances, and we conclude in Section 5.

2. The optimal Pigouvian tax on a negative externality with uncertain social cost

Consider the standard model of an activity (say production) that causes a negative externality (say pollution). We refer to the agents who undertake the activity as emitters and to the quantity of the negative externality generated by agent i at time t, $Q_i(t)$ as the amount of emitter i's emissions at time t. Let $V(Q_i(t))$ be the value to emitter i of the opportunity to emit at level Q_i at time t,[7] and let $D(Q_i(t), M(t))$ be the social cost of the damages caused by emitter i's emissions at time t, where $M(t)$ is a vector of all factors besides $Q_i(t)$ that influence the damages caused by emitter i's emissions. These factors include the remnants of emissions from earlier years (the current ambient level of pollution), total emissions at time t, $Q(t)$, as well as the path of future emissions if $Q_i(t)$ causes damages in future years that depend on the level of pollution in these years. Social efficiency requires that the marginal benefit per unit of emissions equal the marginal cost of the emissions, or

$$\frac{\partial V}{\partial Q_i(t)} = \frac{\partial D}{\partial Q_i(t)}. \qquad (1)$$

[7] All emitters enjoy the same marginal benefit of emissions if markets are competitive, so $V(\cdot)$ does not require a subscript.

A regulator who knows the marginal cost and benefit schedules can provide an incentive to the emitter to emit the efficient quantity by charging him a Pigouvian tax per unit of emissions equal to $\partial D/\partial Q(t)$ at the social optimal level of emissions, $Q(t)^*$.[8]

Actual regulators generally do not know the marginal cost and benefit schedules with certainty. Because market transactions provide information about the private cost and benefits of production, we assume that regulators are able to estimate the benefit of additional emissions, $\partial V/\partial Q(t)$, fairly accurately and we ignore uncertainty about $\partial V/\partial Q(t)$.[9] However, there are several reasons why uncertainty about the social cost of additional emissions, $\partial D/\partial Q(t)$, is generally much larger. First, there is likely to be some uncertainty about how much pollution a unit of emissions causes and how costly this pollution is to society. Second, since the marginal social cost of emitter i's emissions generally depends on total emissions, determination of the optimal Pigouvian tax requires that regulators forecast total time t emissions before they can determine the marginal social cost caused by any one emitter.

Third, the uncertainty about the marginal social cost of emissions is even higher for emissions that do not dissipate quickly and cause additional damages in future years. If the marginal damages of emissions depend on the level of pollution, then the damages caused by the remnants of time t's emissions in future years depend on the path of future emissions up to the time when time t's emissions have dissipated sufficiently to cause no further harm. In this case, in order to estimate the full marginal social cost of time t's emissions, regulators must

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[8] Note that $\partial D/\partial Q(t) = \partial D/\partial Q_i(t)$.

[9] Because uncertainty about $\partial V/\partial Q(t)$ affects the accuracy of traditional Pigouvian taxes and our mechanism in the same way, accommodating such uncertainty would complicate the notation without yielding additional insights into our pricing mechanism.

predict the future course of the ambient density, which requires that they combine a measure of the current ambient density of the pollutant with a forecast of the path of future emissions, in a model of how the pollutant is dissipated.

With uncertain social costs of emissions, there is no specifiable policy that can provide an incentive to emitters to emit exactly the amount at which the marginal benefit per unit of emissions equals the marginal cost of emissions. The best society can do is to discourage activities whose benefits are less than the best estimate of their harm, including the expected harm caused by the fact that the harm is uncertain. To quantify the argument, let the random variable $X(t)$, with probability density function $f(x(t))$, describe the regulator's beliefs about the marginal social cost of a unit of emissions at time t and let the random vector $M(t)$, with joint probability density function $g(m(t))$, describe the regulator's beliefs about the factors that affect the marginal social cost of emissions at time t. The expected marginal social cost of emissions at time t is

$$E[X(t)] = \int (\int_0^\infty x(t) f(x(t) \mid M(t) = m(t))\, dx(t)) g(m(t)) dm(t)\,, \tag{2}$$

where $f(x(t) \mid M(t) = m(t))$ is the conditional density function of the regulator's beliefs about the harm of emissions, depending on a specific set of beliefs about $M(t)$.

