What Will it Cost to Protect Ourselves from Global Warming?

THE IMPACTS ON THE U.S. ECONOMY OF A CAP-AND-TRADE POLICY FOR GREENHOUSE GAS EMISSIONS

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ENVIRONMENTAL DEFENSE FUND
finding the ways that work

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Executive Summary

Important parts of the world are acting to reduce the greenhouse gases that cause global warming, and the United States is now debating whether to join that process. This paper examines the potential impact of a cap on greenhouse gases on the U.S. economy as a whole and on American families.

What will it cost to protect ourselves against the potentially catastrophic consequences of global warming? Advocates of action anticipate minimal costs. Those who want to do nothing sometimes assert that carbon cuts will "bankrupt the economy." Who is right?

This paper conducts the broadest assessment to date of the impacts on the U.S. economy of capping greenhouse gases. This report synthesizes the findings of several state-of-the-art economic models, and arrives at a strong conclusion:

> **The United States can enjoy robust economic growth over the next several decades while making ambitious reductions in greenhouse gas emissions. If we put a cap-and-trade policy in place soon, we can achieve substantial cuts in greenhouse gas emissions without significant adverse consequences to the economy. And in the long run, the coming low-carbon economy can provide the foundation for sustained American economic growth and prosperity.**

But for such a policy to be truly affordable, we must act now. Delay will greatly increase the economic cost of making the necessary emissions reductions, and will risk locking in irreversible climate change. And delay will put the United States further behind the rest of the world in the race to invent and produce the next generation of energy technologies.

What makes our analysis different—relying on a range of forecasts

We surveyed eight policy scenarios analyzed by five highly respected, transparent, and peer-reviewed economic modeling groups in government and academia: the Energy Information Agency (EIA), Research Triangle Institute (RTI), Harvard (the IGEM model), the Massachusetts Institute of Technology (MIT), and Pacific Northwest National Laboratories (PNNL). None of these models is perfect, as no economic model can be. A particular challenge for models is predicting the course and pace of technological innovation—a key economic driver in the transition to a low-carbon economy.

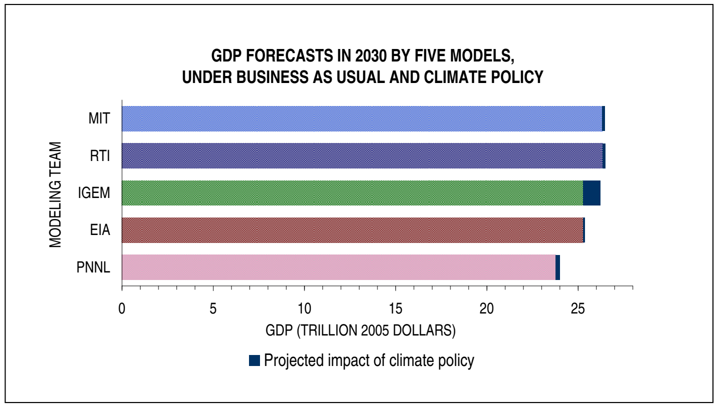
Advocates have cherry-picked the largest or smallest numbers from one or another of these models to support their positions. But sweeping conclusions based on a single model cannot be trusted. Judiciously using a range of current models, however, can inform the policy debate in useful ways.

Ambitious climate policy is affordable

While these models take different approaches to representing the U.S. economy, they share one basic conclusion: the overall impact of climate policy on the U.S. economy will be small.

- The U.S. economy has averaged nearly 3% growth per year in the postwar period, and is projected to continue at nearly that pace. The projected median impact on that annual growth of capping greenhouse gases is three-hundredths of a percentage point (0.03%).

- The U.S. economy is projected to nearly double in size between now and the year 2030. In that year, the median forecasted cost to the U.S. economy of capping greenhouse gas emissions is only 0.58%.
- The projected impact on GDP can be thought of this way: Under business as usual, the total output of the U.S. economy is projected to reach $26 trillion in January 2030. With a cap on greenhouse gases, the economy will get there by April.
- In present-value terms, the median projected impact of climate policy on U.S. GDP is less than one-half of one percent for the period 2010-2030, and under three-quarters of one percent through the middle of the century.
- The range of differences among models about the future size of the economy overwhelms the impact that any of them projects from a cap on carbon; in other words, even under varying assumptions, the impact of climate policy is small. The models vary by as much as 10% in their estimates of what economic output will be in 2030—17 times the estimated 0.58% cost of capping greenhouse gases.



Importantly, none of these models takes into account the damages from allowing global warming to build up unchecked and the value of avoiding them. That is, they look at only one side of the ledger: the costs of acting, not the benefits. These "costs" of reducing emissions actually represent an investment that will pay enormous dividends—by creating a low-carbon economy filled with new opportunity, and by ensuring a livable planet for generations to come.

A cap on greenhouse gases will not adversely affect employment in the American economy

- The overall impact of climate policy on employment, according to government projections, will be very small—a cumulative reduction of less than one-twentieth of one percent (0.05%) over the next two decades, relative to business as usual. That forecast, moreover, considers only current sectors of the economy; by its nature, economic modeling cannot anticipate the emergence of entirely new sectors—and the associated jobs—that will arise in the low-carbon economy.

> The number of manufacturing jobs created or destroyed every three months is much greater than the cumulative projected impact of climate policy over 20 years.

- The manufacturing sector has a high level of job turnover—over 10% of all manufacturing jobs are either created or destroyed every three months. By comparison, the impact of capping greenhouse gases on manufacturing employment will be tiny—a cumulative effect of only a few percentage points over more than two decades. And this is the sector expected to be affected most by a cap on greenhouse gases.
- Of course, no one whose job is lost is comforted by the fact that he or she is one of relatively few affected. The broader trend of job erosion in the manufacturing sector can neither be reversed nor

eased significantly by climate policy—precisely because the effects of such policy are so small. Dealing with volatility in this sector will remain the province of other aspects of American economic and social policy.

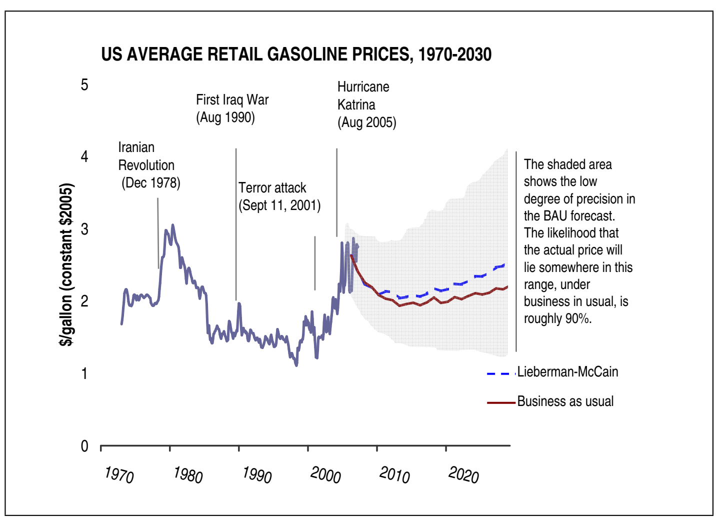
For the average American family, the cost of capping greenhouse gases will amount to less than 1% of household budgets over the next two decades

- Stated as a fraction of household income, capping greenhouse gases will cost families less than a penny on the dollar. This is much less than what Americans already spend in their household budgets to protect themselves and their families. By comparison, more than three cents of every dollar already goes to insurance; nearly four cents goes to national defense; and ten cents goes to Social Security.

The effects of capping greenhouse gases on household energy bills will be modest, and are much smaller than the fluctuations that American families already live with

Household impacts will be most pronounced in the area of energy prices because of our dependence on fossil fuels. Importantly, energy prices are accounted for in the overall impacts described above. But even taken in isolation, the projected effects of climate policy on household energy spending are modest.

- Home energy bills are projected to rise by only a few dollars a month over the next two decades, relative to business as usual, taking into account effects on prices and corresponding shifts in household consumption. And the fact that the overall costs of capping greenhouse gases will be so modest means that we can easily afford programs to offset the burden of these increased costs on low-income households.
- Price fluctuations due to supply bottlenecks and Mideast politics are recurring consequences of relying heavily on imported hydrocarbon fuels. Recent run-ups in the price of gasoline at the pump and in the price of home heating oil and natural gas are several times larger than the predicted effects of capping greenhouse gases.
- By the same token, the uncertainty about what gasoline prices (or other energy prices) will be two decades from now dwarfs the estimated impact from climate policy. For example, one study projects that a cap on greenhouse gases would add about 15% (35 cents a gallon) to the price of gasoline in 2030 relative to business as usual. This is much smaller than the uncertainty surrounding any estimate of gasoline prices that far in the future. This conclusion is in line with other assessments: The median forecast for the studies discussed here is an increase of 13% by the year 2030.



If we act now, a cap-and-trade policy can provide the basis for continued U.S. economic leadership

In the longer term, the transition to a low-carbon economy may offer the United States a comparative advantage in a highly competitive world. A look back at the history of the U.S. economy since World War II teaches a number of lessons:

- American ingenuity and innovation have achieved challenges of much greater magnitude before. The mobilization for World War II involved a complete transformation of the U.S. economy in just two years. If we do not waste our scarcest resource—time—we can make the transition to a low-carbon economy without adverse macroeconomic impacts.
- Technological change is the engine of progress in the American economy. We emerged as the world's economic superpower in the last century by leading every economic revolution—from mass production to aviation to semiconductors and the Internet. Our continued prosperity in the new millennium depends on leading the next transformation: the emergence of a low-carbon economy.
- But innovation does not just happen: It responds to the basic economic drivers of demand and price. A hard, long-term cap on carbon emissions will provide the market signals necessary to spark innovation and unleash the kinds of powerful market forces that propelled our economy in the postwar period. A failure to stimulate innovation through a carbon cap will cede leadership in the low-carbon economy to others.

Introduction

As scientific evidence of global warming mounts, we now know that we must migrate to a low-carbon economy. Important parts of the world are already moving toward that goal. The economy is a complex cauldron of forces: growth and loss; innovation and obsolescence; new jobs replacing old jobs; and among firms, winners and losers. As a nation, we face the task of harnessing these forces and the natural process of economic change to address the looming problem of global warming.

The U.S. Congress is debating legislation to cap carbon emissions. This study aims to inform that discussion. What kinds of economic challenges and opportunities will the transition to a low-carbon economy present? What are the potential burdens, and what steps can we take to maximize growth and minimize disruption and hardship?

To answer these questions, we start in Chapter 1 by emphasizing the economic importance of acting now. In Chapter 2, we discuss economic analysis and climate policy in general terms, and outline the strengths and limitations of macroeconomic models. Chapters 3 and 4 take a close look at what such models can tell us about the likely economic impacts of capping greenhouse gases over the next few decades—the first phases of the transition to a low-carbon economy.

In Chapter 5, we take a look at the historical experience of major economic transitions and consider the drivers of economic growth. Finally, in Chapter 6 we discuss the characteristics of a climate policy that can promote the long-term health of the American economy.

1 The Cost of Delay

As legislators discuss what type of climate policy to enact, it is important to understand the tradeoff between action and delay. To do that, we must return to the underlying reasons for having this debate in the first place.

