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The Economics of 350: The Benefits and Costs of Climate Stabilization

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Economics for Equity and the Environment Network is a national network of economists who are developing and applying economic arguments for active protection of human health and the natural environment.
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Executive Summary

Stopping global warming and protecting the earth's climate is a daunting challenge. To prevent a climate crisis we have to move quickly to transform the ways in which we create and use energy, develop petroleum-free transportation, and much more. These changes will not be free; there is already resistance to paying for the first steps along this road. Some think that reaching for more ambitious mitigation targets, and quicker reductions in emissions, would mean economic disaster. Some economists have become known for advocating only slow and modest responses to climate change, lest the costs of mitigation become too large.

This report demonstrates that the 'go slow' recommendations are unjustified. A number of economic analyses, informed by recent scientific findings and using reasonable assumptions, suggest that more ambitious targets and quicker action make good economic sense. The warnings about climate change are growing steadily more ominous – but it has not, as a consequence, become impossibly expensive to save the planet. We can still afford a sustainable future.

The bad news about climate change relates mostly to the costs of inaction. As greenhouse gas emissions grow, it is the cost of doing nothing that is becoming unbearable, not the cost of taking action. If there is reason for optimism amidst the dire warnings it is this: the costs of insuring the planet against climate disaster are not prohibitive. The best estimates of the costs of a vigorous, immediate effort to rebuild the world economy around carbon-free technologies are still in the range of one to three percent of world output (GDP) per year, even with the more stringent emissions reduction goals we are supporting. Scientific research continues to yield evidence that climate change is occurring faster, and its consequences could be more severe, than previously expected: the costs of climate inaction, or even of delay in mounting a large-scale response to the climate crisis, are getting worse and worse.

We cannot afford a *little* climate policy, half-measures that would leave us all vulnerable to the immense risks of an increasingly destructive climate. We need a big initiative, a comprehensive global deal on protecting the earth's climate by rapidly reducing emissions of greenhouse gases. Because the status quo is not sustainable, the most economical choice is to change, as quickly, cost-effectively, and comprehensively as possible. This study looks at both sides of the equation, beginning with the worsening news about climate risks (i.e., the costs of inaction), then turning to the costs of an adequate response.

A moving target

There are signs of progress in the arena of climate policy. An optimistic reading of European and proposed U.S. policies suggests that the world could be close to getting on track to contain the growing concentration of carbon dioxide (CO_2) in the atmosphere at something close to 450 parts per million (ppm), heretofore considered a "safe" level.

Unfortunately, the target for climate stabilization may be moving more quickly than progress on policy. Recent empirical evidence indicates climate change is taking place considerably faster than scientists had expected only a decade ago. Furthermore, paleoclimatic research indicates that earlier climate change episodes also took place rapidly. If rapid change is occurring, a considerably lower policy target than 450 ppm is justified. The 350 ppm CO_2 goal is only starting to receive attention among policy makers or in the global political discussions over climate, although Rajendra Pachauri, the head of the Intergovernmental Panel on Climate Change (IPCC), and Nicholas Stern, author of the 2006 *Stern Review*, have recently endorsed the 350 ppm target. The chief climate scientist at NASA, James Hansen, argues that a *reduction* from the current level of carbon dioxide in the atmosphere, 385 ppm, to 350 ppm CO_2 by 2100 will be essential to avoid dangerous anthropogenic climate change. The lag in the discussion is in part due to the lack of analyses in the economics literature of the costs and benefits of a 350 ppm CO_2 stabilization trajectory. For this reason, Economics for Equity and the Environment Network (E3) initiated this study of the economics of the 350 ppm target.

Why 350?

There is a consensus among climate scientists that greenhouse gases are transforming our climate and that the potential damage to human communities and natural ecosystems is both far reaching and long lasting. In general terms, the nature of the appropriate response is obvious and widely endorsed: the prevention of "dangerous" levels of climate change. Translating this general mandate into specific action requires two important, and as yet unresolved, judgments: First, what is a safe amount of climate change? Second, what emission patterns over time are consistent with that safe level of change?

For years now, climate scientists have recommended keeping the global average temperature below a 2°C (3.6°F) change from 1990 as a way to reduce the risk of the most devastating climatic changes. The amount of greenhouse gases that the atmosphere can absorb while staying below 2°C is still the subject of some debate. Even in the short time since the 2007 publication of the IPCC's Fourth Assessment Report ("*AR4*"), which reflected research published through 2006, new scientific findings have provided reasons to be even more cautious.

James Hansen is not alone in the scientific community in pointing out what the latest climate science means for public policy. In an important recent paper, Hansen and numerous co-authors reach two key conclusions: first, the global average temperature may be much more sensitive to greenhouse gases in the atmosphere than is commonly believed; second, to avoid dangerous climate change, we may need to reduce the concentration of CO_2 in the atmosphere from today's 385 ppm to 350 ppm CO_2 by 2100, if not sooner.

The scientific literature as of 2006, as summarized in *AR4*, implied that the most likely estimate of climate sensitivity – the global average temperature increase from a doubling of atmospheric CO_2 – was 3°C. Hansen and his colleagues summarize the evidence from the paleoclimatic record supporting a climate sensitivity of 6°C. That is, they argue that the global warming likely to result from any given atmospheric concentration of CO_2 is approximately twice as great as *AR4* projected. They estimate a 25 percent risk of serious harm with 300-500 ppm CO_2 and for this reason argue that getting concentrations below 350 ppm CO_2 by 2100 is a safe reasonable goal.

What does it take to get to 350?

Hansen and his co-authors describe a detailed scenario for reducing greenhouse gas emissions with the goal of reaching 350 ppm CO_2 by 2100:

- Coal burning is phased out or achieves 100 percent carbon capture by 2030.
- Oil and gas prices rise steadily as these finite resources approach exhaustion.
- A combination of ending deforestation and initiating large-scale reforestation causes significant negative emissions (that is, a withdrawal of CO_2 from the atmosphere).

We contrast that scenario with a less demanding but still ambitious trajectory which does not require the world to achieve negative net emissions; assuming a climate sensitivity of 6°C, our scenario reaches 350 ppm CO_2 by 2200.

Both scenarios assume success, within this century, in the vast undertaking of conversion of the world energy system to carbon-free sources. This is the first and foremost challenge for climate policy, the essential hurdle that must be overcome. But it is not all that is needed, especially for the scenario that reaches 350 ppm CO_2 by the end of this century.

Figure ES-1: Comparing Cumulative Emissions for a 350 ppm CO_2 Trajectory (Gt CO_2)

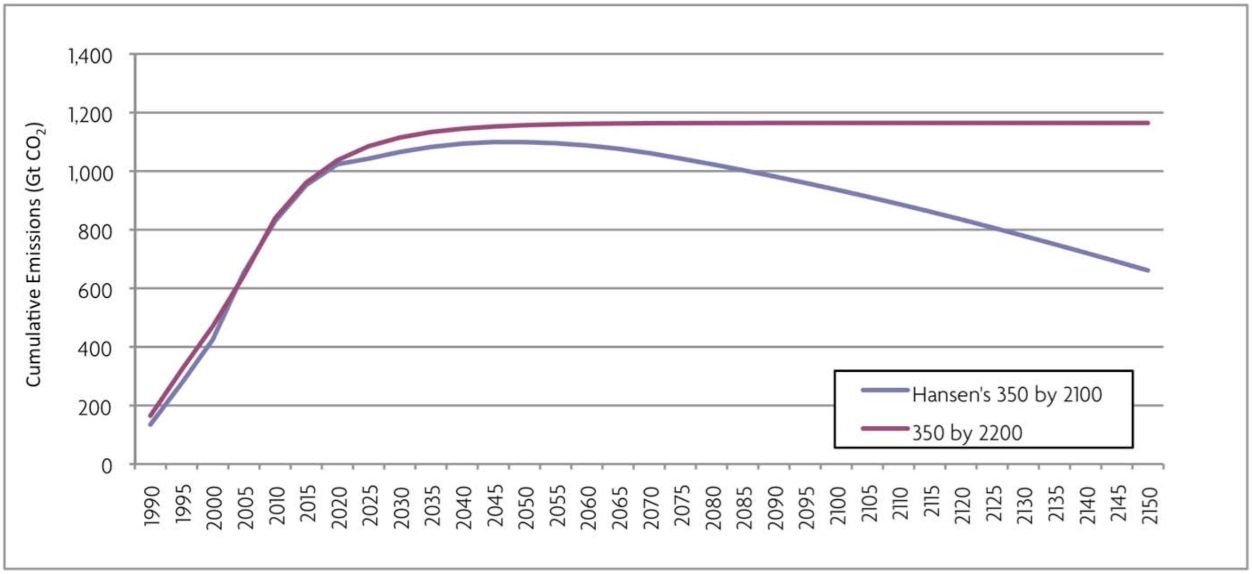

Figure ES-1 shows that cumulative emissions soon start to decline (implying negative annual emissions) for Hansen's 350 by 2100 scenario, but remain roughly constant after a few decades (implying near-zero annual emissions) in our 350 by 2200 scenario. Our scenario represents the most ambitious schedule that we can imagine without relying on negative emissions: emissions are reduced to 54 percent of 1990 emissions by 2020 and 3 percent by 2050. The conversion to renewable energy systems would have to be complete and the world economy would have to be virtually free of carbon emissions by mid-century, a more demanding goal than any of the leading policy proposals under discussion today.

How might it be possible to achieve negative emissions, that is, to remove carbon dioxide from the atmosphere? At present there are three widely discussed methods of carbon removal, of which the first two are currently available and the third is still under development.

First, reforestation (and the prevention of deforestation) is a key component of the path that achieves 350 ppm CO_2 by 2100. New international agreements, institutional structures, and financing arrangements would be needed to achieve the reduction in atmospheric CO_2 concentration. Hansen is not alone in highlighting the importance of reforestation; assuming success in creating the needed institutions, this is not the most expensive part of a 350 ppm scenario.

Second is "biochar": it is possible to convert plant material into charcoal, and then bury it in the soil; that process sequesters carbon, and may have beneficial effects on soil productivity and water retention. Biochar offers an interesting but perhaps limited option for carbon capture.

Third, biomass could be burned with carbon capture and storage (CCS), a much-discussed possibility that needs further development. Biomass – including sugar cane, switchgrass, corn (maize), palm oil, and carbon-rich waste products from the paper and agricultural industries – can be burned in power plants to generate electricity and heat. The use of biomass as a fuel is typically described as carbon-neutral: the CO_2 emissions released in combustion are balanced by the CO_2 removed from the atmosphere by the growth of the plant material (although this common equation ignores other emissions from forestry or agricultural activities that lead to plant growth). To reduce total greenhouse gas emissions, biomass power plants must be combined with CCS. The full life-cycle of biomass energy production with CCS would absorb atmospheric carbon into plants as they grow, burn the biomass to make energy, capture the resulting CO_2 emissions, and store them underground.

The future development of technology is not predictable over the time spans involved in climate policy; there are a number of proposals for removing carbon from the atmosphere, and it is certainly possible to imagine other means of mopping up unwanted CO_2 emissions. The replicators and matter transmitters of *Star Trek* would no doubt easily solve the CO_2 disposal problem. Yet unless science fiction becomes reality, achieving negative net emissions will remain a major challenge. It is important to support the development of new technology – but at the same time, public policy to protect future generations cannot wait for technologies that have not yet been developed.

Costs of emission reduction: a literature review

The literature on the costs of climate policies is extraordinarily diverse, with an array of incompatible scenarios, targets, and cost measurements. In this report, we review several categories of cost estimates. At one extreme, some business lobbies have argued that even the moderate reductions called for in recent U.S. legislation would be crippling to the economy. At the other extreme, some environmental advocacy groups have argued that an extensive agenda of reductions could save money overall by reducing fuel costs. Between these two extremes, there is a large body of research projecting that recent U.S. legislative proposals would have very little economic impact, and that the much more ambitious emission reductions required to reach 350 ppm might have moderate net costs.

At least four European research groups have modeled global scenarios that lead to 350 ppm CO_2; one finds that in a world with unemployed labor and other resources, the stimulus from new climate investments might accelerate economic growth. The other three groups find net annual costs that are generally between 1 percent and 3 percent of world output; their work highlights the importance of assumptions about the development of new technologies, which will be crucial over a time span of one or more centuries. Broadly similar cost estimates for abatement have been developed in the past by the *Stern Review* and by IPCC assessment reports, even though these earlier reports were generally discussing less stringent targets than 350 ppm CO_2.

Suppose that the cost of climate protection turns out to be 2.5 percent of global GDP, toward the high end of the global scenarios just discussed. In an economy that is growing at 2.5 percent per year, a rate that is common for developed countries, spending 2.5 percent of GDP on climate protection each year would be equivalent to skipping one year's growth, and then resuming. Average incomes would take 29 years to double from today's level, compared to 28 years in the absence of climate costs. In an economy experiencing 10 percent annual growth, as China has in many recent years, imposing a cost of 2.5 percent per year is equivalent to skipping 3 months of growth; if 10 percent growth is sustained, average incomes would reach twice the current level in 86 months, compared to 83 months in the absence of climate costs.

Consider another comparison: military spending is greater than 2.5 percent of GDP in 68 countries around the world; it is greater than 4 percent of GDP in both the United States and China. It is difficult, therefore, to believe that we are unable to remove this amount from current consumption in order to defend against a remote but dangerous threat to our way of life. On the strength of a different narrative about potential dangers we already do so, year after year.

Casting DICE for 350

Estimates of the cost of mitigation often look at only one side of the economic story: How much might it cost to reduce atmospheric carbon to a specified target level? While near-term co-benefits (such as reduced air pollution) are commonly netted out in such studies, the important choice of a target level of CO_2 concentrations is considered to be an inherently ethical and political decision. Yet some economists have tried to go farther, and perform a full cost-benefit analysis, setting mitigation costs against an estimated monetary value for all benefits, including those of avoided climate change for all future generations. This is commonly referred to as the determination of an "optimal," or cost-benefit-analysis based, climate policy. Economists taking this approach have often argued that the best policy is to do fairly little, especially at first.

The Dynamic Integrated model of Climate and the Economy (DICE) is one of the best-known models of this type. According to its creator, William Nordhaus, DICE demonstrates that the optimal climate policy follows a "climate policy ramp" that begins with small, slow steps. We investigate whether, with slightly different assumptions, DICE might recommend beginning abatement more rapidly, and stabilizing at 350 ppm CO_2.

We modify the DICE model to use the low discount rate adopted in the *Stern Review*; this places a greater value on future outcomes, for reasons that Stern and others have argued. Our discounting approach implies that investments in climate stabilization are economically warranted if they provide rates of return that are consistent with market returns on relatively safe forms of investment. Then, in addition to a few technical changes, we experiment with several possible values for two key parameters in DICE. One is the climate sensitivity parameter, as discussed in the preceding section. The DICE default value for climate sensitivity is 3°C. The second parameter determines the effect of temperature increases on the economy. DICE assumes, on the basis of little or no evidence, that climate-related economic damages depend on the square of temperature increases. We explore the alternate assumptions of damages based on the cube, fourth, or fifth power of temperature increases.

With the assumption of 6°C climate sensitivity and a damage exponent of 4 or 5, DICE recommends something close to the Hansen scenario: all carbon emissions are eliminated before the middle of this century; peak temperature increases are one degree or less; and atmospheric concentrations of CO_2 are 360 ppm or less at the beginning of the next century.

DICE, in all variants, calculates an optimum scenario from the point of view of achieving the greatest possible human welfare – using a debatable version of human welfare based solely on per capita consumption. Our experiments show that if emissions have a big enough effect on temperatures, and if temperatures have a big enough effect on the economy, then even the DICE version of human welfare is maximized by keeping temperature increases very low, and achieving a completely emission-free world economy within a few decades.

Conclusions and policy recommendations

The most important conclusion involves what we did not find. There are no reasonable studies that say that a 350 ppm stabilization target will destroy the economy; there are no studies that claim that it is desirable to wait before taking action on climate protection. On the contrary, there is strong, widespread endorsement for policies to promote energy conservation, development of new energy technologies, and price incentives and other economic measures that will redirect the world economy onto a low-carbon path to sustainability.

Disagreements emerge at the level of more specific estimates and recommendations. Is a potential cost of 1 to 3 percent of world GDP a large or a small number? The answer depends on how seriously you take the risks of climate change. Recall that the starting point for the discussion of the 350 ppm CO_2 target is the projection of potentially catastrophic climate change if the atmosphere remains above that level. With strong assumptions about damages, even the DICE model will give up its leisurely stroll toward abatement in favor of rapid emissions reductions.

Think of climate risk in terms of insurance. The reason people buy fire insurance is not because they are certain that their house will burn down; rather, it is because they cannot be sufficiently certain that it will *not* burn down. Likewise, the projections of dangerous climate risk if the world exceeds 350 ppm CO_2 in the long run are not certainties; they are, on the contrary, necessarily uncertain. If the worst happens, our grandchildren will inherit a degraded Earth that will not support anything like the life that we have enjoyed. On the other hand, if we prepare for the worst but it does not happen, we will have invested more than, in perfect hindsight, was necessary in clean energy, conservation, and carbon-free technologies. How would we feel about discovering we had done too much about climate change, compared to discovering we had done too little?

The analogy to insurance is important but inexact. There is no company selling planetary climate insurance, no one to whom we can hand 1 to 3 percent of GDP (if that is what it costs) and be confident that the problem will be taken care of. There is, rather, a challenging, long-term problem of technology and public policy to be solved.

The constraints on allowable CO_2 emissions, for stabilization at a level as low as 350 ppm, are painfully tight. A realistic policy scenario, therefore, is almost certain to not only call for maximum progress in pursuing energy efficiency and promoting renewable energy, but also for measures that remove carbon from the atmosphere. Many of the technologies that will be needed do not yet exist in mass-produced, commercially available forms, if at all. Yet the development of new technology is itself heavily influenced by public policy.

The difference between optimists and pessimists is in large part about images of future technology. An assumption of no technical change would be unreasonable; none of the studies that we discuss make this assumption – with the possible exception of the business lobbies opposed to U.S. climate legislation. At the other extreme, what are the limits to what we can achieve through energy efficiency, solar power, carbon capture and storage, and other new technologies? This is a question about an unknowable future: at the time of World War I, who could have anticipated mobile phones, laptop computers, and the internet?

The most optimistic projections also assume high prices for fossil fuels, which make all abatement investments look better. It is a mistake, however, to rely on market prices for fossil fuels to reduce emissions, rather than introducing a carbon price through a tax or a trading system. High oil prices enrich the owners of fossil fuels, and create incentives for environmentally destructive production of energy from oil shale, oil sands, and increasingly deep, dangerous offshore drilling. In contrast, a high price created through policy provides incentives for consumers to conserve, but not for producers to engage in costly, damaging production. A tax or cap-and-trade system transfers revenues to the government, which can use them for environmental investments, other public purposes, or refunds to citizens.

The world is taking important initial steps toward addressing the climate crisis, with increasingly widespread discussion of the need to avoid 2°C of warming. What is less widely recognized is that, according to recent scientific research, staying safely below that temperature limit likely requires stabilization at about 350 ppm of CO_2. Such a low target requires a large-scale, continuing effort throughout this century, and the development of major new technologies, as well as appropriate price mechanisms. Predicting the future is challenging, because it has not yet happened; predicting a century of technological and economic change is inescapably fraught with uncertainty. Nonetheless, the best available estimates imply that we can, indeed, afford the economics of 350. What we cannot afford is too little climate policy, too late.

