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DISTRIBUTIONAL ASPECTS OF ENERGY AND CLIMATE POLICY

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## On the Economics of Climate Policy

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### **Recommendation**

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# On the Economics of Climate Policy\*

Gary S. Becker, Kevin M. Murphy, and Robert H. Topel

## Abstract

We analyze the central features of economic policies to mitigate climate change. The basic structure of Pigouvian “carbon pricing” is shown to follow from a standard Hotelling problem for the intertemporal pricing of an exhaustible resource. We extend this analysis to consider the strength and timing of research incentives, the costs of implementation delay and the impact of anticipated future technologies on current carbon prices. We study a variety of issues related to the valuation of climate investments, including uncertainty as to the future timing and distribution of climate impacts and the appropriate social rate of discount for valuing policies. Under reasonable circumstances the insurance properties of climate investments may warrant unusually low discount rates. We use the same framework to argue that policy makers in developing countries will discount the expected returns from climate investments more heavily, because such investments have weaker insurance value in the developing world.

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## 1. Introduction

Energy is essential to the maintenance and spread of economic welfare. At a point in time, individuals in richer countries such as the US and Canada use much more energy than individuals in poorer countries. Over time, long run growth in living standards is strongly associated with rising energy use, especially in developing countries.<sup>1</sup> There is little to indicate that these patterns might change, so that future growth and the escape of developing countries from current levels of poverty hinge on the existence and use of abundant energy supplies.

Yet rising worldwide demands for energy run up against new evidence of the social costs of energy use. The broad consensus of scientific research is that the continued dependence of economic activity on carbon-based fuels and their associated emission of greenhouse gases (GHG) create risks of substantial future changes in earth's climate, along with associated harm to the welfare of future generations. This "new" knowledge of anthropogenic climate change has motivated national and international efforts to regulate the use of carbon-based energy sources, and to promote the development and use of "clean" energy alternatives. For example, the Obama administration recently "committed" the US to achieve an 80 percent reduction in carbon emissions by 2050, even while enabling legislation to begin the regulation of such emissions languishes in Congress. In Europe, an incipient "cap-and-trade" market for emissions permits is in place, while the state of California is developing unilateral action along the same lines. Broadly-based international efforts have met with little success, as evidenced by the failure of the Kyoto (2000) and Copenhagen (2009) negotiations to achieve implementable frameworks for reducing GHG emissions.

These initiatives must confront several daunting challenges to the successful design and implementation of a useful energy-climate policy. First, current generations—who are the ones that get to decide—must be convinced that the future costs of climate change are worthy of current concern. This hasn't been achieved. Second, current generations must agree to forego use of abundant

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<sup>1</sup> Our point is that economic development (almost) universally expands energy use. Energy use per unit of income—sometimes called the "energy intensity" of income—is generally declining, both worldwide and within countries. This reflects both technical advances in energy use and changes in the composition of GDP within countries. But GDP growth rates over long periods almost always exceed the rate of decline in energy intensity of GDP, so that overall energy demand rises with income, especially in developing countries. For example, between 1980 and 2007 GDP growth in China has averaged 10 percent per year, while energy intensity has declined at "only" 5.3 percent per year. The corresponding figures for India are 6.1 percent GDP growth and 2 percent decline in energy intensity. In the U.S. GDP growth has averaged 2.94 percent since 1980, and energy intensity of GDP has declined at 2.03 percent. For a complete tabulation of energy intensity see World Bank data at:

<http://data.worldbank.org/indicator/EG.GDP.PUSE.KO.PP.KD>

carbon-based energy sources in order to mitigate uncertain harm to generations of the distant future. We know of no good examples of such sacrifice. Third, even if current generations are convinced that mutual sacrifice would be a good thing, effective policies require the largely voluntary yet global cooperation of nations in a setting where non-cooperation offers substantial rewards. Again, we are unaware of the success, or even the formation, of similar policies.

These problems are created by the fact that climate is a “global public good.” In terms of climate impact earth’s atmosphere doesn’t much care where GHG emissions come from—a ton of carbon emitted in India has the same impact as one from Canada, so the atmosphere is over-used by all in a classic example of the tragedy of the commons. Meaningful efforts to successfully correct this externality must then hinge on collective and harmonized action by nations worldwide. Yet efforts at cooperation are hampered by the same free-rider incentives that created the problem in the first place—the benefits of carbon-based energy use are current and highly focused, while the social costs are greatly delayed, difficult to (currently) discern or measure, and highly dispersed. In addition, as we argue below, the social costs of climate change and the benefits of mitigation policies are not uniform, which leads to divergent valuations of social investments in “climate capital.” This is especially true when, as here, the distributions of returns on such social investments are country-specific and highly uncertain. Then policies such as widely-discussed carbon taxes or cap-and-trade schemes offer much different risk-reward tradeoffs to developing countries, such as China or India, than to developed countries like the US. These divergent valuations help explain the current lack of progress in international negotiations over climate policy, such as Copenhagen (2009), and what we believe are the limited prospects for cooperation going forward.

From (very) high altitude, the economics of anthropogenic climate change is a standard problem of externality—current users of carbon-based fuels do not bear the environmental costs of energy consumption, so they use too much of the stuff, and too little of “clean” alternatives. The problem occurs because some resource—here the atmosphere—is unpriced and so overused. The idealized textbook market intervention is to price the overused resource, equating the private and social costs of its use. This can be accomplished via a Pigouvian tax (or its equivalent) equal to the marginal external cost of using a unit of carbon-based fuels. The resulting ideal “carbon-price” would exactly balance the benefits of additional carbon emissions, which occur now, against their costs, which are spread over the near and distant future.

This basic solution to the externality problem is familiar and straightforward. It is central to virtually all serious national and international

policy proposals to deal with climate change, including the Waxman-Markey<sup>2</sup> and Lieberman-Warner<sup>3</sup> bills in the US House and Senate, the design of cap-and-trade policies in the EU, and the tentative framework discussed in the recent Copenhagen negotiations. But its conceptual simplicity is superficial—the actual design and implementation of such policies faces daunting challenges and unresolved questions. Our analysis seeks to contribute to a number of unresolved issues in the design and effects of policies to mitigate climate change. These include:

1. Valuing future costs: The social costs of current GHG emissions are uncertain and spread over the distant future. How should current policy value the costs of climate damage, which will fall mainly on future generations? Should the future benefits of investments in “climate capital” be discounted at market rates or, as some have argued, at much lower rates? How will these valuations differ across major countries, the large majority of which must cooperate to achieve efficient policy outcomes?
2. Uncertainty: How does the great uncertainty regarding the extent and costs of future environmental harm affect current strategies, social investments, and valuations?
3. Catastrophic climate change: Among the uncertainties is the possibility of catastrophic outcomes that could greatly reduce future living standards or endanger future populations. How should current policy value and mitigate these possibilities?
4. Market responses to climate policies: At its barest level, “carbon pricing” is a market-based solution that relies on market responses to efficiently designed incentives. How will markets respond to policy-generated incentives? Will market responses enhance or constrain the effects of policies?
5. Innovation incentives, policy design and the costs of delay: How does an efficient policy affect research incentives and the pace technical progress in alternative energy sources and in mitigation? If technical breakthroughs are likely to be the ultimate solution to the energy “problem,” are incentives to innovate harmed by delays in implementing an optimal policy? How should the prospect of future innovation affect current policy?