Uncertainty of $\partial D/\partial Q$ leads to two types of costs that affect the optimal Pigouvian tax. First, if society is risk averse and thus places a positive risk premium on harm that is uncertain, then the optimal tax exceeds $E[X(t)]$. In principle it is straightforward to adjust Pigouvian taxes to account for the cost of uncertainty. In practice such adjustments require that regulators be able to estimate the degree of social risk aversion with sufficient accuracy. Because estimates of social risk aversion are notoriously difficult to obtain, it would be advantageous to assign the social cost of uncertainty to those who cause the uncertainty, in ways that do not require regulators to estimate this cost.

Second, even in a risk-neutral society, setting the tax equal to $E[X(t)]$ does not lead to efficient emissions whenever the true marginal cost of emissions differs from $E[X(t)]$. Thus when the harm of emissions is uncertain, the expected inefficiency cost of any Pigouvian tax is positive. Given a tax $T(t)$ and a specific belief about the harm of the marginal unit of emissions, $x_0(t)$, let $B(T(t), x_0(t))$ denote either the lost net consumer surplus (if the tax exceeds the harm so that emissions are reduced too much) or the cost of exposure to inefficiently high emissions (if the harm exceeds the tax so that emissions are reduced too little). Figure 1 shows these costs for the case of two beliefs about the harm of emissions, $x_1(t)$ and $x_2(t)$, with $f(x_1(t)|M(t) = m_0(t)) = f(x_2(t)|M(t) = m_0(t)) = ½$. To keep the figure simple, we assume that there is no uncertainty about the elements in $M(t)$, so that $g(m_0)$ has a mass point of 1 at a particular vector of conditions. Given $\partial V/\partial Q$, setting $T = E[X(t)] = ½x_1(t) + ½x_2(t)$ provides emitters with the incentive to reduce emissions from Q_0 to Q^*. However, this reduction is too small if belief $x_1(t)$ is correct, leading to excess emissions cost *abc*, while the reduction is too large if $x_2(t)$ is correct, leading to a loss of consumer surplus *ade*. The expected inefficiency cost of the tax is the weighted average of these costs, or, in general,

$$E[B] = \int (\int_0^\infty B(T(t), x(t)) f(x(t) \mid M(t) = m(t))\, dx(t)) g(m(t)) dm(t)\,. \qquad (3)$$

If the social cost of emissions is known with certainty, then $f(x(t) \mid M(t) = m(t))$ has a mass point of 1 at $\partial D/\partial Q(t)$ and the expected inefficiency cost of tax $T(t) = \partial D/\partial Q(t)$ is zero. If the social cost of emissions is not known with certainty and the costs $B(\cdot)$ are symmetric around the efficient quantity of emissions, as it is the case when the marginal cost and benefit schedules are linear, then $T(t) = E[X(t)]$ minimizes the expected cost $E[B]$.[10] But if these schedules are non-linear, then the tax with the lowest expected cost generally differs from $E[X(t)]$ because $T(t) = E[X(t)]$ minimizes $E[B]$ only by chance.

Equations (2) and (3) indicate that regulators must choose the Pigouvian tax on the basis of their beliefs about the social harm of emissions, as described by $X(t)$. It is intuitive that a tax based on the most accurate and precise beliefs about this harm—that is, the set of beliefs that describes society's knowledge of $\partial D/\partial Q$ as well as possible—is the tax most likely to lead to socially optimal emissions. Because it is unreasonable to expect that regulators' beliefs will always incorporate all statistically valuable knowledge about $\partial D/\partial Q$, it is useful to devise a mechanism that permits Pigouvian taxes to be based on the best information available about the harm of emissions. In the following section, we describe a market in emissions bonds that achieves this goal.

3. A market in emission bonds that prices the uncertain social cost of emissions

Let t be the time when an emission occurs, let s be a later time when an estimate of the cost of time t emissions is made, and let a subscript indicate the time when the estimate is made and a date in parentheses the time when the emission to be priced occurred. Thus the random variable $X_s(t)$ denotes the regulator's beliefs at time s of the social cost of a marginal unit of

[10] This result follows from the fact that with linear marginal benefit and cost schedules, the vertical edge of the cost triangle (the harm per unit of emission) is directly proportional to the area of the cost triangle.

emissions at time *t*, with probability density function $f(x_s(t))$, where $x_s(t)$ is discounted to time *t*. There are two reasons why, at times *t* and *s*, a regulator may have different views as to the optimal tax for time *t* emissions. First, if the social cost per unit of emissions varies with total emissions and if emissions prevail over several years, then the tax at time *t* will have been based on the regulator's forecast of what the path of total emissions would be under the tax. At time *s*, total emissions between times *t* and *s* can be estimated with much greater accuracy than they can be forecast at time *t*, so that the time *s* estimate will almost certainly differ from the time *t* forecast.[11] Thus the tax considered optimal at time *t* will almost certainly not be considered optimal at time *s*. Second, if the regulator's understanding of the social harm of time *t* emissions has improved between time *t* and time *s* so that the mean or variance of $X_s(t)$ differs from that associated with $X_t(t)$, then the tax that the regulator considered optimal at time *t*, given the information available then, is likely to be no longer optimal in retrospect, given the information available at time *s*.

