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Designing Climate Mitigation Policy

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Abstract

Global warming is one of the most critical, and also most daunting, challenges facing policymakers in the twenty-first century. Assessing a globally efficient time path for pricing or controlling greenhouse gas (GHG) emissions is difficult enough, with huge scientific uncertainties, disagreement over the ultimate goals of climate policy, and disagreement over which countries should bear most responsibility for emissions reductions. On top of this, domestic policy design is inherently difficult because of multiple, and sometimes conflicting, criteria for policy evaluation. And at an international level, there are multiple approaches to coordinating emissions control agreements. What should be a rational policy response for such an enormously complex problem.

Key Words: global warming damages, mitigation cost, climate policy, instrument choice, technology policy

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Contents

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1. Introduction

Global warming is one of the most critical and also most daunting challenges facing policymakers in the twenty-first century. Assessing a globally efficient time path for pricing or controlling greenhouse gas (GHG) emissions is difficult enough, with huge scientific uncertainties, disagreement over the ultimate goals of climate policy, and disagreement over which countries should bear most responsibility for emissions reductions. On top of this, domestic policy design is inherently difficult because of multiple, and sometimes conflicting, criteria for policy evaluation. And at an international level, there are multiple approaches to coordinating emissions control agreements. What should be a rational policy response for such an enormously complex problem?

This paper attempts to provide some broad answers to this question, and pinpoint the main sources of controversy, by pulling together key findings from diverse literatures on mitigation costs, damage valuation, policy instrument choice, technological innovation, and international climate policy. Given that our target audience is the broader economics profession (rather than the climate specialist) our discussion is highly succinct and avoids details.

We begin with the broadest issue of how much action to price or control GHGs is warranted in the near and longer term, at a global level. There are two distinct approaches to this question. The cost-effectiveness approach acknowledges that policymakers typically have some ultimate target for limiting the amount of projected climate change or atmospheric GHG accumulations, and the question is what policy trajectory might achieve alternative goals at

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minimum economic cost, accounting for practical constraints, such as incomplete international coordination. The other approach is to weigh the benefits and costs of slowing climate change, which introduces highly contentious issues in damage valuation, dealing with extreme climate risks, and inter-generational discounting.

The second part of the paper deals with issues in the implementation of climate policy. At a domestic (US) level these include a comparison of alternative emissions control instruments and how they should be designed to simultaneously promote administrative ease and minimize efficiency costs in the presence of other policy distortions, abatement cost uncertainty, and possible distributional constraints. We also discuss the extent to which additional policies are warranted to promote the development and deployment of emissions-saving technologies. And we briefly summarize emerging literature on alternative international policy architectures. A final section discusses key areas for future research.

2. Policy Stringency

2.1. Emissions Pricing to Stabilize Global Climate

The cost-effectiveness approach to global climate policy uses models of the economic and climate system (known as integrated assessment models) to estimate the emissions price trajectory that minimizes the discounted worldwide costs of emissions abatement, subject to a climate stabilization target, and possibly other, practical constraints like delaying developing country participation. These models range from bottom-up engineering-economic models with considerable detail on adoption and use of energy technologies, to computable general equilibrium models with a more aggregated and continuous structure that better represents demand responses, capital dynamics and factor substitution. Many models are hybrids containing substantial technological detail in the energy sectors, and more aggregate representation in others. Typically the suite of existing and emerging technologies is taken as given, though some models capture induced innovation through learning-by-doing, and a few have incorporated R&D-based technological change (e.g., Goulder and Matthai 2000).

The choice of model structure is generally less important than assumptions about future baseline data and technology options. Future mitigation costs are highly sensitive to business-as-usual (BAU) emissions, which depend on future population and GDP growth, the energy-intensity of GDP, and the fuel mix. They also depend on the future availability and cost of emissions-saving technologies like nuclear and renewable power, carbon capture and storage, and alternative transportation fuels. Considerable uncertainty surrounds all of these factors.

Given the difficulty of judging which models give the most reliable predictions, we discuss a representative sample of results, beginning with studies that assume emissions reductions are efficiently allocated across countries and time, and using the least expensive technological options (this is known as “where, when, and how” flexibility). The results, summarized in Table 1, are from the US Climate Change Science Program (CCSP, Product 2.1A), based on results from three widely regarded models (see Clarke 2007 et al. for details), and from the Stanford Energy Modeling Forum’s EMF-21 study (reported in de la Chesnaye and Weyant 2006) based on 16 models.

2.1.1. Reference Scenarios

Global CO_2 emissions from fossil fuels have grown from about 2 billion (metric) tons in 1900 to current levels of about 30 billion tons and, in the absence of mitigation policy, are projected to roughly triple 2000 levels by the end of the century (Table 1). The huge bulk of the projected future emissions growth is in “non-Annex 1” (non-industrial) countries—CO_2 emissions from these countries have just overtaken those from “Annex 1” (industrial) countries.[1] These rising emissions trends reflect growing energy demand from population and real income growth outweighing energy- and emissions-saving technological change—traditional fossil fuels still account for around three-quarters of global primary energy consumption by 2100 (Clarke et al. 2007, Table TS1).[2]

About 55 percent of CO_2 releases are immediately absorbed by the upper oceans and terrestrial biosphere while the remainder enters the atmosphere and is removed by the ocean and terrestrial sinks only very gradually (IPCC 2007). The longer term rate of removal of CO_2 from the atmosphere is around 1 percent a year (i.e., CO_2 has an expected atmospheric residence time of about a century), and even this very gradual decay rate might decline as oceans become more saturated with CO_2. Stabilizing atmospheric CO_2 concentrations over the very long term essentially requires elimination of fossil fuel and other GHG emissions.

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[1] The 1990 UN Framework Convention on Climate Change grouped countries into either Annex 1, or non-Annex 1, according to their per capita income at that time. Only Annex 1 countries agreed to reduce emissions under the 1997 Kyoto Protocol.

[2] Land-use changes currently contribute about an additional 5.5 billion tons of CO_2 releases (primarily through deforestation in developing countries for agriculture and timber) though these sources are projected to grow at a much slower pace than fossil fuel emissions (IPCC 2007). Land-use CO_2 emissions are not priced in the models in Table 1.

Atmospheric CO_2 concentrations increased from pre-industrial levels of about 280 parts per million (ppm) to 384 ppm in 2007, and are projected to rise to around 700-900 ppm by 2100 (Table 1). Accounting for non-CO_2 GHGs, such as methane and nitrous oxides from agriculture, and expressing them on a lifetime warming equivalent basis, the CO_2-*equivalent* concentration is about 430 ppm (IPCC 2007). Total GHG concentrations in CO_2-*equivalents* are projected to reach 550 ppm (i.e., about double pre-industrial levels) by around mid century.

Globally-averaged surface temperature is estimated to have risen by 0.74°C between 1906 and 2006, with most of this warming due to rising atmospheric GHG concentrations, as opposed to other factors like changes in solar radiation, volcanic activity, and urban heat absorption (IPCC 2007). Figure 1, from IPCC (2007), shows projected the long run warming associated with different stabilization levels for atmospheric CO_2 *equivalent* concentrations (the climate system takes several decades to fully adjust to changing concentration levels, due to gradual heat diffusion processes in the oceans). If CO_2 *equivalent* concentrations were stabilized at 450, 550 and 650 ppm, mean projected warming over pre-industrial levels is 2.1, 2.9 and 3.6°C respectively. Figure 1 also indicates "likely ranges" of warming about the mean projection, which refer to an approximate 66 percent confidence interval, based on sensitivity analysis from scientific models—for example, the likely warming range for 550 ppm CO_2 *equivalent* stabilization is 1.9–4.4°C. The fundamental concern is that warming might greatly exceed these ranges due to poorly understood feedbacks not represented in these models, such as heat-induced releases of methane stored under the oceans and in the permafrost.

2.1.2. Least-Cost Pricing

Most economic analysis has focused on climate stabilization targets that are approximately consistent with limiting atmospheric CO_2 concentrations to either 450 or 550 ppm (with other GHGs included, CO_2 *equivalent* concentrations would be stabilized at approximately 530 and 670 ppm respectively). The studies in Table 1 examine globally cost-effective pricing of all GHGs that are approximately consistent with these goals.[3]

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[3] The G-8 countries recently adopted a target of limiting projected warming to 2°C above pre-industrial levels. This would require ultimately stabilizing CO_2-*equivalent* concentrations at 450 ppm, which is considerably more stringent than the 450 ppm CO_2 target discussed here. In fact, with current technologies, it is difficult to see how the more stringent target could be achieved (even allowing for transitory overshooting), given that current concentration levels are already approaching this target.

Across the models and stabilization scenarios in Table 1, CO_2 emissions prices (in year 2000 dollars) rise steadily (beginning around year 2012) at approximately 5 percent a year, where this figure is the consumer discount rate plus the atmospheric CO_2 decay rate (Peck and Wan 1996). However, one striking feature in Table 1 is the considerable price variation across models within a stabilization scenario, reflecting different assumptions about future BAU emissions growth and future costs of carbon-saving technologies. The other striking feature is the dramatic differences between the 550 and 450 ppm CO_2 stabilization targets. In the 550 ppm case, CO_2 prices are \$3-26 and \$10-99 per ton in 2025 and 2050 respectively, with global emissions 17-41 percent and 13-56 percent *above* 2000 levels at these dates, respectively. In the 450 ppm case, CO_2 prices are 3-16 times those in the 550 ppm case to mid century, while emissions are 3-14 percent and 36-47 percent *below* 2000 levels in 2025 and 2050 respectively.[4]

Although GDP losses may be an unreliable proxy for efficiency losses we discuss them here as they are the least common denominator reported by the modeling groups. Under the 550 ppm CO_2 target, most models project global GDP losses (from reducing both CO_2 and non-CO_2 GHGs) of less than 1 percent out to 2050, though some models suggest GDP losses could reach 2-3 percent by this date. In present value terms, these losses amount to about \$0.4-12 trillion out to 2050 when applied to a world GDP that is \$60 trillion and growing (Newell 2008, pp. 12). Under the 450 ppm CO_2 target, GDP losses are about 1.0-2.5 percent and 1.5-5.5 percent in 2025 and 2050 respectively or about \$8-43 trillion in present value from 2010 to 2050.