The scientific consensus is clear: Global warming is real, and it is already happening. While nobody can be certain about the exact timing or location of its consequences, the possible severity of those consequences is becoming increasingly clear. Allowing greenhouse gas emissions to increase unchecked is an invitation to catastrophe. The potential consequences of warming include widespread famine, triggered by extreme drought in the major grain-producing areas of the world; the wholesale disappearance of the world's coral reefs; and sea levels rising by several meters over the course of a few centuries. Moreover, scientists are only just beginning to uncover the potential for "feedback effects." For example, rising temperatures could lead to melting permafrost in the arctic tundra, releasing large deposits of carbon dioxide and methane, an even more powerful greenhouse gas.

To avoid the worst consequences of global warming, we will have to limit the increase in average global temperature to roughly two degrees Celsius (2°C) above pre-industrial levels. This requires preventing greenhouse gas concentrations in the atmosphere from exceeding 450 parts per million (ppm) of carbon-dioxide equivalent (CO2e).

This task is complicated by a crucial fact: The greenhouse gases we are already putting into the atmosphere today will remain there for a century or more, continuing to drive global warming. What will determine the future of our planet is the total accumulation of greenhouse gases from now through the end of the century.

Figure 1.1, on the next page, shows several potential time paths for reducing global emissions that would afford us a better-than-even chance of keeping warming below the two-degree threshold. The area under each curve is the same, corresponding to the same total "emissions budget." The longer we wait, the faster we must cut emissions in order to remain below the two-degree threshold.[1]

> The window of opportunity is closing fast. If the world waits even a decade or two to start cutting emissions, catastrophic climate change may be unavoidable.

The message from Figure 1.1 is stark. Had the world started to address this problem already, modest actions combined with the natural rate of decarbonization in the economy would have made this an eminently feasible task.[2] Even now—as the remainder of this report shows—we can embark on this task without significant adverse impact to the economy. But the window of opportunity is closing fast. If we fail to act soon, the most gradual pathways—the ones that have the least possible impact on our economy and allow us the most time in which to adjust—will be lost to us.

As the figure illustrates, even waiting until 2030 would require precipitous emissions reductions that may simply be unachievable. Global emissions would have to be cut by more than half in just twenty years, and by over 95% by the end of the century. This task amounts to reaching and sustaining reductions of over 6% per year—an amount greater than the combined emissions of Germany, France, Spain, and the United Kingdom, or the entire U.S. electric power sector. Cuts of that magnitude would be required each year, every year, for the rest of the century. And such reductions would need to occur despite rapid economic growth in China, India and the rest of the developing world.[3]

Moreover, Figure 1.1 shows what must happen to *global* emissions. As we discuss below, concerted international action will not occur until the United States joins the rest of the industrialized world in reducing its own emissions. For the world's emissions to begin declining by 2020, the United States must act soon.

The time bottleneck

The cost of delay mounts through several interlocking mechanisms.

First, delay in curbing emissions increases the danger of irreversible "climate shocks" that could affect the global economy. Delay also means we must make steeper cuts in emissions over a shorter time frame. This increases the costs of making reductions because of the decreased time available for developing new technologies, investing in new energy infrastructure, and modifying manufacturing and energy generation processes.

A second aspect of the "time squeeze" is the lengthy period required for permitting, planning and constructing new facilities. This affects construction of new power generation facilities, in some cases the retrofit of old facilities, and the development of such ancillary facilities as new power transmission lines and pipelines to carry CO2 to approved storage areas. Delay in adopting a carbon cap allows emissions to go on rising and therefore increases the number and scale of new facilities required once the decision to build new energy infrastructure is finally made. Those increased requirements, in turn, put more pressure on—and trigger further delays from—the congested infrastructure development pipeline.

Figure 1.1: Global emissions pathways consistent with 2°C warming.

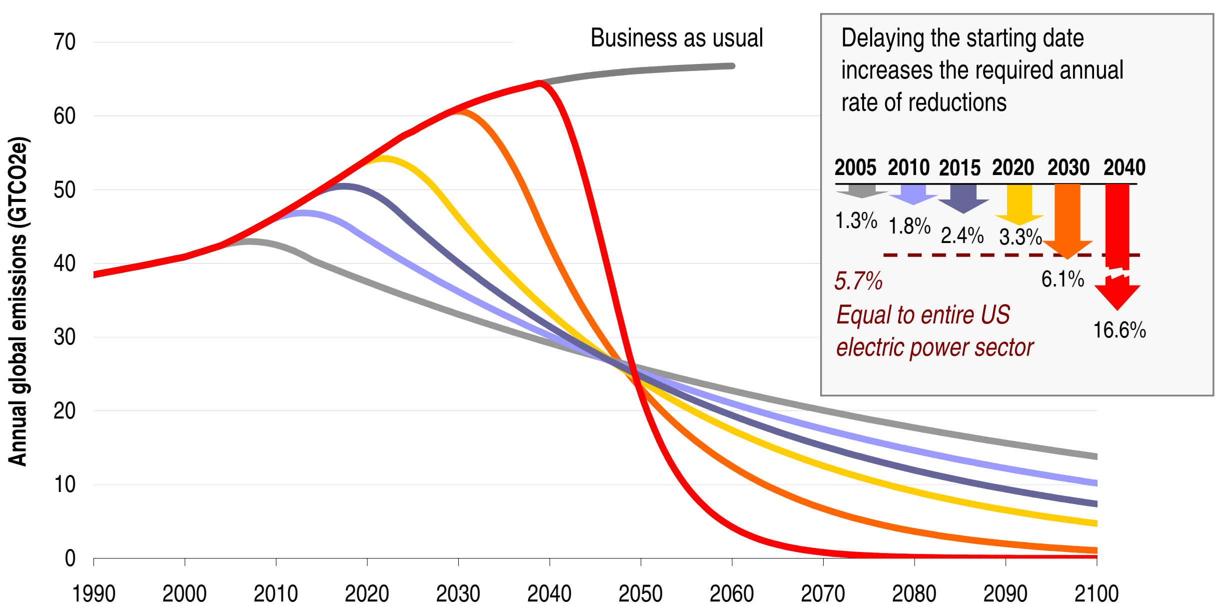


Figure 1.1 illustrates a range of pathways for global greenhouse gas emissions that would yield a better than 50 % chance of avoiding 2°C warming. Note that the area under each pathway is identical. The longer the delay before emissions are reduced, the more steeply they must be cut in subsequent years to meet the goal. (Source: EDF calculations using the MAGICC climate model and IPCC assumptions. See note 1.)

A third and crucial dimension of the time bottleneck concerns the response of the rest of the world to what the United States does. In meeting the challenge of global warming, we are all in it together; either we all succeed or we all fail. If we are to have a chance of conserving a relatively stable and livable climate, we must cut greenhouse gas emissions around the globe—in Europe and Japan, which have already begun to do so; in the growing powerhouses like China and India, which will not even consider reductions until the United States acts; and in the countries undergoing tropical deforestation.

Why the United States must lead

First, the United States is the richest nation, the largest greenhouse gas emitter both in cumulative and current terms, and the country capable of undertaking the transition to a low-carbon economy with the least burden on its citizens.

Second, developing nations racing to modernize see no reason to assume an additional load that will complicate their economic development if the richest and largest emitter, with the resources to adapt relatively easily, will not.

This means the only path that will lead any of us to a livable climate is for the United States to embark now on real reductions in emissions, and for all the nations of the world, developing and developed, rich and poor, to negotiate a global agreement that will establish the terms and instrumentalities under which they can join the global low-carbon transition.

The United States is responsible for nearly 30% of cumulative global emissions above the pre-industrial base, and continues to emit more than 20% of human-produced greenhouse gases each year. If inaction by the United States leads to inaction by others (the present pattern), that will multiply several-fold the effects of U.S. delay alone. It will at the same time increase the danger of severe climate shocks and steepen the emission reduction slope required globally; and it will increase both the global and American costs of climate stabilization.

On the other hand, our position also gives us great leverage. If the United States begins to reduce emissions now, the benefits from such action will be far greater than just the cuts we make. The train will finally leave the station, and everyone will be haggling over the terms on which they will board it rather than waiting to see what we do.

2 Economic Analysis and Climate Policy

Economists characterize global warming as a classic example of *market failure*. We all benefit from electricity, motor vehicles and other products of industrialization. But the full costs of such products are hidden from us and therefore not factored into the decisions we make. Factories and power plants pay for the fuels they burn—but not for the pollution they emit, even though it imposes damages on the rest of society. In such cases, undisciplined markets fail to function efficiently: Each of us lacks incentives to curb our own behavior for the good of ourselves and society at large.

The insight of modern economic theory is this: The antidote is not to abandon the marketplace, but to harness market forces—the most powerful engine of growth and opportunity. To do this, we must establish firm caps on greenhouse gases and then let the market determine the most cost-effective ways to achieve those limits.

The limits of cost-benefit analysis

For run-of-the-mill policy problems, cost-benefit analysis can be a valuable tool. Estimating the benefits and costs of action helped provide the basis for phasing the lead out of gasoline in the 1980s, and has shown that the 1990 Clean Air Act—which achieved deep cuts acid rain pollution through an emissions-trading program—has led to net benefits estimated to be in the hundreds of billions of dollars.

But this is not a run-of-the-mill problem. Although it is impossible to pinpoint the exact timing and nature of the worst consequences of global warming, we know they could be disastrous. When future outcomes are uncertain, standard cost-benefit analysis boils the probabilities down to one set of numbers—expected costs and expected benefits. Applying that simple approach to climate change overlooks the risk of catastrophe—what economists call the "fat tail" in the distribution of possible outcomes. Allowing global warming to continue unchecked is playing roulette with the planet.[4]

Moreover, efforts to attach a price tag to the damages from global warming run up against the sheer scope and scale of the consequences. Existing work has focused on what is relatively easy to measure: for example, the effects of modest temperature increases on the value of agricultural land in the United States, or on energy use for home heating. Much less has been done to estimate the damage to agriculture in hotter areas (where the negative consequences from warming would be greater), or the costs of more powerful hurricanes (although the leading work suggests that the damages may be much greater than previously estimated). And there has been almost no assessment at all of the damages to ecosystems, whether on the warming land or in the acidifying oceans.

But the potentially catastrophic consequences of climate change also make standard cost-benefit analysis beside the point. Even if we cannot know the exact dollar figure, we do know that the benefits of curbing global warming will be enormous—simply because of the scale of the catastrophes that loom if we don't do anything.

How economics can help inform policy

How much will it cost to avoid the worst consequences of global warming? Here economic analysis is of more help, although important uncertainties still remain. Models of the macroeconomy are not crystal balls; nobody can reliably predict economic conditions five years hence, let alone 25 or 50. In an Appendix to this paper, we discuss the key assumptions that economic modelers must make, as well as the limitations inherent in any attempt to predict the future by extrapolating from past experience.

THE CHALLENGE OF PREDICTING TECHNOLOGICAL CHANGE

One of these limitations is especially important to keep in mind. Although they are designed with an eye toward understanding the future, economic models necessarily draw on historical data for information about technology, productivity, economic activity and consumer behavior. This introduces unavoidable blind spots. For example, it is far easier to predict losses to existing economic sectors than to identify gains to entirely new ones.