We argue that the accuracy of the corrective mechanism at time *t* can be improved by replacing the Pigouvian tax that emitters have to pay with a tradable bond that emitters are required to purchase. Assume that every emitter at time *t* is required to buy, for each unit emitted, a special zero-coupon government bond with a maturity of τ years, whose face value equals what regulators believe to be the *upper limit* of reasonable estimates of the social cost of a marginal unit of emissions at time *t*,

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[11] If emissions are observable at low cost or if all emitters can be required to pay the tax, then total emissions between times *t* and *s* will be known with certainty at time *s*. Total emissions need to be estimated if some emissions cannot be measured accurately—for example, because they have natural sources—or if it is too expensive to measure the emissions of small emitters.

$$E[X_t^{MAX}(t)] = \int x_{m_t(t)}^{MAX}(t) g(m_t(t)) dr_t(t), \tag{4}$$

where, for any realization $m_t(t)$, $x_{m_t(t)}^{MAX}$ is the largest value for which $f(x_t(t) \mid M_t(t) = m_t(t)) > 0$. When the bond matures at time $t + \tau$, the regulator will estimate the social cost, discounted to time t, of the marginal unit of emissions at time $t, E[X_{t+\tau}(t)]$. Because the bond's main purpose is to take advantage of future reductions in the uncertainty regarding the harm of today's emissions, τ must be sufficiently long—say 30 years—for such reductions in uncertainty to occur with some reasonable probability.[12] The bond's redemption value at time $t + \tau$ is

$$R_{t+\tau} = \max[E[X_t^{MAX}(t)] - E[X_{t+\tau}(t)], 0]\,(1+i_t)^{\tau}, \tag{4}$$

where i_t is the interest rate for conventional τ-year zero-coupon government bonds that prevailed at time *t*, and the first expectation describes the bond's face value at time *t* while the second expectation represents the regulator's expected value at time $t + \tau$.

The bond's face value must be set at the upper limit of the range of reasonable estimates of harm per unit of emissions, rather than at today's estimate of the most likely harm, to ensure that bond holders pay for the harm of emissions if this harm turns out to exceed the harm that was considered most likely at time *t*. If the redemption value is positive, then an emitter of one unit who buys a bond at time *t* and holds it for τ years will have paid the upper limit of time $t + \tau$ estimates of the costs that he caused τ years earlier by emitting one unit, and

[12] Leach (2007) concludes that it may take thousands of years to learn the complete details of environmental processes and the associated harm of production with reasonable accuracy. However, our mechanism is based on the idea that the uncertainty gets reduced—not resolved—between times t and $t + \tau$. Given the increases in people's understanding of the harm of various externalities (for example, the externalities generated by chlorofluorocarbon, DDT, cigarettes) during the past 30 years, this does not seem an unduly short period.

he will receive a refund for the amount he overpaid in year t, plus accrued interest. If the time $t+\tau$ estimate of the social cost exceeds the time t estimate of the social cost's upper limit, then the bond's redemption value is zero. It seems appropriate for society to bear the burden of any cost that exceeds the maximum social cost that could be expected at time t.

It is worth emphasizing that $x_{m_t(t)}^{MAX}$ represents the upper limit of the harm that can reasonably be expected and not the upper limit of imaginable harm. While the upper limit of imaginable harm can be quite large, the upper limit of the reasonably expectable harm is generally much smaller. For example, some people have expressed concern that the use of the Large Hadron Collider (LHC) near Geneva, Switzerland might create a microscopic black hole that may cause serious damage to Earth. However, the LHC Safety Assessment Group concluded that this would be a very unlikely outcome of the experiments, and that the maximum harm that can reasonably be expected from operating the LHC is close to zero.[13] Similarly the upper limit of imaginable harm that could be caused by the destruction of a nuclear power plant is quite large, while the upper limit of the harm that can reasonably be expected from operating a nuclear power plant over its expected life is much smaller. The density function $f(x_t(t)\,|\,M_t(t)=m_t(t))$ therefore reflects the weights that the regulator assigns to all reasonable estimates of harm. For example, the 2007 IPCC report refers to 100 estimates of the social cost of CO_2 emissions in the range of -\$3 to \$95/tCO_2 and uses these estimates to derive an average value of \$12/tCO_2. Thus \$95/tCO_2 is the largest value for which $f(x_{2007}(2007)\,|\,M_{2007}(2007)=m_{2007}(2007))>0$ and therefore $x_{m_{2007}(2007)}^{MAX}=\$95/\mathrm{tCO}_2$.