Under both the 450 and 550 ppm CO_2 stabilization scenarios the energy system is transformed over the next century (though at very different rates), through energy conservation, improved energy efficiency, and particularly reductions in the carbon intensity of energy. Most of the emissions reductions in the first two to three decades occur in the power sector, largely through the progressive replacement of traditional coal plants by coal with carbon capture and storage, natural gas, nuclear, and renewables (wind, solar, and biomass). However, the projected fuel mix is highly sensitive to speculative assumptions about the relative costs and availability of future technologies. For example, there are considerable practical obstacles to the expansion of nuclear power (because of safety issues), renewables (because sites are typically located far from

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[4] Some analysts express prices per ton of carbon rather than CO_2. To convert to \$ per ton of carbon, multiply by the ratio of molecular weights, 44/12=3.67.

population centers), and carbon capture and storage (because of the difficulty of assigning sub-surface property rights).[5]

As for US CO_2 emissions, in the BAU case they increase by about 30-100 percent above 2000 levels (of approximately 6 billion tons) by mid century (Table 1). Under the 550 CO_2 ppm target, emissions initially rise, then fall to roughly 2000 levels by 2050, and fall rapidly thereafter. Under the 450 ppm target, US emissions are rapidly reduced to roughly half 2000 levels by 2050.[6] US-specific GDP losses are not reported in the studies in Table 1, but allocating a quarter of the global cost to the United States (based on its share in global GDP) implies a present value cost to the United States through mid century of about $0.1-3 trillion (0-1 percent of the present value of GDP) for the 550 ppm target and $2-11 trillion (1-3 percent of present value GDP) for the 450 ppm target.[7]

2.1.3. Deviations from Least-Cost Pricing

Aside from the uncertainty surrounding modeling assumptions, a key qualification to the studies in Table 1 is that they assume globally efficient abatement policies. More likely, particularly given the "common but differentiated responsibilities" recognized in the Kyoto Protocol, participation in global mitigation efforts among major developing country emitters will be delayed, causing marginal abatement costs to differ across regions. For a given climate stabilization scenario, to what extent does this affect worldwide abatement costs and appropriate policies in developed countries?

Edmonds et al. (2008) explore these issues assuming Annex 1 countries agree to impose a harmonized emissions price starting in 2012, China joins the agreement at a later date, and other countries join whenever their per capita income reaches that of China at the time of China's

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[5] The transition away from coal reflects not only the range of substitution possibilities in the power sector, but also the disproportionately large impact of emissions pricing on coal prices. A $10 price per ton of CO_2 in the United States would increase 2007 coal prices to utilities by about 60 percent, wellhead natural gas prices by 9 percent, retail electricity and crude oil prices each by 7 percent, and gasoline prices by 3 percent (from Clarke et al. 2007, Table TS5, and www.eia.gov).

[6] As of 2009, proposed climate policies in the United States embody emission reduction targets approximately equivalent to about of 80 percent below 2000 levels by 2050. However, actual reductions in US CO_2 emissions would be about 60 percent if provisions to exploit domestic and international emission offsets were fully exploited.

[7] US-specific models project emissions price ranges that are broadly consistent with those in Table 1. For example, analyses by Paltsev et al. (2007), EPA (2008), EIA (2008a) and CRA International (2008) project emissions prices of around $40-90 per ton of CO_2 in 2025 for climate legislation that would reduce US CO_2 emissions by about 20 percent below 2000 levels by that date.

accession. In one scenario, they assume new entrants immediately face the prevailing Annex 1 emissions price, while in another the emissions price for late entrants converges gradually over time to the Annex 1 price. The analysis accounts for emissions leakage, that is, the increase in emissions in non-participating countries due to the global relocation of energy-intensive firms, and increased use of fuels elsewhere as decreased demand in participating countries lowers world fuel prices.

Under the 550 ppm CO_2 target, even if China joins between 2020 and 2035, the implications for Annex 1 policies can be significant but are not that striking. Compared with the globally efficient policy, near-term Annex 1 emissions prices rise from between a few percent to 100 percent under the different scenarios, and discounted global abatement costs are higher by 10-70 percent. However, under the 450 ppm CO_2 target, essentially all of the foregone earlier reductions in non-Annex 1 countries must be offset by additional early reduction in Annex 1 countries (rather than more global abatement later in the century). This can imply dramatically higher near-term Annex 1 emissions prices, especially with longer delay and lower initial prices for late entrants. Under these scenarios, discounted global abatement costs are about 30-400 percent higher than under globally efficient pricing, and near and medium term emissions prices can be an order of magnitude larger with China's accession delayed till 2035.

A further key point from Edmonds et al. (2008) is the potentially large shift in the global incidence of abatement costs, underlying the disincentives for early developing country participation. In the globally efficient policy, without any international transfer payments, developing countries bear about 70 percent of discounted abatement costs out to 2100, while they bear "only" 17-34 percent of global abatement costs when China's accession occurs in 2035 and new entrants face lower starting prices.

Finally, insofar as possible pricing non-CO_2 GHGs is also important. According to modeling results in de la Chesnaye and Weyant (2006), GDP costs are 20-50 percent larger when only CO_2, as opposed to all, GHGs are priced, for the same overall limit on atmospheric CO_2-*equivalent* concentrations. This reflects opportunities for large-scale, low-cost options for non-CO_2 abatement in the first half of this century, though practical difficulties in pricing other GHGs are not factored into the models.

2.1.4. Summary

There is a large difference in the appropriate starting prices for GHG emissions, depending on whether the ultimate objective is to limit atmospheric CO_2 concentrations to 450 or 550 ppm—targets that are approximately consistent with keeping the eventual, mean projected warming above pre-industrial levels to 2.7 and 3.7°C respectively (assuming non-CO_2 GHGs are also priced). The 450 ppm target implies emissions prices should reach around $40-90 per ton of CO_2 by 2025, while the 550 ppm target implies prices should rise to $3-25 by that date. Securing early and widespread participation in an international emissions control regime can also be critical for containing costs under the 450 ppm target, while under the 550 ppm target there is greater scope for offsetting the effect of delayed participation through greater emissions reductions in the latter half of the century. Given the considerable difference in GDP losses at stake between the two targets ($8-43 trillion in present value under cost-effective pricing out to 2050 compared with $0.4-12 trillion), it is important to carefully assess what starting prices might be justified by avoiding climate change damages.

2.2. Welfare-Maximizing Emissions Pricing

2.2.1. Marginal Damage Estimates

Estimates of the marginal damages from current emissions begin with a point estimate of total contemporaneous damages from warming, usually occurring around 2100. Total damage estimates from a number of studies are roughly in the same ballpark, for a given amount of warming. According to representative estimates in Figure 2, damages are in the range of about 1-2 percent of world GDP for a warming of 2.5°C above pre-industrial levels, though some estimates are close to zero or even negative (the prospects for negative costs diminishes with greater warming). For warming of about 4.0°C, damage estimates are typically in the order of 2-4 percent of world GDP. However, similarities in aggregate impacts mask huge inconsistencies across these studies, which reach strikingly different conclusions about the size of market and nonmarket damage categories and expected catastrophic risks (Figure 2).

Very few studies attempt to value the damages from more extreme warming scenarios, given so little is known about the physical impacts of large temperature changes. Two exceptions are Nordhaus and Boyer (2000) and Stern (2007) who put expected total damages at 10.2 and 11.3 percent of world GDP, for warming of 6.0°C and 7.4°C respectively, though these figures are necessarily based on extrapolations and subjective judgment. Again, there is little consistency across the estimates. In Nordhaus and Boyer (2000) catastrophic risks and market damages account for about 60 and 40 percent of total damages respectively, with non-market impacts roughly washing out (for example, there gains from leisure activities offset losses from the disruption of ecosystems and settlements). In contrast, non-market impacts account for about half of Stern's overall damage estimate.

Marginal damage estimates are based on assumptions about emissions/concentration relationships, climate adjustment and sensitivity, damages from climate change (inferred from a point estimate of total damages using functional form assumptions), and discount rates. Tol (2009) conducts several meta-analyses of marginal damage estimates, reporting median estimates of $4.1-20.2 per ton of CO_2 (individual studies are not independent however, as they often drawing from the same sources and from each other). Although individual estimates are highly divergent, most are on the low side (see also Newbold et al. 2009). Especially striking is the difference between Stern (2007) at $85 and Nordhaus (2008) at $8 per ton of CO_2—a difference largely dependent on discount rate assumptions (see below).[8]

There is some consensus that marginal damages grow at around 2-3 percent a year in real terms (approximately the rate of growth in output potentially affected by climate change), or about half the rate as under cost-effective emissions pricing. Marginal damages rise with the extent of warming (suggesting a faster rate of increase), but an offsetting factor is that warming is a concave (logarithmic) function of atmospheric concentrations. Although CO_2 concentrations ultimately reach 650 ppm in the twenty-second century in Nordhaus (2008)'s optimal policy, constraining CO_2 concentrations to 550 ppm affects, only modestly, the emission price trajectory to 2050. Thus, optimal near and medium term emissions prices in Nordhaus (2008) are in the same ballpark with those for cost-effective stabilization of CO_2 concentrations at 550 ppm, while starting prices in Stern (2008) are broadly consistent with cost-effective prices to stabilize CO_2 concentrations at 450 ppm, or lower.

2.2.2. Controversies in Marginal Damage Assessment

Differences in marginal damage estimates are largely explained by fundamentally different approaches to discounting rather than differences in total damages from a given amount of warming (Nordhaus 2007). However, the valuation of catastrophic and non-catastrophic damages is also highly contentious.

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[8] Some of the differences in marginal damage estimates reflect different assumptions about the year for which emissions are being priced, and about the extent of future warming. Most estimates of near-term Pigouvian taxes (i.e., marginal damages from the globally optimized emissions trajectory) are similar to marginal damage estimates at BAU emissions levels. One exception is Stern (2007) pp. 344 where marginal damages are considerably reduced when aggressive climate stabilization goals are achieved.

Discounting. The *descriptive* approach to discounting argues that we can do no better than using observed market rates, typically assumed to be about 5 percent.[9] According to this approach, market rates reveal individuals' preferences, as best we understand them, about trade-offs between early and later consumption within their lifecycle, as well as their ethical or intergenerational preferences. And they reflect the return earned by a broad range of private and public investments—the opportunity cost against which other, even intergenerational, investments ought to be measured. Proponents of the descriptive approach view discounting at market rates as essential for meaningful, consistent policy analysis and to avoid highly perverse implications in other policy contexts.