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1. Introduction

Stopping global warming and protecting the earth's climate is a daunting challenge. To prevent a climate crisis we have to move quickly to transform the ways in which we create and use energy, develop petroleum-free transportation, and much more. These changes will not be free; there is already resistance to paying for the first steps along this road. Some think that reaching for more ambitious mitigation targets, and quicker reductions in emissions, would mean economic disaster. Some economists have become known for advocating only slow and modest responses to climate change, lest the costs of mitigation become too large.

This report demonstrates that the 'go slow' recommendations are unjustified. A number of economic analyses, informed by recent scientific findings and using reasonable assumptions, suggest that more ambitious targets and quicker action make good economic sense. The warnings about climate change are growing steadily more ominous – but it has not, as a consequence, become impossibly expensive to save the planet. We can still afford a sustainable future.

The bad news about climate change relates mostly to the costs of inaction. As greenhouse gas emissions grow, it is the cost of doing nothing that is becoming unbearable, not the cost of taking action. If there is reason for optimism amidst the dire warnings it is this: the costs of insuring the planet against climate disaster are not prohibitive. The best estimates of the costs of a vigorous, immediate effort to rebuild the world economy around carbon-free technologies are still in the range of one to three percent of world output (GDP) per year, even with the more stringent emissions reduction goals we are supporting. Scientific research continues to yield evidence that climate change is occurring faster, and its consequences could be more severe, than previously expected: the costs of climate inaction, or even of delay in mounting a large-scale response to the climate crisis, are getting worse and worse.

We cannot afford a *little* climate policy, half-measures that would leave us all vulnerable to the immense risks of an increasingly destructive climate. We need a big initiative, a comprehensive global deal on protecting the earth's climate by rapidly reducing emissions of greenhouse gases. Because the status quo is not sustainable, the most economical choice is to change, as quickly, cost-effectively, and comprehensively as possible. This study looks at both sides of the equation, beginning with the worsening news about climate risks (i.e., the costs of inaction), then turning to the costs of an adequate response.

A moving target

If the climate problem turned out to be much worse than expected, could we still afford to solve it? This is a critical dilemma to unravel: The worse the climate problem, the more expensive it is to correct – and the more dire the consequences of allowing climate damage to occur by failing to make deep enough emissions cuts in the near future.

There are signs of progress in the arena of climate policy. EU governments have already taken on commitments to reduce greenhouse gas emissions and have begun large-scale policy initiatives to address the problem. The United States lags behind, but has finally begun a serious debate about proposals for climate legislation. An optimistic reading of EU and proposed U.S. policies suggests that these countries, accounting for nearly two-fifths of global greenhouse gas emissions, are close to getting on track to contain the growing concentration of carbon dioxide (CO_2) in the atmosphere at something close to 450 parts per million (ppm), heretofore considered a "safe" level – or at the very least to lead to a long-term 450 ppm CO_2 trajectory after a shorter period of overshooting this goal.

Unfortunately, the target for climate stabilization may be moving more quickly than progress on policy. Recent empirical evidence indicates climate change is taking place considerably faster than scientists had expected only a decade ago. Furthermore, paleoclimatic research indicates that earlier climate change episodes also took place rapidly. If rapid change is occurring, a considerably lower policy target than 450 ppm is justified. The 350 ppm CO_2 goal is only starting to receive attention among policy makers or in the global political discussions over climate, although Rajendra Pachauri, the head of the Intergovernmental Panel on Climate Change (IPCC), and Nicholas Stern author of the 2006 *Stern Review*, have recently endorsed the 350 ppm target. The chief climate scientist at NASA, James Hansen, argues that a *reduction* from the current level of carbon dioxide in the atmosphere, 385 ppm, to 350 ppm CO_2 by 2100 will be essential to avoid dangerous anthropogenic climate change. The lag in the discussion is in part due to the lack of analyses in the economics literature of the costs and benefits of a 350 ppm CO_2 stabilization trajectory. For this reason, Economists for Equity and Environment (E3) initiated this study of the economics of the 350 ppm target.

This report addresses the questions, What does it take to lower atmospheric concentrations below today's levels? And, would taking the 350 ppm target seriously cause disastrous economic consequences?

Section 2, *Why 350?,* examines recent scientific developments, including Hansen's arguments for this more stringent greenhouse gas abatement goal. We consider the 350 ppm CO_2 target in the context of the need to avoid dangerous climate change and the now commonplace policy objective of staying below a 2°C average annual temperature change.

In Section 3, *What does it take to get to 350?*, we begin with a subsidiary question: 350 by when? The sooner the world reaches that target, the greater the costs and challenges of the transition to a new energy system – and the smaller the risk of catastrophic climate change. A plan for reaching 350 ppm CO_2 by 2100 is as rapid as seems feasible, barring economic collapse or the appearance of miraculous new technologies. In contrast, moderately ambitious scenarios for emissions reductions, which are now the focus of policy debates, appear to be on track to achieve 350 ppm only by 2200 or later, prolonging the period of more serious climate risk. Large-scale removal of carbon dioxide from the atmosphere – through reforestation, biomass burning with carbon capture, or other new technologies – appears to be crucial for reaching the 350 target by 2100.

What does it cost to get to 350? In Section 4, *Costs of Emission Reductions*, we review the rich literature of abatement cost analyses. A few of the most pessimistic studies find even moderate emissions reduction to be uneconomical; among other studies, a variety of assumptions determine the affordability of the abatement targets under discussion in climate policy today. Uncertainties regarding the cost of future technology development and the price of fossil fuels turn out to have strong effects on the results, but several studies find that – after accounting for these uncertainties – 350 ppm CO_2 plausibly may be achieved at an affordable cost.

Economic models have frequently offered estimates of the costs of various climate proposals, and used those estimates as a basis for recommending an optimal course of action. These recommendations have often suggested that the world should take a very gradual approach to emission reduction; anything faster, some models claim, would cause unnecessary expense.

Section 5, *Casting DICE for 350*, looks at one of the most widely discussed climate economics models, Yale economist William Nordhaus' DICE – a model well known for its cautious, incremental policy recommendations. We use a version of DICE with only minor modifications – in particular, we modify it to assume that climate damages will turn out to be as bad as Hansen predicts – and find that under that assumption, DICE concludes that the world should move as quickly as possible to drive CO_2 concentrations down below today's level.

Section 6 presents a brief summary of the message of the report, focused on its policy recommendations.

Technical appendices explore Hansen's strategy for achieving 350 ppm CO_2, and the modeling we employed to determine the trajectories for reaching 350 at different points in time.

2. Why 350?

The scientific consensus on climate change is unequivocal. Greenhouse gases are transforming our climate; the potential disruption to human communities and natural ecosystems is both far reaching and long lasting.

In general terms, the nature of the appropriate response is obvious and widely endorsed. Article 2 of the 1992 *United Nations Framework Convention on Climate Change* (*UNFCCC*) states that its objective is to achieve

> … stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.[1]

Translating this clear mandate to prevent "dangerous" levels of climate change into action requires two important, and as yet unresolved, judgments: First, what is a safe amount of climate change? Second, what emissions levels are consistent with that safe level of change?

For years now, climate scientists have recommended keeping global average annual temperature below a 2°C (3.6°F) change from 1990 as a way to reduce the risk of the most devastating climatic changes.[2] The latest report of the Intergovernmental Panel on Climate Change (IPCC 2007b), commonly known as *AR4*, or *The Fourth Assessment Report* – representing the consensus of thousands of scientists from around the world – assesses the damages likely to result from allowing global temperatures to change more than 2°C (3.6°F) from 1990 (see Table 1). The *Stern Review* (2006) – an exhaustive assessment of the science and economics of climate change commissioned by the British Government – came to a similar conclusion (see Table 2): Allowing global temperature change to exceed 2°C from 1990 would be dangerous to both human communities and natural ecosystems.

As both Stern and the IPCC suggest, there are several potential climate disasters with uncertain "tipping points." These include catastrophic risks such as the melting of the Greenland and Antarctic ice sheets with the resultant increase in sea-levels of several meters over several centuries, or the disruption of the thermohaline circulation pattern of the Atlantic Ocean. There are also some lesser known, serious threats (Lenton *et al.* 2008; Weitzman 2009). For example, rising temperatures could trigger abrupt, massive releases of methane from undersea geological formations (clathrates) or from permafrost; this could lead to a runaway greenhouse effect (Hall and Behl 2006). Decreased rates of CO_2 uptake by plants (because of changes in climatic conditions or the range of viable species) or the ocean (because of saturation or changes in temperature) are another potentially important feedback process. As the climate changes, the biodiversity of both wild and agricultural species is also at risk of large scale and often irreversible losses (Lenton *et al.* 2008).

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[1] UNFCCC website, http://unfccc.int.

[2] Throughout this report, when global annual average temperature is presented in the literature in terms of the change from pre-industrial, we have subtracted 0.63°C to approximate the change from 1990; for temperature changes from the present day, we have added 0.06°C to approximate the change from 1990. Both of these estimates are taken from NASA/GISS (February 2009) *Global Annual Temperature Anomalies (Land + Ocean)*, http://cdiac.ornl.gov/trends/temp/hansen/data.html.

Table 1: *AR4* High Confidence Projections of the Impacts of Temperature Change

Global Average Annual Temperature Change above 1990		
°C	*°F*	Likely Consequence
2	*3.6*	Agricultural productivity in low latitudes, especially in Africa, will drop sharply Millions exposed to coastal flooding each year Extinction of species will become significant, especially for coral reefs and arctic animals
3	*5.4*	Agricultural productivity and economic output will drop everywhere 30 percent of global coastal wetlands lost Substantial burdens on health services from disease, malnutrition, heat waves, floods, droughts
4	*7.2*	Extinction of species will become widespread
2 to 4.5	*3.6 to 8.1*	Threshold for eventual loss of the Greenland ice sheet, ultimately causing 7 m of sea-level rise

Source: AR4 (IPCC 2007b: Synthesis Report, Table 3.6, p.51)

Table 2: *Stern Review* Turning Points for Dangerous Impacts from Climate Change

Global Average Annual Temperature Change above 1990		
°C	*°F*	Likely Consequence
1.4 to 2.4	*2.5 to 4.3*	"[A] significant fraction of species would exceed their adaptive capacity and, therefore, rates of extinction would rise. This level is associated with a sharp decline in crop yields in developing counties (and possibly developed counties) and some of the first major changes in natural systems, such as some tropical forests becoming unsustainable, irreversible melting of the Greenland ice sheet and significant changes to the global carbon cycle (accelerating the accumulation of greenhouse gases)."
3.4 to 4.4	*6.1 to 7.9*	"[T]he risk of major abrupt changes in the climate system would increase markedly. At this level, global food production would be likely to fall significantly (even under optimistic assumptions), as crop yields fell in developed countries.

Source: Stern (2006, p.293); temperature change converted from pre-industrial by subtracting 0.63°C.

Translating the 2°C target into policies and emission reductions has proved more difficult. The amount of greenhouse gases that the atmosphere can withstand while staying below 2°C is still the subject of some debate. Even in the short time since *AR4* (which reflected research published through 2006), scientific findings have become more troubling. To cite just a few examples:

- The "climate sensitivity," that is the amount of warming that will result from a doubling of the atmospheric concentration of greenhouse gases, may be inherently uncertain – because in a system such as the earth's climate with strong positive feedbacks, small errors in estimating the size of the feedbacks inevitably cause large errors in the outcome (Roe and Baker 2007).
- Low-level clouds, one of the least understood aspects of the climate system until recently, may be a source of additional positive feedback to the warming process; of the major climate models, the one that simulates clouds most accurately is also the one that predicts the most rapid warming (Clement *et al.* 2009).
- Even if carbon emissions came to a complete halt, the increases in temperatures and sea levels might be irreversible for centuries to come – because the decline in radiative forcing (warming) of the atmosphere could be roughly matched by a slowdown in the absorption of heat by the deep oceans (Solomon *et al.* 2009).

It is no surprise, therefore, to find that Hans Joachim Schellnhuber, a leading German climate scientist, has recently written an article entitled, "Global Warming: Stop Worrying, Start Panicking?", in which he concludes that:

> … we are still left with a fair chance to hold the 2°C line, yet the race between climate dynamics and climate policy will be a close one. (Schellnhuber 2008, 14240)

James Hansen, a leading American climate scientist and the director of NASA's Goddard Institute for Space Studies, is not alone in the scientific community in worrying about what the latest climate science means for public policy. After many years of scientific research, Hansen and numerous co-authors have now attempted to connect the dots and draw out the policy implications of the latest findings. They reach two noteworthy conclusions an important recent paper: first, climate sensitivity is much greater than is commonly believed; second, to avoid dangerous climate change, we need to reduce the concentration of CO_2 in the atmosphere from today's 385 ppm[3] to 350 ppm CO_2 by 2100, if not sooner (Hansen *et al.* 2008).

How sensitive is the climate?

"Climate sensitivity," the long-term temperature change that will result from a doubling of atmospheric CO_2 concentrations, is a common measure of the severity of the global warming threat. The scientific literature as of 2006, as summarized in *AR4* (IPCC 2007a), implied that the most likely estimate of climate sensitivity was 3°C. That is, every time atmospheric CO_2 doubles – from today's 385 ppm to 770 ppm CO_2, for example – the global average annual temperature would increase by 3°C. The warming associated with other levels of CO_2 can be extrapolated from this relationship; climate sensitivity can be taken as an indicator of the extent of warming that is expected from any fixed level of greenhouse gases in the atmosphere.

Climate sensitivity is uncertain – perhaps inevitably so (Roe and Baker 2007). *AR4* viewed it as "likely" that the true value fell between 2.0°C and 4.5°C; in IPCC usage, this means that they believed there is a one in six chance that climate sensitivity is actually above 4.5°C. The climate model that does best at simulating clouds (Clement *et al.* 2009, see also Kerr 2009) has a climate sensitivity of 4.4°C.

In "Target Atmospheric CO_2: Where Should Humanity Aim?", the work associated with the call for a 350 ppm CO_2 target, Hansen and his co-authors present significant evidence from the paleoclimatic record supporting a climate sensitivity of 6°C (Hansen *et al.* 2008).[4] That is, they argue that the global warming that will result from any given increase in atmospheric concentration of CO_2 is approximately twice as great as *AR4* projected.

Even at lower levels of climate sensitivity, the requirements for climate stabilization are demanding. In *AR4*, the IPCC (2007b) offers six categories of stabilization trajectories; these are the target atmospheric concentration levels for greenhouse gases, given either just for CO_2, or in terms of "CO_2-equivalents" (CO_2-e) to include the effects of non-CO_2 gases (see Table 3).[5] According to these IPCC classifications, only categories I and II – with CO_2 concentrations in the range of 350 to 440 ppm – are likely to keep global temperature change below or near 2°C from 1990, even with a climate sensitivity of 3°C.

Table 3: *AR4* Classification of Stabilization Scenarios

AR4 Category	CO_2 concentration (ppm)	CO_2-equivalent concentration (ppm)	Global average annual temperature increase above 1990		SRES Scenarios
			°C	°F	
I	350-400	445-490	1.4 to 1.8	*2.5 to 3.2*	
II	400-440	490-535	1.8 to 2.2	*3.2 to 3.9*	
III	440-485	535-590	2.2 to 2.6	*3.9 to 4.6*	
IV	485-570	590-710	2.6 to 3.4	*4.6 to 6.1*	B1, A1T
V	570-660	710-855	3.4 to 4.3	*6.1 to 7.7*	B2
VI	660-790	855-1130	4.3 to 5.5	*7.7 to 9.8*	A1B, IS92a

Source:AR4, (IPCC 2007b: Working Group III, Technical Summary, Table TS.2); categorization of SRES scenario by AR4 category was inferred by the authors from IPCC 2007 (Working Group I, Ch.10, Figure 10.24); SRES scenarios A2 and A1FI have stabilization trajectories higher than 790 ppm CO_2; temperature change converted from pre-industrial by subtracting 0.63°C.

Table 4: *Stern Review* Probability of Exceeding Temperature Thresholds

Stabilization level	Global average annual temperature change from 1990

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[3] Year 2008 data from World Resources Institute (2008) *EarthTrends: The Environmental Information Portal*, http://earthtrends.wri.org/searchable_db/index.php?theme=3.

[4] Hansen *et al.* (2008, p.225): "Additional warming, due to slow climate feedbacks including loss of ice and spread of flora over the vast high-latitude land area in the Northern Hemisphere, approximately doubles equilibrium climate sensitivity."

[5] Another wrinkle in the connection between the atmospheric concentration of greenhouse gases and global mean temperature change is the impact of non-CO_2 gases, especially methane, nitrous oxide, and aerosols. The impacts of non-CO_2 gases are sometimes combined with CO_2 in terms of "CO_2-equivalents" (CO_2-e), or the amount of CO_2 necessary to generate an equivalent climatic impact.

CO_2	CO_2-equivalent	1.4°C (2.5°F)	2.4°C (4.3°F)	3.4°C (6.1°F)	4.4°C (7.9°F)
320	400	33%	3%	1%	0%
350	450	78%	18%	3%	1%
410	500	96%	44%	11%	3%
450	550	99%	69%	24%	7%
550	650	100%	94%	58%	24%
610	750	100%	99%	82%	47%

Source: Stern (2006, Box 8.1, p.195); using the Hadley Centre Ensemble results; converted from temperature change from pre-industrial by subtracting 0.63°C; converted from CO_2-e to CO_2 based on authors' interpretation of IPCC 2007 (Working Group III, Technical Summary, Table TS.2).

The *Stern Review* (2006) presents the relationship between the atmospheric concentration of greenhouse gases and temperature change in terms of the likelihood of exceeding given temperature thresholds (see Table 4).

An 82 percent chance of keeping global temperature change below 2.4°C (4.3°F) from 1990 would require the CO_2 concentration to stabilize at 350 ppm; a 97 percent chance would require a 320 ppm CO_2 "stabilization trajectory" (or long-term concentration level). And like *AR4*, Stern's analysis assumed climate sensitivity levels well below that of Hansen *et al.*: Stern's most likely value for climate sensitivity was 3.0°C, with the possibility that it might go as high as 4.5°C; his high-sensitivity scenario assumed a most likely value of 3.9°C, with the possibility of going as high as 5.4°C.[6]

Since Hansen and his co-authors' research shows a higher climate sensitivity than *AR4* or Stern, they naturally call for an even lower limit on atmospheric concentrations of greenhouse gases in order to avoid dangerous temperature increases. Hansen *et al.* (2008) report a 25 percent risk of serious harm with 300-500 ppm CO_2 and set a goal of getting concentrations below 350 ppm CO_2 by 2100. The more widely discussed goal of 450 ppm CO_2 is, according to Hansen *et al.*'s reading of the paleoclimatic record, roughly the threshold for transition to an ice-free world; loss of all the world's glaciers and ice sheets would entail catastrophic increases in sea levels and changes in water supplies. (The details of Hansen *et al.*'s analysis are somewhat involved; they are explained in Technical Appendix B of this report.) As disturbing as Hansen *et al.*'s conclusions may be, they are not based on worst-case assumptions about all uncertainties; it is not unimaginable that the dynamics of climate change could be even worse than they project.