The paper is organized as follows. Section 2 develops the basic features of optimal carbon pricing, which we relate to a standard Hotelling problem for the

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<sup>2</sup> <http://www.govtrack.us/congress/bill.xpd?bill=h111-2454>

<sup>3</sup> <http://www.govtrack.us/congress/bill.xpd?bill=s110-2191>

intertemporal pricing of a depleting resource. We extend the analysis to consider the strength and timing of research and development incentives, the costs of delay in implementing an optimal policy, and the impact of anticipated future technologies, and their form, on current carbon prices. In Section 3 we analyze a variety of issues related to the valuation of climate policies, including uncertainty as to the future timing and distribution of climate impacts. We pay particular attention to the appropriate social rate of discount for valuing policies, showing that under certain reasonable circumstances the insurance properties of climate investments may warrant unusually low discount rates. We use the same framework to argue that policy makers in developing countries will discount the expected returns from climate investments more heavily, because such investments have weaker insurance value in the developing world. Section 4 concludes.

## **2. Features of Efficient Climate Change Policies**

The scientific foundations for anthropogenic climate change indicate that current emissions of GHGs create environmental and other costs that are (1) greatly delayed, (2) very long-lasting, and (3) highly uncertain.<sup>4</sup> This is because the flow of CO<sub>2</sub> to the atmosphere has a long lasting impact on the stock of atmospheric CO<sub>2</sub>, as reabsorption is very slow. In turn, the growth in global temperature lags the atmospheric stock of CO<sub>2</sub> because, for example, melting of ice caps reduces earth's albedo (reflectivity) and oceans warm slowly. Many costs are likely to lag a rise in temperature—for example, rising sea levels would be driven by melting of ice caps, which would follow a prolonged warming period. Finally, uncertainty as to environmental feedbacks and other impacts includes the prospects for “catastrophes” of various forms. Because of these features, policies that would mitigate these effects must balance costs and benefits over hundreds of years, and subject to large and costly contingencies, which make the problem of policy design a good deal more daunting than the usual project evaluation.

### **2.1 Carbon Pricing as an Exhaustible Resource Problem**

To illustrate central elements of dynamic carbon pricing and its connection to key assumptions about preferences, growth and technology, consider a simple certainty framework in which the target cap on atmospheric concentration of GHGs at some endogenous future date  $T$  (say in  $T=200$  years) is the goal of environmental policy. Denoting the concentration of GHGs at date  $t$  by  $Q_t$ , this

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<sup>4</sup> See Archer (2007) and (2009) for useful summaries of the state of climate science research on global warming.

terminal condition is  $Q_T = \bar{Q}$ . Stated in this way, the optimal policy solves a Hotelling problem for allocating the use of an exhaustible resource over time—where here the exhaustible resource is the capacity of the atmosphere to “safely” hold a given concentration of GHGs.<sup>5</sup>

Let the private social (consumer plus producer) surplus from current emissions,  $q$ , be  $V_t(q_t, b_t, y_t)$  where  $b_t$  is the unit cost of carbon-free energy sources at date  $t$  and  $y_t$  is income. Finally, let the technology for mitigating emissions be represented by the cost  $C_t(s_t, \mu_t^{-1})$ , where  $s_t$  is the amount of period- $t$  emissions avoided through mitigation activities and  $\mu_t$  indexes the evolving efficiency of mitigation—higher values of  $\mu_t$  reduce the costs of emissions mitigation. For example,  $s_t$  might be the amount of period  $t$  emissions that are eliminated by sequestration or other technologies, and  $\mu$  makes the process more efficient. With these definitions, the policy problem is to maximize the present discounted value of social surplus.

$$(1) \quad \begin{aligned} \underset{q, s}{\text{Max}} W &= \int_{t=0}^T (V_t(q_t, b_t, y_t) - C_t(s_t, \mu_t^{-1})) e^{-rt} dt \\ \text{s.t. } \dot{Q}_t &= q_t - s_t - aQ_t \quad \text{and} \quad Q_T = \bar{Q} \end{aligned}$$

where  $r$  is the rate of interest used to discount future environmental costs (the rate of return on investments in environmental capital) and  $a$  is the rate at which atmospheric GHGs are reabsorbed. We shall have much more to say about  $r$  later, but for now we simply take it as given without pondering how large or small it could or should be.<sup>6</sup>

Letting  $V'_t(\bullet)$  denote the derivative of  $V_t(\bullet)$  with respect to  $q_t$ , the basic solution to (1) has a familiar structure:

<sup>5</sup> There need not be a fixed target level of GHG for this analysis to apply. As long as the effects of climate change are simply a function of the stock of GHG at some future date (200 years in our example), the optimal program will need to solve this same Hotelling problem given the optimal level of GHG at the terminal date.

<sup>6</sup> The appropriate rate of return on social investments in climate capital will depend on insurance properties of the investment's return. Projects that pay off by mitigating climate-related catastrophes may have discount rates that are well below the market rates of return on other risky assets, and even below the risk free rate. We take up these issues in Section 3, below.



$$(2a) \quad \begin{aligned} V'_t(q_t, b_t, y_t) &= P_0 e^{(r+a)t} \\ \mu_t^{-1} C'_t(s_t, \mu_t^{-1}) &= P_0 e^{(r+a)t} \end{aligned}$$

In (2a) both the marginal value of using and the marginal cost of eliminating a unit of emissions are equated to the period- $t$  “carbon price”  $P_0 e^{(r+a)t} = P_t$ , which represents the scarcity value of a “unit” of the otherwise unpriced absorptive capacity of the atmosphere. This price is the outcome of an ideal Pigouvian tax or cap-and-trade system, so that  $P_t$  equates the marginal benefit of  $q$  to current users and the (present value of) incremental costs imposed on future generations.<sup>7</sup>

## 2.2 Carbon Pricing, Timing and the Returns to Innovation

The fact that the socially optimal carbon price rises at the rate of interest (plus absorption) is a well-known property of this and other exhaustible resource problems—Nordhaus (2007) refers to the rate of growth  $r+a$  as the “net carbon interest rate.”<sup>8</sup> It is a condition for intertemporal efficiency in the use and mitigation of emissions, equating the value of benefits from creating incremental emissions (due to energy use) to the present value of costs. Less appreciated is how this property of an optimal policy impacts the social value of innovations, incentives to innovate and the cost of waiting to implement the policy.