In contrast the *prescriptive* approach argues that market rates cannot be used when looking across cohorts (rather than within individuals' lifetimes). Instead, the discount rate (r) is decomposed as follows: $r = \rho + x \cdot \eta$, where ρ is the pure rate of time preference, x is the growth rate in consumption, and η is the elasticity of marginal utility with respect to consumption. In Stern (2007), for example, $\rho = 0.1$, $x = 1.3$ and $\eta = 1$, implying $r = 1.4$. Choosing a value for ρ, the rate at which the utility of future generations is discounted just because they are in the future, is viewed as a strictly ethical judgment. And ethical neutrality, in this approach, essentially requires setting the pure rate of time preference equal to zero. Discriminating against people just because they are in the future is viewed as being akin to discriminating against people in the present generation just because they live in different countries (Heal 2009). There is also controversy over the appropriate value for η, which is almost as important as ρ. For example, Dasgupta (2006) argues for using a value of 2 to 4 on normative grounds, while Atkinson and Brandolini (2007) suggest a value below unity is plausible, based on observed government behavior.[10]

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[9] There are many market rates, from the long-term pre-tax real return to equities (about 7 percent) to the after-tax return to government bonds (about 2 percent). Converting all values into their consumption equivalents, and discounting at the consumption rate of interest, narrows the possible range of choice (e.g., Lind 1982). In fact McGratten and Prescott (2003) suggest that the divergence in effective rates of return is actually small, with an average real debt return during peacetime over the last century of almost 4 percent and the average equity return somewhat under 5 percent.

[10] Besides ethical arguments, Sterner and Persson (2008) argue for discounting the non-market impacts of climate change (e.g., ecosystem loss) at below market rates. This is because the value of non-market goods (which are essentially fixed in supply) rises over time relative to the value of market goods (for which supply increases along with demand), assuming market and non-market goods are imperfect substitutes for one another.

Catastrophic Risks. Although Nordhaus and Boyer (2000) and Stern (2007) include catastrophic risks in their damage assessments, the numbers are best viewed as highly speculative placeholders. Nordhaus and Boyer (2000) put the annual willingness to pay to avoid catastrophic risks at 1.0 and 6.9 percent of world GDP, for warming levels of 2.5 and 6.0°C respectively, based on subjective probabilities (from an expert elicitation survey) for these warming levels permanently wiping out about a third of world GDP. In his central case, Stern (2007) assumes the chance of catastrophic climate change is zero up to a warming of about 5°C, beyond which the annualized risk of regional GDP losses of 5-20 percent rises by about 10 percent for each additional 1°C of warming.

Weitzman (2009a) takes a radically different perspective. He shows that if the probability of increasingly catastrophic outcomes falls more slowly than marginal utility in those outcomes rises (with diminished consumption), then the certainty-equivalent marginal damage from current emissions becomes infinite. These conditions apply if the probability distribution for climate sensitivity is a fat-tailed *t*-distribution (i.e., approaches zero at a less than exponential rate) and utility is a power function of consumption. Although marginal utility is probably not unbounded, Weitzman shows that with probabilities of a 20°C temperature change inferred from IPCC (2007), and assuming this temperature change would lower world consumption to 1 percent of its current level, expected catastrophic damages could easily dwarf non-catastrophic damages (even with these impacts delayed a century or more and discounted at market rates).[11]

There are several responses to the Weitzman critique. One is that, most likely, the probability distribution for climate sensitivity may have thin rather than fat tails. If the distribution is thin-tailed, Newbold and Daigneault (2008) and Pindyck (2008) find that damage risks from extreme global warming are typically under 3 percent of consumption (rather than infinitely large).

Second, setting a modest emissions price now does not preclude the possibility of a mid-course correction, involving a rapid phase-down in global emissions, should future learning reveal we are on a catastrophic trajectory (e.g., Yohe and Tol 2009). This argument assumes

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[11] The IPCC report provides probability distributions from 22 scientific studies. Combining these distributions, Weitzman (2009a) suggests that there is a 5 percent and 1 percent probability that eventual warming from a doubling of CO_2 equivalent concentrations will exceed 4.5°C and 7.0°C respectively. However, making an (extremely crude) adjustment for the possibility of feedback effects he infers a distribution where the probability of eventual temperature change exceeding 10°C and 20°C is 5 percent and 1 percent respectively.

policymakers can avoid the catastrophe—it breaks down if this would require *reversing* previous atmospheric accumulations because an abrupt climate threshold has been crossed.

Finally, a costly, rapid stabilization of GHG concentrations is a highly inefficient way to address the very small probability of extreme outcomes, if a portfolio of last-resort technologies could be successfully developed and deployed, if needed, to head off the catastrophe. These include "air capture" technologies for atmospheric GHG removal and "geo-engineering" technologies for modifying global climate.[12] Moreover, these R&D efforts can be led by one or several countries, avoiding the challenges endemic in organizing a rapid emissions phasedown among a large number of emitting countries with widely differing interests. Nonetheless, public R&D into last-resort technologies (virtually non-existent at present) is highly contentious. One objection is that advancing last-resort technologies could undermine support for emissions mitigation efforts. Another is that geo-engineering (though not air capture) could have extreme downside risks (e.g., from overcooling the planet or radically altering precipitation patterns) that may be difficult to evaluate prior to widespread deployment. Whether effective institutions could be developed to prevent unilateral deployment of climate modification technologies prior to rigorous assessment of their risks is also unclear (e.g., Barret 2008, Victor 2008).

In short, the implications of extreme catastrophic risks for emissions pricing are highly controversial. So long as there is some positive likelihood, no matter how small, that the climate sensitivity function is fat-tailed then catastrophic risks can still swamp non-catastrophic impacts. Mid-course policy corrections may come too late to prevent a catastrophe, given that it may take several decades for the full warming impacts of previous atmospheric accumulations to be realized. And the future viability of last-resort technologies is highly uncertain at present. All of these issues—the nature and extent of damages from extreme warming, the feasibility of future, mid-course policy corrections, and the efficient balance between mitigation and investment in last-resort technologies—are badly in need of economic analysis.

Non-Catastrophic Impacts. Although on a different scale than catastrophic risks, controversies abound in the valuation of non-catastrophic damages. These include agricultural impacts, costs of increased storm intensity and protecting against rising sea levels, health impacts

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[12] Besides rapid re-forestation programs, air capture might involve bringing air into contact with a sorbent material that binds chemically with CO_2 and extraction of the CO_2 from the sorbent for underground, or other, disposal. Geo-engineering technologies include, for example, deflection of incoming solar radiation through shooting particles into the stratosphere or blowing oceanic water vapor to increase the cover of reflective clouds.

from heatwaves and the possible spread of vector-borne disease, loss of ecosystems, and so on. Box 1 provides a very brief summary of attempts to value these damage categories (see Eber and Krupnick 2009 for a more detailed discussion). However, due to the rapid outdating of prior research, daunting methodological challenges, and the small number of economists working on aggregate damage assessment, the valuation literature remains highly inconsistent and poorly developed, as a few examples illustrate (Hannemann 2008).

Damage assessments (like those in Figure 2) assume losses in consumer and producer surplus in agricultural markets are equivalent to anything from a net gain of about 0.1 percent to a net loss of 0.2 of world GDP for warming of about 2.5^{o}C occurring in 2100. However more recent, country-specific evidence suggests that output losses could be a lot larger than those assumed in the damage assessments to infer welfare costs to agriculture. For example, Cline (2007) suggests total losses of agricultural output in developing countries in the order of 30 percent, while Guiteras (2008) estimates agricultural losses of 30-40 percent for India. Even for the United States, Schlenker et al. (2005) suggest that the output of individual crops could fall by up to 70 percent by 2100. Similarly, recent evidence on ice melting suggests that sea level rises over the next century may be more extreme than the 25-60 cm and assumed in most previous damage assessments (Box 1). And estimated ecosystem losses of about 0.1-0.2 percent of world GDP seem inconsistent with Fischlin et al. (2007)'s projection that 20-30 percent of the world's species (an enormous amount of natural capital) faces some (though possibly slight) extinction risk.

More generally, scientific models cannot reliably predict local changes in average temperature, temperature variability, and precipitation, all of which are critical to crop yields. The baseline for impact assessment decades from now is highly sensitive to assumptions about regional development (including the ability to adapt to climate change), future technological change (e.g., into climate- and flood-resistant crops), and other policies (e.g., attempts to eradicate malaria or integrate global food markets). Controversies surround the valuing of nonmarket effects (e.g., the value of mortality in poor countries, how much people in wealthy countries value ecosystem preservation in poor countries). There is scant evidence on additional risks, such as extreme local climate change (e.g., from shifting monsoons and deserts) and broader health effects (e.g., malnutrition from food shortages, the net effects of milder winters and hotter summers, and diarrhea if droughts reduce safe drinking water supplies). Most of the impact assessment literature is based on extrapolations from US studies—country-specific studies that account for local factors (e.g. ability to adapt farm practices to changing climate) have only recently begun to emerge. Finally, worldwide results mask huge disparities in regional burdens, and there is disagreement on how to aggregate impacts across regions with very different per-capita income.[13]

2.2.3. Further Issues Posed by Uncertainty.

Finally, we touch on some additional complications for emissions pricing posed by uncertain discount rates, risk aversion, and irreversibility.

In damage valuation, the time path of future discount rates is usually taken as given. However, the discount *factor* applied to damages is a convex function of the future discount rate, so discount rate uncertainty (for a given expected value) increases the certainty-equivalent discount factor (Weitzman 1998). Newell and Pizer (2003) estimated that discount rate uncertainty (inferred from US historical evidence) almost doubles estimates of marginal emissions damages.

Leaving aside extreme risks, should marginal damage estimates include a risk premium? This would be appropriate if the marginal utility of consumption, net of climate damages, were larger in high-damage outcomes, in which case a mean-preserving increase in the spread of possible damages outcomes would increase expected disutility. However, if gross consumption is greater in high-damage scenarios (for example, because rapid productivity growth leads to both high consumption and high emission rates), then the marginal utility of consumption *net* of damages is lower, and possibly even lower than marginal utility in low-damage states. Simulations by Nordhaus (2008), Ch. 7, suggest this might in fact be the case, implying the risk premium is actually negative, though empirically small. On the other hand, we do not know what the probability distribution over damage outcomes is. If policymakers are averse to such ambiguity this may, under certain conditions, imply a higher near term price on emissions, though how much higher is difficult to quantify (Lange and Treich 2009).