350 in politics and economics

Acknowledging the importance of staying below a 2°C (3.6°F) change from either pre-industrial or 1990 temperatures has become commonplace in the international climate policy debate (see Box 1). The goal of reaching a 350 ppm CO_2 stabilization trajectory – while making inroads into popular consciousness (see, for example, *www.350.org*) – has had much less impact on the public policy discourse to date.

Although they resulted in no formal commitments, the June 2008 and June 2009 Tällberg Forums – where more than 100 countries met in advance of the December 2009 Copenhagen Conference of Parties – took 350 ppm CO_2 as an important theme for discussion.[7] Similarly, the Bali Action Plan – a non-binding planning document agreed to by the UNFCCC Conference of Parties in December 2007 – calls for: "A level of stabilization of GHG concentrations in the atmosphere. Parties have proposed levels of around 450 ppm carbon dioxide equivalent (CO_2 eq) or 350 ppm CO_2 eq."(UNFCCC 2009). These concentration levels correspond to 350 ppm and 250 ppm CO_2, respectively.[8]

Box 1: 2°C in the Policy Debate

Note: A 2°C change in global annual average temperature from pre-industrial is equivalent to a 1.4°C change from 1990.

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[6] The "possibility of going as high as" refers to the upper end of the probability distribution for the Monte Carlo analysis employed in the *Stern Review*'s modeling.

[7] European Environment Agency, 23 June 2008, "Climate change targets: 350 ppm and the EU two-degree target," http://www.eea.europa.eu/highlights/climate-change-targets-350-ppm-and-the-eu-2-degree-target; The Tällberg Foundation, "Tällberg Forum 2008," http://www.tallbergfoundation.org/;.

[8] Converted from CO_2-e to CO_2 based on authors' interpretation of IPCC 2007 (Working Group III, Technical Summary, Table TS.2). The conversion of 350 ppm CO_2-e to 250 ppm CO_2 is approximate; this concentration level is lower than any of the *AR4* (IPCC 2007b) scenario categories.

Council of the European Union: “The European Council emphasizes the EU's determination to reinvigorate the international negotiations by developing a medium and long-term EU strategy to combat climate change, consistent with meeting the 2°C objective.... The European Council acknowledges that climate change is likely to have major negative global environmental, economic and social implications. It confirms that, with a view to achieving the ultimate objective of the UN Framework Convention on Climate Change, the global annual mean surface temperature increase should not exceed 2°C above pre-industrial levels.”

The Tällberg Forum: Representatives from over 100 countries discussed the importance of a 2°C above pre-industrial level policy in June 2008 and June 2009. No commitments were made beyond sending an informal letter to the leaders of the G8 emphasizing the urgency of addressing with climate change.

Bali Conference of Parties: The Action Plan resulting from the UNFCCC’s penultimate meeting of 189 countries states that: “Parties concur that 2050 is an appropriate time frame for a long-term goal. A range of options have been identified for quantifying such a goal, based on: (a) A level of stabilization of GHG concentrations in the atmosphere...; (b) A limit to the global average temperature increase. Options for quantifying such a limit put forward by several Parties include around 1.5°C above the pre-industrial level and 2°C above the pre-industrial level. Other Parties have questioned the utility of setting a quantified limit for global temperature increase.”

Countries with Legislation Calling for a 2°C Limit: Chile, Iceland, Norway, and Switzerland.

U.S. Proposed Legislation: Waxman-Markey Bill: “The analysis required under subsection (a)(3) shall address... global average surface temperature 3.6 degrees Fahrenheit (2 degrees Celsius) above the pre-industrial average, or such other temperature thresholds as the Administrator deems appropriate.”[9]

The peer-reviewed economics literature is much further behind in analyzing the impacts of a 350 ppm CO_2 stabilization trajectory, in part due to the inevitable lags in publication. Studies of 450 ppm and 550 ppm CO_2 stabilization targets are much more common in the published academic literature. With a handful of exceptions (discussed in Section 5 of this report), the peer-reviewed economics literature is largely devoid of 350 ppm CO_2 cost assessments.

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[9] Council of the European Union (2005, p.15-16); European Environment Agency, 23 June 2008, “Climate change targets: 350 ppm and the EU two-degree target,” http://www.eea.europa.eu/highlights/climate-change-targets-350-ppm-and-the-eu-2-degree-target; The Tällberg Foundation, “Tällberg Forum 2008,” http://www.tallbergfoundation.org/; UNFCCC (2009); Hare (2009); Waxman and Markey (2009).

3. What does it take to get to 350?

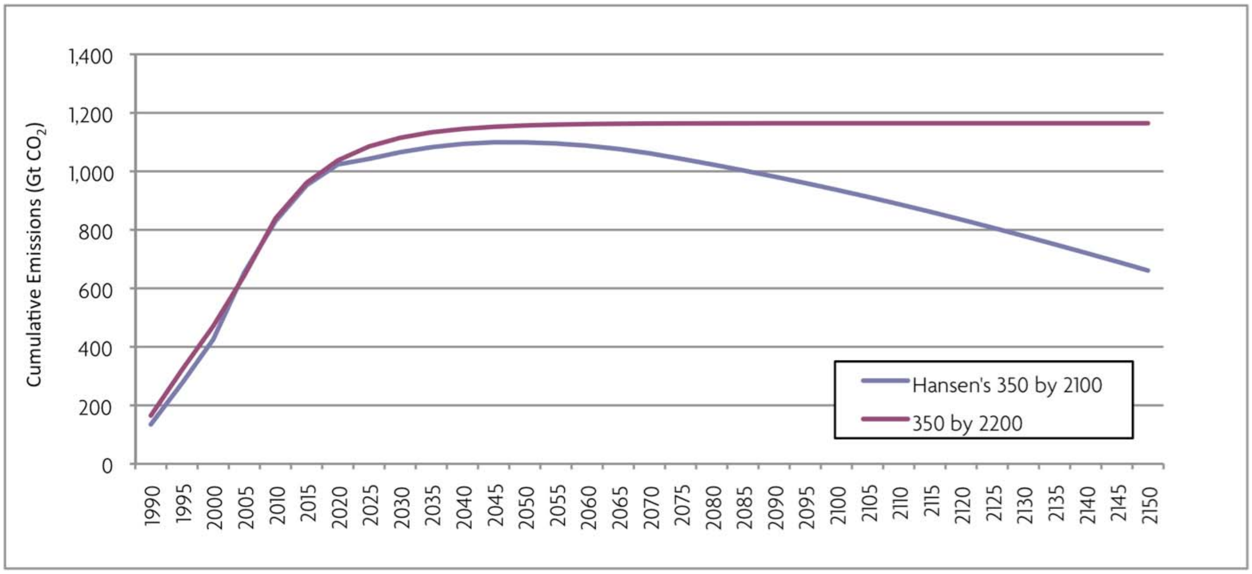
As background to the economic analysis of a 350 ppm CO_2 stabilization trajectory, this section investigates the technical feasibility of reaching this goal, and the importance of the speed with which it is achieved. The political resistance to more moderate climate goals could suggest that 350 ppm is simply beyond the pale; here we demonstrate that the 350 target is entirely feasible, if challenging, to reach.

A crucial question in the discussion, determining the degree of difficulty in meeting the target, is "350 by when?" Hansen *et al.* (2008) describe a detailed scenario for reducing greenhouse gas emissions with the goal of reaching 350 ppm CO_2 by 2100 (see Technical Appendix B for a more thorough explanation):

- Coal burning is phased out or achieves 100 percent carbon capture by 2030.
- Based on the IPCC estimate of oil and gas reserves, these fuels require no restrictions; they can be used as their market prices allow (assuming, as economic theory suggests, that prices will increase and demand will decrease as reserves shrink). If, however, the Energy Information Agency's (EIA's) higher estimate of reserves is correct, then cumulative use of oil and gas must be restricted to the amount estimated by IPCC.
- A combination of ending deforestation and initiating large-scale reforestation and biochar initiatives bring land use emissions to zero by 2015 and cause significant negative emissions (that is, a withdrawal of CO_2 from the atmosphere) by 2030, staying constant thereafter.

We contrast Hansen *et al.*'s scenario with a less demanding but still ambitious trajectory, which does not require the world to achieve negative net emissions; assuming a climate sensitivity of 6ºC, our scenario reaches 350 ppm CO_2 by 2200 (see Technical Appendix C for a detailed description of this scenario). Figure 1 compares cumulative emissions in Hansen *et al.*'s 350 ppm CO_2 by 2100 scenario with our scenario for reaching 350 by 2200.

Figure 1: Comparing Cumulative Emissions for a 350 ppm CO_2 Trajectory (Gt CO_2)



Source: Authors' calculations using MAGICC 5.3 software; Hansen et al. (2008).

Both scenarios assume success, within this century, in the vast undertaking of conversion of the world energy system to carbon-free or low-carbon sources such as wind, solar, geothermal, hydro, nuclear, and biomass-fueled power. This is the first and foremost challenge for climate policy, the essential hurdle that must be overcome. But it is not all that is needed, especially for the scenario that reaches 350 ppm CO_2 by the end of this century.

Both scenarios have very similar emissions through 2020. Then, within a few decades, Hansen *et al.*'s assumptions of complete carbon capture from coal and large CO_2 withdrawals from land-use changes make yearly emissions in their scenario negative and begin to decrease the stock of atmospheric CO_2 over time. The level of optimism regarding technical advances in carbon capture and storage and political advances that would make large-scale reforestation possible determines whether we project reaching 350 ppm CO_2 in 2100 or in 2200. The difference in consequence between these two trajectories could be important but is highly uncertain. The peak temperature change from 1990 in Hansen's 350 by 2100 scenario is 1.0°C (1.8°F) in 2050, compared to a peak of 1.5°C (2.3°F) in 2100 for the 350 by 2200 scenario.

Figure 1 shows that cumulative emissions (measured in Gt CO_2) soon start to decline for Hansen's 350 ppm CO_2 by 2100 scenario, but remain roughly constant after a few decades (implying near-zero annual emissions) in our 350 ppm CO_2 by 2200 scenario. Our scenario represents the most ambitious schedule that we can imagine without relying on negative emissions: emissions are reduced to 54 percent of 1990 emissions by 2020 and 3 percent by 2050. The conversion to renewable energy systems would have to be complete and the world economy would have to be virtually free of carbon emissions by mid-century, a more demanding goal than any of the leading policy proposals under discussion today. To achieve 350 before 2200 without net negative emissions in any year, global emissions would have to be reduced even faster. (Zero emissions beginning in 2015 results in 350 ppm CO_2 by 2085; see Technical Appendix C.) In essence, these calculations demonstrate why many years of negative net emissions are needed in order to reach 350 by 2100, and even perhaps by 2200.

Another approach to gauging the emissions allowable while avoiding dangerous climate impacts emphasizes cumulative emissions rather than atmospheric concentration. Writing in a recent issue of *Nature*, Allen *et al.* (2009) propose a permanent cumulative CO_2 emissions budget of 1,835 Gt CO_2, starting in the current year, with the goal of staying below 1.4°C (2.5°F) from 1990. In the same issue of *Nature*, Meinshausen *et al.* (2009) associate a range of year 2000 to 2050 cumulative CO_2 emissions budgets with the chance of exceeding 1.4°C (2.5°F) from 1990 (see Table 5; note that both studies focus on a safe limit of 2ºC above pre-industrial temperatures, which we have translated to 1.4ºC above 1990).[10]

Allen *et al.*'s 2010 to 2400 cumulative CO_2 emissions budget is far higher than Hansen *et al.*'s 350 by 2100 or our 350 by 2200 scenarios.[11] Meinshausen *et al.*'s lowest 2000 to 2050 cumulative CO_2 emissions budget resembles that of Hansen *et al.*'s 350 by 2100 scenario or our 350 by 2200 scenario. Note the large negative 2010 to 2400 cumulative emissions assumed by Hansen and his co-authors, primarily from reforestation. Both Allen and Meinshausen use *AR4* or similar estimates for climate sensitivity, which is one reason why their emissions budgets tend to be more expansive than Hansen *et al.*'s.

Table 5: Cumulative Emissions (in Gt CO_2)

	Cumulative Emissions (Gt CO_2)	
	from 2010 to 2400	from 2000 to 2050
Allen 2009 to stay below 1.4°C (5-95% confidence interval: 0.7-3.3°C)	1,835	
Meinshausen *et al.* 2009		
20% (8-37%) risk of exceeding 1.4°C		886
25%(10-42%) risk of exceeding 1.4°C		1,000
33% (16-51%) risk of exceeding 1.4°C		1,158
50% (29-70%) risk of exceeding 1.4°C		1,437
Hansen 350 by 2100	(1,603)	824
E3 350 by 2200	521	831

Note: Global annual average temperature change given from 1990; temperature change converted from pre-industrial by subtracting 0.63°C.
Source: Allen et al. (2009); Meinshausen et al. (2009); Authors' calculations based on MAGICC 5.3 software.

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[10] Both Allen *et al.* (2009) and Meinshausen *et al.* (2009) argue that cumulative emissions are a more accurate way of setting goals to avoid dangerous climate change. Allen *et al.* further claim that cumulative emissions impact on peak temperature is "remarkable insensitive" to the pathway or timing of emissions. Our experience with modeling in MAGICC 5.3 (Wigley 2008), DICE (Nordhaus 2008), and analyses done for this report does not support this assertion: We find that emissions in early decades have less effect on peak and long-range temperatures than do emissions in later decades.

[11] The Allen *et al.* carbon budget, however, falls between MAGICC's WRE350 and WRE450 scenarios described in Technical Appendix A.

Achieving negative greenhouse gas emissions

Climate stabilization, in a world of high climate sensitivity, requires more than just rapid reduction in CO_2 emissions (and emissions of other greenhouse gases[12]). To succeed, the world will have to go beyond reductions, to the point of achieving net negative emissions – that is, removing more greenhouse gases from the atmosphere than are emitted each year. At present there are three widely discussed methods of carbon removal, of which the first two (reforestation and biochar) are currently available and the third (biomass burning with carbon capture and storage) is still under development.

Reforestation

Reforestation (and the prevention of deforestation) is a key component of Hansen *et al.*'s (2008) plan to achieve 350 ppm CO_2 by 2100. Specifically, that plan assumes that 5.9 Gt CO_2 can be sequestered annually through reforestation starting in 2030. This assumption is within the range of reforestation rates discussed in other recent analyses. The technical potential (the rate of reforestation possible if money were no object) has been estimated to range from 20 to 110 Gt CO_2, while estimates of economically feasible reforestation presented in IPCC's (2001) *Third Assessment Report* (*TAR*) and *AR4* (IPCC 2007b) range from 1 to 14 Gt CO_2. These estimates are relatively small compared to "net primary product," i.e. the total forest growth that occurs each year (see Table 6).

Table 6: Annual Sequestration from Reforestation

	Net Primary Product *g C/m^2/year*	Land Available for Reforestation *million km^2*	Sequestration from Reforestation *Gt CO_2* /year
Alexandrov *et al.* 2002 and Benitez *et al.* 2007: Technical Potential			
Low	186	26	*20.5*
High	1,023	35	*112.5*
Hansen 2008			5.9
Watson *et al.* 2000 and IPCC 2001 (TAR)			
Low (boreal/temperate/tropical)	40 150 400	*12*	4.0
High (boreal/temperate/tropical)	120 450 800	*6*	5.9
IPCC 2007 (AR4): Economic Potential			
Bottom-up model: Low			1.3
Bottom-up model: High			4.2
Top-down model			13.8

Source: Alexandrov et al. (2002, p.302); Benitez et al. (2007, p.575-576); Hansen et al. (2008); Watson et al. (2000); IPCC (2001); IPCC (: Working Group III, Technical Summary, p.69); values in italics are authors' calculations.

Two analyses reported in a recent study by the UNFCCC (2008) also offer hopeful views of the affordability of large-scale forest sequestration. One set of projections of the feasible potential for emission reduction by 2030 identifies 12.5 Gt CO_2 in forestry, 12.4 Gt of which are located in developing countries. UNFCCC estimates, with considerable uncertainty in the economic assumptions, that the forestry reductions in developing countries in 2030 might cost only $21 billion, or less than $2 per ton of CO_2 (UNFCCC 2008, 53). In a shorter time frame, bottom-up estimates of mitigation potential in developing countries suggest that forestry could account for 2.0 Gt CO_2-e by 2020, with most of these reductions available for less than $15 per ton of CO_2 (UNFCCC 2008, 66-68).

The search for low-cost global opportunities for mitigation repeatedly leads to a focus on tropical forest management. Nicholas Stern's "blueprint" for a new global deal on climate change involves spending $15 billion per year to combat deforestation in tropical countries; he estimates that this would buy 3 Gt per year of reduction at an average cost of $5 per ton of CO_2-e (Stern 2009, 165-169).

New international agreements, institutional structures, and financing arrangements for implementation, monitoring and enforcement will be needed to achieve these potential emission reductions. While the reductions are global priorities, they will occur primarily in a handful of countries with substantial tropical forest

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[12] The importance of the non-CO_2 gases to the Hansen scenario is discussed in Technical Appendix B.

resources. This raises questions of equity in sharing the global costs of forestry measures; it would not be reasonable to expect the heavily forested countries to bear the financial burden alone. Hansen and his co-authors are not alone in highlighting the importance of this area – and assuming success in creating the needed institutions, this is not the most expensive part of their scenario.

Biochar

It is possible to convert plant material into charcoal, and then bury it in the soil; that process sequesters carbon, and may have beneficial effects on soil productivity and water retention. Biochar offers an interesting but perhaps limited option for emission reduction. Hansen *et al.* (2008) assume that 0.6 Gt CO_2 can be sequestered annually via biochar.

Biomass burning with carbon capture and storage

Biomass – including sugar cane, switchgrass, corn (maize), oil palm trees, and carbon-rich waste products from the paper and agricultural industries – can be burned in power plants to generate electricity and sometimes heat. The use of biomass as a fuel is typically described as carbon-neutral: the CO_2 emissions released in combustion are balanced by the CO_2 removed from the atmosphere by the growth of the plant material. For biomass crops, especially those grown in an industrial agricultural setting, this equation is more complex – emissions removed in plant growth still equal emissions released in combustion, but biomass farming is also responsible for emissions caused by tractors and other farm equipment, from the production of pesticides and fertilizers, and in some cases by land use changes, as when forest is converted to agricultural land for the purpose of biomass farming.

To use biomass energy as a tool to reduce greenhouse gas emissions a second step is necessary: biomass power plants must be combined with carbon capture and storage (CCS). The full life-cycle of biomass energy production with CCS would absorb carbon in plant material, burn that material to make energy (thereby avoiding greenhouse gas emissions from fossil fuels), and then capture the resulting CO_2 emissions and store them underground.