Predicting the course and pace of technological change is a particularly daunting task. Because models use past experience as a guide, they are poorly suited to anticipate improvements in industrial processes that come about in response to the incentives created by new policies. One of the most important drivers of technological change and increased industrial efficiency would be a carbon cap, because a cap would spur companies to search for new, low-carbon ways of producing goods and services so that they could sell, rather than have to purchase, carbon allowances. A simple way to express the effect of all this would be to say: A cap drives innovation and efficiency, which drives productivity, which drives growth. While the common sense of this is accepted, the ability of models to incorporate it is extremely limited.

THE ROLE OF ECONOMIC MODELING

Despite their blind spots, models of the macroeconomy can—if used correctly—provide an important tool for policy makers. Their greatest usefulness lies in their capacity for comparison. Models offer a level platform for analyzing how the economy is likely to be affected by different approaches to climate policy—while holding other key variables (captured by the model's core structure and assumptions) fixed. For example, a common theme from macroeconomic models is the enormous cost savings that can be realized if we employ market-based policies such as cap-and-trade systems to achieve emissions reductions, rather than prescriptive "command-and-control" approaches such as mandatory technology requirements.

Modeling analyses have also convincingly demonstrated the significant cost savings from the following: letting firms "bank" carbon allowances over time; defining mandatory caps not only with respect to carbon dioxide alone but for other greenhouse gases such as methane and nitrous oxide; developing an international market for greenhouse gases rather than taking a country-by-country approach; and providing credit for land use changes that offset greenhouse gas emissions.

Nonetheless, policy makers will inevitably seek to rely on macroeconomic models as a means of predicting the magnitude of the economic impacts of a cap on greenhouse gas emissions—if for no other reason than that such tools exist. For that reason, it is important to take a hard look at their forecasts—both to glean useful implications about what it might cost to avert dangerous climate change, and to provide perspective on the proper use of modeling results.

3 Results from Economic Forecasts

What do the models have to say about the costs of a well-designed cap on greenhouse gas emissions? The most surprising message is how small the overall effects are predicted to be. For the United States as a whole, the forecasted impacts appear so small as to be immeasurable against the backdrop of a dynamic, growing economy. When we drill down to the household level, we find that averting the worst consequences of global warming will be affordable for the average American family.

At the same time, there will be winners and losers from any change as significant as the transition to a low-carbon economy. Some sectors and regions are likely to feel a deeper impact as the economy adjusts; others will gain as new industries emerge. Some aspects of household budgets will be more affected than others, and there may be potential hardship for the least well off among us. In this paper, we take a first cut at identifying and assessing those areas of greatest vulnerability. As we argue below, these distributional issues warrant continued analysis. They should—and can—be addressed in the context of ambitious climate policy.

Data and methods

We focus on the most recent studies of U.S. climate policy available, employing five widely-cited and well-respected economic models. Our use of a range of analyses is faithful to a cardinal rule about models: Don't trust any single number. The uncertainties and limitations inherent in models are large enough that the forecast from any given model tells us more about the assumptions employed by its creators than it does about the actual impacts of climate policy.

THE ECONOMIC ANALYSES WE CONSIDER

The analyses we consider fall into two groups. The first set of studies examined specific legislation proposed in the U.S. Senate during 2007: a bill introduced by Senators Lieberman and Warner in the fall of 2007 and reported out of the Environment and Public Works Committee in December, and earlier legislation introduced by Senators Lieberman and McCain in July 2007.

The Lieberman-Warner legislation ("America's Climate Security Act of 2007") is the leading active bill and is expected to be brought to the Senate floor later this year. Covering a broader swath of the U.S. economy (roughly 85% of emissions), the bill calls for a steadily declining cap, reaching 15% below 2005 levels by the year 2020 and 70% below 2005 levels by 2050. We consider three assessments of the bill's potential impact on the U.S. economy.[5] In March 2008, the Environmental Protection Agency released its analysis of the bill, drawing on the results from two economic forecasting models: the ADAGE model developed at Research Triangle Institute (RTI) in North Carolina; and the IGEM model run by a consulting firm founded by Dale Jorgenson, a professor at Harvard.[6] A third, independent analysis of the bill was released by researchers at the Massachusetts Institute of Technology (MIT), using their Emissions Prediction and Policy Analysis (EPPA) model.[7]

The Lieberman-McCain bill was somewhat less ambitious; for the nearly 80% of the economy regulated by the bill, greenhouse gas emissions would have been capped at 22% below their 1990 levels starting in the year 2030, and 60% below 1990 levels starting in 2050. Although this bill is no longer under active consideration, it is the subject of the most up-to-date analysis by the Energy Information Administration, using its "in-house" model, the National Energy Modeling System (NEMS). The EIA analysis provides a valuable additional reference point for assessing the costs of climate policy. And as we emphasize throughout this paper, the usefulness of models lies in their collective message, rather than in any single forecast.

The second set of studies performed a different sort of exercise. Rather than investigate a particular piece of proposed legislation, they represent a so-called "bounding analysis" meant to explore the economic impacts of comprehensive, economy-wide climate policy. The original study was done by researchers at MIT; analyses of the same scenarios were subsequently carried out by the RTI group and by a group of researchers at the University of Maryland and the Department of Energy's Pacific Northwest National Laboratories (PNNL).[8]

All three research groups (MIT, RTI, and PNNL) considered a generic policy that would reduce total greenhouse gas emissions in the United States to 50% below 1990 levels by the year 2050. In addition, the MIT group modeled an even more ambitious policy, corresponding to reductions of 80% below 1990 levels by 2050. Both of these generic policy scenarios are more stringent than the legislation proposed in Congress.[9]

COMPARING CLIMATE POLICIES TO BUSINESS AS USUAL

All of the studies we examine here compared a particular climate policy scenario with a "reference scenario" corresponding to the model's projection of "business as usual"—that is, a world in which the economy continues on its current course with carbon emissions unchecked. All assume that a climate policy would be implemented in the year 2012—although its effects would begin in 2010 or even earlier, as businesses and individuals prepared to meet the policy. Most of the analyses we consider project economic impacts through the year 2050; the exception is the EIA model, which runs only through 2030. The macroeconomic impacts of climate policy are typically framed in terms of the U.S. Gross Domestic Product (GDP), and we follow this convention.[10]

Like most macroeconomic models used to forecast the costs of capping greenhouse gases, these analyses look at only one side of the ledger. They evaluate the costs of reducing greenhouse gas emissions, but do not measure the resulting payoff—the benefits of averting dangerous climate change. Nor do they consider the ancillary benefits, such as the improved local air quality that would come with deep cuts in fossil fuels.

Table 3.1: Forecasted impact of a cap-and-trade policy on U.S. economic output

Abbreviation	Research team and model name	Policy considered	Projected reduction in GDP vs BAU* 2010-2030	2010-2050
IGEM	Dale Jorgenson Associates (IGEM model)	Lieberman-Warner	2.15	3.59 %
RTI	Research Triangle Institute (ADAGE model)	Lieberman-Warner	0.44	0.78
RTI	Research Triangle Institute (ADAGE model)	50% below 1990	0.81	1.39
PNNL	DOE Pacific Northwest National Lab (SGM model)	50% below 1990	0.47	0.88
MIT	MIT (EPPA model)	Lieberman-Warner	0.46	0.59
MIT	MIT (EPPA model)	50% below 1990	0.51	0.65
MIT	MIT (EPPA model)	80% below 1990	0.44	0.61
EIA	Energy Information Administration (NEMS model)	Lieberman-McCain	0.23%	n/a
	Median		0.47	0.72
	Average		0.67	1.05

* GDP impact expressed as the percent change from "business as usual," expressed in present value terms using a 3% discount rate. EIA runs through 2030 only.

One implication of this one-sided approach is that the models' projections of "business as usual"—that is, what happens if we do nothing about global warming—describe a scenario that is no longer an option. Failing to curb greenhouse gas emissions will lead to a future of catastrophic climate change that will be anything but "business as usual." (We continue to use that phrase for convenience, but its fictional quality should be kept firmly in mind.)

When economic forecasting models compare climate policy to a business-as-usual scenario, they ignore the consequences of global warming. If we fail to take action on climate change, however, the future will be anything but "business as usual."

A second implication is that the models overlook the reason for taking action in the first place. In effect, the "costs" these models predict can equally well be thought of as an investment in the future, in a new mode of generating and using energy, and one that will pay handsome returns in the form of cleaner air and a livable planet.

The estimated impact on the U.S. economy of a cap on greenhouse gases

Addressing a problem as serious as global warming will not be free—but the projected adverse impact on the economy is minimal. We first consider forecasts of the effects of emissions reductions on the present value of GDP.[11] For the period 2010-2030, the projected cost to the economy of capping greenhouse gases ranges from 0.23% of the present value of GDP (in the EIA analysis of Lieberman-McCain) to 2.15% (in the IGEM analysis of the Lieberman-Warner bill). The estimates of the other studies fall toward the lower end of that range. For example, the MIT analysis forecasts that a policy to cut greenhouse gas emissions by 80% below 1990 levels would reduce the present value of GDP over the period 2010-2030 just 0.44% below business as usual. The projected impacts are only slightly larger for the period 2010-2050, ranging from 0.59% (in MIT's analysis of Lieberman-Warner) to 3.59% (in the IGEM analysis), with most of the studies clustered near the low end.

The wide range of forecasts reflects the different assumptions and structure of these models. Simply put, what sets the IGEM model apart is its somewhat counterintuitive view that when the price of energy (and other goods and services) rises, people respond by choosing to work *less* than they otherwise would. This effect magnifies the impact of emissions reductions on economic output.

Keeping in mind that model forecasts are best used in bunches, the most useful single number is the median. For the studies considered here, the median projected impact on GDP is 0.47% for the period 2010-2030, and 0.72% through the middle of the century. Table 3.1 summarizes these results, and Figure 3.1 plots the models' projections.

Those who wish to do nothing about global warming typically characterize the predicted impacts of climate policy as "losses" to the economy. It is important to remember that such losses are relative to a projected level of GDP that is vastly higher than today's. As Figure 3.1 shows, under *all* scenarios, the U.S. economy is expected to be more than twice as large in 2030 as it was in 2005. In the RTI analysis of Lieberman-Warner, for example, GDP grows from \$12.4 trillion in 2005 to a projected value of \$26.2 trillion in 2030—versus \$26.4 trillion under "business as usual." In short, these models show that we can enjoy robust economic growth while achieving deep reductions in greenhouse gas emissions.

Figure 3.1 also suggests an important truth about these forecasts: The projected impact of climate policy is much smaller than the uncertainty about the size of the economy a few decades from now. To see this, suppose we ask: What will U.S. GDP be in the year 2030 under business as usual? (We use the year 2030 as our "comparison year" for the simple reason that it lies in the middle of the period 2010-2050; moreover, the EIA model ends in that year, and common sense suggests that our ability to forecast impacts more than 20 years in the future is severely limited.)

The MIT and RTI models predict U.S. GDP of about $26.5 trillion for the year 2030. The IGEM modelers put the figure at just over $26 trillion; EIA says $25 trillion and change; PNNL pegs the figure at less than $24 trillion. Those various estimates—reflecting the underlying assumptions about productivity growth and other economic forces embedded in the "black boxes" of these models—vary by 10%, or more than $2 trillion.