To fix ideas with a not-entirely-fanciful example, think of a current investment in technology that could eliminate one unit of carbon emissions at some arbitrary future date,  $t$ —a one-period “carbon eating tree.”<sup>9</sup> The present value of this unit reduction in future emissions is  $P_t e^{-rt} = P_0 e^{(r+a)t} e^{-rt} = P_0 e^{at}$ , which implies that the time profile of values is independent of the interest rate,  $r$ . If  $a=0$ , the present discounted value of the innovation is independent of how far in the future it pays off,  $t$ , because the value of the gain rises at the interest rate. And if  $a>0$  the present value actually rises with  $t$  because the time- $t$  value of the innovation rises faster than the interest rate. In effect, the value of the innovation is undiscounted.

The result is even stronger if innovation is scalable. Think of an innovation that would reduce the incremental cost of mitigation at some future  $t$ ,

<sup>7</sup> Nordhaus (2007a,b) and (2008) are good summaries of the state of economic modeling applied to global warming and climate policy. Many of the same analytical tools appear in Stern (2006).

<sup>8</sup> The original statement is in Hotelling (1931). Treating  $\bar{Q}$  as an exhaustible resource, the condition is that “owners” of the resource must be indifferent between selling a unit today and holding it for future use. Here  $P_t$  is the per-period shadow value of relaxing the constraint on GHG concentrations,  $\bar{Q}$ .

<sup>9</sup> E.g. Dyson (2008).

raising  $\mu_t$  by  $d \ln \mu_t > 0$ . The present value of this cost reduction (per unit change in  $\ln \mu$ ) is

$$\begin{aligned} & e^{-rt} \mu^{-1} C'_t(s_t, \mu_t^{-1}) s_t \\ &= e^{-rt} P_t s_t \\ &= P_0 e^{at} s_t \end{aligned}$$

Here the unit value of the innovation is independent of  $r$ , and also of  $t$  if  $a=0$ , but the reduction in incremental cost is scalable because it applies to all units,  $s_t$ . But  $s_t$  rises over time because  $P_t$  is increasing, so the present value of the innovation also rises with  $t$ —the gain has larger present value the farther in the future it occurs. Applied to all periods, a scalable technical advance in mitigation that applies from the present day forward is worth

$$(3) \quad W_{\ln \mu} = P_0 \int_{t=0} s_t e^{at} dt$$

Even with  $a=0$ , the value of the gain applies to the quantity of mitigation in all future periods with equal weights. If  $a>0$  then future periods get more weight than the present. And of course the result applies to other types of innovation, such as an advance that would improve the consumption efficiency (surplus) per unit of emissions, like a change in fuel efficiency of cars. All such gains are valued at the rising Pigouvian price  $P_t$ , which “undoes” the effect of discounting in present value calculations.

These conclusions may appear anomalous, and it is easy to extend the policy problem (1) to include factors that would cause the optimal atmospheric price  $P_t$  to rise more slowly, so that delay is more costly. For example, if we amend the optimal policy to include possible environmental damages  $D(Q_t)$  from rising atmospheric concentrations along the trajectory to  $T$ , then the current optimal carbon price is continuously updated, incorporating the impact of current emissions on future damages:

$$\frac{d \ln P_t}{dt} = r + a - P_t^{-1} D'(Q_t)$$

where  $D'(Q_t) > 0$  is the current period marginal damage from emissions, equivalent to the effective current period “rental price” of atmosphere. This

reduces the growth rate of  $P_t$  relative to the standard Hotelling solution, but without negating the broader point, which is that innovations yield greatest value when the carbon price is high, and in the optimal policy that price is rising over time.

The central lesson about valuing progress in (3) is simple, but it has important implications for interpreting both the form of policy responses to climate change as well as the urgency with which those policies are implemented and the costs of delay. The slow progress of international negotiations in gatherings such as Kyoto and Copenhagen is widely lamented, as is similarly slow progress in crafting and adopting enabling legislation in the US and other countries. Do these delays adversely impact incentives to find “solutions” in the form of technologies that would reduce the carbon impact of energy consumption? Is a sense of urgency warranted?

If we assume that slow progress toward implementing a policy is just that—slow progress that will eventually result in widely applied carbon pricing that reflects social costs—then equation (3) indicates that the costs of delay are small. To illustrate, use (3) for the present discounted value of a cost-saving innovation that requires substantial up-front R&D effort. Realization of these incentives requires two things: an initial incentive,  $P_0$ , that signals the current scarcity value of emissions, and a commitment to a time path for that value in the future. Given these, delaying the start of this payoff for  $d$  years would not much affect its present value, even if the initial  $d$  years of a payoff stream were foregone. And if the whole program is simply pushed back the payoff would likely rise because the initial price  $P_d$  would increase by more than simple interest (because interim unpriced emissions tighten the ultimate constraint), which also raises  $s$ . The result is that the current value of innovation incentives and the social gain from innovations are not much harmed and may even be increased by delay.

This analysis assumes that an optimal carbon pricing program is eventually implemented—that negotiations and legislation result in something useful in terms of price signals and commitment to policy. The message is not that delay is costless—the tighter constraint and necessarily higher carbon price caused by delay demonstrate the costs—but rather that the returns to climate-related innovations are not much reduced by delay in implementing well-designed incentives. And if the ultimate efficiency gain is likely to derive from currently unforeseen innovations driven by carbon pricing, rather than simply by business as usual along a rising price path, it is likely that delays of a few years don’t much impact that outcome. Put differently, it is far more important to get the form of policy right—including believable commitments to the level and time path of future carbon prices—than to get a policy done quickly.

### 2.3 Factors Affecting the Impact of Policy

Conditions (2a) for the rate of change price of the carbon price embed the properties of evolving demand and supply for carbon-based fuels, via the social surplus  $V_t(\cdot)$ , as well as changes in the availability of substitutes,  $z$ , and the evolution of technology. It's worth being explicit about these, because expectations of how demand and technology will evolve in the future are essential ingredients of current policy and the optimal level and timing of mitigation activities. Using the usual notation for time rates of change (e.g.  $\dot{q} \equiv \frac{dq}{dt}$ ) displacement of (2a) gives the rates of change of emissions ( $q$ ) and mitigation ( $s$ ):

$$(2b) \quad \begin{aligned} \dot{q}_t &= -\xi_t[r+a] + \sigma_t \dot{b}_t + \eta_t \dot{y}_t \\ \dot{s}_t &= \phi_t[r+a] + [1 + \phi_t] \dot{\mu}_t \end{aligned}$$

Here,  $\sigma$  is elasticity of emissions with respect to the cost of its substitute,  $b$ ,  $\eta$  is the income elasticity of demand for emissions generating activities,  $\phi$  is the elasticity of mitigation supply (the inverse of the elasticity of marginal cost) and  $\xi$  is the price elasticity of current emissions,  $q$ , which embeds both supply and demand responses to changes in  $P$ .<sup>10</sup>

Equations (2b) have several important implications. First, absent technical progress in reducing emissions ( $\dot{\mu}_t = 0$ ) and with negligible reabsorption ( $a=0$ ), the growth rate of mitigation is proportional to the rate of interest. The factor of proportionality is the elasticity of mitigation supply,  $\phi_t$ , so optimal mitigation grows more rapidly when supply is more elastic or when the rate of interest is high. But with  $\dot{\mu}_t > 0$  the growth rate of mitigation is augmented by anticipated technical progress (the rate of decline in costs) in emissions reduction. Given the dependence of emissions mitigation on technology and research, and expectations that costs of emissions reductions actually will fall over time, this means that “waiting” to achieve emissions reductions is a central element of dynamically efficient policy. In a broader context, however, the magnitude of  $\mu$  is endogenous to current policy, because it is an outcome of current and future R&D

<sup>10</sup> In a competitive market  $\xi$  will be given by the harmonic mean of supply and demand elasticities,  $\xi = (\xi_S^{-1} + \xi_D^{-1})^{-1}$ .

efforts, and our previous discussion indicates that incentives to innovate are powerful, provided that innovators can collect on the value of their innovations.