Burning biomass for energy is a wide-spread practice around the world, and much has been written about just how carbon neutral various biomass farming practices really are. Combining biomass energy with CCS, however, is still a work in progress.[13]

CCS stops greenhouse gas emissions from getting into the atmosphere by trapping CO_2 from power plants (burning biomass or fossil fuels) and storing it beneath the ground. If it could be developed on a commercial scale, it could be used for more than biomass plants; it could also allow continuing use of coal while still reducing emissions. Without CCS, it is difficult to fit large-scale use of coal into scenarios for rapid emission reduction. This potential for "redeeming" coal may account for some of the current interest in CCS. Full-scale, industrial CCS, however, is not expected to be available and commercially viable for another 10 or 20 years. So far, experimental programs exist for a number of different CCS technologies:

- Pre-combustion CCS removes carbon from fossil fuels before combustion, often through coal gasification.
- Post-combustion CCS removes carbon dioxide from power plant smokestacks, before it can enter the atmosphere.
- Oxyfuel CCS burns fuels in a pure oxygen atmosphere, which limits smokestack effluent to just water vapor and CO_2; cooling the smokestack gas is sufficient to separate the two into liquid water and gaseous CO_2.

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[13] For more information on biomass energy see Union of Concerned Scientists website, "How Biomass Energy Works." http://www.ucsusa.org/clean_energy/technology_and_impacts/energy_technologies/how-biomass-energy-works.html; U.S. Energy Information Administration website, "Biomass for Electricity Generation." http://www.eia.doe.gov/oiaf/analysispaper/biomass/; and Read (2008).

CO_2 storage options are the same for all three capture processes. CO_2 must be transported to the site of storage and injected 800 meters or more into the ground. Beneath the soil CO_2 may mix with ground water to form a fizzy seltzer, or may become trapped underneath rock formations. Potential storage sites include former oil and gas fields, and deep aquifers.[14]

The future development of technology is not predictable over the time spans involved in climate policy; it is certainly possible to imagine some other means of mopping up unwanted CO_2 emissions. The replicators and matter transmitters of *Star Trek* would no doubt easily solve the CO_2 disposal problem. Yet unless science fiction becomes reality, achieving net negative emissions will remain an enormous challenge.

CCS may not win the race to demonstrate that carbon can be economically removed from the atmosphere; numerous other inventions and proposals are beginning to appear. For example, recent scientific efforts to extract CO_2 directly from the air have attracted the attention of investment capital.[15] It is important to support the development of new technology – but at the same time, public policy cannot wait for or count on technologies that have not yet been developed.

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[14] For more on CCS technology see CCSReg Project (2008); Ansolabehere *et al.* (2007); MIT Energy Initiative (2009); Teske *et al.* (2008).

[15] See "Sucking Carbon Out of the Air" by Nicola Jones, NatureNews, December 17, 2008. Available at http://www.chichilnisky.com/pdfs/papers/commentary.pdf

4. Costs of emissions reduction: a literature review

What will it cost to achieve a dramatic reduction in greenhouse gas emissions? The question seems as if it should have a precise, well-defined answer, regardless of who you ask. After all, in ordinary economic life, costs should be independent of the political leanings and assumptions of the analyst who calculates them. The costs of windmills, rooftop solar photovoltaic installations, or nuclear power plants, are specific, empirical, researchable questions; with enough data, proponents and opponents of these technologies should, in principle, agree on the answers.

Cost estimation is much more complex for a global reduction in carbon emissions than for a single energy facility. Emissions reduction, on the scale that is needed, will require decades of investments in many countries and sectors; the projected total cost depends on a wide range of assumptions and judgments about the future. The devil is decidedly in the details: under the assumptions used in some studies, even a modest reduction in emissions would cripple major industrial economies; under other assumptions, there would be little or no net cost to setting off down a different, low-carbon technological path.

The cost of reduction is typically modeled as the difference in costs between two hypothetical future scenarios for the economy: a business-as-usual scenario, with no new climate protection programs, and a policy scenario, incorporating the least-cost route to achieving the required reductions. Business as usual typically would involve more rapid economic growth and higher incomes, but would also lead to greater climate damages. The policy scenario would involve greater costs, slower growth, and lower incomes, but would also reduce the magnitude and risks of climate damages. The relevant bottom-line question is *not*, Do the costs of the policy scenario sound like a big or a small number? Rather, the question that matters is, How likely is it that the damages avoided by the policy scenario are more important than the additional costs?

Much has been written about the risks of climate change, and we will not attempt to review that literature here. As noted in an earlier section, however, the analysis by James Hansen that launched the discussion of a 350 ppm target argues that enormous damages will result if atmospheric concentrations of CO_2 remained above that level in the long run. Costs for climate stabilization on the order of a few percent of world output per year might or might not be prohibitively expensive, depending on one's beliefs about the magnitude and probability of the damages avoided.

The literature on the costs of climate policies is extraordinarily diverse, with an array of incompatible scenarios, targets, and cost measurements. In this section, we review several categories of cost estimates.

Although our focus is on global costs, we begin with two sets of studies of U.S. policy costs. The United States is a significant part of the global picture, accounting for about 20 percent of current emissions, and an even larger share of the responsibility for worldwide emissions reduction under many proposals for equitable distribution of costs. Moreover, if reduction in greenhouse gas emissions is too expensive for one of the richest countries in the world, it is undoubtedly too expensive for everyone else as well. A few studies sponsored by business lobbies have argued that climate policy is unaffordable for the United States; other studies by major modeling groups have found that there would be very low costs from the moderate emissions reductions mandated by recent U.S. legislative proposals.

We then turn to the peer-reviewed academic literature on climate policy costs. While this literature focuses on global rather than U.S. costs, it tends to lag behind the policy debate; most published cost estimates focus on targets well above 350 ppm CO_2, or 450 ppm CO_2-e. Extrapolation from the range of published cost estimates, as in a recent meta-analysis, is largely driven by small variations in older studies of achieving higher targets. Newer studies that focus on targets as low as 350 ppm CO_2 are just starting to appear.

Finally, there is an additional category of analyses that reach optimistic conclusions on abatement costs. The estimates of marginal abatement costs, as seen in the studies by the McKinsey consulting firm for example, provide a bottom-up assessment of least-cost opportunities to reduce emissions, resulting in costs well below those found in much of the economics literature. Major environmental groups have produced detailed technology and cost scenarios, also reaching distinctly upbeat conclusions about the feasibility and the price of emissions reductions. Our literature review concludes with a look at these studies.

U.S. pessimists — the big engine that couldn't

Will policies mandating a sharp reduction in greenhouse gas emissions lead to intolerable economic costs for the U.S. economy? A small but well-publicized group of analysts have made this claim. The American Council for Capital Formation (ACCF), National Association of Manufacturers (NAM), and other business interests have commissioned several studies of leading legislative proposals, such as the Lieberman-Warner Climate Security Act of 2007-2008 (Lieberman and Warner 2007). These studies have frequently described the cost of the legislation in catastrophic terms, as if it would cause devastating economic ruin.

The Lieberman-Warner proposal, which was never adopted, was much less ambitious than the scenarios for reaching 350 ppm CO_2 considered in this report. It covered sectors of the economy producing about 85 percent of U.S. emissions; in those sectors, Lieberman-Warner called for 15 percent reduction below 2005 emissions by 2020, and 70 percent reduction below 2005 levels by 2050. This is equivalent to about a 65 percent reduction below 1990 levels by 2050; if the whole world proceeds at that pace, CO_2 concentrations reach 432 ppm CO_2 in 2100, 398 ppm in 2200, and do not reach 350 ppm in the next four centuries.[16]

Initially, ACCF and NAM commissioned Charles River Associates (CRA) to study the economic impacts of Lieberman-Warner. CRA uses a proprietary model, MRN-NEEM, described as a computable general equilibrium model of the U.S. economy, combined with a more detailed model of electricity markets. The CRA study (2008) found that by 2050 the average costs from Lieberman-Warner could reach more than $2,000 per household per year; the annual reduction in GDP could reach 3.5 percent; and the net change in employment could be 7 million fewer jobs than in the baseline scenario.

Since the MRN-NEEM model is proprietary, and has never been fully described in public documents, many questions about it cannot be answered. The job loss estimates are puzzling, since computable general equilibrium models normally assume full employment in all scenarios. No explanation of CRA's methodology for employment estimates has been published, and CRA economist Anne Smith did not respond to a request for information on this subject (Nelson *et al.* 2008). One possibility is that the model was first used to estimate a reduction in GDP attributable to Lieberman-Warner; that reduction could then have been multiplied by an assumed fixed ratio of employment to GDP (an assumption that is contrary to the underlying logic of computable general equilibrium models like MRN-NEEM) to produce an *ad hoc* estimate of job loss. Another possibility, more consistent with the logic of this type of model, is that a reduction in real wages leads some people to drop out of the paid labor force, thus reducing GDP (Nelson *et al.* 2008). Note that those who leave the labor force are enjoying additional leisure or engaging in non-market household production, which should count as benefits in the framework of standard economic theory that drives computable general equilibrium results.

The CRA study also introduces rigid assumptions about technology in general, and renewable energy in particular, which bias the results toward finding higher costs. Technological change occurs at a fixed rate, governed by an assumed "autonomous energy efficiency improvement" parameter, which is independent of any climate policy decisions. That is, the higher price of carbon emissions does not provide incentives for any new carbon-reducing innovations (Nelson *et al.* 2008). According to CRA, renewable energy is relatively expensive, and does not become cheaper over time, so the modeled costs of carbon reduction remain high.

In the face of these and other criticisms, the business lobbies that had backed the CRA study introduced a different study of Lieberman-Warner, although one that reached broadly similar conclusions. The new study, conducted by Science Applications International Corporation (SAIC), used a version of the National Energy Modeling System (NEMS), a detailed model of energy markets developed by the U.S. Energy Information Administration. To distinguish it from other applications of NEMS, the SAIC study refers to the "NEMS/ACCF/NAM" model. The NEMS/ACCF/NAM model extended only to 2030; it projected that by that year Lieberman-Warner could lead to the creation of 4 million fewer jobs and 2.7 percent lower GDP, and more than $6,700 in annual costs per household, relative to the baseline scenario (American Council for Capital Formation 2008).

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[16] Using the methodology described in the appendices for constructing 350 scenarios, we matched the Leiberman/Warner reductions as closely as possible. A 14 percent emission reduction in every 5-year period results in a 17 percent emission reduction from 2005 by 2020 and a 66 percent reduction by 2050. The CO_2 concentrations presented in the text use 6°C for climate sensitivity. At a more conservative 3°C climate sensitivity, this scenario reaches 406 ppm CO_2 in 2100, 372 ppm in 2200 and 350 ppm by 2310.

NEMS is an extraordinarily complex model, with thousands of input parameters and assumptions describing the current and potential future supply and demand for energy. NEMS does not have a single forecast; rather, it has been used by many researchers to produce different forecasts, based on different assumptions. While "NEMS/ACCF/NAM" anticipated large costs from Lieberman-Warner, another NEMS analysis of the same legislation projected that it would cause negligible changes in employment and income (Clean Air Task Force 2008).

NEMS/ACCF/NAM assumptions included extreme pessimism on non-fossil-fuel energy; neither renewable energy nor nuclear power was assumed to expand at a noticeable rate as a result of Lieberman-Warner. Nor was carbon capture and storage (CCS) technology assumed to be widely available for coal plants (Pooley 2009). As a result, the study modeled the response to climate policy in an economy that was assumed to have virtually no alternatives to fossil fuels and conventional technologies. In the case of electricity, an increased price for carbon emissions was projected to cause higher retail prices and lower demand, and substitution of natural gas for coal – and not much else (American Council for Capital Formation 2008). NEMS/ACCF/NAM thus demonstrates that if there were no options for innovation, diversification, or investment in efficiency and low-carbon energy, an increased price for carbon emissions would simply be passed along to consumers via higher energy prices, reducing emissions largely by reducing consumption.

Media reports on the NEMS/ACCF/NAM results typically described the study's projections not as slightly slower growth, but, inaccurately, as losses of existing jobs and incomes due to Lieberman-Warner (Pooley 2009). In fact, employment and GDP were projected to continue growing, with or without the legislation; the difference between the baseline (no new policy) scenario and the Lieberman-Warner policy scenario was a matter of slightly different rates of economic growth, not any literal declines in jobs or incomes.

Despite its limitations, NEMS/ACCF/NAM was a rhetorical success on at least two levels. It included estimates of income and job losses by state, allowing a long series of press conferences to release the study's results to the local media in many state capitals. And more broadly, it created the impression that there was a serious, ongoing debate between those who think that even modest steps toward climate protection are impossibly expensive, and those who think we can somehow afford it. For reporters who were unfamiliar with the subject, it was easy to fall into a superficially balanced, "he said, she said" style of reporting, treating this shoddy analysis as one end of the spectrum of professional opinion on the economic costs of climate policy (Pooley 2009).

U.S. abatement costs — estimates from major modeling groups

In contrast to the alarming reports and projections from the business lobbies, other modelers have found much lower costs from the climate policies under active consideration in U.S. government circles. A review by Nathaniel Keohane and Peter Goldmark, respectively a climate economist and a climate policy analyst at Environmental Defense Fund (Keohane and Goldmark 2008), summarizes eight recent policy scenarios from five modeling groups (with names of models in parentheses): the Energy Information Administration (NEMS), MIT researchers (EPPA), Research Triangle Institute (ADAGE), the Department of Energy's Pacific Northwest National Lab (SGM), and a consulting firm headed by Harvard economist Dale Jorgenson (IGEM).

These modelers considered several policy options, all entailing moderate emissions reductions: Lieberman-Warner; a slightly less ambitious variant, Lieberman-McCain; and 50 percent and 80 percent reductions below 1990 emissions.[17] The median forecast projected that emission reduction would lower the growth rate of the U.S. economy by 0.03 percentage points. By 2030, the models projected that the U.S. economy would nearly double in size; the median cost of climate policy in that year was 0.58 percent of output (or three months delay in the time required to double the current GDP). Costs to the average household were likewise under 1 percent of the household budget. Differences among models about the projected future size of the economy were much larger than any of their projections of climate policy costs.

The median forecast implied that home energy bills would rise by a few dollars a month, and gasoline prices by 35 cents per gallon, by 2030 – amounts that may be hardships for the poorest households, but not for the

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[17] According to Keohane and Goldmark (2008), the modeled scenario of 50 percent reduction from 1990 emissions was a more demanding target than Lieberman-Warner, because it applied to all U.S. emissions, and excluded the option of international purchases of allowances.

average family. According to the only one of the five models to project employment, EIA's NEMS model, employment in 2030 would be lowered by less than 0.04 percent, or 60,000 jobs, as a result of the Lieberman-McCain legislative proposal.

In short, there appears to be a consensus among a number of well-known modelers that the costs to the U.S. economy of moderate climate policies, along the lines of Lieberman-Warner, will be entirely affordable – not quite free, but small relative to other uncertainties about the future growth of the economy. Analyses that were not sponsored by business lobbies have in general found very different results from those that enjoyed direct business support (Pooley 2009).

Academic studies of global abatement costs

In many areas, including IPCC discussions of climate change, the peer-reviewed academic literature is assumed to represent the gold standard of reliable evidence. There are numerous peer-reviewed studies of the costs of reducing greenhouse gas emissions, typically focusing on global rather than national costs. The process of peer review in academic journals, however, introduces delays for formal preparation of results, review and revision, and finally, after acceptance, waiting in the queue for publication. The result is that peer-reviewed publications are a lagging indicator of the state of policy debate. In a fast-moving field such as climate policy, only the very latest publications will be directly relevant to current concerns, such as the cost of achieving 350 ppm CO_2.

One topic that is relatively new to the academic literature turns out to be of great importance for estimating the costs of achieving 350 ppm: the treatment of technical change. Older and simpler models, such as DICE, often assumed that technical change occurs at a set rate, independent of policy initiatives; the advances in low-carbon technology were assumed to occur at the same rate under business-as-usual conditions as when vigorous climate stabilization policies were applied. In the jargon of economics, technical change was assumed to be "exogenous." Newer modeling efforts have acknowledged that the pace and direction of technical change is influenced by public policy; it is referred to as "induced" or "endogenous" to the model. Advances in wind power technology, for example, have resulted from decades of public investment, in the U.S. and Europe; these advances would not have happened nearly as rapidly in the absence of policies supporting renewable energy. There is not yet a consensus about exactly how to model endogenous technical change, but many of the models discussed here attempt to include it.

In this section we describe a recent literature review of the marginal costs of abatement; although published in 2009, it contains work done only through 2006. We then turn to some of the latest work by several research groups that have explored the costs of achieving 450 ppm of CO_2-e (roughly equivalent to 350 ppm CO_2).

A recent meta-analysis of the marginal costs of abatement includes 59 estimates from 26 different models (Kuik *et al.* 2009). Although the meta-analysis was published in 2009, its database consists of articles published in 2006. In articles published that year, often reflecting work done one or more years earlier, little attention was paid to targets as low as 350 ppm CO_2, or 450 ppm CO_2-e. Almost all of the estimates in Kuik *et al.* were for much higher targets of either 550 or 650 ppm of CO_2-e (or 450 to 550 ppm CO_2), as seen in Figure 2.

As Figure 2 suggests, the range of published estimates for abatement costs on a trajectory to 550 ppm CO_2-e was, on average, slightly higher than the range of estimates for 650 ppm CO_2-e trajectories. To be precise, the averages are €72 (US$101[18]) per ton of CO_2-e for the 550 ppm scenarios, and €55 (US$77) for 650 ppm scenarios. The two ranges, however, overlap quite extensively. There appears to be little basis for inferring a cost for achieving 450 ppm CO_2-e (or 350 ppm CO_2) from these observations – although the authors of the meta-analysis, in effect, drew one particular shape of curve through these points and extrapolated well beyond most of their sample, leading them to estimate that the marginal cost of abatement in 2050, on a 350 ppm CO_2 trajectory, would be €225 (US$315) per ton of CO_2-e.[19]

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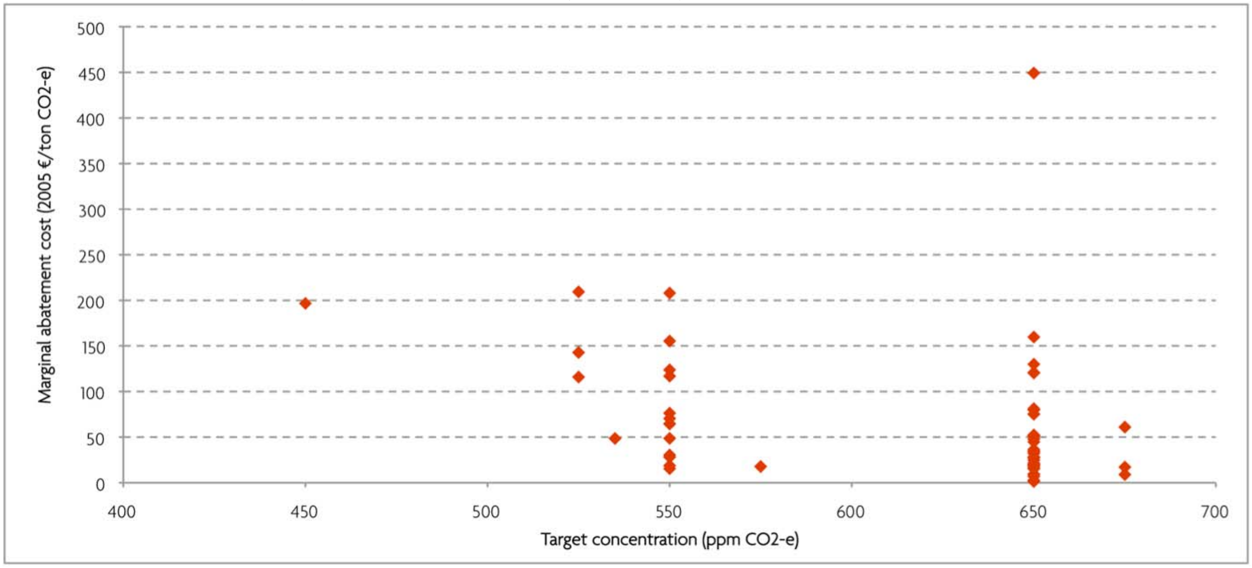
[18] Conversion between euros and U.S. dollars in this report assumes an exchange rate of €1.00 = US$1.40.