By comparison, the estimated impact of capping greenhouse gases is an order of magnitude less. Among the models considered here, the median forecasted impact of climate policy on GDP is just 0.58% for the year 2030, relative to business as usual.[12]

Figure 3.2 makes this comparison explicit by comparing the different models' projections for economic output in the year 2030, with and without climate policy. (For modeling teams such as RTI and MIT that examined multiple policy scenarios, we depict the projections for the Lieberman-Warner legislation.)

The disagreement among the models on what GDP will be under business as usual overwhelms the differences any of them predict as a result of capping greenhouse gases. In these forecasts, the impact of climate policy on the economy is insignificant when measured against the crude, long-term differences in estimated GDP a quarter of a century from now.

In fact, the small projected impact of climate policy is just about the only thing these models have

Figure 3.1: GDP projections for business as usual and a range of climate policy scenarios

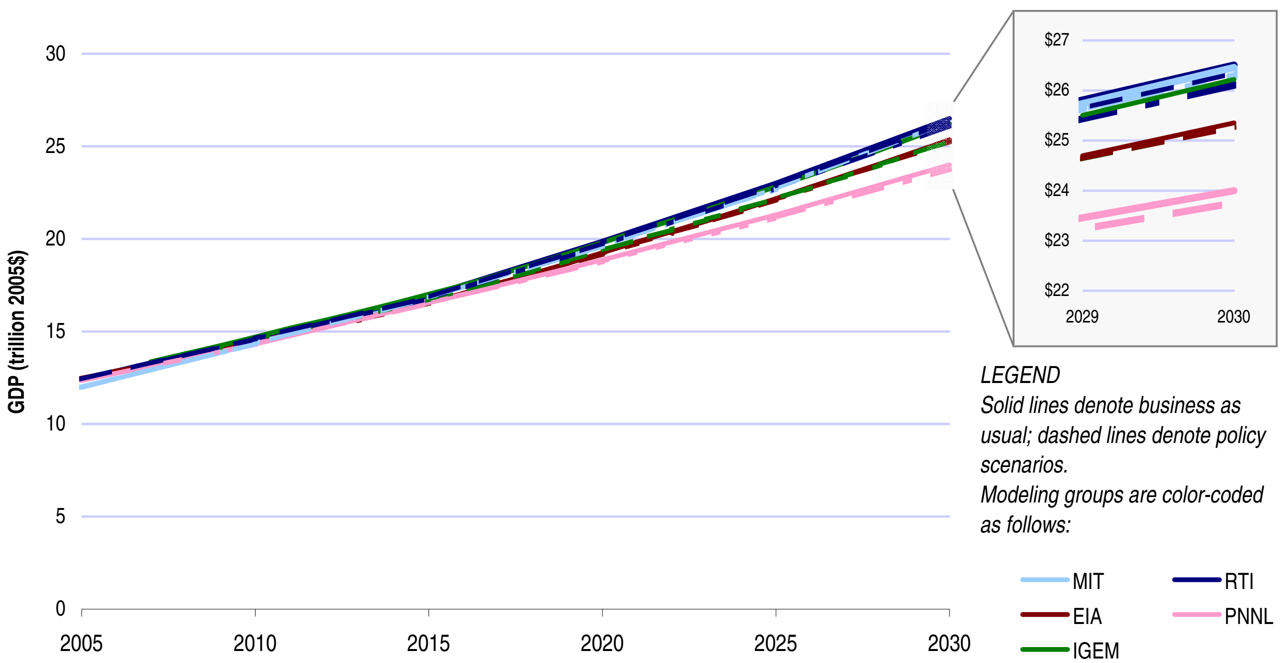


Figure 3.1 shows U.S. GDP through 2030, according to the forecasts of five economic models for a range of policy scenarios. The inset shows projections for 2030. (Source: EDF analysis of data from economic forecasting models described in text.)

Figure 3.2: GDP forecasts in 2030 by five models: Business as usual and climate policy

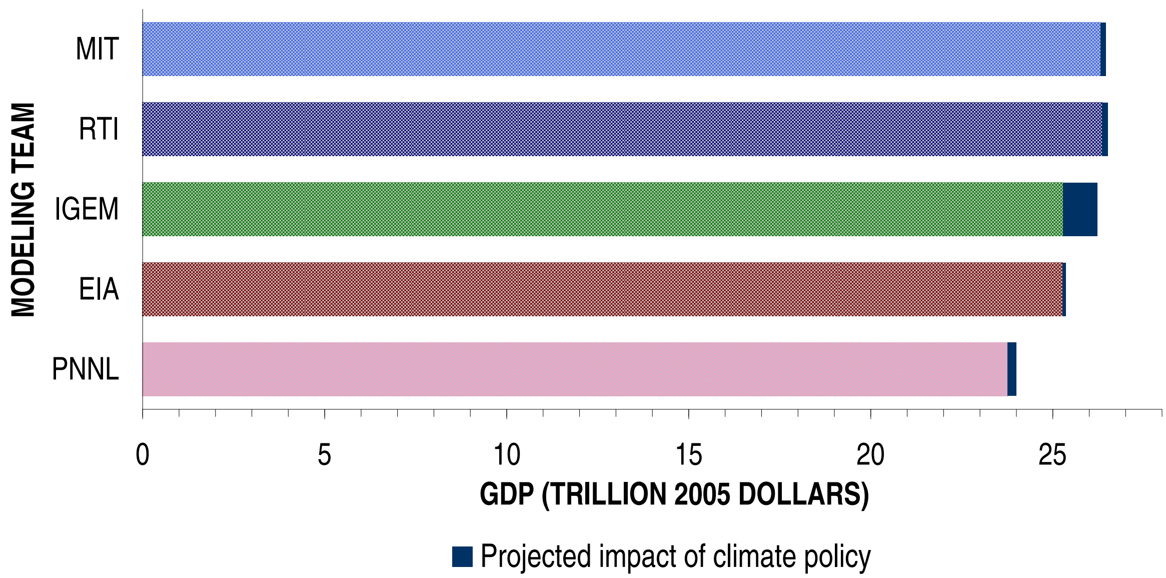


Figure 3.2 shows the projected U.S. GDP in the year 2030 under five economic models. The full length of each bar represents estimated GDP under business as usual, while the blue tip represents the effect of climate policy. (Source: EDF analysis of data from economic forecasting models described in text.)

in common. They may disagree about where we will end up in 25 years (and indeed all of them will be wrong to some degree)—but in every case they agree that the impact of climate policy is miniscule.

> The disagreement among models about what U.S. GDP will be in the year 2030 under business as usual is an order of magnitude greater than the projected impact of a carbon cap.

Putting the GDP forecasts in context

Let us be clear. These same model results can be presented in other ways. Opponents of taking action will cherry-pick the largest numbers and focus on them—as if any single model in isolation were a reliable guide to the future. They will frame these numbers in terms of their accumulation over time—as such-and-such billions of dollars between now and 2030. They will seek to scare people by presenting these figures alone, out of context. The economic output of the United States is so mind-bogglingly large that any change, however small, will sound large when added up over decades.

The reality is that the estimated impacts of climate policy are tiny when measured against the backdrop of the dynamic economy. This becomes clear when the model forecasts are expressed in terms of the change in the projected annual growth rate of GDP—a figure we are used to dealing with on a day-to-day basis. Using this metric, the EIA analysis foresees a business-as-usual annual growth rate for GDP of 2.86% from 2010 to 2030, vs. 2.84% under a carbon cap—a drop of two-hundredths of a percentage point. In fact, nearly all the analyses project a virtually imperceptible effect on growth of only a few hundredths of a percentage point per year; the median across the models considered here is three basis points, or 0.03 percentage points. Even the most pessimistic analysis, from the IGEM model—

Figure 3.3: U.S. economic growth, 1950-2005

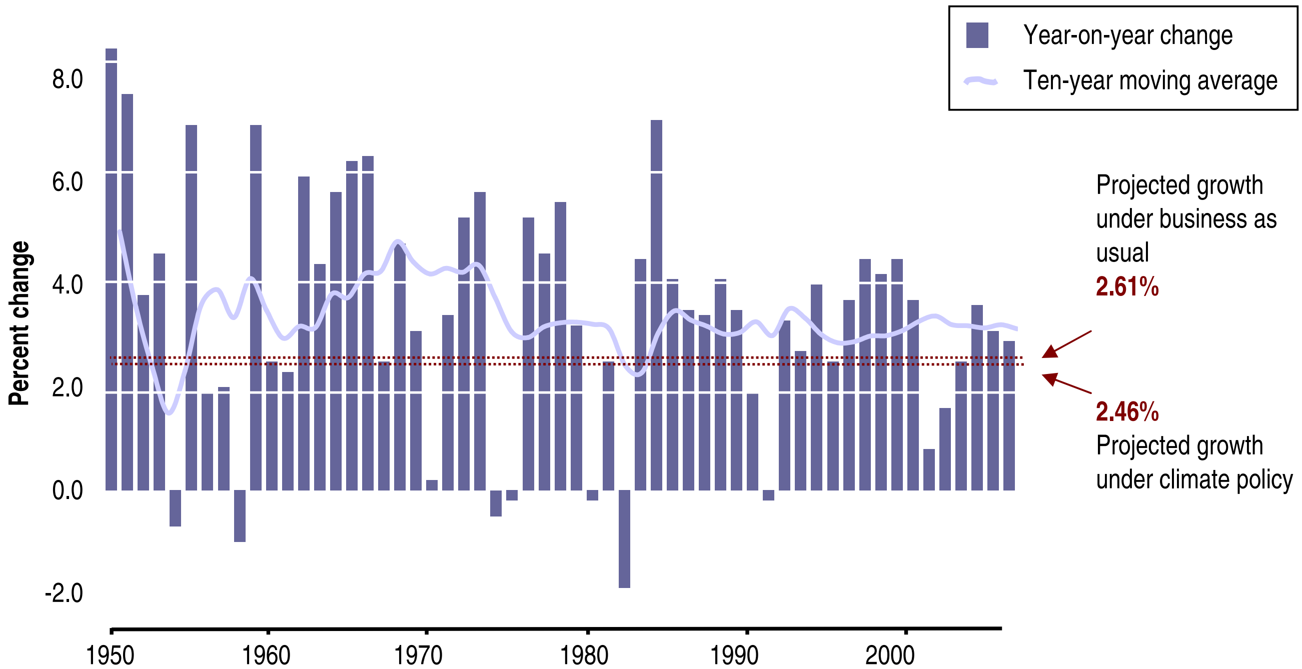


Figure 3.3 depicts postwar U.S. economic growth. The bars are annual changes; the solid line is a moving average for the previous ten years. The dashed lines compare projected growth rates under business as usual and climate policy for the IGEM model—the model in which that difference is largest. (Source: Annual GDP changes are taken from the chained U.S. GDP data series, Bureau of Economic Analysis.)

which as we've noted is an outlier in terms of GDP impacts—anticipates a reduction in annual growth rates of just fifteen basis points (0.15 percentage points).