Returning to the issue of irreversibility and future learning, is there is an option value (which should be reflected in the emissions price) gained from delaying atmospheric GHG accumulations until more is known about how much damage they will cause? Option values arise if such delay increases the potential future welfare gains from responding to new information about damage risk (Pindyck 2007). If damages are linear in GHG concentrations, changes in the

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[13] Most studies aggregate regional impacts using weights equal to the region’s share in world GDP or world population. More generally, use of distributional weights can increase total damage estimates up to about 300 percent (e.g., Pearce 2005).

inherited concentration level do not affect marginal damages from additional, future accumulations. In this case, the welfare effects of policy interventions at different time periods are de-coupled (at least from the damage side), and there is no option value. If instead, damages are convex in atmospheric GHG accumulations the prospect of future learning *reduces* the optimal near-term abatement level, to the extent that the damages from near-term emissions can be lowered through greater abatement in future, high-damage scenarios. Moreover, to the extent that current abatement involves (non-recoverable) sunk investments in emissions-saving technologies, there is another source of option value, from delaying long-lived emissions-saving investments until more is known about the benefits of emissions reductions (Kolstad 1996a). For these reasons, theoretical analyses suggest that the prospect of future learning justifies *less* near-term abatement (Kolstad 1996b, Fisher and Narain 2003, Pindyck 2007). However, as already noted, the critical exception to this is when there is a possibility of crossing a catastrophic threshold in atmospheric concentrations *prior* to future learning, which is essentially non-reversible given the non-negativity constraint on future emissions.

2.2.4. Summary

Most estimates of near-term marginal damages are in the order of \$5-\$25 per ton of CO_2. This range is in the same ballpark as near-term emissions prices consistent with least-cost stabilization of atmospheric CO_2 concentrations at 550 ppm. These prices represent a lower bound on appropriate policy stringency. Much higher prices (that are consistent with 450 ppm, or even more stringent, CO_2 stabilization targets) can be implied by low discount rates and, possibly, extreme catastrophic risks (depending on the shape of the climate sensitivity distribution). Thus, whether moderate or aggressive emissions pricing is currently warranted largely hinges on one’s view of discounting, whether radical mid-course corrections in response to future learning about catastrophes are feasible, and the prospects for development of last-resort technologies.

3. Policy Design

3.1. Choice and Design of Domestic Emissions Control Instruments

Debate over the choice of instrument for a nationwide carbon control program is no longer about the superiority of market-based approaches over traditional forms of regulation (like technology mandates) but rather between the two market-based alternatives, emissions taxes and cap-and-trade systems.[14] In a world where the emissions externality is the only market distortion, and there is no uncertainty, either instrument could achieve the first-best outcome, if the emissions cap at each date equals the emissions that would result under the Pigouvian tax. Whether allowances are auctioned or given away for free has distributional consequences but does not affect efficiency in this setting, so long as firm behavior does not influence their future allowance allocations. If firms were free to bank and borrow emissions allowances, the policies would still be equivalent, if the permit trading ratios across different time periods were equivalent to the ratio of Pigouvian emissions taxes at those dates (Kling and Rubin 1997).

The equivalence between the two instruments potentially breaks down in the presence of pre-existing tax distortions, when distributional impacts are a concern, and when there is uncertainty. Despite these complications, to a large extent permit systems can be designed to mimic the effect of a tax, and vice versa, and therefore the choice of instrument per se is less important than whether the chosen instrument is well designed (Goulder 2009). Aside from policy stringency, key design features relate to the point and scope of regulation, the allocation of policy rents, and possible provisions to limit price volatility.

3.1.1. Point of Regulation

Either a CO_2 tax or cap-and-trade system can be imposed upstream where fuels enter the economy (the minemouth for coal or wellhead for oil and natural gas) according to a fuel's carbon content or, as in the European trading program, to downstream emitters at the point where fuels are combusted. Upstream systems would require monitoring some 2,000-3,000 entities in the United Sates or European Union, while downstream systems would apply to 10,000 or more power plants and large industrial smokestacks (Hall 2007).[15] For a given total emissions

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[14] Market-based instruments equalize marginal abatement costs across all abatement opportunities within the firm, across heterogeneous firms, across production sectors, and across households and firms, by establishing an economy-wide emissions price (Dales 1968, Kneese and Bower 1968, Baumol and Oates 1971, Montgomery 1972). In contrast, for example, a requirement that all electric utilities generate a fraction of their power from renewables will not achieve any of these efficiency conditions. Some opportunities at the firm level (e.g., substituting natural gas and nuclear power for coal), are not exploited; marginal costs will differ across heterogeneous power companies; household electricity prices will not reflect the cost of the remaining (unpriced) emissions; and abatement opportunities outside of the power sector are unexploited. For a broad reviews of the literature on environmental policy instrument choice see Hepburn (2006) and Goulder and Parry (2008).

[15] If introduced at the same points in the economy, CO_2 taxes and cap-and-trade systems are likely to have very similar administrative costs. Under cap-and-trade, costs also include those from administering trading markets, as well as the transactions costs of the trades themselves, though these are relatively small (Stavins 1995).

reduction, the estimated economic costs of downstream programs out to 2030 are not dramatically larger than those for comprehensive upstream systems—about 20 percent larger according to Goulder (2009)—even though downstream programs cover only about half of total US and EU CO_2 emissions. This is because the huge bulk of low-cost abatement opportunities are (initially) in the power sector. Moreover, the infeasibility of monitoring emissions from vehicles, home heating fuels, and small-scale industrial boilers in a downstream system can be largely addressed through supplementary midstream measures targeted at refined transportation and heating fuels, which further narrows the cost discrepancy between upstream and downstream systems.

There are a couple of other notable differences between the two systems. One is that upstream programs must be combined with a crediting system to encourage development and adoption of carbon capture and storage technologies at coal plants and industrial sources. (The tax credit should equal the amount of carbon sequestered, as measured by continuous emission monitoring systems, times the emissions price). The other is that, at least for the United States where many states retain cost-of-service regulation, the opportunity cost of freely allocated emissions allowances to electric utilities in a downstream system may not be passed forward into higher generation prices. As a result, incentives for electricity conservation could be a lot weaker, resulting in a significant loss of cost-effectiveness, compared with upstream programs or downstream programs with full allowance auctioning (Burtraw et al. 2001).

3.1.2. Scope of Regulation

Domestic programs that fail to cover embodied carbon in products imported from countries with sub-optimal or no emissions controls may cause significant emissions leakage. The problem is most relevant for downstream, energy-intensive firms competing in global markets (e.g., chemicals and plastics, primary metals, petroleum refining), where reduced production at home may be largely offset by increased production in other countries with higher emissions intensity than in the United States. According to some models, as much as 15–25 percent of economy-wide US CO_2 reductions could be offset by extra emissions elsewhere, although the majority of the leakage stems from changes in global fuel prices rather than re-location of footloose capital (Gupta et al. 2007, Ho et al. 2008, Babiker and Rutherford 2005, Fischer and Fox 2007, 2009). Possible policy responses to the latter source of leakage include imposing taxes, or permit requirements, according to embodied carbon in product imports (and symmetrical rebates for exporters) or to subsidize the output of leakage-prone industries (e.g., through output-based allocations of free emissions allowances). However, all these approaches may run afoul of international trade obligations.

Certain non-CO_2 GHGs are easily monitored (e.g., vented methane from underground coalmines, fluorinated gases used in refrigerants and air conditioners) and could be directly integrated into a CO_2 mitigation program through taxes, or permit trading ratios, reflecting their relative lifetime warming potential. Other gases are far more difficult to monitor, and are better incorporated, insofar as possible, through offset provisions, where the onus falls on the individual entity to demonstrate valid reductions relative to a credible baseline. For example, methane from landfills and livestock waste might be collected, using an impermeable cover, and flared or used in onsite power generation, while nitrous oxide might be reduced through changes in tilling and fertilizer use (e.g., Shih et al. 2006, Hall 2007).

Finally, CO_2 abatement through forest carbon sequestration (e.g., from reducing deforestation, reforesting abandoned cropland and harvested timberland, modifying harvest practices to reduce soil disturbance) appears to be relatively cost effective. According to Stavins and Richards (2005), as much as 30 percent of US fossil fuel CO_2 emissions might be sequestered at a cost of up to about \$20 per ton of CO_2. Coupling a domestic mitigation program with offset provisions for forest carbon sequestration will require measuring regional forest inventories to establish baselines, monitoring changes in forest use (through remote sensing and ground-level sampling) relative to the baseline, and inferring the emissions implications of these changes based on sampling of local tree species and age. However, even if these monitoring challenges can be overcome, further problems remain. One is that, without an international program covering major forested countries, domestic reductions can be offset through emissions leakage via changes in world timber prices (Murray et al. 2002 estimate the international leakage rate could be anywhere from less than 10 percent to over 90 percent depending on the type of activity and location in the United States). Another is that sequestered carbon in trees is not necessarily permanent if trees are later cut down, decay or burn, requiring assignment of liability to either the offset buyer or seller for the lost carbon.

3.1.3. Allocation of Policy Rents

In their traditional form, emissions taxes raise revenues for the government, while cap-and-trade systems create rents for firms receiving free allowance allocations. However, through allowance auctions, cap-and-trade systems can generate comparable revenues to a tax, while rents can be provided under a tax through infra-marginal exemptions for emissions or carbon content. Under either instrument, the fraction of policy rents accruing to the government rather than private firms, and how revenues are used, are extremely important for efficiency and distributional incidence.

Fiscal Linkages. The implications for emissions control policies of pre-existing tax distortions in factor markets have received considerable attention in the broader environmental economics literature (e.g., Bovenberg and Goulder 2002), though these distortions are typically not integrated into energy-climate models. This raises two issues: to what extent is there a cost saving from policies that raise revenues and use them to offset distortionary taxes like income and payroll taxes, and to what extent do models that ignore prior tax distortions produce inaccurate estimates of policy costs?