[13] See Ellis *et al*. (2008)

The ongoing debate about the safety of nuclear power plants and the storage of nuclear waste indicates that even the upper limit of harm that can reasonably be expected may be quite large. In some cases $x_{m_t(t)}^{MAX}$ may be large enough for liquidity constraints to prevent potential emitters from buying the bonds and thus from engaging in the harmful activity. It seems appropriate to prevent potential emitters from operating if they are unable to make a deposit that covers the largest harm that can reasonably be expected. Similarly, if at time t the regulator believes that there is a noticeable positive probability that emissions will lead to a catastrophic event whose discounted costs are infinite, then no finite face value for the bond will be adequate and the activity should be prohibited.

If $X_{t+\tau}(t) = X_t(t)$, then an emitter of one unit who buys a bond at time t and holds it for τ years receives a refund at time $t + \tau$ for the overpayment that was anticipated at time t, plus interest. Thus if beliefs about the social cost of time t emissions do not change between time t and time $t + \tau$, then the emitter's net payment per unit of his emissions is the same as what he would have paid under a traditional Pigouvian tax with $T = E[X_t(t)]$. If, however, beliefs about the harm of time t emissions change between time t and time $t + \tau$, then the bond's redemption value reflects these changes, and the emitter's net payment differs from what he would have paid under a traditional Pigouvian tax.

Because the ultimate payment for time t emission equals $E[X_{t+\tau}(t)]$ as long as this amount does not exceed $E[X_t^{MAX}(t)]$, the requirement that emitters purchase emission bonds minimizes the expected inefficiency cost $E[B]$ if the marginal benefit and cost schedules are linear, but not necessarily if these schedules are non-linear. Nevertheless, this should not be counted against our mechanism, at least when it is compared with traditional Pigouvian taxes. First, because it is generally difficult to estimate non-linearities in cost and benefit schedules with sufficient accuracy, any Pigouvian mechanism—not just ours—may need to be based on linear approximations of these schedules in practice. Second, the difference between the expected inefficiency costs of a payment equal to $E[X_s(t)]$ and the payment that minimizes $E[B]$ generally increases with the dispersion in beliefs about the magnitude of the social cost of emissions. Because the dispersion in beliefs is likely to decrease between time t and time $t + \tau$ as additional information becomes available, the difference between the expected inefficiency costs of $E[X_s(t)]$ and the payment that minimizes $E[B]$ is likely to decrease as well.[14] Thus the expected inefficiency cost of a corrective payment based on $E[X_s(t)]$ is likely to be closer to the minimum inefficiency cost than that of a Pigouvian tax based on expected cost at time t.

The second part of our pricing mechanism is a market in emission bonds. This market ensures that at any point in time, s, the bond's price reflects the present value of the bond's expected redemption value at time $t + \tau$. Because risk averse traders discount uncertain future payments at higher rates than certain future payments, the bond's price at any time $s < t + \tau$ reflects the fact that the harm of time t emissions is uncertain.[15] The requirement that emitters purchase emission bonds at $E[X_t^{MAX}(t)]$ thus ensures that emitters bear the cost of the uncertainty that they cause, and no separate estimate of the cost of uncertainty is needed. The

[14] For example, the models by Kelly and Kolstad (1999) and Leach (2007) that assume Bayesian learning show that the variances in the beliefs about uncertain parameters decrease over time.

[15] For example, Piazzesi and Swanson (2008) show that federal funds futures contain a risk premium and thus reflect the uncertainty of future monetary policy.

bond market also enables emitters to pay others who are better bearers of uncertainty to bear the cost of the uncertainty until the uncertainty is resolved at time $t + \tau$.

As long as the market does not expect the cost of time t emissions to exceed $E[X_t^{MAX}(t)]$ with positive probability, the market price predicts the regulator's time $t + \tau$ estimate of the harm of one unit of emissions in year t. This is not the case if there is a positive probability that the bond's redemption value will be zero. But because emitters will not be held responsible for harm above the upper limit of today's estimates, the bond's price nevertheless predicts the bond's redemption value and thereby permits straightforward assessment of the liabilities of emitters. The bond market also provides emitters with liquidity, because emitters who do not wish to hold bonds can sell their bonds and thereby recover the present value of the current prediction of their overpayment. Thus there should be no concern that the requirement to buy bonds at $E[X_t^{MAX}(t)]$ instead of $E[X_t(t)]$ might lead to inefficiently low emissions as a consequence of liquidity constraints. A value of $E[X_t^{MAX}(t)]$ that is so high that liquidity constraints effectively eliminate the market in these bonds indicates that the harm that can reasonably be expected is so large that it is appropriate to prohibit all emissions.