How do these estimates stack up against the performance of the U.S. economy? Figure 3.3 shows U.S. economic growth over the postwar period—both in terms of year-to-year changes (bars) and a ten-year moving average of the growth rate (solid line). The dashed lines indicate the forecasted growth rates in the IGEM model under the business-as-usual and Lieberman-Warner scenarios. (We chose the IGEM model because the effects of climate policy in the other analyses are too small to see on the graph.) The take-away message from Figure 3.3 is that the projected impact of climate policy is miniscule relative to the "natural" yearly or even decadal swings in the growth rate of the economy.

Thinking in terms of growth rates provides a useful frame for understanding the projected impacts of capping greenhouse gases. In the models considered here, the U.S. economy is projected to grow at an average annual rate of 2.5 to 3% (at or somewhat below its average postwar pace). At that pace, it takes ten to twelve weeks to close a gap of 0.58% (the median reduction in GDP in 2030 relative to business as usual).

> Economic models predict that U.S. GDP will reach $26 trillion around January 2030, under business as usual. With a carbon cap, it will get there by April.

The estimates can be thought of this way: Under business as usual, according to these models, the total output of the U.S. economy will reach $26 trillion by January 2030. With a cap on greenhouse gases, the economy will reach that level by April.

We stated that addressing global warming will not be free. What is more surprising is how affordable it will be—even if we take ambitious steps to curb our emissions. The guidance offered by models strongly suggests that the impact of climate policy will be a far less significant factor than other dynamic forces that drive jobs and growth. The bottom line from these economic forecasts is that any drag on the economy from climate policy will be insignificant, and very possibly too small to measure.

4 Impacts on Families

The previous chapter showed how small the projected impact of capping carbon will be on the U.S. economy as a whole. But overall economic indicators like GDP can seem pretty abstract compared with the cost to the American family. What will be the impact on energy bills, household expenditures and jobs? What follows is a look at the impacts of capping greenhouse gases through the prism of the economic factors and decisions facing the family.

Household energy budgets

Over the next few decades, as the economy undergoes its transition to a low-carbon world, we will continue to burn fossil fuels—but the costs of those fuels will reflect the carbon dioxide being pumped into the atmosphere. Taking those true costs into account will level the playing field and encourage the development of new, cleaner sources of energy. How will it affect household energy budgets?

ELECTRICITY

The most direct impact on households is likely to come in the form of higher electricity bills—reflecting the centrality of fossil fuels in general, and coal in particular, to our current electric power infrastructure. To estimate this impact, we look first to the EIA analysis, because it is the only one to forecast residential energy consumption as well as prices. The EIA study forecasted an increase of $3.30 (about 3.5%) in the average household's monthly electricity bill under Lieberman-McCain, relative to business as usual, over the period 2012-2030.[13]

The monthly increase is the product of two factors. The first is the direct effect of climate policy on the price of electricity per kilowatt hour. The second is the fall in consumption that will follow, as households respond to higher prices by cutting back on electricity, through the use of energy-efficient appliances and other energy-saving measures. This latter "substitution effect" is crucial to understanding the overall impact of climate policy on household budgets.

To illustrate the fundamental different between energy *prices* and energy *bills*, we can take a look back at actual household spending patterns. The average American household's monthly electricity bill was virtually the same in 1990 as in 2005 (after adjusting for inflation)—even though the average residential electricity price was 24% *higher* in 1990 than in 2005. In other words, even though electricity rates were substantially higher fifteen years ago, the average American family spent no more on electricity than they do today.[14]

In the same way, looking forward in time, a given percentage rise in energy prices will lead to a much smaller change in energy bills. This principle is evident in the EIA's projections of future household energy expenditures. The EIA projects electricity prices in the year 2020 to be 9% higher than business as usual under the Lieberman-McCain legislation. But the EIA also expects electricity consumption to be 6% lower than it would otherwise be. The net effect is a projected increase of just 2.4%—about $2.30—in monthly electricity bills in that year.

These results show how increases in energy efficiency can help offset increases in electricity rates. In fact, under plausible assumptions, the gains from energy efficiency could result in cost savings to consumers. To illustrate this point, the Clean Air Task Force commissioned an analysis of the Lieberman-Warner bill, using EIA's own model. To represent the bill's provisions to stimulate investment

Figure 4.1: Average household energy bills, 1990-2005 with projections to 2030

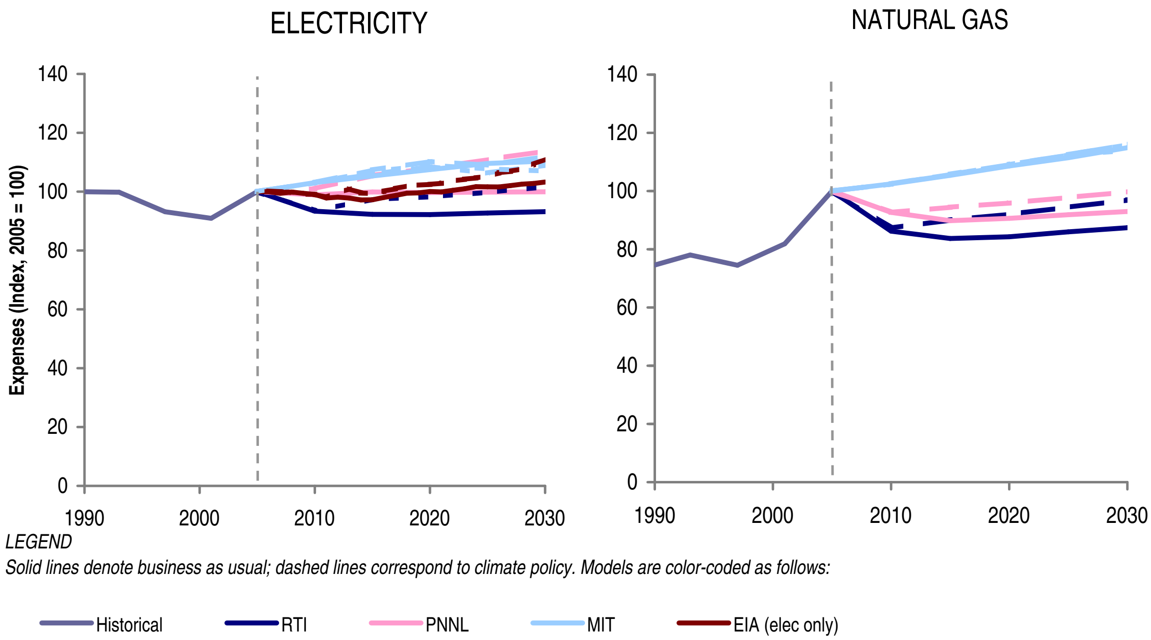


Figure 4.1 presents estimated average household energy bills for electricity (left-hand panel) and natural gas (right-hand panel), according to various model forecasts for a range of scenarios. (Source: Budgets for 1990-2005 are based on data from the EIA's Residential Energy Consumption Surveys. Estimated energy budgets for 2005-2030 in EIA's analysis are based on reported projections for price and quantity. Estimated energy budgets for the other analyses infer quantity from projected prices. See text for details.)

and innovation in energy efficiency, CATF assumed that the legislation would lead to more widespread use of energy-efficient equipment—household appliances, lighting, heating systems, and the like—in the residential and commercial sectors. As a result, in the CATF analysis household energy bills go *down* under Lieberman-Warner, relative to business as usual. Like any single modeling result, this one depends on the underlying assumptions. But it illustrates the importance of taking energy consumption—and not just price—into account when considering the impact of climate policy on household energy bills.[15]

Computing the projected change in monthly electricity bills is more involved for the other analyses, which (unlike EIA's model) do not forecast household consumption. However, we can obtain back-of-the-envelope estimates of consumption from the price changes projected in the analyses by RTI, PNNL, and MIT.[16] The key step in relating price changes to consumption changes is determining the sensitivity of energy demand to price—what economists call *price elasticity*. As we've already noted, when the price of energy rises, people consume less. If we know the size of this effect—that is, the price elasticity—then we can compute how a given change in prices will translate into a change in consumption, and therefore into a change in household budgets.

For our analysis, we use two different estimates of price elasticity to arrive at two different forecasts of how climate policy will affect household budgets. As a first cut, we use the long-run price elasticity implied by EIA's model, and apply it to the differences projected by the other models in the price of electricity under business as usual and climate policy. Using this approach leads to a projected increase in monthly electricity bills of around 10% relative to business as usual in the year 2030—as low as 6% in the MIT analysis of Lieberman-Warner, ranging up to 13% in the RTI analysis of the 50%-below-1990 policy.[17] While these are very rough numbers, they impart a general sense of the costs. They also underscore the importance of accounting for how households would respond to higher prices.

We can arrive at a slightly more sophisticated back-of-the-envelope estimate of household electricity budgets by looking at the predicted price path within each scenario. This approach relies on the price changes over time—for a given policy—rather than looking at the price differential across policies in a particular year.[18]

Figure 4.1 shows how these estimated impacts compare with recent experience. The left-hand panel plots past and projected household electricity bills for an average American household, calculated in constant-dollar terms and expressed as an index relative to actual 2005 budgets. Figures for 1990 to the present reflect actual data on prices and consumption, while the figures for 2005 to 2030 are the projections discussed above. The effect of climate policy predicted by any one model is given by the vertical gap between solid and dashed lines of the same color.[19]

> The median projected increase in the average household's electricity bill for the period 2010-2030, across a range of models, is just $3.30 per month.

As Figure 4.1 illustrates, while climate policy is expected to raise electricity bills somewhat, the effect is fairly modest. Over the period 2010-2030, the median projected increase in the average household electricity budget relative to business as usual, across all of these models considered here, turns out to be the EIA's forecast—just $3.30 a month, or about 3.5%. (The average projected increase is $3.15.)

Moreover, the electricity bills implied by all of the models fall well within the range of recent experience. For example, the most recent analysis of the Lieberman-Warner bill (by RTI) suggests that households would spend about the same amount on electricity under climate policy, in real terms, as they did in 2005.

In considering these forecasts, it is also worth keeping in mind the difficulty of predicting technological change. This challenge arises with particular force in the area of electricity generation. Under a cap-and-trade program, the enormous economic rewards to be gained from producing clean power will provide ample incentive for entrepreneurs to find better ways of doing so. But many models fail to capture that. For example, MIT's long-run forecast of electricity generation from renewable sources other than hydropower (wind, solar, and biomass) is the same under business as usual as under any climate policy—including the most ambitious. The likely result of this inability to model adequately the sweeping power of technological change—endemic to economic forecasting—is to overstate the costs of capping greenhouse gases.

NATURAL GAS AND HOME HEATING OIL

While any cap on greenhouse gases is likely to raise electricity prices, the consequences for other household energy sources, like natural gas and home heating oil, depend on the details of policy design. For example, some proposals (including the Lieberman-McCain bill) have been advanced that would exempt the residential sector from the cap-and-trade program. Such a policy would likely reduce household expenditures on heating oil and natural gas, rather than raising them.