The efficiency gain from recycling revenues in other tax reductions (relative to returning them lump sum or leaving policy rents in the private sector) is simply the amount of revenue raised times the marginal excess burden of taxation. Although there is uncertainty over behavioral responses in factor markets, a typical assumption is that the marginal excess burden of income taxes (with revenue returned lump sum) is around \$0.25 for the United States, or perhaps as high as \$0.40 if distortions in the pattern of spending created by tax preferences (e.g., for employer medical insurance or homeownership) are taken into account. For modest carbon policies, the efficiency gain from revenue recycling can be large relative to the direct efficiency cost of the policy, or Harberger triangle under the marginal abatement cost schedule. For example, if a \$20 tax on US CO_2 emissions (currently about 6 billion tons) reduces annual emissions by 10 percent, the Harberger triangle is \$6 billion, while the revenue-recycling benefit is roughly \$30-40 billion per year.

However, this does not necessarily mean that revenue-neutral CO_2 taxes, or auctioned allowance systems, produce a "double dividend" by reducing the costs of the broader tax system, in addition to slowing climate change. There is a counteracting, "tax-interaction" effect (e.g., Goulder 1995). Specifically, the (policy-induced) increase in energy prices drives up the general price level, which reduces real factor returns, and thereby (slightly) reduces factor supply and efficiency. Most analytical and numerical analyses of environmental tax shifts find that the tax-interaction effect exceeds the revenue-recycling effect, implying no double dividend, and that abatement costs are actually higher due the presence of pre-existing tax distortions. A rough rule of thumb from these models is that the costs of revenue-neutral emissions taxes are about 15 percent greater, due to interactions with prior tax distortions, implying the optimal tax is 15 percent lower than the Pigouvian tax (e.g., Bovenberg and Goulder 2002). However, the cost increase is far more substantial for policies that do not exploit the revenue recycling effect (i.e., cap-and-trade with free allowance allocation or CO_2 taxes with revenues not used to increase economic efficiency). According to formulas derived in Goulder et al. (1999), the increase exceeds 100 percent when the emissions reduction is below 30 percent.[16]

More generally, there are many ways that carbon policy revenues might be used, such as funding technology programs, climate adaptation projects, deficit reduction, energy efficiency programs, rebates to electricity consumers, and any number of complex adjustments to the tax system, though the efficiency implications of these recycling options are often not well understood. Although in recent years there has been more interest in permit auctions, in some cases it is unclear how the revenues will be spent.[17] Unless legislation accompanying carbon policies specifies offsetting reductions in other distortionary taxes, there is ambiguity in to what extent this shift implies a reduction in the overall costs of carbon policies.

Distributional Considerations. The distributional impacts of emissions control policies are potentially important for both equity and feasibility.

On equity grounds the difference between (revenue-neutral) CO_2 taxes/auctioned allowances, and allowance systems with free allocation to firms, can be quite striking. Under the latter policy, permit rents are reflected in higher firm equity values, and therefore (through dividend and capital gains income) ultimately accrue to shareholders, who are concentrated in upper income groups. Dinan and Rogers (2002) estimated that, for a 15 percent reduction in CO_2 emissions, US households in the lowest-income quintile would be worse off on average by around $500 per year, while households in the top-income quintile reap a net gain of around $1,000 (i.e., increased stockholder wealth overcompensates this group for higher energy prices).

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[16] There are some caveats here. One is that the proportionate increase in abatement costs may be much smaller in other countries if tax wedges in factor markets are smaller than those in the United States, or if labor markets are dominated by institutional wage setting (e.g., Bosello et al. 2001). Another is that the tax-interaction effect is weaker if, due to regulated pricing and/or infra-marginal rents on coal technologies that bear some of the burden of emissions pricing, there is incomplete pass through of emissions prices into electricity prices (Bento and Jacobsen 2007, Parry 2005). Finally, the revenue-recycling effect can dominate the tax-interaction effect when tax preferences cause significant distortions or when a large share of revenues are used to cut taxes on capital as opposed to labor (see Parry and Bento 2000 and Bovenberg and Goulder 1997 respectively).

[17] For example, in the first two phases of the European Union's CO_2 trading program (2005-2007 and 2008-2012), over 95 percent of the allowances were given away free to existing emissions sources. However, partly in response to the large windfall profits earned by power companies, the plan is to transition to full allowance auctions for that sector by 2020, with the decision on how to use revenues largely left to the member states (Sijm et al. 2006, CEC 2008). In the Regional Greenhouse Gas Initiative in the United States, covering power sector CO_2 emissions from ten Northeastern and Mid-Atlantic states, allowances are auctioned with revenues earmarked for energy efficiency and other clean technology programs.

This inequitable outcome could be avoided under emissions taxes and auctioned allowance systems if revenues were recycled in income tax reductions (e.g., Metcalf 2009).

As regards feasibility, compensation for adversely affected industries may be part of the political deal-making needed to first initiate, and progressively tighten, emissions controls (e.g., Ellerman 2005). Compensation, through free allowance allocation or tax relief, may be required for both formally regulated sectors and downstream sectors vulnerable to higher energy prices (e.g., energy-intensive firms competing in global markets). However, given the tension between providing industry compensation, and the fiscal and (household) equity reasons for raising revenue, it is important to know how much compensation is needed to keep firms whole. At least for a moderately scaled CO_2 permit system, only about 15-20 percent of allowances are needed to compensate energy intensive industries for their loss of producer surplus, so the huge bulk of the allowances could still be auctioned (Bovenberg and Goulder 2001, Smith et al. 2002). Although there are reasons for phasing out compensation over time, firms may still be amenable to this if they receive excess compensation in the early years of the program (e.g., Stavins 2007).[18]

3.1.4. Price Volatility

Another reason CO_2 taxes and cap-and-trade systems may produce different outcomes stems from uncertainty over future abatement costs reflecting, for example, uncertainty over energy prices, technological advances, and substitutes for fossil fuels.

Price Versus Quantity Instruments in their Pure Form. If the goal is welfare maximization, abatement cost uncertainty strongly favors emissions taxes over cap-and-trade systems in their pure form. This is most easily seen in a static setting where the marginal benefits from abatement are constant. In this case, a Pigouvian emissions tax automatically equates marginal benefits to marginal abatement costs, regardless of the position of the marginal abatement cost schedule. In contrast, when emissions are capped to equate marginal benefits with expected marginal abatement costs, ex post abatement will either be too high or too low

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[18] One reason for phasing out allowance allocations is that they must initially be based on a firm's historical emission rates (prior to program implementation), which may be viewed as increasingly unfair as firms grow or contract at different rates, or change their fuel mix, over time. However, any updating of baselines based on firm performance will likely introduce distortions in firm behavior (Rosendahl 2008). Free allowance allocation may also retard the exit of inefficient firms from an industry, if firms lose their rights to future allocations when they go out of business.

depending on whether the marginal abatement cost schedule is higher or lower than expected (Weitzman 1974, Roberts and Spence 1976, Yohe 1978).

This basic result carries over to a dynamic context with a sequence of annual (Pigouvian) taxes or emissions caps, and where environmental damages depend on the accumulated atmospheric stock of emissions. Here, we have strong reasons to believe that the marginal benefits from global emissions reductions are essentially constant, as abatement in any one year has minimal impact on the atmospheric stock. In fact, with abatement cost uncertainty, simulation analyses suggest that discounted welfare gains under (globally-imposed) CO_2 taxes might be several times those under (equivalently-scaled) permits (e.g., Pizer 2003, Hoel and Karp 2002). A qualification to this is that the welfare advantage of taxes is less pronounced if abatement cost shocks persist over time and the emissions cap can be adjusted in response to those shocks (e.g., Karp and Zhang 2005, Newell and Pizer 2003).

Stabilizing Allowance Prices. Emissions price volatility under cap-and-trade systems can be contained by allowing firms to bank permits when permit prices (and marginal abatement costs) are low, and borrow permits from future periods when prevailing prices are high. In fact, if banking and borrowing were completely unlimited and costless, expected allowance prices would rise at the interest rate, and the system would be largely equivalent to that of an emissions tax growing at the interest rate. Alternatively, through establishing appropriate ratios for trading permits across time, the allowance price trajectory could mimic the growth in marginal emissions damages over time (e.g., Kling and Rubin 1997).

In fact, most existing cap-and-trade systems (e.g., the federal SO_2 and regional CO_2 programs in the United States and the European Union's CO_2 program) now incorporate banking and borrowing provisions, though in response to concerns about default risk, borrowing is penalized through unfavorable trading ratios and/or quantitative limits. Fell et al. (2008) estimate that banking and borrowing provisions contained in leading US federal climate proposals obtain about one quarter to one half of the cost savings from emissions taxes over equivalent cap-and-trade systems without these provisions.

An alternative approach is to limit price volatility through a "safety valve", where the government sells additional permits at a fixed price to prevent allowance prices from rising above a ceiling price (e.g., Jacoby and Ellerman 2004). Expected welfare under this policy is maximized by essentially designing it to mimic a Pigouvian tax—that is, setting the safety valve price equal to marginal emissions damages and the emissions cap tight enough so the safety valve binds nearly all the time (Pizer 2003). Intermediate cases (with higher safety valve prices and/or less stringent caps) generate intermediate welfare gains between those of the pure tax and emissions quota. A further alternative is a collar which combines a price ceiling with a price floor. This approach encourages additional abatement when allowance prices are low (to offset reduced abatement when allowance prices are high) and avoids the potentially harmful impacts of the price ceiling only on incentives to invest in emissions-saving technologies. According to Fell et al. (2008) the annualized cost savings between emissions taxes and fixed emissions quotas in the United States would be about \$4 billion for an emissions price of around \$20 per ton of CO_2, with safety valves and price collars yielding intermediate cost savings.

One final twist in instrument choice is that the price flexibility afforded by a cap-and-trade system with (unhindered) allowance borrowing and banking could actually be advantageous from a social welfare perspective, when there is learning about future damages and emissions taxes can only be adjusted at discrete intervals (Murray et al. 2009).[19] Under the former policy, new information about damages will be immediately reflected in the time path of current and expected future allowance prices, as speculators anticipate an adjustment of future emissions targets in response to that information. In contrast, it may take some time before emissions taxes can be adjusted to reflect new information, leaving emissions prices sub-optimal during the period of policy stickiness.