As a numerical example, consider the social harm caused by CO_2 emissions and the estimates reported by the IPCC that we cite in the introduction. In 1995, the IPCC reported estimates of the social cost per ton of CO_2 emissions between \$5 and \$125/tCO_2. For the sake of the argument, we assume that the 1995 estimate of the social cost per ton of CO_2 emissions was the average of the estimates, \$23.40/tCO_2, and that this would have been the 1995 tax rate for a conventional Pigouvian tax.[16] Under our alternative pricing mechanism, an emitter in 1995 would have been required to purchase, for each ton of CO_2 emissions, a 30-year bond at a price of $125. Assume, again for the sake of the argument, that $23.40/t$CO_2$ was also the best guess in 1995 of the 2025 estimate of the social cost per ton of 1995 CO_2 emissions. Since the 1995 zero-coupon rate of 30-year bonds was about 9 percent, bond holders would have expected to receive a payment in 2025 of $(\$125 – \$23.40) * 1.09^{30}$ = $1,348 per bond, and the bond would have traded at $125 – $23.40 = $101.60 immediately after emitters had purchased it. Thus an emitter who did not want to hold the bond for 30 years could have sold it at this price and would therefore have paid the same amount as he would have paid under the traditional Pigouvian tax.

In 2007, the IPCC reported a mean value of all estimates of the social cost of CO_2 emissions of $12/t$CO_2$. If we assume that this would also have been the best guess in 2007 of what the regulator's 2025 estimate of the social cost of 1995 CO_2 emissions will be, then bond holders in 2007 could have expected a payment in 2025 of $(\$125 – \$12) * 1.09^{30}$ = $1,499.25 per bond, and, at a prevailing discount rate of about 4 percent in 2007, the bond would have traded at $\$1,499.25/1.04^{18}$ = $740. However, if bond holders had expected the best estimate of the social cost of CO_2 emissions to continue to fall at an annual rate of 5.72 percent (the annualized rate at which the estimate fell between 1995 and 2007), then they would have expected the regulator's 2025 estimate to be $4.41/t$CO_2$ for a redemption value of $(\$125 – \$4.41) * 1.09^{30}$ = $1,599 per bond, so that the bond's 2007 value would have been

[16] Because the IPCC reports neither individual values nor an average value for 1995, the location of our estimate within the reported range of estimates corresponds to the location of the average value of $12/t$CO_2$ that the IPCC reports for the 2007 range of -$3 and $95/t$CO_2$.

$1,599/1.04^{18} = $789.78. If the estimate of $4.41/t$CO_2$ turned out to be correct, then an emitter who held the bond for 30 years would be as well off as if he had paid $4.41/t$CO_2$ for his 1995 emissions and had invested $120.59 in a 30-year bond at 9 percent interest. Under the conventional Pigouvian tax, however, he would have had to bear the entire cost of 18.99/tCO_2 at which the regulator overestimated the social cost of CO_2 emissions in 1995. In contrast, if the 2025 estimate of the social cost of 1995 emissions turns out to be above $23.30, then under a conventional Pigouvian tax society will bear the entire cost of the 1995 underassessment. Under our mechanism the additional cost, up to $101.60, would be borne by some or all of the persons who held the bond between 1995 and 2025, and the proceeds from the bonds could be used to compensate those who were harmed by the emissions. Society would bear only those costs that exceed the maximum harm of $125/t$CO_2$ that could reasonably have been predicted in 1995.