Although surprising at first, upon reflection this makes a great deal of sense. An important consequence of a carbon cap will be to dampen demand for fossil fuels, as energy users cut their own consumption and shift to carbon-free sources. And as is true in any market, lower demand means lower prices. If residential customers are exempted from paying the cost of carbon allowances in the fuels they consume directly, they are likely to end up paying less for those fuels than if there were no constraint on carbon at all and the fuels were in high demand. Of course, if residential emissions are covered by the cap, residential energy prices are likely to rise.[20]

As we saw in the case of electricity, the change in monthly bills represents the combination of two factors: a rise in price and a corresponding reduction in consumption. Just as we did before, we can use price forecasts, along with an estimate of how sensitive energy demand is to price, to gauge the likely impact of climate policy on household energy bills. Doing so leads to estimated increases in the year 2030 on the order of 5% for home heating oil and 14% for monthly natural gas bills, relative to business as usual, although there is considerable variation among the models.[21]

> The recent run-up in natural gas prices had a larger impact on household spending than the cumulative impact of climate policy projected over the next twenty years.

As we did for electricity, we can also infer consumption from the year-to-year changes in prices forecasted by these models. The right-hand side panel of Figure 4.1 plots the corresponding household expenditures on natural gas. Importantly, all of the policy scenarios considered in the figure assume that natural gas would be included under the cap-and-trade program.

Once again, the projected effects on household budgets are modest. Using this approach, the median impact on household natural gas bills over the period 2010-2030 is just $2 a month (approximately 2.7%); the average impact is only slightly higher, at $4 a month.[22] And as was the case with electricity bills, projected expenditures under climate policy are in line with what households currently pay. As the figure shows, PNNL's analysis and both RTI studies project that household natural gas bills will be *less* than they were in 2005, with or without climate policy. While the MIT model foresees rising budgets over time, the predicted effect of climate policy is very small—less than a dollar a month, by our calculations.

The historical data presented in Figure 4.1 also helps to put these estimates in context. As the figure reveals, the modest increases in energy budgets forecasted to occur under climate policy are small relative to the changes that American families are already familiar with. In particular, the run-up in natural gas bills due to rising prices between 2000 and 2005 swamps the cumulative forecasted effect of a carbon cap on natural gas prices over the next 20 years.

GASOLINE PRICES

Figure 4.2 shows the projected impact of climate policy on gasoline prices at the pump. (The figure shows projections from EIA's analysis of Lieberman-McCain because they are on an annual basis, and allow for an estimation of forecast uncertainty, as discussed below.) The jagged line plots monthly average retail gasoline prices in the United States from 1973 to 2007. From 2007 through 2030, two projections are shown: one corresponding to business as usual, the other to caps on greenhouse gases.[23]

As the figure shows, a climate policy such as that proposed in the Lieberman-McCain legislation is projected to add about 16% to the price of a gallon of gasoline at the pump in 2030 (an increase from $2.21 to $2.56 per gallon, expressed in year-2005 dollars). This is actually somewhat larger than the impact projected by the other analyses: The median forecast for the studies discussed here is an increase of 13%, relative to business as usual, in the year 2030.

Figure 4.2: U.S. average retail gasoline prices, 1973-2006 with projections to 2030

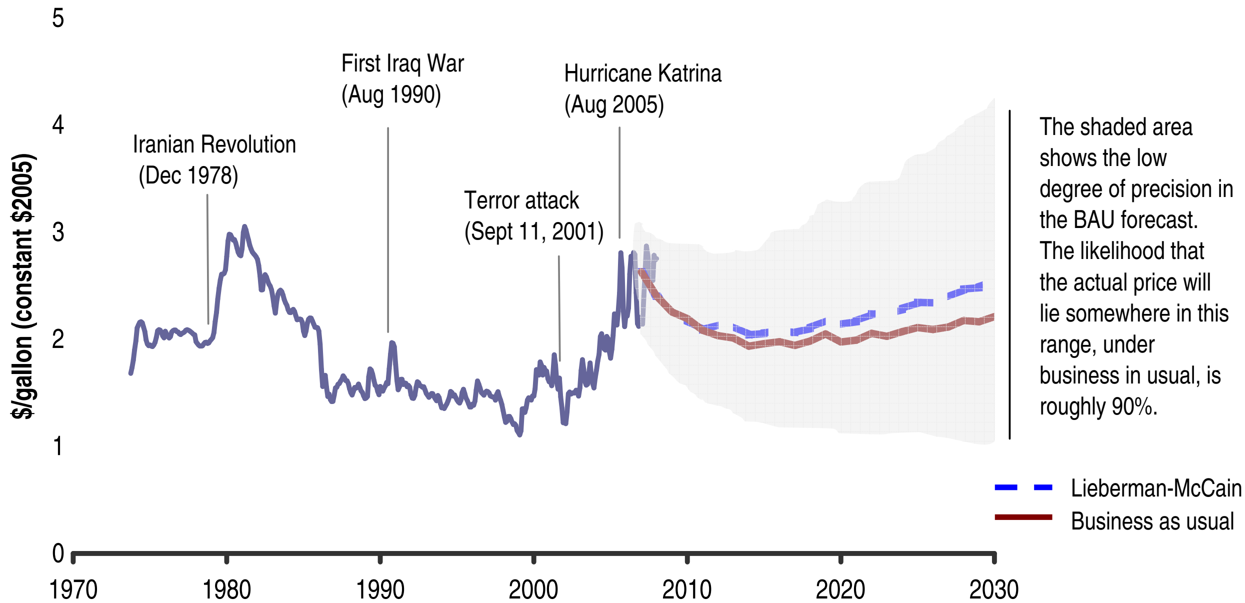


Figure 4.2 shows the average price of gasoline at the pump in the United States. The shaded area shows the precision of the forecast, based on historical volatility. See text for discussion of gasoline price projections from other models. (Source: Prices for 1973-2006 are historical data from the EIA; prices for 2006-2030 are EIA projections.)

Of course, nobody really knows what gasoline prices will be next year, let alone 20 years from now. As Figure 4.2 shows, gasoline prices have been volatile over the past several decades, responding sharply to weather events and geopolitical conditions.

A recent reminder of this volatility came early in 2007, when average retail gasoline prices rose $1.10 per gallon, or more than 50%, between the end of January and the end of May—simply because of a combination of refinery outages, a drop in imports (partly due to a strike at a French port), and high consumer demand.[24] That sharp increase—which came on the heels of a similarly sharp run-up and decline in prices a year earlier—dwarfs the estimated impact of climate policy from now to 2030.

THE CHALLENGE OF PREDICTING ENERGY PRICES

One key question for evaluating these price forecasts is this: How large is the projected effect of capping carbon relative to the ups and downs inherent in energy markets? The more volatile prices are, the harder it is accurately to predict what they will be in the future. The shaded area in Figure 4.2 illustrates this basic point. Using past movements in gasoline prices as a guide, and taking EIA's reference scenario as a best guess, the likelihood that actual future prices fall inside this area—assuming business as usual—is roughly 90%.[25] Of course, the EIA projection represents the expected change in gasoline prices from capping greenhouse gases, relative to business as usual. What the figure shows is that this projected impact is small relative to historical experience and relative to the precision (or lack thereof!) of our best guesses about future prices. (One important factor that is not captured in these economic forecasts is: To the degree that capping carbon reduces the use of imported fossil fuels, it may help moderate the severity of gas price shocks.)

ASSISTING THE MOST VULNERABLE HOUSEHOLDS

We have shown that on average, a cap-and-trade program for greenhouse gases is expected to have only a modest impact on household energy expenses. However, the ability of individual households to bear these increased costs will vary greatly across the spectrum of income. Unless climate policy is carefully designed, its impacts may be felt disproportionately by low-income households. For most households, an increase in the cost of electricity on the order of a few dollars a month would be relatively easy to absorb. But such a rise in electricity costs would be felt adversely by families who are already struggling.

Because the effects of climate policy on economic growth are so small in aggregate, there is no question that we can afford generous measures to help low-income families.

The proper response is neither a shrug of the shoulders nor a retreat to inaction, but rather a firm commitment that we will make this transition to a low-carbon economy in a way that protects the most vulnerable among us. This could be done through a package of policies—including not only generous funding of home energy assistance programs, but also an expansion of the earned income tax credit and extension of aid through existing electronic benefit transfer systems. In this context, it is worth remembering the good news from our earlier analysis of overall economic impacts. Because the effects of climate policy on economic growth are so small in aggregate, there is no question that we can afford generous measures to help low-income families.[26]

Household consumption

For the bundle of goods and services consumed by an average household, capping carbon is expected to raise prices slightly, as the effects of higher energy prices ripple through the economy. The anticipated effect is modest. For example, the EIA model provides a forecast of the consumer price index; in its analysis of Lieberman-McCain, EIA predicts that in the year 2030 consumer prices will be 1.69 times their levels in 2005 if a cap is enacted, compared with 1.66 times the 2005 level under business as usual. This translates into an increase in prices of 2% in the year 2030 attributable to a cap on greenhouse gases. The other models considered here do not report consumer price indices; but analyses in the economics literature have estimated impacts of similar magnitude.[27]

The simple rise in the price index, however, misstates the practical effect on households. That is due to one of the basic principles of economics: When the price of a good rises, people buy less of it and consume more of other goods in its place. Capping greenhouse gases will make carbon-intensive goods relatively more expensive; in response, households will substitute relatively cheaper ones. For example, as we have discussed above, in the face of higher electricity prices, households can reduce energy consumption by buying energy-efficient appliances. As a result, the impact of carbon caps on total consumption—the real value of goods and services bought—will be much less than the rise in prices. In its analysis, for example, EIA found that real household consumption would be only 0.4% lower in the year 2030 with carbon caps than under business as usual.

A more relevant metric for most households is the effect on consumption from 2010 through 2030, rather than the effect in any one year. Using an annual discount rate of 3%, the present value of household consumption in EIA's forecast falls by just 0.3% relative to business as usual. The other models produce similar results, ranging from 0.2% in the RTI analysis of Lieberman-Warner to 0.9% in the MIT analysis of the most stringent policy (achieving 80% reductions below 1990 levels); the median estimate is 0.47%.

Figure 4.3: Protection expenditures in the American household's budget

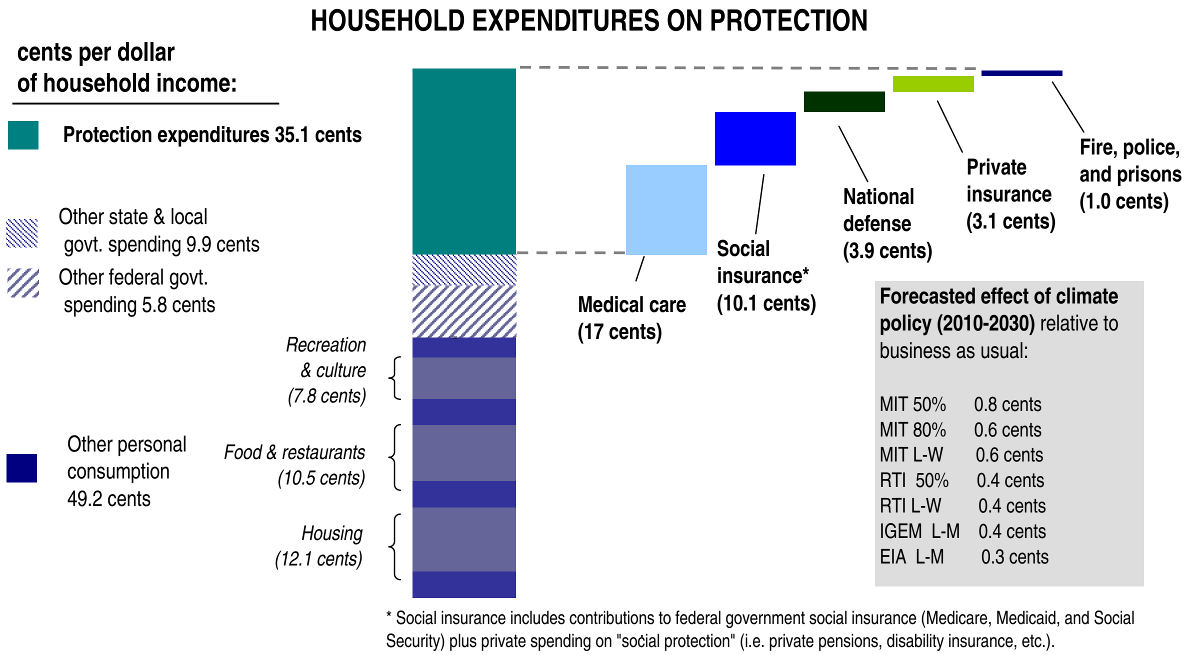


Figure 4.3 depicts spending by the average American household. The left-hand side bar breaks down the average household's dollar of income. The bars on the right side of the figure show how much of each household's dollar of income is spent on household protection and security, whether directly (e.g. private insurance), indirectly via government (e.g. fire and police, national defense), or in some combination (e.g. medical care). (Source: Authors' calculations using data from the Bureau of Economic Analysis, the Census Bureau, and other sources; see note 28.)