[19] This is the projection from a regression analysis in Kuik *et al.* (2009) that relates the log of marginal abatement costs to the log of the target concentration and 10 other variables (only 3 of them significant at p=.05), for the 47 observations for which complete data were available; $r^2 = 0.56$. Other specifications of the model used in the regression analysis would produce different estimates.

Other recent studies from several research groups have directly addressed the costs of a 350 ppm CO_2 or 450 ppm CO_2-e target. All agree that the prospects for reaching that target depend on the further development of technologies and measures that are at or beyond the frontier of available, affordable options today. Technology, however, does not stand still, particularly when there are such intense needs and pressures for its development. Modeling the rate of technical change that is induced by climate policy is one of the unsolved problems that creates uncertainty in long-term cost forecasts — but zero does not seem like a good estimate for the expected rate of progress in the development of low-carbon energy. Several studies have concluded that, for scenarios that overshoot and then return to 350 ppm CO_2, the costs could be less than 2 percent of world output.

Figure 2: Kuik *et al.* Meta-analysis of Marginal Abatement Costs in 2050



Source: Kuik et al.(2009)

Detlef van Vuuren, Michel den Elzen, and others at the Netherlands Environmental Assessment Agency (MNP) have modeled the costs of achieving low stabilization targets using the IMAGE modeling framework (e.g., van Vuuren *et al.* 2007). Their 450 ppm CO_2-e scenario relies initially on energy efficiency and on reduction of non-CO_2 greenhouse gases; in later years, the potential of these low-cost sources is largely exhausted, so that further reductions depend on changes in energy use. They project moderate increases in solar, wind, and nuclear power, and a huge increase in biomass energy, relying on extensive tree plantations in areas unsuited for agriculture. CCS technology is essential, accounting for one-third of the overall reductions in energy-related CO_2 emissions. By the end of this century, their 450 ppm CO_2-e scenario shows that fossil fuel use has been virtually eliminated (the small continuing uses are for electricity production with CCS); biomass energy production with CCS removes large amounts of carbon from the atmosphere.

The costs of this scenario look high when expressed in terms of the cost of carbon emission permits, under a cap and trade system: US$164 (€117) per ton of CO_2-e by mid-century, rising to US$217 (€155) per ton by 2100. The high price is required to induce carbon-free alternatives in transportation and agriculture; electricity production is assumed to be carbon free at permit prices above US$81 (€58) per ton of CO_2-e. These costs, however, apply to a rapidly diminishing quantity of carbon. Expressed as a percentage of GDP, the cost of the scenario peaks at about 2 percent of world output in mid-century; the discounted cumulative value of abatement costs over the century is 1.2 percent of the present value of world GDP.[20]

Analysis of the regional impacts of this scenario, carried out with an extension of the same modeling framework, shows that costs would be high for the Middle East and North Africa and the former Soviet Union,

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[20] Both abatement costs and GDP are measured as present value, assuming a 5 percent discount rate. Costs reported here are for the van Vuuren *et al.* (2007) analysis using the IPCC's SRES B2 scenario as the business-as-usual baseline. Costs are lower using B1, and higher using A1B; but even measured from an A1B scenario, the present value of abatement costs for this century is less than 2 percent of the present value of world GDP.

the regions most dependent on oil and gas production. OECD countries would experience medium costs, while other regions would have lower costs or even gains (den Elzen *et al.* 2008). Similar regional impacts have been found in other studies, such as (DeCanio 2009); as DeCanio suggests, it is only the nations that rely most heavily on oil and gas revenues that stand to lose under a global climate deal.

The GET model, developed by Christian Azar and Kristian Lindgren at Chalmers University in Sweden, also has been used to project the costs of a 350 ppm CO_2 stabilization target (Azar *et al.* 2006). It assumes a somewhat different energy scenario than the IMAGE analysis discussed above, with smaller roles for wind and nuclear power, but a growing role for solar-powered hydrogen fuel production in the second half of this century. CCS technology is essential in this scenario, applied both to all remaining fossil fuel use and to the substantial biomass energy sector by the end of the century. The discounted cumulative value[21] of mitigation costs over this century for the 350 ppm scenario drops from US$26 trillion without CCS, to US$6 trillion with CCS applied to both fossil and biomass energy. Costs peak at 5 percent of GDP in 2030 for 350 ppm CO_2 without CCS – or at 3 percent of GDP in 2070–2080 for 350 ppm CO_2 with CCS.

Terry Barker and his colleagues at the Cambridge Centre for Climate Change Mitigation Research (4CMR), at the University of Cambridge, have also studied the costs of achieving low stabilization targets. In a widely cited 2006 literature review and meta-analysis (Barker, Qureshi *et al.* 2006), relied on in the *Stern Review*, they reviewed the costs of mitigation in models with induced technical change. That analysis, based on earlier literature, largely focused on higher stabilization targets. In a background paper for the 2007 Human Development Report, Barker and Katie Jenkins (Barker and Jenkins 2007) extended the same analysis to project the costs of stabilizing at 450 ppm CO_2-e or lower. They concluded that:

> If the models allow for (1) all the mitigation options agreed as feasible in the literature, i.e. including biomass, bio energy and land sinks, (2) induced technological change, and (3) the co-benefits of GHG mitigation, mainly in the form of reduced damages for air pollution on human health and crop productivity, the analysis suggests that the global costs by 2030 in trajectories towards stabilization at concentrations of 450 ppm CO_2-e by 2100 are around 2 to 3% of GDP. However, these costs are without international emission permit trading. With permit trading, the global average costs fall to 1 to 2% of GDP by 2030. (Barker and Jenkins 2007, p.1)

Barker and his colleagues have added another dimension to the analysis, examining the economic stimulus that can result from new investments in mitigation, and from fiscal recycling of the revenues from carbon taxes or permit auctions (that is, using these revenues to reduce taxes on labor, capital, or exports). Their E3MG model combines this effect with endogenous technical change and other economic and environmental details; it finds that more stringent CO_2 reduction standards can lead to more rapid economic growth (Barker, Pan *et al.* 2006).

Finally, Ottmar Edenhofer and his colleagues at the Potsdam Institute for Climate Change Research (PIK) have also engaged in extensive studies of low stabilization targets. In a major EU research project, PIK researchers have compared the projections of four different models for the costs of achieving stabilization targets from 400 to 550 ppm CO_2-e (Knopf *et al.* 2008). The E3MG model projects economic gains from the investments in mitigation. The other three models, MERGE, REMIND, and POLES, from different research groups, make relatively consistent projections, showing cumulative GDP losses through 2100 of 1.7 percent or less, even for the 400 ppm CO_2-e target (approximately 300 ppm CO_2, a lower target than those considered in most of this report). In terms of technology choices, the models differ in detail, but the broad conclusions are similar to those of the other researchers discussed above: the potential for biomass energy and CCS technology is crucial, as this combination allows removal of carbon from the atmosphere. Nuclear power, in contrast, is only a secondary factor; the baseline scenarios already include significant amounts of nuclear power, and unless fast breeder reactors are assumed to be available, uranium supplies are a constraint on further nuclear development.

The model results discussed here express costs as percentages of GDP, a measure that is natural to economists but may seem opaque to other readers. Most of the scenarios discussed here estimate that the costs of mitigation will be between 1 and 3 percent of global GDP. This should be interpreted as an annual, recurring cost that will have to be paid for many years. It is not, however, an impossible economic burden.

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[21] Costs are measured as net present value, assuming a 5 percent discount rate.

Suppose that the cost of climate protection turns out to be 2.5 percent of global GDP, higher than some of the scenarios just discussed. In an economy that is growing at 2.5 percent per year, a rate that is common for developed countries,[22] spending 2.5 percent of GDP on climate protection each year would be equivalent to skipping one year's growth, and then resuming. Average incomes would take 29 years to double from today's level, compared to 28 years in the absence of climate protection costs. In an economy experiencing 10 percent annual growth, as China has in many recent years, imposing a cost of 2.5 percent per year is equivalent to skipping 3 months of growth; if 10 percent growth is sustained, average incomes would reach double the current level in 86 months, compared to 83 months in the absence of climate protection costs.

Consider another standard of comparison: there are 68 countries in the world where military spending is greater than 2.5 percent of GDP.[23] In both the United States and China, military expenditures exceed 4 percent of GDP. Military spending in France and India, among others, is at or just above 2.5 percent of GDP. It is difficult, therefore, to believe that we are unable to remove this amount from current consumption in order to defend against a remote but dangerous threat to our way of life; we already do so, year after year.

Technological optimists

Assumptions about technical change are crucial to the economics of a 350 ppm CO_2 stabilization target, as illustrated by the academic studies discussed above. Clearly, there will be technical progress in energy efficiency and low-carbon/no-carbon energy production in the future. The rate of progress is uncertain, but is undoubtedly endogenous: if we try harder and devote more resources to the effort, we will progress faster.

A final group of studies embody a decidedly optimistic view of the technical potential for reducing emissions. With rapid enough technical change, and high enough prices for fossil fuels, the entire process of abatement of CO_2 emissions – or at least its first stages – could save money overall. This is a different, stronger statement than the projections of net economic gains from the E3MG model discussed above (Barker, Pan *et al.* 2006; Knopf *et al.* 2008). That model's forecasts depend on the indirect economic stimulus of new carbon-reducing investments and the benefits of reducing other taxes using carbon tax or permit revenues. In contrast, the technological optimists argue that the fuel savings from new investments alone will outweigh the investment costs.

We examine three studies projecting economic gains from rapid abatement: McKinsey & Company's "Pathways to a Low-Carbon Economy"; the "Energy [R]evolution" strategy from Greenpeace, and the "National Blueprint for a Clean Energy Economy" from the Union of Concerned Scientists.

McKinsey & Company, an international consulting firm, has performed several detailed, bottom-up studies of the costs of greenhouse gas abatement. These have attracted widespread attention, serving to reframe much of the discussion of short-term costs of emission reduction. Their latest study (McKinsey 2009) examines the potential and the costs of more than 200 abatement opportunities for the time period from now through 2030. They find that there is the technical potential to reduce global emissions 35 percent below 1990 levels, or 70 percent below business as usual, by 2030 – if all measures with costs below €60 (US$84) per ton CO_2-e are adopted. The total investment would be €200-350 billion (US$280-490 billion) annually by 2030, or less than 1 percent of global GDP in that year. Financial requirements could rise to 5-6 percent above business-as-usual investment needs, an amount that financial markets could handle, according to the McKinsey analysts. The McKinsey study identifies the potential for saving 38 Gt CO_2-e annually by 2030, reducing emissions from 70 Gt under business-as-usual to only 32 Gt. This would put the world on a trajectory that, if continued, would overshoot to perhaps 510 ppm CO_2-e, then stabilize at 450 ppm CO_2-e (350 ppm CO_2) by 2200 (McKinsey 2009). The first 12 Gt of reduction would have negative costs; the necessary investments would more than pay for themselves in energy savings. Costs rise only gradually beyond that point, keeping the total costs low.

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[22] The United States economy has exceeded this rate of growth in real GDP on average for the last 20 years (1989-2008), and in 14 of those 20 years on an annual basis. Calculated from U.S. Bureau of Economic Analysis, "National Economic Accounts," http://bea.gov/national/nipaweb/Index.asp.

[23] U.S. Central Intelligence Agency, "The World Factbook / Country Comparisons: Military Expenditures," https://www.cia.gov/library/publications/the-world-factbook/rankorder/2034rank.html , accessed August 27, 2009. Data are latest available for each country, most for 2005 or 2006.

In addition to identifying the substantial opportunities for negative-cost emission reduction (many of them in the area of energy efficiency), McKinsey also points out that the cost estimates are sensitive to the price of oil. As the price of oil rises, the costs of investment in emission reduction are largely unchanged, but the value of the saved energy increases – implying a lower net cost. The basic McKinsey forecast assumes an oil price of US$60 per barrel; every US$10 per barrel increase, if accompanied by proportional increases in other energy prices, cuts average abatement costs by €3 (US$4) per ton of CO_2-e (McKinsey 2009, p.53). Although the report does not spell it out in these terms, this formula implies that at an oil price of US$90 per barrel, the entire 38 Gt CO_2-e of emission reduction would have zero net cost.[24]

McKinsey's projected savings of 38 Gt CO_2-e of annual emissions by 2030 consist of three roughly equal categories:

- energy efficiency opportunities, such as more fuel-efficient cars, better insulated buildings, and more advanced manufacturing controls;
- low-carbon energy supply, shifting from fossil fuels to wind, nuclear, or hydro power, as well as equipping fossil fuel plants with CCS; and
- forestry and agriculture changes, halting deforestation, switching to rapid reforestation, and changing agricultural practices to increase carbon sequestration in soils.

Another ambitious, technologically optimistic study is Greenpeace's "Energy [R]evolution," (Teske *et al.* 2008) based on research by Germany's national aeronautics and space laboratory (DLR). Greenpeace provides a detailed global energy scenario to 2050, with more summary results to 2100. Emissions are reduced 50 percent below 1990 levels by 2050, and continue to plummet in the second half of the century. Global emission reductions at the pace of Greenpeace's short-term reductions, if continued, would achieve 436 ppm CO_2 in 2100, 412 ppm in 2200, but do not reach 350 ppm in the next 400 years.[25]

The Greenpeace scenario assumes extensive improvements in energy efficiency in the early years[26], along with a rapid switch to renewable sources of electricity. Explicit assumptions about the rate of technical progress imply that there will be rapid growth of solar, wind, and geothermal energy. Biomass energy and CCS are present but play a smaller role than in some other studies. Unlike other studies reviewed here, Greenpeace assumes that nuclear power is fully phased out by 2050. After 2050, decarbonization of the economy continues, with electric vehicles replacing oil-powered ones. By 2090, renewable sources supply 98 percent of all primary energy demand.

Oil prices are assumed to rise from US$100 per barrel in 2010 to US$140 per barrel in 2050; natural gas prices quadruple and coal prices double in the same period. As with the McKinsey study, this makes fuel savings look valuable. The annual average investment cost from 2005 to 2030 (i.e., increase over business-as-usual) is US$138 billion (€98 billion); the resulting fossil fuel savings is US$750 billion (€530 billion) (Teske *et al.* 2008, p.108).

A final study, from the Union of Concerned Scientists, looks only at U.S. emissions (Cleetus *et al.* 2009). Although opening with a call for the United States to reduce its emissions 80 percent below 2005 levels by 2050, the report focuses on the targets and opportunities for reduction through 2030. By that year, it projects a reduction of 56 percent below 2005 levels – a pace which, if projected globally, would reach 397 ppm CO_2 in 2100, 374 ppm in 2200, and 350 ppm in 2340[27] – but still an ambitious target relative to many U.S. policy

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[24] This assumes the upper limit cited in the text, €350 billion (US$490 billion), as the annual cost in 2030 for 38 Gt CO_2-e of reduction, at the default assumption of US$60 per barrel oil. According to the McKinsey report (2009, p.53), an increase to US$120 per barrel oil would reduce the total cost of abatement by €700 billion (US$980 billion) annually by 2030. Thus zero net cost should occur at US$90 per barrel.

[25] Using the methodology described in the appendices for constructing 350 scenarios we matched the Greenpeace reductions as closely as possible. A 12 percent emission reduction in every 5 year period results in a 51 percent emission reduction from 1990 by 2050. The CO_2 concentration presented here use 6°C for climate sensitivity. At a more conservative 3°C climate sensitivity, this scenario reaches 418ppm CO_2 in 2100, 383ppm in 2200 and 350ppm by 2370. While Greenpeace is ambitious about technical change, it may project slower reduction in carbon emissions because, unlike other scenarios considered here, it is simultaneously trying to phase out nuclear power.

[26] Opportunities to increase energy efficiency are assumed to be exhausted by 2060.

[27] Using the methodology described in the appendices for constructing our E3 350 scenarios we matched the UCS reductions as closely as possible. A 20 percent emission reduction in every 5 year period results in a 28 percent emission reduction from 2005 by 2020 and a 54 percent reduction by 2030. The CO_2 concentration presented here use our central case for climate sensitivity, 6°C. At a more conservative 3°C climate sensitivity, this scenario reaches 383 ppm CO_2 in 2100, 353 ppm in 2200 and 350 ppm by 2215.

proposals. It projects continuing economic growth, virtually no change in employment as a result of climate policies, and significant savings to households: US$900 per household per year by 2030, about two-thirds of that amount in lowered transportation expenses, and the rest in lower electricity and heating bills. The national totals, in 2030, are US$160 billion of additional investments, more than offset by US$414 billion of energy bill savings.

As in the Greenpeace study, this finding reflects the combination of technical optimism and relatively high oil prices. The reduction in U.S. demand for petroleum is projected to reduce world prices in 2020-2030 from US$100 per barrel in the reference case, to US$80–88 per barrel with the emission reduction policies (Cleetus *et al.* 2009, p.142). The analysis of emissions, done with the NEMS model, projects that power plant emissions fall 84 percent below 2005 levels by 2030, largely from reducing the use of coal, increasing energy efficiency, and increasing the use of wind, solar, geothermal, and biomass energy. Emissions from cars and light trucks drop 40 percent below 2005 levels by 2030, thanks to greater vehicle efficiency and wider use of ethanol. Smaller changes occur throughout many sectors of the economy; 4 percent of the emission reduction occurs through international purchase of carbon offsets, and 7 percent through domestic offsets in forestry and agriculture.

The three studies discussed in this section are not identical in their degree of optimism: with oil at US$90 per barrel, McKinsey projects no net costs or benefits for a massive agenda of abatement investments, while both the Greenpeace and UCS analyses imply that large net economic benefits are available at that price. All three, however, project that, at a point well below the high oil prices seen in 2008, rapid reduction in carbon emissions will be a bargain.

Attributing immense savings to high projected oil prices is, in a sense, logically inconsistent: rapid progress in reducing emissions will imply reduction in the demand for oil, which will make the price fall. Ironically, the more successful we are in reducing emissions, the lower the avoided fuel costs — one of the principal economic benefits of energy conservation — will become.

The savings identified by Greenpeace and UCS, however, are not exclusively due to their relatively high oil price projections. Both reports project energy savings that will be worth more than twice the cost of the required investments. This means that if energy prices fell to half the assumed level, cutting the savings in half but leaving the cost of investments unchanged, there would still be net economic gains in both studies. At half of the assumed energy prices in the Greenpeace and UCS studies, oil would be roughly at (Greenpeace) or even below (UCS) the actual price in mid-2009 — and far below the level at which McKinsey projects net economic benefits from emission reduction.