4. Comparison of our pricing mechanism with conventional Pigouvian taxes and tradable allowances

The implementation of conventional Pigouvian mechanisms requires that regulators estimate and charge emitters the cost of the harm of their emissions at time t when the emissions occur.[17] Our pricing mechanism requires (1) regulators to set an upper limit of the cost of this harm at time t, (2) emitters to purchase bonds corresponding to this upper limit of the cost, and (3) regulators to assess at time $t + \tau$ the harm of emissions that had occurred τ years earlier and

[17] For tradable allowances, regulators must assess the social cost of emissions to determine the optimal number of allowances that they issue. Emitters who do not receive allowances free of charge must pay this cost to acquire the initial allowances from the regulator.

refund, to those who hold the bonds at time $t + \tau$, the difference between the initial time t payment and the time $t + \tau$ assessment, plus interest. The attractiveness of any such corrective mechanism depends on the incentives that regulators have to assess, as accurately as they can, the cost of emissions. If regulatory mechanisms come to be based on political considerations rather than on the best estimates of what control parameters are optimal, then those mechanisms are unlikely to lead to more efficient emissions. We therefore evaluate our pricing mechanism under two models of government—we first assume that regulators are motivated primarily by efficiency considerations (which is a standard assumption in most of the literature that uses computable models to investigate the effects of environmental regulation), and then that regulators are motivated by considerations other than efficiency. We argue that our pricing mechanism is more attractive than conventional Pigouvian mechanisms for both types of regulators.

4.1 Efficiency-motivated regulators

Let $c_t(t)$ be the net cost of emissions to an emitter at time t if he buys the required bonds and immediately sells them in the secondary market. Our pricing mechanism leads to more efficient emissions at time t than traditional Pigouvian mechanisms if $c_t(t)$ is a more accurate estimate of the social cost of time t emissions than an estimate made by a regulator at time t.

Although there is no reason to expect that one estimate will *always* be more accurate than the other, we can reasonably expect that $c_t(t)$ will be more accurate *on average*. There is considerable evidence that futures and prediction markets lead to more accurate predictions than other forecast mechanisms, and our emission bond market works essentially like such markets.[18] Regulators who seek to provide producers with the incentive to operate at socially efficient levels of emissions have an incentive to estimate the social cost of emissions as accurately as possible, update their estimates when new information becomes available, and make their new estimates public if they believe that producers will act more efficiently if they have access to the regulators' estimates. The participants in the bond market therefore know how regulators expect to assess the social cost of time t emissions at time $t + \tau$. In addition, they can also draw on every piece of additional information about the social cost of emissions that they expect to change the regulators' assessments in the future. Thus if regulators are motivated by efficiency considerations, then the information that they use to determined the bond's face value is a subset of the information that determines $c_t(t)$. We would therefore expect the market to predict the future assessment of social cost at least as accurately as regulators, and more accurately if market participants have access to information that is unavailable to regulators. In addition, regulators may form their expectations about the cost of emissions in ways that are inferior to those used by better informed market participants. Roos (2008) provides evidence that the expectations of lay persons differ from the expectations of experts. While regulators are likely to have some knowledge of the emissions they are regulating, it is unlikely that they are generally as well informed as those who undertake active research in medicine, biology, and climatology. Thus our pricing mechanism is likely to achieve a more efficient reduction in emissions than conventional emission tax mechanisms.

Conventional mechanisms can accommodate improvements in society's understanding of the social cost of certain activities through adjustments in either the number of allowances or

[18] See Plott (2000), Wolfers and Zitzewitz (2004, 2006), Hahn and Tetlock (2006), and Berg *et al.* (2008a, 2008b). Hanson *et al.* (2006) provide evidence that prediction markets are reasonably robust to manipulation.

the tax rate. These adjustments provide those affected by the regulation with an incentive to change their behavior from the point in time at which the adjustments become effective onwards, and they affect earlier behavior only to the extent to which (1) these adjustments have been expected and (2) behavior before the adjustment affects profits after the adjustment. Our tradable emission bond incorporates improvements in understanding of the social cost through a bond market that adjusts the expected redemption value of newly issued as well as existing bonds. With respect to *newly issued* bonds, our pricing mechanism thus affects the behavior of emitters in the same ways as existing regulatory mechanisms do, although the market automatically adjusts the bonds' expected redemption values and thus the cost of emitting. Furthermore, unlike existing regulatory mechanisms, our pricing mechanism also adjusts the expected redemption values of *existing* bonds and thereby incorporates future improvements in society's understanding of social costs into the eventual liability for all emissions after the date of implementation.

Our pricing mechanism therefore differs from bankable allowances—while the value of unused banked allowances changes with adjustments in the emissions cap, these unused allowances only affect the cost of *current and future* but not *past* emissions, and they do not ensure that emitters bear the cost of the uncertainty that they cause. Similarly, our bond market differs from existing futures markets for emission allowances (for example, the European Climate Exchange). Such futures markets permit emitters to hedge their risk with respect to increases in the price of *future* emissions. In contrast, our bond market permits emitters to hedge their risk with respect to their eventual liability for *current and past* emissions.