THE HOUSEHOLD CONSUMPTION NUMBERS IN CONTEXT

A useful way to put these consumption forecasts in context is to compare them to what Americans already spend to protect themselves and their families. This may take the form of health care, or fire and property insurance, or tax payments that go to hospitals or police and fire services. Spending on climate security—protecting ourselves against potentially catastrophic climate changes—falls in the same category.

Figure 4.3 shows how much of every dollar of household income an American family spends, on average, on protection and security.[28]

The middle bar represents a dollar of household income; the three largest categories of "Other personal consumption" (recreation, food, and housing) are highlighted. The bars on the right show what the average household spends on protection and security. (Note that personal savings is near zero for the average American household, and thus does not show up on the chart.)

On the same chart, we have shown how the reduction in household consumption forecasted by the various models (in terms of the present value of consumption over the period 2010-2030) stacks up against those other household expenditures. To provide an apples-to-apples comparison, we compute the estimated effect of climate policy on consumption in terms of cents per dollar of household income. (Doing so scales down the numbers by the percentage of income that goes to consumption, which is 85%.)

As the figure shows, capping greenhouse gases will add only a small amount to the current level of household spending on such protection. The estimated reduction in consumption due to carbon caps amounts to a fraction of a cent for every dollar of household income. Even in the most ambitious scenario (the MIT 80% below 1990 policy), the effect is substantially less than a penny on the dollar.

> The estimated reduction in household consumption due to a carbon cap amounts to less than a penny for every dollar of household income.

By way of comparison, on average more than three cents of every dollar of household income go towards private insurance, almost four cents go towards national defense, and a penny goes to fire and police.[29] And these expenditures pale compared to spending on medical care (including government spending on hospitals and household spending on medical treatment and equipment) or social insurance programs such as Social Security.

Jobs

Detailed estimates of the job impacts from capping carbon are few and far between: Most economic models do not attempt the level of precision required to estimate employment, especially at the industry level. The EIA's model is the only one of the group considered here that does make job projections. (Our earlier warning about not relying on just one model remains valid; these numbers should be seen as illustrative.) In its analysis of the Lieberman-McCain bill, EIA forecasted a reduction of 60,000 jobs by the year 2030—relative to total employment of 170 million. That represents a drop of less than 0.04%—insignificant relative to the precision of the model itself. Simply put, the analysis suggests that a cap on greenhouse gases will have essentially no effect on the number of American jobs.

THE MANUFACTURING SECTOR

Although total employment is not expected to change, the impact will vary across sectors. And the manufacturing sector—the most energy-intensive sector of the economy—is likely to feel an impact. The hard truth is that those jobs are already being lost, not only relative to the rest of the economy but also in absolute terms. The number of manufacturing jobs in January 2005 (14.1 million) was well below its peak of nearly 20 million in late 1979, and only slightly higher than the number in January 1950 (13.1 million)—even as total employment in the economy had nearly tripled.

Causes of the decline in manufacturing include a shift in consumer spending away from manufactured goods, in favor of services; a steady increase in labor productivity, which allows firms to produce more with fewer workers; and competition from foreign producers.[30]

These are fundamental changes in the structure of the U.S. economy. They have undeniable impacts on American families, and deserve to be addressed by public policies designed to distribute more widely the gains from increasing productivity and international trade. They are real, they are already taking place, and they will continue to unfold regardless of what we choose to do about global warming.

THE DYNAMIC AMERICAN ECONOMY

Despite these structural changes, the American economy remains the most dynamic in the world. According to data from the U.S. Census Bureau, since 1950 the U.S. manufacturing sector has generated new jobs at an average rate of nearly 6% of employment every quarter—while other jobs have been destroyed at nearly the same rate.[31]

The numbers for annual job flows tell a similar story: Each year, newly created jobs represent about 9% of total manufacturing employment in this country, while job losses amount to 10%.[32]

Figure 4.4: Employment and "job churn" in U.S. manufacturing, 1950-2005.

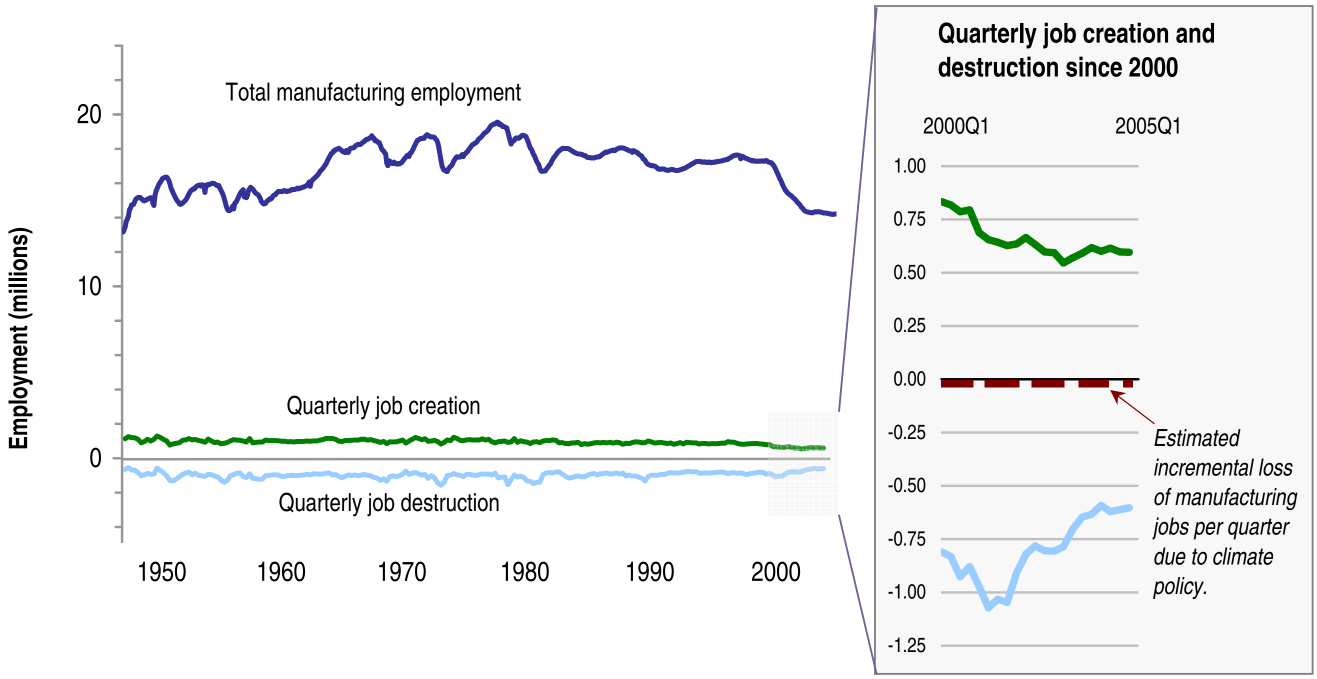


Figure 4.4 shows monthly employment and quarterly job creation and destruction, for the U.S. manufacturing sector. The inset plots the projected impact of climate policy along with recent job creation and destruction. (Source: Authors' calculations based on data from the Bureau of Labor Statistics and the Census Bureau; see note 33.)

Against this dynamic backdrop, what will be the impact of climate policy? Again, we rely on EIA's analysis for some insight. That study predicts that total manufacturing employment will be 12.5 million in the year 2030 under business as usual, versus 12.2 million with a cap on greenhouse gases—a difference of 2.5%. (Note that both numbers represent a continued absolute decline in manufacturing relative to today's level.) In other words, the total number of manufacturing jobs projected to be lost over 20 years due to capping greenhouse gases is substantially below the rate of jobs created and destroyed in the economy *every three months*.

Figure 4.4 puts these numbers into historical perspective. The top line in the main graph shows total manufacturing employment from 1950 to 2005; the areas on the bottom indicate the "job churn," or gross job creation and destruction.[33] The inset at right, with magnified scale, shows how the projected incremental impact of climate policy on manufacturing jobs stacks up against recent job creation and destruction.

> Nearly twenty percent of manufacturing jobs are created or destroyed every year—ten times more than the cumulative projected impact of climate policy over two decades.

On an annual basis, the incremental effect of climate policy is projected to be on the order of 0.14%—less than *one-hundredth* of the number of jobs that are created or destroyed in the manufacturing sector every year. Capping greenhouse gases may create a slight drag on manufacturing jobs over the next two decades; but this impact will be overwhelmed by the natural flux of jobs created and lost as part of the fundamental dynamics of the economy.

5 Lessons from History

The previous chapters demonstrate that a thoughtful assessment of economic models, taking into account their strengths and limitations, concludes that the costs of capping greenhouse gases will be small and manageable over the next few decades—the transition period during which we can slow, stop and then begin to reverse growth in greenhouse gas emissions.

Nonetheless, stabilizing the climate will require a fundamental shift in the world economy. The models may predict a modest impact—but they also assume that we have the political will to take action *soon* to cut greenhouse gases, to drive the investments in new technologies and new infrastructure that will be needed to see this job through.

The challenge of global warming is of a different magnitude than that of other environmental problems like acid rain or even the ozone hole. It is not localized, either in space or in time; it is a global problem stretching over many decades that will affect broad strands of everyday life. The scale of the solution corresponds to the scale of the challenge: To avert the catastrophes that might attend a changing climate, we will have to convert our economy from one reliant on fossil fuels to one driven by low-carbon technologies, some of which have yet to be developed. In the short-run, the costs of this transition will not be significant. But can we make a long-term, fundamental transition of this magnitude successfully?

To explore this question, we turn to the past for guidance. While the scale of the challenge before us is daunting, the lessons of history provide a basis for optimism. We have undergone a number of economic transformations over the past century, and each time have emerged stronger than before. The only constant is that technological change is the engine of our economy: we have been at the forefront of every major technological revolution of the past century. Our continued prosperity depends on our willingness to lead the world into the next great technological revolution: the low-carbon economy.