Similarly, the benefits of deferral are larger when the elasticity of mitigation supply is large, and especially when large values of  $\phi_t$  are likely to evolve from future technical advances. Large values of  $\phi_t$  mean that marginal costs of mitigation at a point in time do not rise sharply with  $s$ —mitigation activities are easily “scalable”—so there is not much cost to sharply ramping up mitigation in later periods when emissions reductions will be most valuable. But when  $\phi_t$  is small the marginal cost of mitigation increases rapidly with  $s$ —there is a large cost penalty if mitigation efforts are concentrated in fewer periods. Then it is worthwhile to do things in smaller pieces by spreading mitigation activities over time. Then the optimal policy is to ramp up mitigation efforts sooner rather than later.

This interpretation of the elasticity  $\phi_t$  is the “certainty” equivalent of a broader point about scalable technologies—they can be deployed as needed on large scale without much cost penalty. As we show below, development of highly scalable (high  $\phi$ ) technologies is especially valuable if we extend the analysis to incorporate uncertainty and the possibility that future environmental effects of GHGs may turn out to be much more costly than currently anticipated, or that low-probability but high-damage outcomes may occur. Then scalable technologies to reduce emissions have high option value, precisely because they can be deployed on a large scale when mitigation is most critical. Notice also that technical advances that enhance scalability ( $\phi$ ) or enhance the efficiency of mitigation ( $\dot{\mu}_t$ ) are complementary—the social benefits from higher  $\dot{\mu}_t$  are proportional to  $\phi$ , and conversely.

Similar implications apply to the “value” side of (2b). Since the price of emitting carbon rises at the “net” interest rate  $r+a$ , this price rise induces conservation in proportion to the price elasticity  $\xi$ . Note that  $\xi$  embeds both production and consumption responses to carbon pricing—for example, the fact that carbon-based fuels are abundant and in fairly inelastic supply on the world market suggests that  $\xi$  is likely to be small.<sup>11</sup> Together with demand growth ( $\dot{y}_t > 0$ ) on the world market, the implication is that substantial conservation relative to business-as-usual is unlikely. Then policy success is critically dependent on technical advances that would promote mitigation by enhancing  $\phi$

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<sup>11</sup> That is, the burden of  $P$  is likely to fall on suppliers of carbon emitting energy sources, who would supply roughly the same quantities at substantially lower after-tax prices. Then imposition of emissions pricing may not much impact fuel use or emissions through conservation.

and  $\mu$ , or substitution toward non-carbon-based energy alternatives with declining costs ( $\sigma_t \dot{b}_t < 0$ ). In other words, the point of optimal emissions pricing is not so much to induce conservation on the demand side—which is likely to have small effects—as it is to guide the research incentives that will result in greater supply of clean energy alternatives in the long run.

#### ***2.4 Evolving Expectations and Changing Incentives***

For a given rate of interest the rate of growth of the optimal carbon price is determined. The other key to incentives is  $P_0$ —the initial or current carbon price—which determines the level of the entire future price path. This is affected by the entire array of technology and substitution effects, and the way they are anticipated to evolve, as in (2b). Factors that reduce the anticipated growth of  $q$  or raise the growth of  $s$  will reduce  $P_0$  and delay the ultimate date  $T$  when net additions to the stock  $Q$  optimally cease. For example, the expected emergence of technologies ( $\phi$ ) that make  $s$  more scalable allow for lower net emissions ( $q-s$ ) along a flatter path, making  $T$  longer, and so on.

The prices  $P_t$  that support optimal net emissions in problem (1) could be generated by an ideal set of emissions taxes or by cap-and-trade determination of an emissions price. Though we don't wish to join a full debate over the relative merits of carbon taxes versus cap-and-trade schemes—see Nordhaus (2007c) for a good discussion—our framework does highlight some key issues that have not been emphasized in previous literature. While we have framed the optimal policy in a certainty-equivalent framework, the fact that the optimal initial price,  $P_0$ , depends on expectations of future market responses and technologies means that an efficiently updated policy should adjust the current price level,  $P_0$ , as information evolves. For example, an innovation that reduces expected future mitigation costs will reduce  $P_0$ , exactly as a new “find” that increases the future availability of an exhaustible resource (such as oil) will reduce its current price, even if the newly discovered units are not currently recoverable. In an ideal cap and trade framework in which total acceptable emissions  $\bar{Q}$  (as opposed to year-by-year emissions) are fixed and unchanging, and tradable over time, the collection of information and the formation of expectations about such future innovations and technologies is decentralized to market participants—a clear advantage in terms of incentives. But the possibility of governments manipulating the variable they control,  $\bar{Q}$ , invites rent-seeking, which is the foundation of many economists' critique of cap-and-trade schemes and their consequent preference for tax-based incentives.

Yet tax-based schemes also have powerful disadvantages. Tax-based carbon pricing sacrifices the substantial advantage offered by market-based expectations—when carbon prices are set by governments the formation of “expectations” that determine both the level and growth of the optimal emissions tax is necessarily centralized in government, which is responsible for setting and updating the entire price (tax) path  $P_t$ . There is little reason to believe that governments would do well in this regard, and the opportunities and incentives for inefficient choices and rent-seeking appear to us just as powerful with taxes as with cap-and-trade.