Finally, while it is straightforward in principle to require emitters to pay for their initial allowances, emission trading mechanisms often provide emitters with free allowances. Pricing mechanisms make it more difficult to obscure the fact that every unit of emissions can be regarded as the “marginal unit” that ought to bear the cost of the harm that it causes. However, it may be inappropriate for emitters to bear the entire burden of purchasing our mandatory bonds, because, to the extent that past socially valuable capital investments make it unreasonably costly to cut emissions rapidly in the short run, having emitters bear the entire burden assigns unfair liability to emitters. Pezzey (2003) has argued that proposed price control mechanisms should exempt some level of emissions because it is politically infeasible to require emitters to pay taxes for all of their emissions. For our pricing mechanism, this can be accomplished by giving each emitter bonds for some specified level of emissions for a specified length of time. Because emitters would receive the bonds regardless of their levels of emission, such compensation would be lump-sum compensation and would therefore preserve incentives for emissions to be efficient.

For our pricing mechanism to be efficient, the total cost of administering the bonds, implementing the bond market, and measuring emissions must not exceed the saving from more accurate pricing. Because the sole purpose of the bonds is to generate a return on overpaid funds, it is possible to use zero-coupon versions of existing 30-Year US Treasury bonds and add contract clauses that specify the rules that determine the share of the bond’s face value that the bond holder will receive. Experience with the Iowa Electronic Markets and other prediction markets suggests that such markets can be implemented at low cost. Experience with tradable allowance schemes indicates that it is possible to obtain measurements of emissions from large emitters at fairly low cost. Thus our pricing mechanism is likely to be no more expensive and no more difficult to implement than existing tradable allowances. Assuming that the administration of the bonds is about as expensive as the collection of corrective taxes, our mechanism would also be no more expensive than conventional pricing mechanisms.

4.2 Non-efficiency-motivated regulators

A general problem of regulatory mechanisms is that it is fairly easy for regulations to come to be based on political goals rather than on the best estimates of what control parameters are optimal. We argue that our mechanism makes it more difficult for regulators to follow goals other than promoting efficiency. First, the fact that the redemption value of the emission bonds will be determined in year $t + \tau$ makes it harder to implement regulation in year t that deviates from the best understanding of the social cost of emissions in year t. If the bond's redemption value is set too low, then the bond's price will quickly fall to zero, thereby making the official underassessment of the social cost visible. This will make it more difficult to defend such a low assessment of the social cost again in the following year when setting the redemption value of next year's bonds. Conversely, if the redemption value is set higher than what the market expects to be necessary, then the bond's price in the market will be correspondingly higher, permitting emitters to escape the overly strict regulation by selling their bonds in the market. Although the price of tradable allowances also varies with the number of allowances, markets for emission allowances lack a mechanism that indicates when the number of allowances is set too low, and therefore they do not provide a guard against overly strict regulation.[19]

Second, there is no guarantee that year ($t + \tau$)'s estimate of the social cost of emissions in year t will not be affected by undue political considerations. However, the political considerations in year $t + \tau$ are likely to be different from those that affect conventional regulatory mechanisms in year t. While corrective taxes and tradable allowances have a direct impact on *today's* emissions, the estimate that determines the redemption value of our bonds refers to emissions that have already occurred τ years earlier; it therefore affects only the ultimate liability for these earlier emissions but not the emission themselves. Because those who were responsible for the emissions at time t may not be among the bondholders at time $t + \tau$, it is not meaningful to either punish or reward bondholders for past emissions. Thus considerations besides efficiency that might affect the estimate of the bond's redemption value in year $t + \tau$ differ from those that might affect the choice of the tax rate or the allowances in year t.

Nevertheless, to the extent that the estimates of the social cost of emissions in earlier years may serve as signals to current emitters about their future liabilities, political considerations similar to those that affect corrective taxes and tradable allowances could still play a role. As long as the assessment of the social cost requires human decisions, it is impossible to ensure that the bond's redemption value is determined without any inappropriate

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[19] Comparison of the bond's price with its redemption value may also alert citizens to corruption among regulators (see, for example, Frederiksson and Svensson, 2003, and Frederickson and Wollscheid, 2008). See Wagner *et al*. (2009) for an analysis and discussion of some of the social costs related to corruption.

political considerations. Thus our mechanism it is likely to reduce—though not eliminate—the propensity to consider goals other than achieving efficiency in the regulation of externalities.