3.2 Promoting Technology Development and Diffusion

Several studies have demonstrated the central role that the availability and cost of advanced energy technologies plays in determining the future costs of GHG emission targets (e.g., Clarke et al. 2006, Edmonds et al. 2000, Gillingham et al. 2008). For example, Clarke et al. (2006) found that if ambitious goals for technology development are achieved, this can reduce discounted global abatement costs by 50 percent or more. Establishing a price on CO_2 emissions is the single most important policy for encouraging the innovation that might bring about advanced technology development. However, additional measures to promote applied R&D, more basic research, and technology deployment, may be justified to the extent they address market failures at different stages of the innovation process.

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[19] Uncertainty over the marginal benefit schedule, in the absence of learning, would not affect the choice between emissions taxes and cap-and-trade because, on average, cumulated emissions reductions, and hence expected environmental benefits, are the same under both instruments (e.g., Stavins 1996).

3.2.1. R&D Policy

One market failure stems from the inability of private sector inventors or innovators to fully appropriate spillover benefits to other firms that might copy a new technology, imitate around the technology if it is under patent, or otherwise use knowledge about the technology to advance their own research programs (Jaffe et al. 2003). Numerous empirical studies suggest that technology spillovers cause the (marginal) social return to (commercial) R&D to be several times the (marginal) private return.[20]

The appropriability problem implies that R&D incentives will be sub-optimal, even under Pigouvian emissions pricing. One response would simply be to set emissions prices at a level higher than warranted by externalities. However, this would generate efficiency losses from excessive short-term abatement, and would not differentiate incentives across technologies that might face very different market impediments. In fact, no single instrument—either emissions pricing or R&D incentives—can effectively correct both the emissions externality and the knowledge appropriability problem: using one instrument alone may involve considerably higher costs than employing two complementary instruments (Fischer and Newell 2008, Goulder and Schneider 1999).

Unfortunately, available literature provides limited guidance on the design of complementary R&D instruments. It is not clear which instrument among, for instance, research subsidies, strengthened patent rules, or technology prizes, is most efficient, as this depends on the magnitude of technology spillovers, the scope for monopoly pricing under patents, and asymmetric information between governments and firms about the expected benefits and costs of research (e.g., Wright 1983). And just how much applied R&D in the energy sector should be expanded is difficult to estimate, given uncertainty over the productivity of research and the risk

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[20] For example, Griliches (1992), Mansfield (1985), Jones and Williams (1998). Although there is a possibility of excessive competition for a given amount of innovation rent, analogous to the excessive competition for open-access resources, this problem is generally thought to be dominated by the imperfect appropriability effect (Griliches 1992). In fact, the problem of suboptimal innovation incentives may be especially severe for GHG-saving technologies, compared with commercial technologies. For example, skepticism over long-term commitments to emissions pricing, and the desirability of retaining policy discretion to respond to future scientific knowledge, undermines the durable and substantial incentives needed for encouraging GHG-saving technology investments with high upfront costs. Limited patent lifetimes may also discourage firms from launching R&D programs until a high enough emissions price is established (Gerlagh et al. 2008).

Still, efficiency gains from correcting the R&D market failure appear to be smaller than those from correcting the CO_2 emissions externality (Parry et al. 2003).

of crowding out socially valuable research elsewhere in the economy (e.g., Nordhaus 2002, Goulder and Schneider 1999).

3.2.2. Basic Research

Appropriability problems are most severe for more basic research, which is largely conducted by universities, other nonprofits, and federal labs, mostly through central government funding. While it is not practical to assess the efficient allocation of funding across individual programs, Newell (2008), pp. 32, suggests that a doubling of US federal climate research spending (currently about $4 billion a year) is likely warranted, based on plausible assumptions about the rate of return on such spending. To avoid crowding out, this should be phased in to allow a progressive expansion in supply of college graduates in engineering and science.

3.2.3. Deployment Policy

In principle there are several possibilities for market failures at the technology deployment stage. For example, through learning-by-doing early adopters of a new technology (e.g., a cellulosic ethanol plant or solar photovoltaic installations) may lower production costs for later adopters (e.g., van Bentham et al. 2008). But since the potential for these spillovers may vary greatly depending on industry structure, the maturity of the technology, etc. any case for early adoption subsidies needs to be considered on a case-by-case basis.

Another possible market failure is consumer undervaluation of energy efficiency, which has been a key motivation for regulations governing auto fuel economy and household appliances. However, although there is an empirical literature suggesting that households discount savings from energy efficiency improvements at much higher rates than market rates, whether this is evidence of a market failure as opposed to hidden costs or borrowing constraints remains an unsettled issue (e.g., Gillingham et al. 2009). Other market imperfections might include asymmetric information between project developers and lenders, network effects in large integrated systems, and incomplete insurance markets for liability associated with specific technologies. However because solid empirical evidence is lacking, little can be said about the seriousness of all these market failure possibilities, and whether or not they might warrant additional policy interventions.

3.3. International Policy Design

Proposed architectures for international emissions control regimes can be loosely classified into those based on bottom-up versus top-down (i.e., internationally negotiated) approaches and cap-and-trade systems versus systems of emissions taxes (e.g., Aldy and Stavins

2007). There is disagreement over which type of architecture is most desirable, and most likely to emerge in practice. In the bottom up approach, norms for participation might evolve from small groups of countries launching regional programs that progressively expand and integrate, or by explicit linking of domestic cap-and-trade programs (e.g., Carraro 2007, Jaffe and Stavins 2008, Victor 2007). Alternatively, countries might regularly pledge emissions reductions with periodic reviews by a formal institution (e.g., Schelling 2007, Pizer 2007). Here we focus on top-down approaches, given that advocates of rapid climate stabilization tend to favor internationally binding commitments.

The most daunting challenge is designing an architecture that encourages participation among some three or four dozen of the world's largest GHG emitters—the Kyoto framework failed to do this as non-Annex 1 countries, including China, Brazil, South Africa, Mexico and Indonesia, had no emissions control obligations, while the United States withdrew from the agreement.[21] Broad participation is needed—at least over the longer term and possibly also the near term under a stringent climate stabilization target (see above)—to promote the cost-effectiveness of any international agreement, and limit concerns about international competitiveness and emissions leakage. Participation of developing countries through the Clean Development Mechanism (CDM), as at present, does not reduce global emissions—it only lowers the cost to developed countries of meeting their emissions goals by allowing firms to purchase (lower cost) emissions reductions elsewhere on a project-by-project basis. Moreover, there is considerable concern that some CDM credits may not represent truly additional reductions, due the difficulty of establishing a baseline against which reductions can be measured, in which case the CDM serves to *increase* global emissions (e.g., Keeler and Thompson 2008, Rosendahl and Strand 2008).

To be successful, each country must perceive an emissions control agreement as equitable in terms of sharing the burden of global mitigation costs. Usually this means that industrial countries bear a disproportionately greater cost burden due to their higher per capita

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[21] China's CO_2 emissions now exceed those for the United States, while India's exceed those of Japan (EIA 2008b, Table A10). In fact, 50 non-Annex 1 countries now have per capita income greater than that of the poorest Annex 1 countries.

income and greater contribution to historical GHG accumulations.[22] However, as noted above, under a globally cost-effective pricing agreement with no side-payments, developed countries may bear two-thirds or more of discounted global abatement costs over the next century. Negotiations are further hampered, under a Kyoto type of framework, by the need to agree on emissions quotas for every participating country, and to periodically re-negotiate these quotas, which can be contentious if economies expand at different rates during interim periods.

Frankel (2009) offers a global cap-and-trade proposal that addresses equity through imposing no cost burden on developing countries in the early years, and subsequently a cost burden comparable to those previously borne by others at a similar stage of economic development. Global cost effectiveness is preserved, and emissions leakage avoided, by establishing a harmonized emissions price through immediately incorporating all countries into the global trading system, with low-income countries initially allocated emissions caps equal to their projected emissions. Effectively, the pattern of stringent and lax quota allocations among developed and developing countries creates a system of side payments from developed countries (who are net permit buyers) which compensates developing countries (who are net permit sellers) for the costs of their emissions reductions. Furthermore, negotiations are greatly simplified by the establishment of simple formulas that automatically start reducing developing country quotas once their per capita income, or per capita emissions, cross certain thresholds.

A globally harmonized CO_2 tax can be designed to essentially replicate this cap-and-trade system, so there appears to be little reason, in this regard, for preferring one instrument over the other. Instead of agreeing on a global emissions cap, and how it adjusts over time, countries would need to agree on a harmonized tax rate, and how this rate is increased over time. And instead of negotiating over rules relating quota allocations to the evolution of per capita income (or emissions) over time, countries would need to agree on rules for explicit side payments related to a country’s per capita income (or emissions).

However, under either the cap-and-trade or tax-based approach, there is an obvious tension between compensating developing nations and policy stringency. For example, Jacoby et al. (2008) estimate that under a global policy that stabilizes CO_2 concentrations at

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[22] There is some dispute over historical responsibilities, however. Although industrial countries are responsible for about 80 percent of previous fossil fuel emissions, when releases from land-use changes are taken into account Mueller et al. (2007) suggest that poor countries are responsible for 45 percent of the increase in atmospheric CO_2 accumulations.

(approximately) 450 ppm, compensation for developing countries would entail (explicit or implicit) side payments by the United States of $200 billion in 2020 (or ten times current US development assistance), which calls into question the credibility of such compensation schemes. Even with less than full compensation, the international transfers are of unprecedented scale. A critical lesson here is to keep down compensation to the minimum amount needed to entice developing country participation. In this regard, granting these countries initial quota allocations equal to their BAU emissions is wasteful, as it provides roughly twice the compensation needed to cover abatement costs (in the absence of other distortions, excess compensation is the integral between the emissions price and the marginal abatement cost curve).

As regards verification of policies, one potential problem with an emissions tax is that countries may undermine its effect through reductions in other energy taxes. In principle, countries might be pressured to adjust their emissions tax rate to offset changes in other energy tax provisions, based on periodic reviews of country tax systems, and progress on emissions reductions, by an independent agency like the International Monetary Fund. Measuring other energy tax provisions in terms of their equivalent tax (or subsidy) on CO_2 would be contentious however, because of opaque systems of tax preferences for energy investments, the possible role of energy taxes in correcting other externalities like local pollution and road congestion, and the possibility of non-tax regulations that further penalize or subsidize energy (e.g., fuel economy standards, energy price regulations). On the other hand, most countries have established tax ministries that would be able to implement a new tax on (the carbon content of) fossil fuels. In contrast, many developing countries may lack the capacity to enforce permit requirements and property rights due to weak environmental agencies and judicial institutions.