### **2.5 Discounting Future Climate Costs and Returns**

Ignoring reabsorption,  $a$ , for any given future marginal damage from incremental emissions, say  $P_T = \$500$  per ton of CO<sub>2</sub> emissions in  $T=100$  years, the strength of initial incentives,  $P_0$ , is determined by the rate of interest;  $P_0 = e^{-rT} P_T$ . Higher  $r$  means low  $P_0$  and a gradual ramping up of incentives and responses. Low  $r$  means that conservation and mitigation efforts are more front-loaded. If we base  $r$  on historical market rates of return on physical and human capital, then a value in the neighborhood of  $r=.06$  is reasonable. This yields  $P_0 = \$1.24$  if  $P_{100} = \$500$ . In contrast, the UK government’s 2006 *Stern Review of the Economics of Climate Change* argued that policies should reflect much lower interest,  $r = .015$ , based on the *Review’s* notion that that it is ethically improper to heavily discount the costs that current emissions impose on future generations. Then the current tax or price is  $P_0 = \$500 \times e^{-.015 \times 100} = \$112$ , which is almost 100 times larger than with  $r=.06$ . As pointed out by Nordhaus (2007b) and Weitzman (2007), among others, this philosophical choice of a (very) low discount rate for investments in climate capital accounts for virtually all of the differences between the *Stern Review’s* draconian recommendations for current action and the more gradualist policies advocated by other economists. Much then hinges on the choice of a social rate of discount for climate capital,  $r$ , which we take up below.<sup>12</sup>

### **3. Valuing Future Climate Damages**

The fact that current economic activity and policy affect uncertain climate outcomes and costs over vast time periods may be the most daunting challenge of climate policy. Possible future outcomes—including the possibility of

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<sup>12</sup> Moreover, since the analysis in the Stern Review assumes that the cost of GHG concentrations are proportional to GDP and that GDP grows substantially over time, the implied net discount rate is even smaller (and is essentially zero). See Nordhaus (2007b) for a clear discussion of this issue.

environmental catastrophes that could harm large populations or greatly reduce productivity—must be both envisioned and valued, and then balanced against the current cost of mitigating such harms.

We address three issues related to the current valuation of uncertain future damage. First, given the possibility of various types of catastrophe, what does economic analysis say about the costs that should be incurred today in order to avoid them? At standard discount rates, events that have even substantial impacts on productivity and population-wide living standards in the distant future have only small present value. We show that these values substantially increase, however, when climate-related damages are unequally distributed, when future lives are at risk, and when we allow for uncertainty as to when the damaging events might occur (holding constant the expected time to occurrence). Even at “market” rates of discount, not-implausible values for the magnitudes of future catastrophes imply substantial current willingness to pay to avoid them.

We then extend the analysis to the valuation of climate investments with uncertain future returns. We show that appropriate social discount rates for investments in climate capital may be well below market returns on other forms of capital, reflecting the insurance value of climate investments. We also find that distribution matters. The global public good nature of harmonized climate policies is challenged by heterogeneity of valuations—projects that have high insurance value to developed countries because they reduce future risks are likely to be much less valuable to developing countries, for whom the possibility of rapid economic growth is likely more important.

### ***3.1 The Costs of Future Catastrophic Outcomes***

Future catastrophic outcomes may include substantial damages to productive capacity, sustained reductions in economic growth, threats to living standards or lives of particular populations, or permanent environmental harm that reduces welfare for any given level of economic activity. To frame these possibilities, we begin with the standard infinite-horizon model of intergenerational utility that underlies most work in economic growth and climate policy.<sup>13</sup> Write the current value of generational welfare over the indefinite future as:

$$(4) \quad U_0 = \int_{t=0} u(c_t) e^{-\rho t} dt$$

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<sup>13</sup> Pindyck and Wang (2009) provide a dynamic general equilibrium approach to valuing catastrophic outcomes, including parameterized distributions for both the arrival rate and distribution of harm from catastrophes. Weitzman (2009) allows the distribution of future harm from climate change to have “fat tails”, which can greatly impact the current value of avoidance.



In (4)  $\rho$  is the rate of time preference, or in an intergenerational context the rate at which earlier generations discount the well being of later ones, and  $c_t$  represents the per-capita flow of goods and services (consumption) available to generations alive at future date  $t$ , which may include valuations of environmental factors. We continue to abstract for the moment from issues of uncertainty.

One form of calamity that can be represented in (4) is a permanent reduction in future living standards that is known to commence at some future date  $T$ , say in 100 years. So assume that future productivity is reduced by a constant percentage, resulting in a permanent change in future consumption of  $d \ln c$  from  $T$  onward. For example  $d \ln c = -.01$  represents a permanent 1-percent reduction in per-capita income and consumption. Assume a constant elasticity of the marginal utility of consumption,  $\omega$ , and steady state economic growth of  $g$ . Then we can apply the Ramsey Equation linking the equilibrium interest rate to time preference and economic growth,  $r = \rho + \omega g$ . The current value of this harm as a fraction of current (time zero) national income is:

$$(5) \quad \frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{e^{-(r-g)T}}{r-g} d \ln c$$

where  $(r-g)^{-1} d \ln c$  is the damage valued at date  $T$  and  $e^{-(r-g)T}$  discounts the date- $T$  value to the present, allowing for economic growth. How large is (5)? Assume  $r=.06$  and  $g=.02$ —fairly standard values in a growth framework—and let  $d \ln c = -.01$  (a one percent permanent reduction in future incomes). Then with  $T = 100$  years the right side of (5) is equal to  $-.0046$ , or about half of one percent of current income. For the US with a national income of about \$13 trillion, this implies a present discounted value of future harm of about \$59 billion. Viewed as a long term project to avoid such damage, the expenditure flow at 6 percent interest is about \$3.6 billion. Cutting the horizon to  $T=50$  years substantially impacts the estimates. Then a permanent 1 percent reduction in future income is worth about 3.4 percent of current income (\$440 billion), or a flow expenditure of \$26.4 billion per year. By comparison, with these same parameters a current permanent reduction in consumption of one percent would be worth roughly \$3.25 trillion or a flow of expenditure equal to roughly \$195 billion per year.

Adding uncertainty about when such climate-related damages might occur substantially raises the present value of avoiding them.<sup>14</sup> To demonstrate this in a simple way, hold constant the expected time until damage occurs at  $T=100$  years, but assume that the damage is equally likely to commence at any future date.

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<sup>14</sup> Karp (2009) makes a related point.

This implies an arrival rate (hazard) for the damaging event of  $h = T^{-1}$ . The present value of future expected damages as a fraction of current income is then:

$$(6) \quad \frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{1}{1+(r-g)T} \frac{1}{r-g} d \ln c$$

Using the same values as above, a permanent 1 percent reduction in living standards with expected time to occurrence of  $T=100$  years has present value equal to 5 percent of current income, which is roughly 11 times greater than when the damage was known to commence in 100 years. This is worth about \$650 billion to the US in 2010, equivalent to a flow expenditure of \$39 billion per year at 6 percent interest. At  $T=50$  ( $h=.02$ ) the cost is 8.3 percent of current national income, or a flow of \$65 billion. Our point is that uncertainty over the time at which climate change will have an adverse effect can greatly increase its current valuation.

Formulas (5) and (6) express the current value of marginal losses in future per capita consumption—everyone consumes one percent less than otherwise. This is consistent with most of the existing analysis of valuing climate costs, where those costs are framed in terms of reductions in future GDP, or costs as a fraction of GDP, as if the burden of climate impacts is equally spread among the future population. But much of the concern about climate-related damages has to do with the distribution of harm, where some groups are harmed much more than others. Concave  $u(c)$  means that reductions in  $c$  have rising marginal cost to those who experience them, so a given reduction in aggregate income is more costly when it is highly concentrated. For example, with  $\omega=2$  a catastrophe that reduces incomes by half among 2 percent of the population is twice as costly as an across-the-board reduction in living standards of one percent, even though both events reduce overall per-capita income by the same amount (one percent). Taken a step further, a climate-related catastrophe that reduces future national incomes by one percent by killing off one percent of the population, while leaving others unharmed, may be very costly. Such catastrophes are not “marginal,” reducing everyone’s income proportionally. Instead they wipe out consumer surplus—or in the extreme case the value of life—for a swath of the population.