5. Conclusion

Our main motivation for developing our pricing mechanism arises from our expectation that future scientific research will reduce the uncertainty about the physical, social, and economic consequences of many of today's activities that are currently believed to cause negative externalities. In cases in which our expectation turns out to be overly optimistic and the future assessments are as uncertain as today's assessments, our mechanism will have mainly introduced an additional layer of uncertainty about the prices of these activities. If, in these cases, pricing reflects the best understanding of costs and if those who are required to purchase bonds sell them immediately in the secondary market, then their payments today for their emissions will not differ from those that they would have to pay under conventional emission taxes with rates set to include the cost of the fact that the social costs of the negative externalities are uncertain. Thus the damage that our mechanism could cause if it is adopted in place of conventional regulatory mechanisms seems small.

However, the fact that our understanding of the consequences of a number of harmful activities has increased considerably over time suggests that our mechanism is likely to be superior to conventional mechanisms. Our understanding of the negative effects of the use of pesticides, cooling agents, and smoking, has increased noticeably over the past 30 years, and it seems reasonable to expect that our understanding of the effects of today's externalities will continue to improve. Our mechanism assures that the price that today's emitters take into account when deciding how much to emit is the best available estimate of the combination of the expected social cost of the emission and the cost of the uncertainty about that cost. Furthermore, it assures that someone will pay the future estimate of the cost of all current emissions, up to today's maximum estimate of the harm.

For our pricing mechanism to be attractive, the bonds' future redemption price must be determined primarily by efficiency rather than political considerations. As long as the participants in the bond market believe that the bond's redemption price will be more closely based on efficiency considerations than a price today would be, our mechanism provides better protection than conventional regulatory taxes and allowances against undue political influence today. There can be no guarantee that the total payment for today's emissions will be based exclusively on the best future estimate of the emissions' harm. But if citizens find it impossible to put minimal trust in the regulators who would value and administer the bonds, then it is unlikely that they will find any regulatory policy acceptable.

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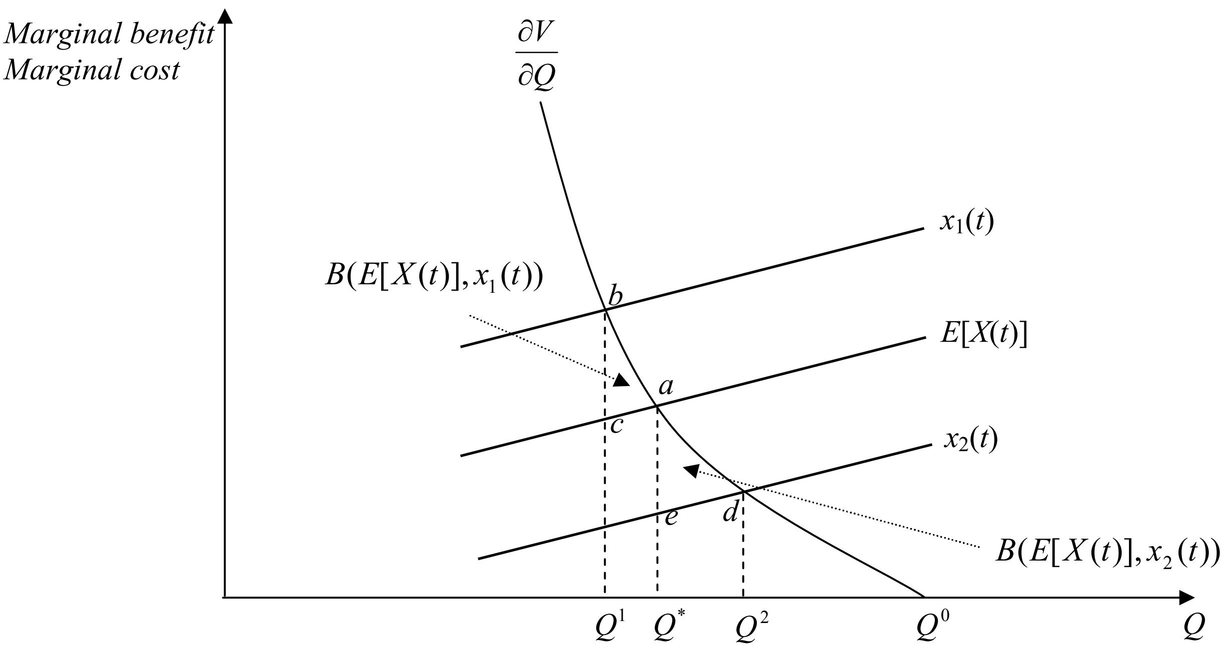

Figure 1. The inefficiency cost of Pigouvian taxes if there is uncertainty about the social cost of emissions