Finally, although not incorporated in most energy/climate models, the forest sector appears to offer some of the easiest and least expensive opportunities for cutting CO_2 emissions. For example, under a 550 ppm CO_2 stabilization target, Tavoni et al. (2007) estimate that forest sinks can contribute one-third of total abatement by 2050, and thereby decrease the required price on CO_2 emissions by around 40 percent. This is mainly achieved through avoided deforestation in tropical forests, though it could be sustained in the second half of the century through aforestation and enhanced forest management. Emission credits for slowed deforestation were not permitted under the 1997 Kyoto framework, but since then analysts have become somewhat more optimistic about the feasibility of integrating deforestation into an international emissions control regime, despite the practical challenges noted above (e.g. DeFries et al. 2006). However, broad participation in any agreement among major tropical forest regions would be critical to avoid the risk of serious emissions leakage.

3.4. Summary

A revenue-neutral CO_2 tax has multiple desirable properties from an efficiency standpoint. Although allowances can be auctioned, and emissions price volatility contained, why implement a more elaborate cap-and-trade system if its purpose is to largely mimic the advantages of a tax? A likely answer is that political factors appear to favor the latter instrument (e.g., Goulder 2009). Emissions taxes, at least in the United States, appear to be highly unpopular, while cap-and-trade systems are popular among environmental advocates given their focus on binding emissions targets and they also have active supporters in the financial sector, who see them as opportunities to make money. But whichever instrument is chosen, getting the design details right is critical for cost-effectiveness—especially broad coverage of emissions, raising and efficiently using revenues, and containing price variability.

While most analysts agree that mitigation policies should be supplemented with additional policies to promote basic and applied research into emissions-saving technologies at government, university, and private institutions, the level of support and the specific instruments that should be employed are far less clear. And there is little consensus about the case for further policy intervention at the technology deployment stage—this depends on the specifics of the industries or processes involved and assumptions about consumer behavior that are in need of further study.

At an international level, the choice between cap-and-trade and emissions taxes is also nuanced. Either system can be globally cost-effective and accommodate transfers to developing countries. And while cap-and-trade systems are immune to the possibility of offsetting changes in the broader energy tax system, they may face larger implementation obstacles in developing countries. The biggest problem in transitioning away from the CDM towards an integrated global emissions trading system is the possibility of a large gap between the compensation that might be demanded by developing countries in exchange for their participation and the amount of compensation that developed countries are willing to provide—a gap that could be especially large under rapid atmospheric stabilization targets. Finally, integration of carbon forest sequestration into international emissions control agreements is potentially important for containing the burden of mitigation costs.

4. Research Priorities

While a great deal has been learned about climate policy design over the last couple of decades, much economic analysis remains to be done.

Energy/climate models provide some rough bounds on near-term emissions pricing trajectories, and associated GDP losses, implied by climate stabilization scenarios, and the range of uncertainty may narrow as more is learned about the costs of new technologies and behavioral responses to emissions pricing. Nonetheless, there are many research priorities in this area, such as trying to narrow disagreement over BAU emissions assumptions (e.g., through better population projections); improving the representation of endogenous technological change, prior policy distortions, and possible market power in world oil and natural gas markets; quantifying the benefits of major technological breakthroughs to guide R&D efforts; and further exploring the cost and distributional implications of deviations from globally efficient emissions pricing.

Some of the biggest challenges facing climate economists are to develop, and apply, methodologies for valuing the wide array of market and non-market impacts across different regions, time periods, and scenarios for climate change (ecological, health, and extreme sea level impacts in particular, are poorly understood). However, in terms of shedding more light on whether there is a solid economic basis for aggressive, as opposed to more moderate, near-term emissions pricing, the most critical issues in need of study appear to be the nature and magnitude of damage risks from extreme warming scenarios and the extent to which the possibility of future, mid-course corrections, and deployment of last-resort technologies, in response to future learning, lowers the near-term emissions price. More research on discount rates might also be valuable, especially in trying to reconcile different approaches (e.g., Beckerman and Hepburn, 2007).

On the design of domestic mitigation schemes, one topic badly in need of study, given the potentially large revenues from carbon policies, is the efficiency and distributional implications of the diverse array of options for revenue use. Additional research priorities include the design of practical, and cost-effective, provisions to address international emissions leakage and incorporate incentives for abatement of non-CO_2 GHGs and forest carbon sequestration.

As regards complementary technology policy, research is needed on both the appropriate level, and the relative efficiency, of alternative instruments to encourage applied R&D, as well as the amount and composition of basic energy R&D. Empirical research is also needed to ascertain whether or not there are additional market failures that justify further policy intervention at the technology deployment stage. Even if the empirical basis for such market failures is weak, research is still needed on the interactions, and possible redundancies, between all kinds of increasingly prevalent climate and energy-related regulatory interventions. For example, in the transportation sector this would include interactions between carbon policies, fuel taxes, fuel economy standards, low-carbon fuel standards, hybrid vehicle purchase subsidies, and subsidies and mandates for renewable fuels. In the power sector it would include interactions with regulations governing the efficiency of buildings, appliances, and lighting and inducements for renewable and other low-carbon fuels.

Finally, a critical issue at an international level is the design of rules for accession and graduated responsibilities for developing countries that are widely perceived as being fair. At the same time, agreements should minimize deviations from cost-effective emissions pricing as well as minimizing the risks of excessive transfers to developing countries.

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Tables and Figures

Box 1. Valuation of Noncatastrophic Climate Damages
(for Warming of 2.5°C or Thereabouts Occurring Around 2100)

Agriculture. Estimates of consumer and producer surplus losses in agricultural markets from predicted changes in regional temperature and precipitation use evidence on crop/climate sensitivity from laboratory experiments and on regressions of land values or farm performance on climate variables (e.g., Adams et al. 1990, Reilly et al. 2001, Mendelsohn et al. 1994, 2001). Laboratory studies can control for confounding factors like soil quality and the fertilizing effect of higher CO_2 concentrations, while regression analyses account for farm level adaptation (e.g., changes in crop variety and planting/harvesting dates). Worldwide agricultural impacts have been built up using extrapolations from US studies, adjusting for differences in local agricultural composition and climate, and, more recently, country-specific evidence that captures local factors like adaptive capability. Studies show a pattern of gains in high latitude and temperate regions (like Russia), where current temperatures are below optimum levels for crop growth, counteracting damages in tropical regions, where current temperatures are already higher than optimal.

Sea Level. The annualized costs of future global sea level rises, due to thermal expansion and melting of sea ice, have been estimated using projections of which coastal regions will be protected, engineering data on the costs of dikes, sea walls, beach replenishment, etc., and estimated losses from abandoned or degraded property in unprotected areas. Some studies assume efficient behavior by local policymakers in their choice of which areas to protect and at what time, while others assume all currently developed areas will be protected (Yohe 2000). Nordhaus (2008) also includes an estimate of property losses from increased storm intensity due to greater wind speed and waves coming off a higher water level. Whether storm frequency will increase with more humid air is uncertain (IPCC 2007). Worldwide sea level impacts have been extrapolated from US evidence, adjusting for the fraction of local land area in close proximity to the coast, though recently there have been some local studies that account for the slope and elevation of coastal land and prospective population growth (e.g., Ng and Mendelsohn 2005 on Singapore). Overall, estimates are relatively modest, for example they amount to 0.32 of world GDP in Nordhaus (2008).

Some scientists project that sea levels could increase by several meters by 2100 (Hansen 2007) rather than the 25-60 cm projected by IPCC (2007). This would have major impacts on New York, Boston, Miami, London, Tokyo, Bangladesh, the whole of the Netherlands, and so on, and would completely inundate several small island states. Based on extrapolations from sea level protection costs in Holland, the global costs of this more extreme sea level rise may be at least an order of magnitude or more greater than for a moderate sea level rise, especially if coastal protection cannot be constructed expeditiously (Nicholls et al. 2008, Olsthoorn et al. 2008). Another possibility is that warming may cause changes in ocean circulation patterns. However, IPCC (2007) projects that warming from climate change will dominate any cooling effect on Europe from a weaker Gulf Stream.

Other market sectors. Studies suggest other market impacts are relatively minor. With most forests along the increasing part of the inverted-U relation between forest productivity and temperature, Sohngen et al. (2001) find positive overall impacts from warming on global timber markets. Most studies find a net loss for the energy sector, as increased costs for space cooling dominate savings in space heating (e.g., Mendelsohn and Neumann 1999). Impacts on water availability also tend to be negative, as increased evaporation reduces freshwater supplies, and the value of these losses is compounded with greater demand for irrigation (Mendelsohn and Williams 2007).

Health. There have been some attempts to quantify future health damages. For example, using statistical evidence on climate and disease, Nordhaus and Boyer (2000) put health risks from the possible spread of vector-borne diseases like malaria at 0.10 percent of world GDP. Broader health risks are even more speculative. According to McMichael et al. (2004), there were 166,000 excess deaths worldwide in 2000 from climate change to date. Of these, "only" 16 percent were from malaria, 46 percent reflected greater malnutrition due to food shortages, another 28 percent more diarrhea cases as droughts reduce safe drinking water supplies and concentrate contaminants, while 7 percent were from temperature extremes (most in Southeast Asia). However, malnutrition projections are extremely sensitive to assumptions about whether, over the next century, currently vulnerable regions develop, become more integrated into global food markets, and are able to adopt hardier crops. And increased incidence of water-borne illness might be counteracted by future development and adoption of water purification systems. Monetizing mortality effects is also contentious as there are very few direct estimates of the value of a statistical life for poor countries.

Ecosystems. All aspects of future climate change are potential stressors to natural systems. Combining projections of ecosystems at risk from climate change with evidence on the medicinal value of plants and willingness to pay for species and habitat preservation, Fankhauser (1995) and Tol (1995) put the value of ecosystem loss in 2100 at 0.21 and 0.13 percent of world GDP respectively. Nordhaus and Boyer (2000) put the combined risks to natural ecosystems and climate-sensitive human settlements at 0.17 percent of world GDP in 2100, assuming the capital value of vulnerable systems is 5–25 percent of regional output, and an annual willingness to pay equal to 1 percent of capital value. These estimates are highly speculative, given that very little is known about ecological impacts and how people value large scale (as opposed to marginal) ecosystem loss.