A framework for valuing such catastrophes is provided by the economic literature on the value of a statistical life (*VSL*), which measures people’s willingness to pay for a reduction in the probability of death that would save one “statistical life.” For example, if in a population of 10,000 persons each would be willing to pay \$600 per year to reduce the per-year probability of accidental death by 1 in 10,000, then  $VSL = \$6$  million, which is about the value used by the US Environmental Protection Agency for cost-benefit analyses of regulations or projects that would reduce mortality risks. Murphy and Topel (2006) use this

value to calibrate the value of a life-year  $v(c) = u(c)/u'(c)$ , which is the “consumer surplus” achieved by being alive and consuming amount  $c$ , where  $c$  includes leisure and other factors that people value. They find that the value of a life year is about six times current income, so if we think of  $v(c) = \psi(c)c$  the data suggest that  $\psi(c) \approx 6$  at current income levels. Then the above calculations would increase by at least a factor of 6 for life-threatening events that cause an equally-calibrated reduction in future “income.”

The analyses in Murphy and Topel (2006) and Hall and Jones (2007) also indicate that  $\psi(c)$  rises with income, so the value of life is income elastic. Then if future generations are richer than us, the value of lives saved from mitigating future catastrophes will be proportionally greater than today. For example, an income elasticity of  $\zeta = 1.2$  and long run economic growth at 2 percent yields  $\psi(c) \approx 9.0$  in 100 years. The result is that a randomly occurring event that causes a “concentrated” change in future costs because of climate-related mortality has much higher current value:

$$(7) \quad \frac{1}{c_0} \frac{dU_0}{u'(c_0)} = \frac{\psi(c_0)}{1 + (r - \zeta g)T} \frac{1}{r - \zeta g} d \ln c$$

With a constant hazard rate and an expected arrival time of  $T = 100$  years, with  $\zeta = 1.2$  and  $\psi(c_0) = 6$ , a “catastrophic” event that reduces per-capita output by killing off  $d \ln c = -.01$  of the population has present value equal to 36 percent of current income. Letting  $T = 1000$ —a catastrophe that could occur every thousand years, on average—the current value is about 4.5 percent of income. And of course the value is highly sensitive to the choice of  $r$ : a reduction in the discount rate from .06 to .04 raises the current value of avoiding such a catastrophe from 4.5 percent to 22 percent of current income.

These results indicate that uncertainty over the future timing, magnitude and distribution of losses from climate change can greatly impact our assessments of current cost, even if future costs are discounted at conventional rates of return of, say, 6 percent.

### 3.2 Discounting the Returns on Climate Capital

One of the most controversial aspects of debates over climate change policy is the appropriate social discount rate to be applied to future damages. At the extreme among economists, the *Stern Review's* advocacy for a very low interest rate of  $r = .015$  accounts for almost all of its severe recommendations. Behind the *Stern Review* recommendations is the notion that the welfare of future generations

should be weighted equally with current ones, it being ethically repugnant (in *Stern's* view) to discount their welfare. Then the only source of a positive discount rate on real cash flows is the growth of consumption over time, because future generations are richer than we and utility is concave— $\omega > 0$  in our earlier notation. And in the *Stern* recommendations even that is given little weight in reaching the desired result. Similarly, non-economists such as Archer (2009) have argued that economic analysis is itself ill-equipped to deal with intertemporal valuations spanning a generation or more. Like *Stern*, Archer argues for effectively zero discounting because current action is a moral imperative.

The slowly ramping policy profiles offered by Nordhaus (2008) and others are based on higher discount rates that reflect historical long run returns on other types of capital. In contrast, while critiquing the analytical foundations of the *Stern* rates, Weitzman (2009) offers a “Dismal Theorem” based on the possibility of extreme catastrophes that drive consumption near zero and the marginal utility of consumption beyond the moon. Policies that can avoid such outcomes can have unbounded value under particular assumptions about the distribution of climate effects on  $c$ —they should have “fat tails”—and the rate at which marginal utility rises as consumption falls. The more general and useful point is that uncertainties about the distributions of climate damage and the payoffs from mitigation investments may greatly affect valuations. Climate policies that effectively insure against large downside risks (when the marginal utility of consumption would be large) needn't have large expected returns, so the typical market benchmarks for  $r$  might be inappropriate for valuing investments in climate capital. We return to this point shortly.

From an economic and empirical perspective the choice of a discount rate is not about the philosophical choice of the correct ethical weight to be applied to the welfare of our and other peoples' great-grandchildren, nor is it about the way we “should” discount marginal dollars of their income because they will be richer. As in all analyses that must balance costs and benefits, the issue is opportunity cost. The fact that costs and returns are so uncertain and widely spaced in time adds practical difficulties but not conceptual ones.

Consider a current project costing \$1 million that would reduce the impact of climate change 100 years from now. Assume that, absent the project, the resulting climate change would impose a real cost of \$20 million on future generations. The logic of *Stern* (2006) and Archer (2009) suggests that we should implement the project if, and only if, we value giving \$1 to the current generation less than we value giving \$20 to the future generation. That is, the question of whether the mitigation project is worthwhile allegedly depends on the relative values we place on the consumption of current and future generations.

This is not correct—our choice does not depend on our relative preference for current versus future generations.

Assume we wish to give the future generation the \$20 million benefit they would derive were we to implement the project today. If undertaken, the rate of return on the current project is 3 percent, which is the solution for  $r$  in the equation  $\$1 \times e^{100r} = \$20$ . But if the market rate of interest is 6 percent, \$1 million invested at the market rate of return would yield \$403 million in 100 years, compared to the \$20 million benefit generated by the climate mitigation project. This means that future generations would gain (a lot) if the current generation were to forego the climate project and invest in other assets that yield higher returns. Alternatively, it would take only \$49,000 invested at 6 percent to provide the future generation with the \$20 million needed to compensate them for the harm from climate change. Our point is that it is the market rate of return—not our attitudes toward future generations or our moral view of discounting—that determines the appropriate discount rate. To evaluate climate mitigation policy with a lower rate of return unnecessarily harms either current or future generations, or both. Future generations would not thank us for investing in a low-return project.

It is appropriate to discount the costs and benefits of climate change policies at a “market” rate of return because the market rate measures the opportunity cost of such investments—returns available from investing the same amount in physical or human capital—so long as such opportunities exist. But what “market rate” should we use? At the low end one might benchmark by the risk free rate as represented by the returns on government bonds. An alternative would be the much higher historical returns on risky investments such as physical capital or equities. Offered the opportunity to invest for the benefit of our great-grandchildren in 2110—who by any reasonable expectation will be much richer than us<sup>15</sup>—would we opt for Treasury bills and an annual return of perhaps 3 percent when the historical equity premium consistently provides long run returns in the neighborhood of 6 to 8 percent? Most would choose equities.