Other studies and models have not identified the same opportunities for economic gain (with the exception of E3MG, with its different logic); nonetheless, there is a wealth of detailed research embodied in these optimistic studies. McKinsey's marginal abatement cost curves rest on an extraordinarily detailed, intensive evaluation of individual technologies in different economic sectors and countries around the world, and are taken as the new standard by many other researchers. Greenpeace and UCS have both presented detailed narratives of assumptions about future costs of specific technologies; these are clearly at the optimistic end of the spectrum of opinion, but should be examined by those who are interested in pushing the technological frontier in a climate-friendly direction.

5. Casting DICE for 350

In some of the detailed studies described in the last section, and in other analyses, economists have often relied on “integrated assessment models” (IAMs) of the costs and benefits of climate change. The Dynamic Integrated model of Climate and the Economy (DICE-2007) (Nordhaus 2008) is one of the best known IAMs in the current literature.[28] DICE, like a number of other IAMs, is known for projecting that the optimal climate policy is one of very gradual abatement; in the words of William Nordhaus, the creator of DICE, the model calls for a “climate policy ramp” that begins with small, slow steps (Nordhaus 2008). In this section we investigate whether, with slightly different assumptions, DICE might recommend a trajectory that begins abatement much more rapidly, and leads to stabilization at 350 ppm CO_2.

For our analysis, we use an adjusted version of DICE, in which we have:

- updated the population projections to match the latest United Nations forecasts;
- changed DICE’s treatment of non-CO_2 greenhouse gases to be consistent with more detailed emissions modeling, and to allow abatement efforts to reduce future emissions of these gases; and
- substituted the low rate of time preference used in the *Stern Review*, to place a greater value on future outcomes.

These changes are described more fully in Box 2.

In addition to these adjustments, we experimented with several possible values for two key parameters in DICE. One is the climate sensitivity parameter; its importance was explained in the preceding sections. A larger value for climate sensitivity means that the same amount of emissions give rise to a greater temperature increase. The DICE default value for climate sensitivity is 3°C.

The second parameter we varied is one that determines the effect of temperature increases on the economy. DICE assumes that climate-related damages to the economy depend on the square of temperature increases. Our review of the literature has uncovered no rationale, whether empirical or theoretical, for adopting a quadratic form for the damage function — although the practice is endemic in IAMs.[29] We changed the exponent on temperature increases to explore the alternate assumptions of damages based on the cube, fourth, or fifth power of temperature. The larger the value of this damage function exponent, the more rapidly a given temperature increases causes significant economic harm.

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[28] For a review of the current climate economics modeling literature see Stanton *et al.* (2009).

[29] Risbey *et al.* (1996) refer to this practice as the “wholesale uncritical adoption of archetypal models.”

Box 2: Changes to DICE for our analysis

Our DICE-Adjusted model contains the following modifications to DICE-2007:

- The exogenous DICE-2007 population function has been replaced by a time series that corresponds to the medium variant in UNDESA's most up-to-date population projections.[30] This change, made for sake of greater accuracy, increases the population slightly in all periods.
- The DICE-2007 rate of pure time preference, or utility discount rate, of 1.5 percent has been replaced by a lower rate of 0.1 percent. This rate is consistent with the returns paid by a balanced portfolio of safe and risky financial instruments[31]. The DICE discount rate results in the treatment of damage and abatement costs in future years as less important to human welfare than current costs. The lower rate of 0.1 percent treats costs as having roughly the same impact on welfare regardless of the time period in which they occur.[32] The 0.1 percent rate is the same rate that was proposed in the *Stern Review* (2006). This is not the only way to represent intergenerational equity; indeed, it could be argued that it is not the best way to do so (Howarth 1998). It is, however, the method that involves the least change to the current structure of DICE.
- The DICE-2007 exogenous non-CO_2 radiative forcings function has been replaced by a time series that corresponds to MAGICC's WRE non-CO_2 radiative forcings.[33] (For explanation of the MAGICC emissions model and WRE scenarios, see Technical Appendix A.) DICE's non-CO_2 forcings in the absence of policy rise to 0.3 W/m^2 by 2100 whereas MAGICC's WRE non-CO_2 forcings rise to 0.6 W/m^2 in a similar time period. The MAGICC WRE assumptions are more consistent with no-policy, business-as-usual runs like IPCC's A1 and A2.
- The radiative forcing function has been modified such that non-CO_2 forcings are reduced by abatement policy in the same proportion as CO_2 emissions. If, for example, 80 percent of CO_2 emissions are abated in a given period, then our modified model assumes that 80 percent of non-CO_2 emissions are also abated. In the original DICE-2007 model, abatement only affects CO_2 emissions, and never reduces other greenhouse gases.

In addition, we experiment with varying values for climate sensitivity and for the damage function exponent, as explained in the text.

While DICE is normally run for a single set of "best guesses" at key parameters, it can also be run in Monte Carlo mode, to determine the effects on the model of uncertainty in key parameters. For an extensive Monte Carlo analysis of DICE, focusing on variation in climate sensitivity and the damage function exponent, see Ackerman *et al.* (2008). For the purposes of this report, we ran the DICE-Adjusted version of the model for a limited set of parameters – the 16 possible combinations of climate sensitivity 1.5, 3, 6, and 10°C, and damage exponents 2, 3, 4, and 5.[34] This includes both DICE's assumed parameters – climate sensitivity 3°C and damage exponent 2 – and results for a range of damage exponents at the default climate sensitivity used throughout this report, 6°C.

DICE-2007 vs. DICE-Adjusted: How different are the results?

Results for the 16 runs of the DICE-Adjusted model are presented in Table 7. The DICE-2007 original model is best compared to the DICE-Adjusted results for climate sensitivity 3°C and damage exponent 2, marked in red in this table. For these parameters, DICE-Original achieves 100 percent emissions abatement in 2205, forty years after DICE-Adjusted, and reaches a peak temperature change a full degree Celsius (nearly 2°F) higher than that of our modified model. Atmospheric concentrations of CO_2 are 56 ppm higher in DICE-original and 350 ppm CO_2 is reached 60 years later, in the year 2595.

In short, DICE-Adjusted takes climate change more seriously (by assuming a lower rate of time preference) and it possesses more tools to keep temperatures in check (the option of abating non-CO_2 emissions). Slightly higher population trends in DICE-Adjusted also play a role: a larger population means a larger economy, generating

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[30] Data for 2005 through 2050 taken from UNDESA (2008) *World Population Prospects: The 2008 Revision Population Database*, medium variant, http://esa.un.org/unpp/. Data for 2100 taken from UNDESA (2004) *World Population to 2300*, http://www0.un.org/esa/population/publications/longrange2/WorldPop2300final.pdf. Population for 2055 to 2095 are a linear trend from cited data points. Population is assumed to be constant after 2100.

[31] If DICE is calibrated so that a 1.5% pure rate of time preference leads to a 6% return on capital investment, then cutting the pure rate of time preference to 0.1% would cut the return on investment to 4.6%. This figure is well within the range of observed market rates, lower than the 7% return on stocks but higher than the 1% return on safe forms of investment.

[32] See the *Stern Review* (2006), Ackerman *et al.* (2009), and Stanton *et al.* (2009).

[33] Specifically, these are the MAGICC WRE350 total non-CO_2 radiative forcings from 1765 with climate feedbacks turned off (to match the logic of the DICE climate module) at climate sensitivity 3°C.

[34] See Stanton *et al.* (2009) for a discussion of damage exponents in the climate economics literature. See Ackerman *et al.* (2008) for an analysis of the likelihood of higher damage exponents.

more emissions and hence more risk of climate damages. Year 2100 damages are 2 percent of GDP in DICE-Original and 1.6 percent in the analogous run of DICE-Adjusted, again reflecting the latter model's greater concern with and greater ability to address climate change, and its stronger actions to keep temperatures and damages lower. For these same reasons, DICE-Adjusted is willing to spend more on abatement: 0.3 percent more of GDP in 2055 than DICE-Original.

Yet in the broader picture, both the original and adjusted versions of DICE-2007, run with climate sensitivity 3 and damage exponent 2, agree that there is not much to worry about. The two models differ on whether to take 160 or 200 years to get around to achieving a carbon-free economy; they differ on which decade in the 26th century will see atmospheric concentrations of CO_2 dip below 350 ppm for the first time. Neither version appears to be engaged in the same discourse as the climate scientists quoted above.

DICE-Adjusted with different inputs

The story told by DICE changes markedly with variation in the key inputs, as shown in Table 7. The runs with Hansen's assumption of 6°C climate sensitivity are shown in blue in the table. With that climate sensitivity and with a damage exponent of 4 or 5, DICE-Adjusted recommends something close to the Hansen scenario: all carbon emissions are eliminated before the middle of this century; peak temperature increases are one degree or less; atmospheric concentrations of CO_2 are 360 ppm or less at the beginning of the next century (although more time is required for concentrations to sink back all the way to 350 ppm, because DICE does not include net negative emissions options).

Table 7: DICE-Adjusted Results

First year of 100% Emissions Control

		Damage exponent			
		2	3	4	5
Climate sensitivity (°C)	1.5	2235	2195	2185	2195
	3	2165	2115	2095	2085
	6	2115	2065	2045	2025
	10	2085	2045	2015	2015

Peak temperature change in °C from 1990

		Damage exponent			
		2	3	4	5
Climate sensitivity (°C)	1.5	1.4	0.9	0.7	0.6
	3	1.8	1.1	0.8	0.7
	6	2.2	1.3	1.0	0.9
	10	2.4	1.5	1.3	1.3

Year 2105 CO_2 Concentration (ppm)

		Damage exponent			
		2	3	4	5
Climate sensitivity (°C)	1.5	623	568	531	508
	3	542	450	406	387
	6	455	377	360	354
	10	408	361	352	352

First Year Under 350ppm CO_2 Concentration

		Damage exponent			
		2	3	4	5
Climate sensitivity (°C)	1.5	2595	2595	2545	2495
	3	2535	2345	2265	2225
	6	2345	2195	2145	2115
	10	2275	2145	2105	2105

Year 2105 Damages as a Share of GDP

		Damage exponent			
		2	3	4	5
Climate sensitivity (°C)	1.5	0.8%	0.9%	0.9%	0.8%
	3	1.6%	1.6%	1.2%	0.9%
	6	2.2%	2.0%	2.0%	2.3%
	10	2.5%	2.7%	3.7%	6.9%

Year 2055 Abatement Costs as a Share of GDP

		Damage exponent			
		2	3	4	5
Climate sensitivity (°C)	1.5	0.1%	0.2%	0.4%	0.6%
	3	0.4%	1.1%	1.9%	2.5%
	6	1.0%	3.2%	3.6%	3.6%
	10	1.7%	3.6%	3.6%	3.6%

Notes: Results for the DICE original parameters — climate sensitivity 3°C and damage exponent 2 — are in red. Results for climate sensitivity 6°C are in blue. Temperature changes, reported in DICE as "change from 1900", are adjusted to "change from 1990" by subtracting 0.67°C (DICE's assumed temperature change from 1900 to 2000 less historical climate change from 1990 to 2000. Historical data taken from World Resources Institute (2007) EarthTrends database, "Global Climate Trends 2005", http://earthtrends.wri.org/pdf_library/data_tables/cli5_2005.pdf).

Source: Authors' calculation using a modified version of DICE-2007 (Nordhaus 2008).

DICE, in all variants, calculates what it considers to be the optimum scenario from the point of view of achieving the greatest possible human welfare – using a debatable version of human welfare based solely on per capita consumption. What our experiments show is that if emissions have a big enough effect on temperatures (climate sensitivity of 6°C or higher), and if temperatures have a big enough effect on the economy (damages depend on the fourth or fifth power, not the square, of temperature), then DICE calculates that human welfare is maximized by keeping peak temperature increases very low, and achieving a completely emission-free world economy within a few decades. We do not present our modified version of DICE as a perfect analysis of the economics of climate change; it is merely a demonstration that the cautious policy recommendations usually associated with IAMs such as DICE result from their "no worries" input assumptions, not from any theoretical or empirical insights about economics, climate, or their interactions.[35]

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[35] See (Ackerman *et al.* 2008) for a more detailed discussion of similar modifications to DICE-2007.

How much more costly is the response to climate change, in the scenarios where DICE is worried about the future? Comparing the extreme values in the 16 runs of DICE- Adjusted reported here, there is only a modest difference in growth rates. For the year 2055:

- In our worst case, with climate sensitivity 10°C and a damage exponent of 5, abatement costs are 3.6 percent of GDP and climate damages are another 3.8 percent of GDP; global mean per capita consumption is $12,500.
- In our best case, with climate sensitivity 1.5°C and a damage exponent of 2, abatement costs are 0.1 percent of GDP and climate damages are another 0.4 percent of GDP; global mean per capita consumption of $13,700.

In both cases, per capita consumption has grown sharply from its initial value of less than $7,000 in 2005.

In short, there are plausible combinations of values for key, uncertain parameters which would lead DICE to echo the call for reaching 350 ppm CO_2 in about a century – while still projecting rising incomes, with only slightly slower economic growth.

6. Conclusions and policy recommendations

The most important conclusion involves what we did not find. There are no reasonable studies that say that a 350 ppm stabilization target will destroy the economy; there are no studies that claim that it is desirable to wait before taking action on climate protection. On the contrary, there is strong, widespread endorsement for policies to promote energy conservation, development of new energy technologies, and price incentives and other economic measures that will redirect the world economy onto a low-carbon path to sustainability.

Disagreements emerge at the level of more specific estimates and recommendations. There is a wide range of estimates of the costs of greenhouse gas abatement scenarios. At one extreme, some business lobbies have argued that even the moderate reductions called for in recent U.S. legislation would be crippling to the economy. At the other extreme, some environmental advocacy groups have argued that an extensive agenda of reductions (although still more moderate than is required for stabilization at 350 ppm CO_2 in the next three centuries) could save money overall by reducing fuel costs. Between these two extremes, there is a body of research finding that U.S. legislative proposals would have very little economic impact, and that the much more ambitious reductions in emissions required to reach 350 ppm CO_2 might have net costs of 1 to 3 percent of world output.

Is 1 to 3 percent of world GDP a large or a small number? The answer depends on how seriously we take the risks of climate change. Recall that the starting point for the discussion of the 350 ppm CO_2 target is the projection of potentially catastrophic climate change if the atmosphere remains above that level. With strong assumptions about damages, even the DICE model will give up its leisurely, multi-century stroll toward abatement in favor of rapid emission reductions.

It may help to think of climate risk in terms of insurance. The argument for buying fire insurance is not that one is certain that his or her house will burn down; it is, rather, that they are not, and cannot be, sufficiently certain that it will *not* burn down. The authors of this report are not certain that the parameters that lead DICE to call for rapid emission reductions are the right ones; but there is, at present, no way to be certain that those parameters are the wrong ones.

Likewise, the projections of dangerous climate risk by Hansen and others if the world exceeds 350 ppm CO_2 in the long run, are not certainties; they are, on the contrary, necessarily uncertain. If the worst happens, our grandchildren will inherit a degraded Earth that does not support anything like the life that we have enjoyed. How much should we pay for insurance against a credible risk of that magnitude? On the other hand, if we prepare for the worst but it does not quite happen, we will have invested more than, in perfect hindsight, was absolutely necessary in clean energy, conservation, and carbon-free technologies. How would we feel about discovering we had done too much about climate change, compared to discovering we had done too little?

The analogy to insurance is important but inexact. There is no company selling planetary climate insurance, no one to whom we can hand 1 to 3 percent of GDP (if that is what it costs) and be confident that the problem is solved. There is, rather, a challenging, long-term problem of technology and public policy to be solved.

The constraints on allowable CO_2 emissions, for stabilization at a level as low as 350 ppm, are painfully tight, as shown by the scenarios discussed in Section 2. A realistic policy scenario, therefore, is almost certain to call for not only maximum progress in pursuing energy efficiency and promoting renewable energy, but also for measures that remove carbon from the atmosphere. Large-scale reforestation (and, of course, ending deforestation) is one approach; developing biomass energy, with capture and storage of the carbon emissions, is another. The technologies that will be needed, over the coming century of intensive effort, do not yet exist in commercially viable forms, if at all. Yet the development of new technology is itself heavily influenced by public policy. It is not surprising that the detailed studies of a 350 ppm CO_2 stabilization trajectory involve projections of technology choices, and speculation about the technologies that will be available in the second half of this century. Several major research groups project that the necessary choices will be available, at a cost the world can clearly afford to pay.

The difference between optimists and pessimists is in large part about images of future technology. An assumption of no technical change is not consistent with historical experience; none of the studies that we have discussed make this assumption – with the possible exception of the business lobbies opposed to U.S. climate legislation. At the other extreme, are there limits to what we can achieve in promoting efficiency, solar power, carbon capture and storage, and other key technologies? Is solar-powered hydrogen fuel one of the answers for the later years of this century? And how much will it cost to bring these hopes to reality? Everything depends on the answers to these questions, although they are questions about an unknowable future; at the time of World War I, who could have anticipated mobile phones, laptop computers, and the internet? The studies cited here contain a wealth of detail on projections of future technologies; it is interesting to note, for example, that none of the studies relies much on expansion of nuclear power, but none of them except Greenpeace proposes phasing out the existing uses of nuclear power, either.

Another key feature of the optimistic projections is the assumption of high prices for fossil fuels, which make all abatement investments look better. The price of a fuel-efficient car is about the same regardless of the price of oil, but it saves roughly twice as much money at the gas pump when oil costs $100 per barrel rather than $50. It is a mistake, however, to wait for high market prices for fossil fuels to solve the problem, rather than introducing a carbon price through a tax or a trading system. Even if the effect on, say, the purchase of fuel-efficient cars looks about the same, it is much better for the high fuel price to be imposed by the government than by market forces. When oil prices soar, as in 2008, the extra revenues go to oil producers, not to the public. When oil prices remain high, incentives are created for environmentally destructive production of energy, from oil shale, oil sands, and increasingly deep, dangerous offshore drilling. In contrast, a high price imposed by policy creates incentives for consumers to conserve, but not for producers to engage in costly, destructive production from easily damaged locations. An oil tax transfers revenues to the government, which can use them for environmental investment, other public purposes, or refunds to citizens.

The world is taking important initial steps toward addressing the climate crisis, with increasingly widespread discussion of the need to avoid 2°C of warming. What is less widely recognized is that, according to recent scientific research, avoiding that temperature limit likely requires stabilization at about 350 ppm of CO_2. Such a low target requires a large-scale, continuing effort throughout this century, and the development of major new technologies, as well as appropriate price mechanisms. Predicting the future is challenging, because it has not yet happened; predicting a century of technological and economic change is inescapably fraught with uncertainty. Nonetheless, the best available estimates imply that we can, indeed, afford the economics of 350. What we cannot afford is too little climate policy, too late.