TABLE 1. LEAST-COST POLICIES TO STABILIZE GLOBAL CLIMATE

	2025			2050			2100		
CCSP[a]	MERGE	MiniCAM	IGSM	MERGE	MiniCAM	IGSM	MERGE	MiniCAM	IGSM
Global CO_2 emissions, relative to 2000									
Reference	1.27	1.46	1.70	1.59	1.98	2.59	3.42	3.21	3.45
450 CO_2 stabilization	0.92	0.97	0.86	0.53	0.57	0.64	0.24	0.39	0.55
550 CO_2 stabilization	1.25	1.35	1.22	1.32	1.56	1.20	0.79	0.71	0.81
CO_2 concentration, ppm[b]									
Reference	422	430	436	485	507	544	711	746	875
450 CO_2 stabilization	412	416	408	434	440	430	426	456	451
550 CO_2 stabilization	421	427	421	478	490	472	535	562	526
CO_2 price, \$/ton[c]									
450 CO_2 stabilization	41	36	88	157	127	230	166	173	1651
550 CO_2 stabilization	3	6	26	10	19	67	127	115	475
% reduction in world GDP[d]									
450 CO_2 stabilization	0.8	0.5	2.6	1.8	1.6	5.4	1.4	1.4	16.1
550 CO_2 stabilization	0.0	0.0	0.7	0.2	0.2	1.8	0.7	1.0	6.8
US CO_2 emissions, relative to 2000									
Reference	1.25	1.10	1.40	1.27	1.20	2.00	1.63	1.34	2.93
450 CO_2 stabilization	0.79	0.83	0.88	0.42	0.43	0.54	0.02	0.27	0.40
550 CO_2 stabilization	1.24	1.05	1.04	1.02	0.98	1.13	0.29	0.37	0.59
EMF-21[e]	lower end	median	upper end	lower end	median	upper end	lower end	median	upper end
Global CO_2 emissions, relative to 2000									
Reference	1.33	1.48	1.64	1.64	1.88	2.23	2.11	2.93	3.52
550 CO_2 stabilization	1.17	1.25	1.41	1.13	1.25	1.41	0.66	0.90	1.25
CO_2 price, \$/ton[c]									
550 CO_2 stabilization	3	13	21	12	33	99	31	92	166
% reduction in world GDP[d]									
550 CO_2 stabilization	0.1	0.1	0.8	0.2	0.6	3.1	0.3	5.1	8.2
US CO_2 emissions, relative to 2000									
Reference	1.19	1.26	1.38	1.31	1.65	1.97	0.95	1.85	2.29
550 CO_2 stabilization	1.05	1.14	1.22	0.76	1.02	1.26	0.36	0.53	1.05

Notes

[a] Results are from the Integrated Global Systems Model (IGSM), the Model for Evaluating Regional and Global Effects (MERGE) and MiniCAM Model. See Clarke et al. (2007) for details.

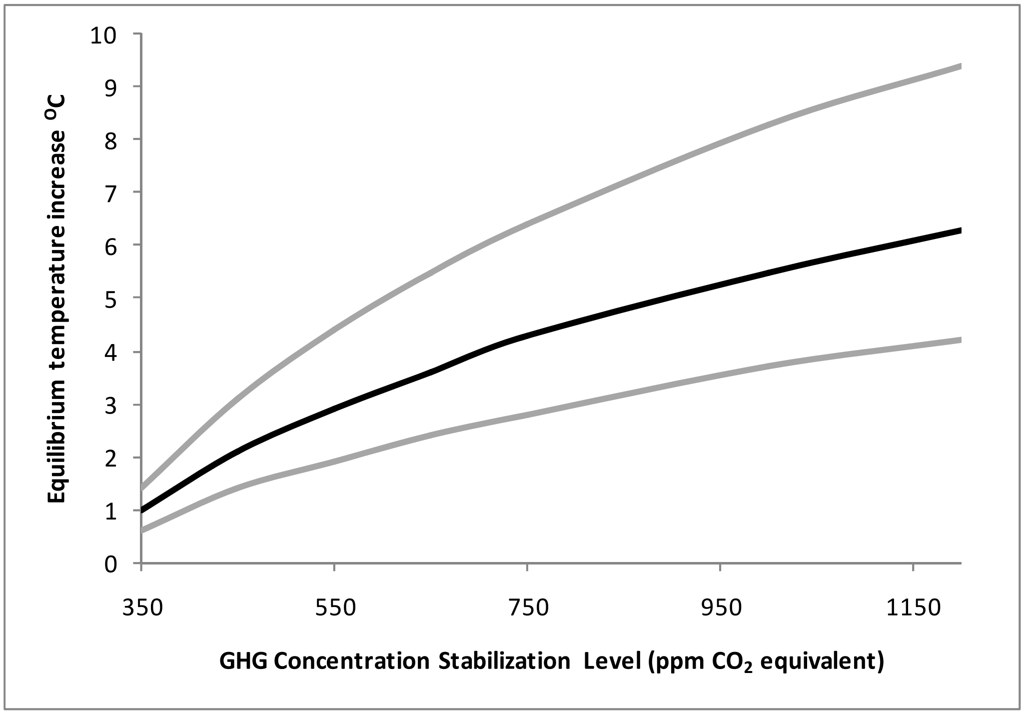
[b] The models stabilize concentrations of all GHGs, rather than CO_2 alone (i.e., the CO_2 equivalent concentration level is higher than the CO2 concentration). Actual CO_2 concentrations may temporarily overshoot the long run targets.

[c] In year 2000 dollars or thereabouts.

[d] GDP losses are not broken out by region in the models. Losses include those from pricing CO_2 and other GHGs on an equivalent basis. The figures do not account for the benefits of reduced climate change.

[e] Modeling results from Stanford's Energy Modeling Forum, reported in de la Chesnaye and Weyant (2006). The results are from 16 models for CO_2 prices and 12 models for GDP. Lower and upper ends correspond to lower and upper two-thirds of model results. Atmospheric CO_2 concentrations are not reported.

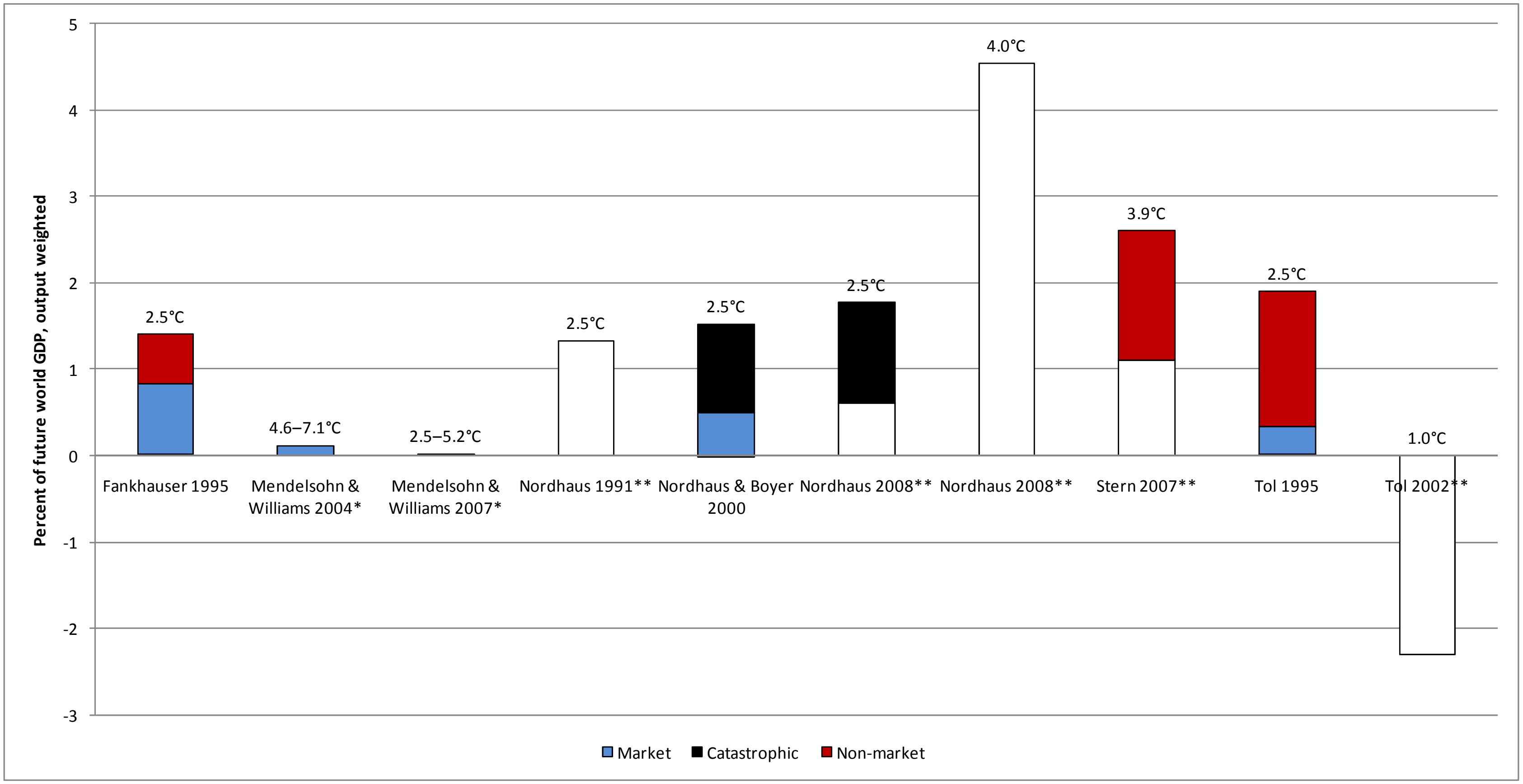
Figure 1. Steady State Warming Above Preindustrial Temperatures from Stabilization at Different GHG Concentrations



Source: IPCC (2007), Table 10.8.

Note: The black curve indicates the central case projection and the grey curves indicate the 66 percent confidence interval.

Figure 2. Selected Estimates of Contemporaneous World GDP Damages from Global Warming Occurring Around 2100



Notes:

* Only market damages were estimated in these studies. And the above figure is the midpoint of a range of damage estimates.

** Damage categories are not precisely de-lineated in these studies.