Yet the fact that most of us would choose equities reflects an implicit but appropriate (in this context) belief that those assets correctly gauge the opportunity cost for long-term financial investments, including allowance for risk. The weakness in this argument is that it is not obvious that the risks and returns on climate investments align with those on other physical assets or equities. If the returns on climate investments are uncorrelated with returns on the market portfolio, or if by eliminating calamitous harm to overall productivity and living standards climate investments pay off exactly when other productive assets do

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<sup>15</sup> At 1.5 percent annual growth, per capita income in 2110 will be about 4.5 times the current level. At 2 percent the multiple is 7.4. Growth rates in developing countries such as China or India are expected to be much higher.

not, then the appropriate rate of return and discount rate for climate projects should be lower than for other assets, perhaps even lower than the risk-free rate. Further, though the climate impacts of investments in climate capital are global, the risk properties of those effects, and hence their value, may differ greatly across the countries whose participation in global agreements is essential.

### 3.3 *Expected Social Returns on Climate Capital*

The risk properties of the returns on climate investments derive from at least four stochastic drivers: (1) global economic growth, because greater growth likely means greater emissions; (2) the impact of emissions on climate; (3) the impact of climate on environment, productivity and welfare; and (4) the effectiveness of current investments in mitigating future harm.

To illustrate the determinants of an appropriate discount rate for climate investments, consider a standard asset pricing framework for valuing a current (time 0) project that offers uncertain returns at some future date,  $F$ .<sup>16</sup> Assume that the current generation can invest in  $\lambda$  units of a climate project, with current cost  $K(\lambda)$  and marginal cost  $k(\lambda) = K'(\lambda)$ . The investment offers uncertain future returns of  $x$  per unit, where  $x$  may be interpreted as the project's future impact on GHG concentrations, or other measures that would mitigate climate impacts. With this setup, the social planner's intertemporal problem is

$$(8) \quad \underset{\lambda}{\text{Max}} U = u(y_0 - K(\lambda), \psi_0) + \rho E \left[ u(y_F(\lambda x), \psi_F(\lambda x)) \right]$$

The representative individual in (8) derives utility from income (consumption)  $y$  and the state of the environment  $\psi$ , both of which can be affected by current climate investments. The factor  $\rho < 1$  reflects pure time preference between the present ( $t=0$ ) and future ( $t=F$ ), and  $E$  is the expectations operator reflecting uncertainty over the joint distributions of  $y$ ,  $\psi$  and  $x$ . We interpret this social valuation problem as country-specific, so that the distributions of outcomes may be quite different for, say, China than for the US.

The choice of investment in the climate project solves

$$(9) \quad \begin{aligned} k(\lambda) &= E[m_F X_F] \\ &= e^{-r_f} E(X_F) + \text{cov}(m_F, X_F) \end{aligned}$$

<sup>16</sup> See Cochrane (2005) for a clear presentation of asset pricing and discounting issues.

where  $r_f$  is the risk-free rate of return,  $m_F$  is the marginal rate of substitution between future and current consumption, and  $X_F$  is the future generation's value of the income and environmental payoffs on the investment:

$$(10) \quad X_F = (y'_F + v_F \psi'_F)x$$

where  $v_F = u'_\psi / u'_y$  is future willingness to pay for environmental improvements. Divide (10) by  $k(\lambda)$  to obtain marginal returns per dollar invested ( $R_F = X_F / k(\lambda)$ ) and solve for the required return on the environmental asset, which yields the familiar CAPM form for required expected returns on the investment,  $r_E$ :

$$(11) \quad \begin{aligned} r_E &= r_f - \text{cov}(m_F, R_F) \\ &= r_f - \beta_{m,R}(r_M - r_f) \\ &= r_M - (1 + \beta_{m,R})(r_M - r_f) \end{aligned}$$

In (11),  $r_M$  is the market rate of return on equities and  $r_M - r_f = \text{var}(m)$  is the equity premium. The term  $\beta_{m,R} = \text{cov}(m, R) / \text{var}(m)$  is the environmental project's "beta." We have expressed  $\beta$  in terms of the covariance of  $R$  with  $m$  instead of the more traditional covariance with growth in income because of the presence of environment in welfare,  $u(\cdot)$ .

According to the third line in (11), the required expected return on the environmental asset will be smaller than the market rate so long as its market "beta" ( $-\beta_{m,R}$ ) is smaller than 1.0. This has the usual risk-return interpretation— if the environmental asset offers greater payoff than the market when  $m$  is high, then it reduces risk and should have a lower than market expected return. While this may seem likely, so  $r_E < r_M$  is plausible, the first line of (11) offers a more aggressive point about risk and return for investments in climate projects—the expected return on an environmental project may fall below the risk-free rate if  $\text{cov}(m, R) > 0$ . Because  $m$  falls with income, positive covariance of  $m$  and  $R$  is not relevant for most financial assets. But climate projects are alleged to have the potential of averting disasters, so they may pay off precisely in states of the world where willingness to pay,  $m$ , is greatest. For example, if climate change may greatly reduce future productivity and living standards, or cause widespread harm and death in some states of nature, then projects that avert such outcomes (see equation (10)) may be highly valued even if the payoff is rare—they have low

expected return but high market value because they pay off when mitigation of damage is most valuable.

### 3.4 Scalable Technologies and the Effectiveness of Current Investments

Our earlier discussion emphasized the importance of “scalable” technologies in mitigating extreme climate outcomes. Scalable technologies are particularly likely to warrant low rates of discount because they can greatly reduce the risk of extreme climate outcomes. This point can be demonstrated in the current context by putting a bit more structure on the form of future environmental harm and the technology of mitigation.

Let future income in the absence of mitigation be  $y_F = \bar{y}_F - \theta_F Q_F$ , where  $Q_F$  is the future stock of global atmospheric GHGs above some base and  $\theta_F > 0$  is the extent of future economic damage per unit of  $Q_F$ .<sup>17</sup> Both  $Q_F$  and  $\theta_F$  are currently unknown— $Q_F$  is determined by global economic growth and carbon-based energy use, while the distribution of  $\theta_F$  represents current uncertainty about the future cost of GHG concentrations. Their interaction means that extreme values of  $\theta_F$  can cause future environmental “catastrophes” when  $Q_F$  is large. In anticipation of such damage, we assume that the current generation can invest in units of climate capital,  $\lambda$ , which can be combined with future variable inputs  $Z_F$  to mitigate  $G_F(\lambda, Z_F)$  units of environmental harm once  $Q_F$  and  $\theta_F$  are known. For example,  $G_F$  may represent units of  $Q_F$  removed from the atmosphere, or emissions that are avoided by deploying clean energy technologies. Assume that mitigation has constant returns, so  $G_F(\lambda, Z_F) = \lambda g_F(z_F)$ , where  $z = Z / \lambda$ . Let  $\Delta_F$  be the fixed future cost of deploying the technology. If deployed, future income net of mitigation is:

$$(12) \quad y_F = \bar{y}_F - \theta_F [Q_F - \lambda g(z_F)] - \lambda z_F - \Delta_F$$