Technical Appendix A: MAGICC 5.3 and the WRE Scenarios

To model the technical relationships between emissions, atmospheric concentrations, and temperature levels, we use the *Model for the Assessment of Greenhouse-Gas Induced Climate Change* (MAGICC 5.3) developed at the U.S. National Center for Atmospheric Research (Wigley 2008). Among its suite of 49 pre-set scenarios, MAGICC includes the five well-known "WRE"[36] scenarios for CO_2 stabilization trajectories of 350, 450, 550, 650 and 750 ppm (Wigley *et al.* 1996). MAGICC's representation of the WRE350 scenarios sets emissions such that atmospheric concentrations approach and stabilize at the given target concentration assuming a climate sensitivity of 3°C (see Figure A1). Because of climate feedbacks from temperature to atmospheric concentration, MAGICC's CO_2 concentration levels vary based on the assumed climate sensitivity.[37]

Figure A1 shows two sets of results for WRE350: one using MAGICC's pre-set scenario, and a second version adjusted for historical accuracy.[38] Concentrations for the "WRE350 corrected" emissions are similar to those of WRE350 but slightly higher throughout the four centuries modeled by MAGICC. Temperature trends in the resulting WRE350-corrected scenarios are as follows:

- For climate sensitivity 1.5°C: global annual average temperature peaks at 0.6°C (1.1°F) above 1990 and stabilizes at about 0.2°C (0.4°F)
- For climate sensitivity 3°C: temperature peaks at 1.1°C (2.0°F) and stabilizes at about 0.5°C (0.9°F)
- For climate sensitivity 6°C: temperature change peaks at 1.9°C (3.4°F) and stabilizes at about 1.5°C (2.7°F)
- For climate sensitivity 10°C: temperature change begins to level off at 2.6°C (4.7°F) around 2100, but continues to grow more slowly reaching 2.9°C (5.2°F) by 2400

The WRE350-corrected scenario keeps temperature change from 1990 below 2°C (3.6°F) for climate sensitivities equal to or less than 6°C. Note, however, that the actual CO_2 stabilization trajectory for MAGICC's WRE350 is 370 ppm at climate sensitivity 6°C and 400 ppm at 10°C.

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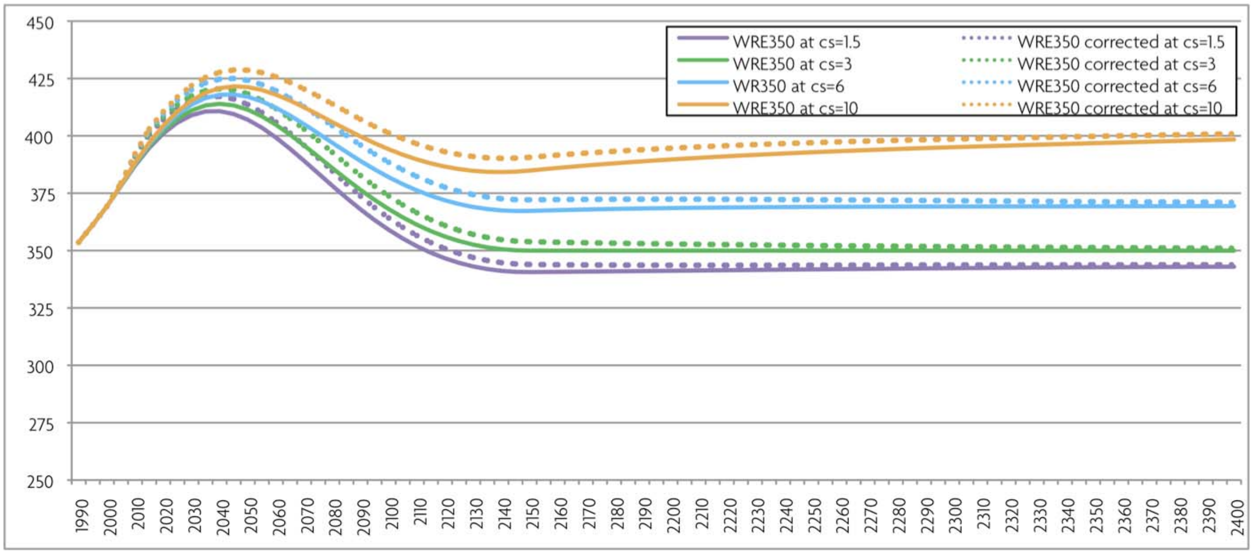
[36] "WRE" refers to the last names of the research group that introduced these emissions profiles into the literature: Wigley, Richels and Edmonds (1996).

[37] With a higher climate sensitivity, the same greenhouse gas emissions and concentrations translate into higher temperatures. These higher temperatures have a variety of positive feedback effects that increase concentrations in the next period (Wigley 2008).

[38] MAGICC's WRE scenarios are not historically accurate from years 1990 to 2005. Our "WRE350 corrected" scenario uses historical emissions for this period for both fossil fuel and land use CO_2. Data are from the Carbon Dioxide Information Analysis Center (2009) *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2006*, http://cdiac.ornl.gov/ftp/ndp030/global.1751_2006.ems, and (2008) *Carbon flux to the Atmosphere from Land-Use Changes 1850-2005*, http://cdiac.ornl.gov/trends/landuse/houghton/houghton.html. CO_2 emissions from fossil fuels for 2010 are assumed to be 34Gt CO_2, following the trend of recent years. CO_2 emissions from land use are assumed to follow a linear trend beginning with 2005 historical emissions and ending at 0 Gt CO_2 in 2090; this trend replicates that of MAGICC's WRE350 projected CO_2 emissions from land use for that period.

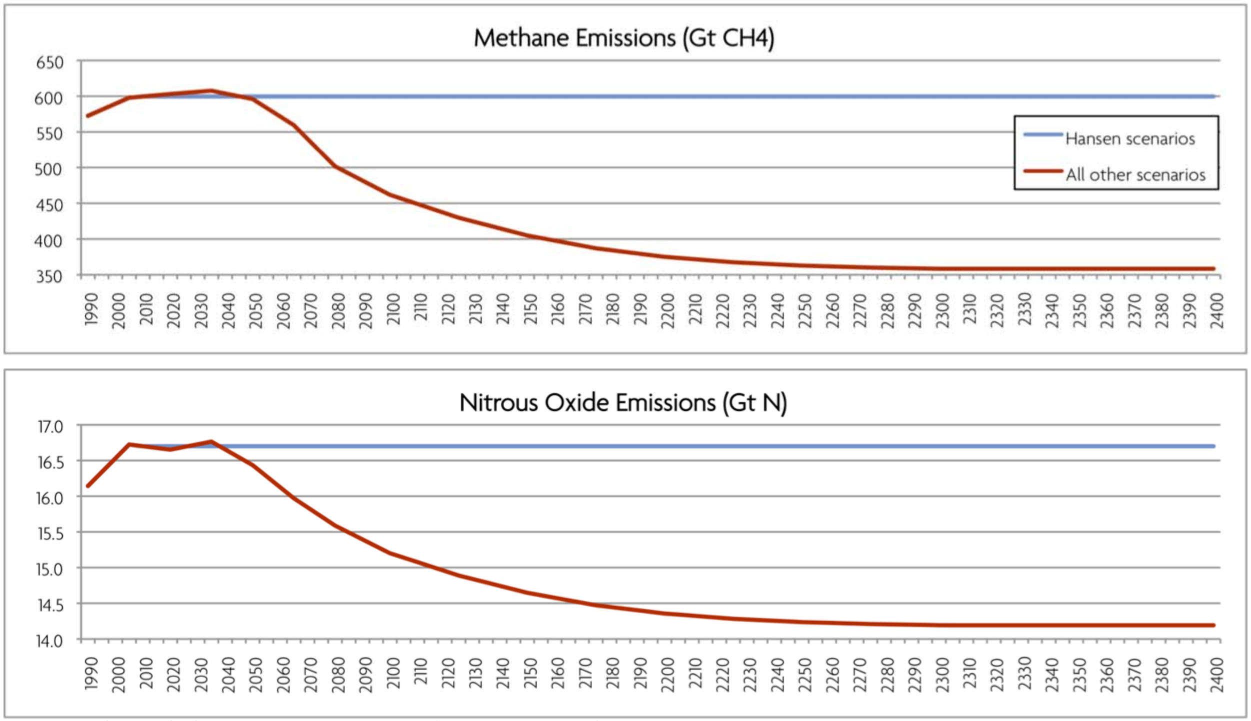
Figure A1: WRE350 CO_2 Concentration (ppm) using MAGICC, at Varying Climate Sensitivities



Note: Cs = climate sensitivity.
Source: Authors' calculations using MAGICC 5.3 software.

In modeling non-CO_2 emissions, all of the scenarios addressed so far in this report take as their starting point MAGICC's WRE scenario non-CO_2 emissions. For Hansen's scenarios, we repeat the MAGICC WRE 2010 non-CO_2 emissions for all years after 2010. For the WRE350, WRE350-corrected and the E3 350 suite of scenarios we use MAGICC's pre-set WRE non-CO_2 emissions (see Figure A2).

Figure A2: Non-CO_2 Emissions



Source: Authors' calculations using MAGICC 5.3 software; Hansen et al. (2008).

Technical Appendix B: Understanding Hansen's 350

Hansen *et al.* (2008) translates the goals of avoiding dangerous climate change or staying below 2°C (3.6°F) from 1990 into an allowable stabilization trajectory for CO_2 in our atmosphere. Hansen's 350 ppm CO_2 target is based in part on the work of L.D. Danny Harvey (2007), who has quantified the likelihood of serious harm from a range of temperature changes and greenhouse gas concentrations. According to Harvey (2007, p.14), there is a 25 percent chance of "unacceptable" harm with a 2.2°C (4.0°F) increase in the global annual average temperature, and a 10 percent chance of harm with a 1.9°C (3.4°F) increase.[39]

Hansen reports a 25 percent risk of serious harm with 300-500 ppm CO_2 and sets a goal of getting concentrations below 350 ppm CO_2 by 2100. This assessment combines the work of Harvey with Hansen's own research estimating a climate sensitivity of 6°C. Harvey creates two sets of probability density functions (pdfs): 1) for three representations of the relationship between temperature and harm; and 2) for two versions of the likelihood of climate sensitivities ranging from 0 to 10°C. Results for the allowable CO_2 concentration in ppm using Harvey's "moderate" or central risk of harm pdf and each of his climate sensitivity pdfs are presented in Table B1.

Table B1: Harvey's Allowable CO_2 concentration (ppm) for "Moderate" Risk of Harm Scenario

25% risk of harm	Future non-CO2 gases at:				10% risk of harm	Future non-CO_2 gases at:		
	Zero	Half-present	Present			Zero	Half-present	Present
CS Low	476 (378-554)	428 (339-498)	384 (305-447)		CS Low	424 (351-476)	381 (315-428)	342 (281-384)
CS High	384 (334-420)	344 (300-303)	309 (270-338)		CS High	352 (319-376)	316 (287-338)	284 (257-303)

Note: Range of ppm CO_2 reflects Harvey's "stringent" and "loose" risk of harm scenarios.
Source: Harvey (2007, Table 2, p.16)

Hansen's conclusion, that 6°C is the most likely climate sensitivity, better corresponds with Harvey's "high" climate sensitivity pdf, in which the cumulative probability for a climate sensitivity under 6°C is 80 percent (compared to nearly 100 percent in his "low" pdf). Hansen's assertion that 300–500 ppm CO_2 corresponds to a 25 percent chance of harm is consistent with Harvey's results under the assumptions that non-CO_2 gases either remain at their current levels or decline, and that aerosols have no effect on temperature.[40] According to Harvey, with non-CO_2 gases assumed to decline to one-half their current levels, using his central case for the temperature-harm relationships, and assuming "high" climate sensitivities:

- Without aerosols there is a 25 percent risk of unacceptable harm at 344 ppm CO_2, and a 10 percent risk at 316 ppm CO_2.
- With aerosols there is a 25 percent risk at 460 ppm CO_2, and a 10 percent risk at 400 ppm CO_2.[41]

With non-CO_2 gases assumed to remain at their current levels, using Harvey's central case for the temperature-harm relationships, and assuming "high" climate sensitivities:

- Without aerosols there is a 25 percent risk of unacceptable harm at 384ppm CO_2, and a 10 percent risk at 342ppm CO_2.[42]

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[39] This temperature-risk relationship represents Harvey's central or "moderate" case. For the purpose of sensitivity analysis, he also presents more "stringent" and more "loose" cases with a range of 1.3 to 2.9°C, or 2.3 to 5.2°F, corresponding to a 25 percent chance of harm, and 1.0 to 2.4°C, or 1.8 to 4.3°F, corresponding to a 10 percent chance of harm.

[40] Harvey's latter assumption – that aerosols have no effect on temperature – is very conservative. Most aerosols have the effect of decreasing global mean temperatures, and their emission is strongly correlated with the burning of fossil fuels. As emissions from fossil fuels decrease, so too will the countervailing impact of many aerosols. That the positive impacts of aerosols will fall to zero in the short or medium terms is, however, unlikely.

[41] It should be noted that Harvey (2007, p.16-17) refers to these projections for future aerosol emissions as "unrealistic": "Even though the above approach accounts for uncertainty in present-day aerosol radiative forcing, there are at least two reasons why the potential partial offset of GHG forcing by aerosols should not be included when deducing the allowable GHG forcing. First, as noted above, aerosol emissions are likely to be significantly reduced during the coming decades due to increasing concerns over acid rain pollution and the increasing willingness of an increasingly prosperous global society to address these concerns. Second, in combining aerosol radiative forcing with GHG radiative forcing, it is implicitly assumed that the spatial pattern of climatic change associated with aerosol forcing is the same as (but opposite in sign to) that associated with GHG forcing. While this is true for temperature in the majority of coupled atmosphere–ocean models… this is not true for precipitation."

None of Harvey's scenarios consider the possibility of non-CO_2 (and non-aerosol) emissions increasing over time; his worst case is for these emissions to remain at their present values. This being said, Harvey focuses on, and Hansen repeats, results for the conservative scenarios in which there are no countervailing effects from aerosols. If non-CO_2 gas emissions increase over time, Harvey's results suggest that even lower CO_2 concentration than 350 ppm will be necessary to avoid dangerous harm.

Replicating Hansen

Hansen *et al.* (2008) describes a detailed scenario for reducing greenhouse gas emissions with the goal of reaching 350 ppm CO_2 by 2100, and refers in more general terms to two other scenarios (see Figure B1 below, for a comparison of emissions from Hansen's scenarios and WRE350):

Hansen's 350 by 2100 scenario:

- This scenario focuses only on CO_2 emissions. Hansen assumes that all non-CO_2 emissions stay constant at their current levels, and non-CO_2, non-aerosol gases' positive impacts on temperature are approximately equal to aerosols' negative impacts. (To replicate Hansen's plan we modified MAGICC's WRE scenarios such that non-CO_2 emissions, including aerosols, remained constant at 0.02 W/m^2, the level in 2010, for all subsequent years.)[43]
- Coal burning is phased out or achieves 100 percent carbon capture by 2030. (We used data for coal emissions to 2005[44], assumed zero emissions from coal in 2030, and employed a linear trend for the years in between.)
- Oil and gas require no restrictions; they can be used as their market prices allow (assuming a "Hotelling curve" such that prices increase and demand decreases as reserves shrink). Hansen projects that if the IPCC's estimate of oil and gas reserves is correct, these reserves will be entirely depleted by 2150. If, however, the Energy Information Agency's (EIA's) higher estimate of reserves is correct, then cumulative use of oil and gas must be restricted to the IPCC's incorrect, lower estimate. (We used the emissions from burning the IPCC's estimated oil and gas reserves as reported in Hansen from 2010 onward; earlier years' data are taken from historical sources.[45])
- A combination of ending deforestation and initiating large-scale reforestation and biochar initiatives bring land use emissions to zero by 2015 and -6.5 Gt CO_2 by 2030, staying constant thereafter. (We used historical data for land use emissions to 2005, with a linear trend to zero in 2015 and a second linear trend to -6.5 Gt CO_2 in 2030.)

Hansen's 350 by 2050 scenario:

- Getting to 350 ppm CO_2 by 2050 follows the 350 by 2100 plan but requires further, unspecified, cuts to oil and gas. (To replicate we cut emissions from oil and gas by an equal percentage – as compared to Hansen's 350 by 2100 gas and oil emissions – in every year after 2005 until 350 ppm CO_2 by 2050 was achieved. An 80 percent reduction in use from the IPCC reserves was necessary to achieve this goal.)

Hansen with EIA reserves scenario:

- If the EIA's larger estimate of oil and gas reserves is correct, then allowing these reserves to deplete according to the market price (and following Hansen's 350 by 2100 plan in all other respects) would not achieve 350 ppm CO_2 until a later date. (To replicate we replaced the IPCC reserves with Hansen's estimates of the use of EIA reserves over time. This scenario reaches 350 ppm CO_2 in 2195.)

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[42] Harvey (2007) only presents results with aerosol effects included for scenarios in which non-CO_2 gases decline to one-half their current emissions levels.

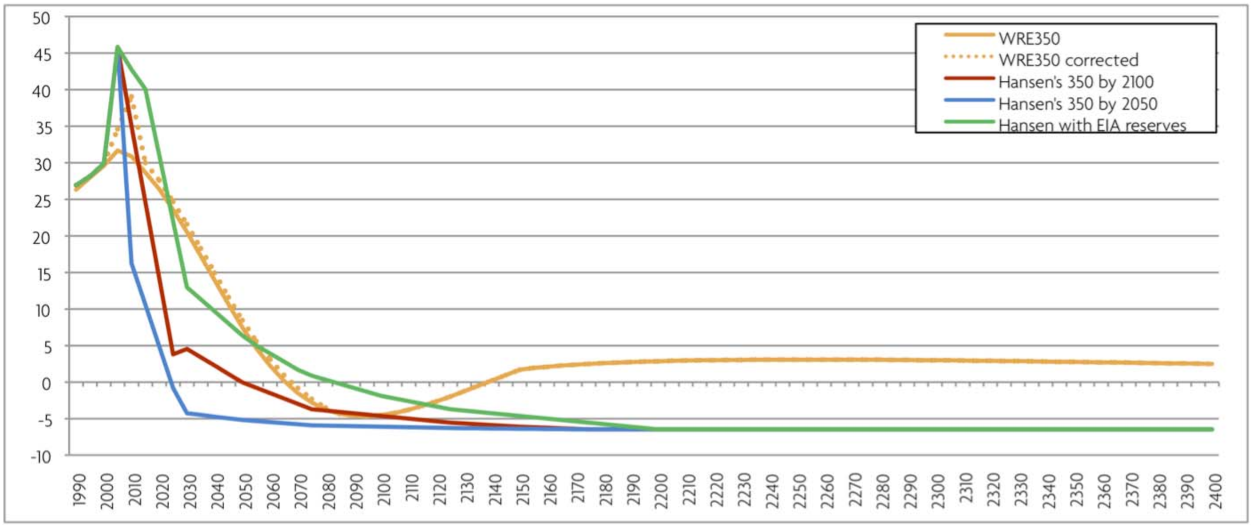
[43] The effect of emissions on temperatures in terms of "radiative forcings" in W/m^2 is discussed below. In the MAGICC WRE scenarios, non-CO_2 emissions reach their minimum radiative forcing in 2010.

[44] Historical data are for "solids" from the Carbon Dioxide Information Analysis Center (2009) *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2006*, http://cdiac.ornl.gov/ftp/ndp030/global.1751_2006.ems.

[45] Historical data are for "gas" and "liquids" from the Carbon Dioxide Information Analysis Center (2009) *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2006*, http://cdiac.ornl.gov/ftp/ndp030/global.1751_2006.ems.