Let  $g_F(z)$  be iso-elastic;  $g_F(z_F) = A_F \alpha^{-1} z_F^\alpha$ , where  $A_F$  is the unknown future productivity of currently chosen environmental capital. Then the optimal date- $F$  choice of  $z$  yields

$$(13) \quad y_F = \bar{y}_F - \theta_F [Q_F - \lambda \phi^{-1} A_F^{1+\phi} \theta_F^\phi] - \Delta_F$$

<sup>17</sup> If future harm is convex in  $Q_F$  then average harm per unit,  $\theta_F(Q_F)$ , will be increasing in  $Q_F$ . We ignore this so not to complicate the analysis.



where  $\phi = \alpha(1-\alpha)^{-1}$  is the elasticity of supply of mitigation, which indexes the scalability of the investment project—a perfectly scalable (constant marginal cost) project has  $\alpha=1$ . The marginal return on the environmental asset is then

$$R_F = \frac{(A_F \theta_F)^{1+\phi}}{\phi k(\lambda)}.^{18}$$

According to (13), the extent of mitigation increases with the scale of the investment in climate capital,  $\lambda$ , the state of future productivity,  $A_F$ , and with the damage from future GHG concentrations,  $\theta_F$ . For given values of  $A_F$ , and  $\theta_F$ , mitigation is greater when the project is more “scalable”—that is, when  $\phi$  is large.

Some investments such as reducing current GHG emissions are not scalable in that they cannot be cheaply adjusted once the values of  $A_F$  and  $\theta_F$  are realized;  $\phi$  is small and marginal cost rises sharply with mitigation efforts. Others—such as development of clean energy technologies or investments in the capacity to remove carbon from the atmosphere or sequester emissions—can be deployed in large scale based on the future demand for climate mitigation. A perfectly scalable technology,  $\alpha=1$ , would provide a great deal of insurance by effectively truncating the distribution of harm in what would otherwise be the most damaging states of nature, when  $\theta_F$  is large, yielding  $y_F = \bar{y}_F - \Delta_F$  because excess concentrations of GHG are eliminated. Even technologies that are not perfectly scalable can have substantial value. Larger values of  $\phi = \alpha(1-\alpha)^{-1}$  mean that the payoff from implementing the technology is more sensitive to the realized marginal value of environmental improvements,  $\theta_F$ , which enhances the positive covariance between  $m$  and  $R$ . This further reduces the implied rate of discount for such projects because highly scalable technologies provide additional insurance—they are deployable as needed by varying  $Z_F$ . The magnitude of this advantage depends on the uncertainty about  $\theta_F$  (and  $A_F$ ). Greater uncertainty raises the (current) value of ex-post scalability.

This is our earlier point about the value of scalable technologies—research and development investments in mitigation technologies that can be deployed in large scale in the event that damages are large can offer important insurance against looming catastrophe. Such projects should not be heavily discounted.

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<sup>18</sup> With fixed cost,  $\Delta_F$ ,  $R_F=0$  for low values of  $A$  and  $\theta$  because the technology will not be deployed. At the other extreme, *marginal* returns are zero when  $A$  and  $\theta$  are very large, or when  $\phi$  is large, because all excess emissions are mitigated. It is also plausible that scalable (high  $\phi$ ) technologies are more costly to develop, so current costs are  $K(\lambda, \phi)$ .

More broadly, much of the discussion surrounding climate investments stresses that they are meant to avert future catastrophes, which we interpret to mean that they yield dividends when willingness to pay,  $m$ , is highest. Our analysis provides a positive economic case for discounting them lightly. This is, we think, the less extreme and more relevant implication of Weitzman's "Dismal Theorem" analysis.

### 3.5 Heterogeneous Valuations

Much has been made of the fact that effective climate policies require harmonized international efforts, because earth's atmosphere is a global public good. Free-riding and the tragedy of the commons aside, our analysis suggests an additional impediment to cooperation and harmonization, based on heterogeneous valuations of climate investments between developed and developing countries.

Consider China ( $CH$ ) and the United States ( $US$ ) as extremes of the relevant development scale. In terms of our notation above, any reasonable growth scenario implies  $m^{CH} < m^{US}$ ; that is, China will continue to grow faster than the US, so the ratio of future to current marginal utility of consumption is lower in China. And states of nature where China grows fastest correspond to the smallest values for  $m^{CH}$ —these are the good states of nature from China's perspective, because they are rich. The danger of harmful climate outcomes increases with global GHG emissions, which increase with economic growth. So it is reasonable to assume that future GHG concentrations will be greatest if China (and India, and others) grows rapidly, possibly approaching the living standards and energy consumption now observed in the US. This means that "good" states of nature from China's growth perspective are, climate-wise, most damaging to the US, especially if US living standards are harmed. Climate projects valued highly by the US because of strong insurance properties ( $\text{cov}(m^{US}, R)$  is high) may have little current value to China because  $\text{cov}(m^{CH}, R)$  is weak or even negative. In effect, a world with greater climate damage is one in which China gets rich, and they are more willing to bear the future cost that the US would like to avoid.

This discussion can be framed in terms of current efforts to establish a harmonized price for carbon emissions. With rapid economic growth, China's real future willingness to pay for a unit reduction in GHG concentrations may be equal to that of the US. But China discounts this return more heavily, because it only occurs when China prospers. Expressed as a preference for a current tax on GHG emissions, policy makers in China and the rest of the developing world will rationally prefer a lower (or no) tax that is less of a hindrance to attaining prosperity, while the US and other developed countries prefer a higher tax that

insures the prosperity they already have. Even ignoring other challenges to international accord, the likelihood of an effective global policy in such a world appears to us slim.

#### **4. Conclusions**

The basic designs of economic policies to mitigate anthropogenic climate change and its effects are not novel. They are rooted in well-understood methods for dealing with externalities, which remedy market failure by pricing an otherwise over-used resource—here the capacity of the atmosphere to safely absorb GHG emissions. Implementing such policies is more challenging, for two basic reasons. First, the external costs of GHG emissions are global rather than local, so useful policies that would price or regulate current emissions require harmonized action worldwide. Second, the harms that policies seek to value and internalize are both highly uncertain and spread over future generations—all of the benefits of using carbon-based energy occur today, while the possible social costs are far removed.

Our analysis has sought to extend previous work on both the form and substance of climate policies, particularly in the area of valuing uncertain future costs of GHG emissions and the benefits of policies that would mitigate those costs. An important finding is that “gradualist” policies advocated by most economists—setting a low initial emissions price that would rise at a “market” rate of interest—are based on the implicit assumption that returns on climate investments have a similar payoff structure to other forms of investment in physical or human capital. This assumption ignores the possible insurance value of social investments in climate capital, which may pay off precisely when other forms of capital do not.

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