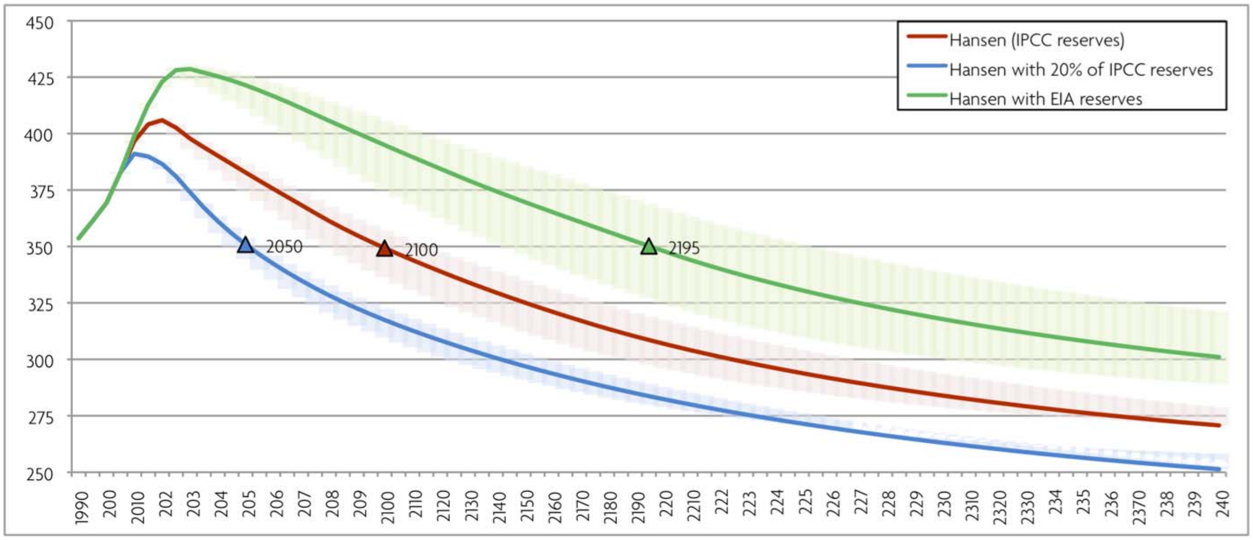
Figure B2 reports atmospheric CO_2 concentrations for Hansen's three scenarios; the curve for each scenario uses Hansen's estimate of the most likely climate sensitivity as 6°C while the error bars (shown in lightly shaded colors) represent the range of concentrations resulting from climate sensitivities 1.5 to 10°C. The year when Hansen's scenario utilizing the full IPCC reserves reaches 350 ppm CO_2 is 2100 with climate sensitivity 6°C, but ranges from year 2080 to 2115 with climate sensitivities 1.5 to 10°C. With 20 percent of IPCC reserves, 350 is achieved in 2050 with a range of 2045 to 2055. Using the full EIA reserves, 350 is achieved in 2195 with a range of 2145 to 2250.

Figure B1: Hansen and WRE350 CO_2 Emissions (Gt CO_2)



Source: Authors' calculations using MAGICC 5.3 software; Hansen et al. (2008).

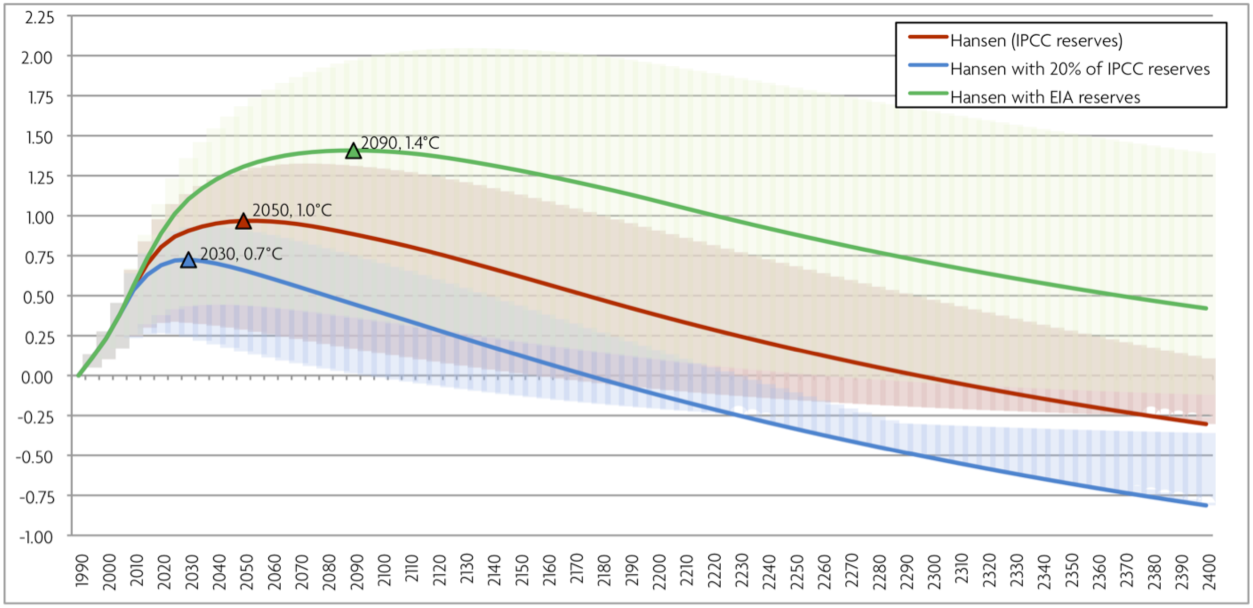
Figure B2: Hansen's CO_2 Concentration (ppm)



Note: Results are for climate sensitivity 6°C. Error bars represent range of values from climate sensitivity 1.5 to 10°C.
Source: Authors' calculations using MAGICC 5.3 software; Hansen et al. (2008).

Global average annual temperature change for Hansen's scenarios are reported in Figure B3 (again, with climate sensitivity 6°C as the central case and error bars representing the range of climate sensitivities from 1.5 to 10°C). With the full IPCC reserves, Hansen's 350 ppm CO_2 by 2100 scenario has a peak temperature change from 1990 of 1.0°C (1.8°F) in 2050 (with the peak ranging from 0.3 to 1.3°C, 0.5 to 2.3°F, with climate sensitivities 1.5 to 10°C). With 20 percent of IPCC reserves, Hansen's 350 by 2050 scenario peaks at 0.7°C (1.3°F) in 2030 (the peak ranges from 0.3-0.9°C, 0.5-1.6°F). Using the EIA reserves, the change in temperature peaks at 1.4°C (2.5°F) in 2090 (the peak ranges from 0.4-2.0°C, 0.7-3.6°F). Even in Hansen's highest emissions scenario – following his plan for emission reductions but assuming the EIA reserves – temperatures do not exceed 2°C (3.6°F) for climate sensitivities up to 10°C.

Figure B3: Hansen's Global Average Annual Temperature Change (°C from 1990)



Note: Results are for climate sensitivity 6°C. Error bars represent range of values from climate sensitivity 1.5 to 10°C.
Source: Authors' calculations using MAGICC 5.3 software; Hansen et al. (2008).

Non-CO_2 emissions

Greenhouse gas emissions are often modeled in terms of their "radiative forcing", or the impact in W/m^2 of emissions on temperature change. To give radiative forcing values some context, the *AR4* estimates that a 350 ppm CO_2 scenario causes 2.5 W/m^2 in radiative forcing (IPCC 2007b: Working Group III, Technical Summary, Table TS.2):

- AR4 Category I scenarios (350–400 ppm CO_2): 2.5 to 3.0 W/m^2
- AR4 Category II scenarios (400–440 ppm CO_2): 3.0 to 3.5 W/m^2

Current emissions of non-CO_2 greenhouse gases (excluding aerosols) have been estimated to cause:

- 1.15 W/m^2 in radiative forcing by Harvey (2007)
- 1.21 W/m^2 in radiative forcing in MAGICC's WRE Scenarios[46]

Current forcings from aerosols are reported in Table B2. Of the aerosols tracked by the IPCC (2007b), only black carbon from fossil fuels has positive radiative forcings (increasing temperature); most aerosols have a countervailing impact (negative radiative forcings that decrease temperature) such that burning fossil fuels creates both large positive radiative forcings from CO_2 and smaller negative forcings from aerosols. The combined radiative forcings from aerosols is -1.18 W/m^2.

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[46] Data for 2005 for methane, nitrous oxide, halocarbons, and tropospheric ozone only.

Table B2: *AR4* Radiative Forcings from Aerosols

	Mean Forcings W/m²	
Sulphate	-0.40	(-0.20 to -0.60)
Fossil fuel organic carbon	-0.05	(0.00 to -0.10)
Fossil fuel black carbon	0.20	(0.35 to 0.05)
Biomass burning	-0.03	(0.09 to -0.15)
Nitrate	-0.10	(0.00 to -0.20)
Mineral dust	-0.10	(0.10 to -0.30)
Indirect cloud albedo	-0.70	(-0.3 to -1.80)
Sum	-1.18	(-0.36 to -2.00)

Note: Range of radiative forcings is one standard deviation above and below.
Source: AR4 (IPCC 2007b: Working Group I, Technical Summary, p.29-30)

Together, all non-CO_2 gases including aerosols contribute radiative forcings close to zero in the current year. Hansen *et al.*'s (2008) assumes that these combined radiative forcings will remain at zero throughout the period of forecast, which seems unlikely unless specific measures are taken to decrease the emission of important non-CO_2 greenhouse gases like methane, nitrous oxide, halocarbons, and ground-level ozone. With no such measures in place, the impact of non-aerosol non-CO_2 greenhouse gases is likely to grow over time even as the countervailing effect of aerosols from fossil fuels shrinks; indeed, all of the IPCC's (2001; 2007b) SRES scenarios include the assumption of increasing non-CO_2 gases, at least in the short to medium term.[47]

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[47] For growth trends in non-CO_2 greenhouse gases in the SRES scenarios see the MAGICC 5.3 emissions profiles for these scenarios (Wigley 2008). For non-CO_2 emissions in the SRES A1FI scenario see the IPCC's Data Distribution Centre database (2009), *DDC Home, Environmental Data, Atmospheric Data*, "The SRES A1FI Emissions Scenario", http://www.ipcc-data.org/sres/ddc_sres_emissions.html.

Technical Appendix C: 350 by When?

This appendix introduces four new scenarios for reaching 350 ppm CO_2, with emissions gauged to reach 350 in the years 2200, 2150, 2100, and 2085; the latter is the earliest year possible without allowing negative emissions. (The 350 by 2200 scenario is also discussed in the body of the report.) All of these scenarios use the assumptions described above for the historically corrected WRE350 scenario for years 1990 to 2010; non-CO_2 emissions (including aerosols) are also identical to those used in MAGICC's pre-set WRE scenarios throughout the modeled period. For CO_2 emissions, each scenario has the same percentage reduction in every five-year period from 2015 to 2400, respectively, 37.5, 55, and 85 percent for the 2200, 2150, and 2100 scenarios; the 2085 scenario requires an immediate 100 percent reduction. Table C1 reports basic statistics for our suite of scenarios Figure C1, Figure C2, and Figure C3. report these scenarios' emissions, concentrations, and global average annual temperature changes. As seen in Figure C1, emissions are very close to zero by 2070 or earlier in all four scenarios.

Our scenarios use a climate sensitivity of 6°C as their central case, but results are presented for the range of climate sensitivities from 1.5 to 10°C. For our 350 by 2100 scenario, for example, 350 ppm CO_2 would be reached in 2060 with a climate sensitivity of 1.5°C and in 2210 with a climate sensitivity of 10°C (see Table C1). To reach 350 by 2100 – using our assumptions – emissions must be reduced to just 3 percent of 1990 levels by 2020; Hansen's 350 by 2100 scenario allows for a slower reduction of emissions in the early decades by assuming that negative emissions (where sequestration is greater than emissions) are achievable in the medium term. Our 350 by 2200 scenario requires CO_2 emissions to be halved by 2020 but precludes negative emissions in future years. All four our 350 scenarios keep global average annual temperature change below 2°C (3.6°F) at climate sensitivity 6°C, but the 350 by 2200 scenario slightly exceeds 2°C at climate sensitivity 10°C.

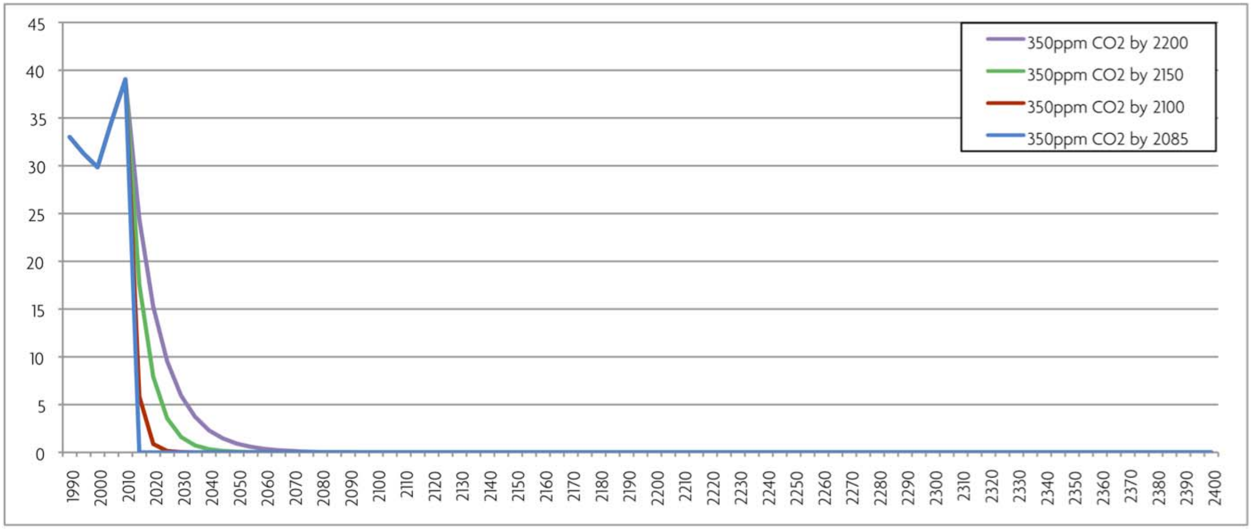
Table C1: Four 350 Scenarios, Year Reaching 350 ppm CO_2 and Share of 1990 Emissions

350 ppm CO_2 by:	2200 (2095 to 2350)	2150 (2075 to 2270)	2100 (2060 to 2210)	2085 (2055 to 2190)
Share of 1990 Emissions:				
by 2020	53.4%	27.7%	3.1%	0.0%
by 2030	20.9%	5.6%	0.1%	0.0%
by 2050	3.2%	0.2%	0.0%	0.0%
Peak Global Average Annual Temp Change (°C from 1990):				
	1.5 (0.4 to 2.2)	1.4 (0.4 to 2.0)	1.3 (0.3 to 1.8)	1.2 (0.3 to 1.8)

Note: Concentration levels and temperatures use the assumption of climate sensitivity at 6°C; range in parentheses is for climate sensitivity 1.5 to 10°C.

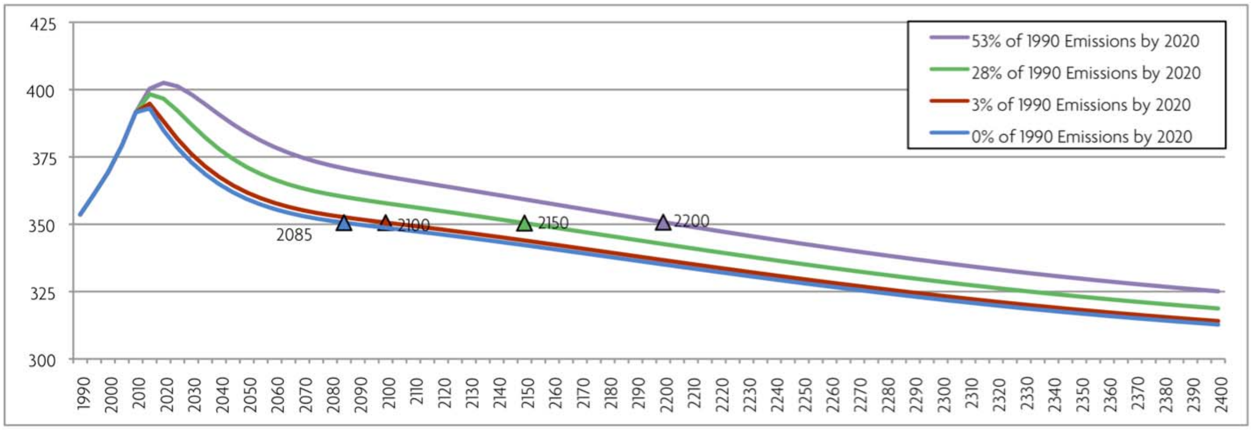
Source: Authors' calculations using MAGICC 5.3 software.

Figure C1: CO$_2$ Emissions (Gt CO$_2$) in 350 Scenarios



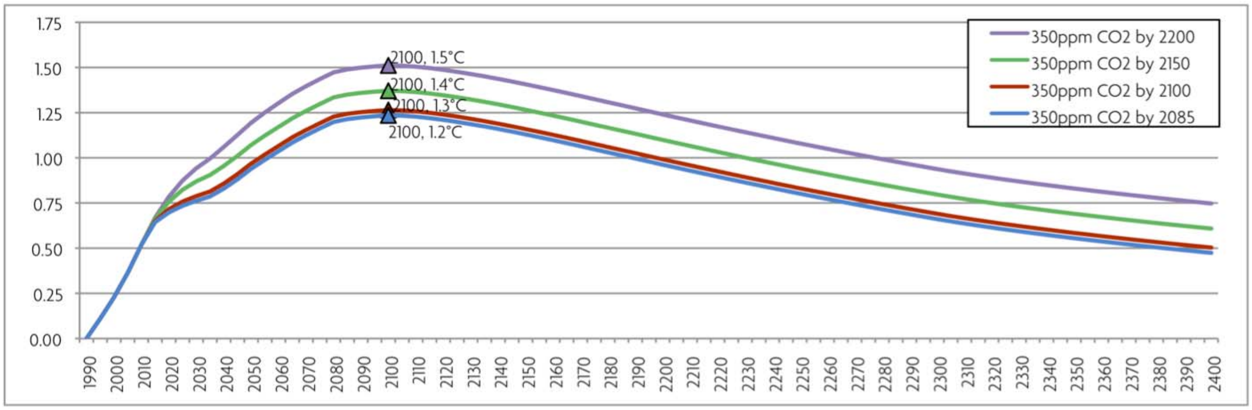
Source: Authors' calculations using MAGICC 5.3 software.

Figure C2: 350 Scenarios CO$_2$ Concentration (ppm)



Note: Results are for climate sensitivity 6°C.
Source: Authors' calculations using MAGICC 5.3 software.

Figure C3: 350 Scenarios Global Average Annual Temperature Change (°C from 1990)



Note: Results are for climate sensitivity 6°C.
Source: Authors' calculations using MAGICC 5.3 software.

All of these scenarios, even 350 ppm CO_2 by 2200, are vastly more ambitious about near-term reductions than any policy proposals currently under discussion. For this reason, detailed analyses of the prospects for stabilization at 350, as discussed in the text, typically involve options for negative emissions, such as reforestation, or biomass energy production combined with carbon capture.

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