The mobilization for World War II

The most useful historical analogy is a surprising one: the mobilization of the American economy to fight World War II. In the space of two years, virtually the entire American economy was redirected. Private companies were asked to produce different goods, and had to work out how to do that against deadlines that at first looked impossible. The ramp-up in production involved in this mobilization was breathtaking. Consider the Army Air Force, which had 2,400 aircraft in service in the fall of 1939. By the end of 1941, that number had increased five-fold; in 1942, the Air Force added more than 20,000 aircraft, and in 1943 another 30,000. At the peak of the war, in mid-1944, the total air fleet was 80,000.

The task of making such a fundamental change in direction affected the entire economy. Detroit converted its auto factories to munitions production. Fireworks factories made military explosives; basement lathe shops switched from gas meters and potato chip machinery to gun barrels and cartridge cases; the AC Gilbert company in New Haven put its tiny model electric-train motors to work operating airborne navigational instruments (Hoehling 1966). As Roosevelt said in his "Arsenal of Democracy" speech of December 29, 1940:

> American industrial genius, unmatched throughout all the world in the solution of production problems, has been called upon to bring its resources and its talents into action. . . But all of

> our present efforts are not enough. We must have more ships, more guns, more planes—more of everything. And this can only be accomplished if we discard the notion of "business as usual."

That transformation was accomplished in roughly two years. If we do not waste our scarcest resource—time—we have perhaps a quarter of a century in which to complete the transition to a low-carbon economy.

A TALE OF TWO INDUSTRIES: RUBBER AND SHIPS

The tales of two major industries transformed by wartime mobilization effort remind us what can be accomplished by American determination and ingenuity. The first is the synthetic rubber industry, which had to be created virtually from scratch after Japanese conquests in the Far East cut off supplies of natural rubber. Before 1941, only a few thousand tons of synthetic rubber were produced each year, strictly for niche applications such as cable casings. By 1944, domestic production had reached 765,000 tons a year, almost 90% of it for general-purpose use. By the mid-1950s, synthetic rubber was higher in quality and cheaper to produce than natural rubber, and accounted for more than half of U.S. rubber consumption.[34]

The other story concerns the Liberty ships built to supply Europe and overwhelm losses from German U-boat attacks. In 1941, American shipyards produced 1.1 million deadweight tons of shipping. In 1942, total output was 8 million tons; and in 1943, it exceeded 19 million tons (Elphick 2001). This staggering rate of growth was made possible in large part by a remarkable improvement in the rate of production resulting from economies of scale and learning-by-doing. During World War I, cargo ships a third smaller than the Liberty ships took 10 to 12 months to deliver. At the start of World War II, the first Liberty ship took almost as long—244 days. By 1944, the average production time was 42 days, and some yards were turning out new ships every 17 days.[35]

These cases represent two very different but equally powerful stories of sweeping technological change—change that proceeded at a pace unfathomable until it actually occurred.

Technology and U.S. economic growth

The history of WWII teaches us that American ingenuity and innovation have achieved tasks that were considered impossible. We have undertaken large transitions before, and we have done it in considerably shorter time periods. It is difficult to believe that we could not successfully undertake the transition to a low-carbon economy over a period of 25-30 years if we set our minds to it.

A second lesson is that the engine of progress in the American economy is technological innovation. We emerged from World War II with a lead in technology that we have retained ever since. We have led the way in the major economic transitions of the past century: the emergence of wide-scale mass production; the development of semiconductors; the space age; the Internet age.

> Technological innovation is the engine of progress in the American economy.

The story of the semiconductor era captures the vital importance of technology to U.S. economic growth. From the invention of the transistor at Bell Laboratories in 1948, to the introduction of silicon and the development of integrated circuits in the 1950s and 1960s, to the emergence of logic chips in the 1990s—at each stage, the United States has led the world, and our technological leadership in this area has been the foundation for postwar growth.

THE IMPETUS FROM ECONOMIC INCENTIVES

But history also teaches that innovation does not just happen: It responds to incentives, including the basic economic drivers of demand and price.

The example of the synthetic rubber industry provides an illustration. The basic techniques to synthesize rubber had been known for years before World War II; only when natural rubber became scarce did firms have an economic incentive to develop that technology and improve upon it. Once that incentive materialized, firms not only scaled up production—they also figured out how to make synthetic rubber that was cheaper and better than the natural product.

> Innovation does not just happen: It responds to incentives, including the basic economic drivers of demand and price. In the case of carbon, those incentives must be created by a hard cap on emissions.

Similarly, the rise of the U.S. semiconductor industry shows how the lure of large-scale demand can be a powerful incentive for private investment. The military provided the market boost to help the industry develop in the 1950s and 1960s, giving it an early lead it never relinquished. In the case of low-carbon technologies, the government has a different but equally important role to play. A hard cap on carbon emissions will guarantee demand for cutting-edge technologies, harnessing the same forces of innovation and change that propelled the semiconductor industry half a century ago.

The moonshot proposed by President Kennedy in 1961 is equally instructive, in a different way. We committed to a national goal of landing a man on the moon by the end of the decade, and we made that commitment at a time when the Russians were ahead in the space race. In the race to a low-carbon economy others, notably the Europeans and the Japanese, are ahead of us today. But the race will be long, the ingenuity and power of the American economy are huge, and if we begin soon, there is still time to get there in the front ranks rather than somewhere behind the leaders.

The power and pace of technological change

Technological change stimulates shifts in the way goods are produced, declines in their cost and changes in the types of goods produced. Such changes are nearly impossible to model, and this is why so many economic transitions wind up actually creating jobs and generating growth, whereas predictions, which have difficulty taking technical change into account, often forecast more pessimistic outcomes.

The only certainties about technological change are that it will happen, that it will be powerful and that we won't know in advance how it will happen.[36] A directly relevant example of this principle is provided by the response to the 1990 Clean Air Act Amendments, which established a market in emission allowances for sulfur dioxide, the pollution that causes acid rain.

The costs of the program have turned out to be a fraction of what was predicted because of technological innovations that no one foresaw. Some of these represented major breakthroughs, as when a team at General Electric working to improve methods of scrubbing sulfur dioxide out of smokestack emissions figured out how to oxidize the gas all the way to gypsum that could be sold for fertilizer or sheetrock. But innovations also arrive in more mundane form. One of the most important factors driving down costs came from the tinkering of anonymous power plant operators who figured out how to burn low-sulfur Wyoming coal in boilers designed for high-sulfur Eastern coal. Both of these innovations were spurred by emissions trading—firms who figured out ways to cut their emissions could profit by doing so.

REASONS FOR OPTIMISM

To meet the challenge of climate policy, we must start by capping carbon—effectively making something that has been abundant (fossil fuels) into something scarce. This paper has shown what economic forecasting and experience tell us: We can make the transition to a low-carbon economy without significant or measurable disruption.

In fact, we have been here before. In 1972, the Club of Rome published its pessimistic polemic *Limits to Growth*, predicting that we would run out of natural resources and face economic ruin. In response, the Yale economist William Nordhaus demonstrated that such "doomsday" predictions of economic collapse depended upon the extremely implausible assumptions that technological change would be minimal and that substitution possibilities were nonexistent.[37]

The arguments Nordhaus made more than 30 years ago apply with equal force to current debates about the prospects for economic growth in a low-carbon world. Once more the doomsayers are warning that steps to reduce carbon emissions and fossil fuel use will spell economic ruin. There is nothing in the numbers or in recent experience to suggest that the doomsayers are correct. The record of human ingenuity and economic history are against them.

6 The Implications for Climate Policy

In this analysis, we looked at different models, different assumptions and different slices of the economy. We considered everything from Gross Domestic Product to family budgets. Over and over again we got the same answer: Curbing our emissions of global warming pollution will have little impact on economic growth, household spending and jobs. In the long run, the transition to a low-carbon economy holds tremendous opportunity for the U.S. economy.

The one danger we detected was the possibility of hardship for the poorest families in our economy as a result of cost increases in electricity and home heating fuel. Further analysis is needed to determine the exact dimensions of that problem, but it is clear that the tools to address that hardship exist, and the resources to do so are easily available within the framework of a national carbon cap.

What, then, does a well-designed climate policy look like? What policy can most successfully maximize growth in jobs, productivity and the economy as a whole?

The elements of a well-designed climate policy:

- Predictable requirements for emission reductions, with a long time horizon, winding up at 70-80% below current levels.
- A transparent, fairly enforced, economy-wide cap-and-trade system that rewards innovation and punishes inefficiency in the marketplace and permits a wide range of offsets to drive the price of reducing emissions down.
- Removal of barriers and subsidies that artificially choke off the flow of investment in new technologies and processes.
- Measures to protect the poorest families from budget pressures that may arise from climate policy.

Positioning the United States to lead

A cap-and-trade system that embodies these strategic pillars will position the United States competitively for growth in the global transition to a low-carbon economy. It is an advantage for the United States that it will be starting before China, India and other emerging economies. We will have some catching up to do vis-à-vis Europe and Japan, which already have started down this road. But eventually all countries will join the international system to limit carbon emissions. The nations that take the lead in the hunt for low-carbon technologies will find that an enormous market awaits them.

Developing countries are likely to make this transition at a different pace—although they must make it eventually, and emerging powerhouses such as China should be urged to take on mandatory caps as soon as possible. To ensure a level playing field in the interim, it may be necessary to require countries without a cap to accompany exports to the United States and elsewhere with carbon allowances reflecting the greenhouse gas emissions associated with their manufacture.

The planet is going low-carbon. The die is cast, and a failure to invest and compete would haunt us for a generation or more. Failure to act would withhold the signals and incentives that can empower the American economy to modernize jobs, services and technologies, and allow the country to emerge from this next phase of global change and competition in the leadership position it holds today.

Appendix
A Consumer's Guide to Economic Models

Economic forecasts of the costs of global warming are sometimes presented as if modelers had a crystal ball that could perfectly foretell the future. Those at the other extreme reject economic forecasts out of hand, saying that since simplified models can never fully replicate the real world, why bother trying? We take the middle ground and try to apply the insights that the thoughtful use of models can offer.

An important starting point for any discussion about economic models is the wide variation in model results. Such variation stems from the inevitable disagreements about how to represent economic relationships, and reflects the strengths and weaknesses of different modeling groups. The lesson is that no single model has all the answers—and that no single number should be taken on its own. This Appendix provides a sort of "user's handbook" for interpreting model results and understanding the most important reasons why the models diverge.

For one example of variability in modelers' forecasts, consider 15 models that participate in the Energy Modeling Forum organized by Stanford University and the U.S. EPA. In a recent symposium (EMF21), these models contemplated a hypothetical international climate agreement starting in 2013 with the goal of stabilizing mean global temperature at 3 ° Celsius above pre-industrial levels.[38] (Note that this is a less ambitious policy than the set of policies considered in the main body of our report.) Figure A-1 shows the model forecasts of the resulting impacts on the U.S. economy, expressed as a percentage change in forecasted GDP vs. "business as usual" (i.e., without greenhouse gas controls).

The most pessimistic model (FUND) predicts a loss of GDP of just over 0.65% for the year 2030. At the other extreme, the AIM model foresees a gain of 0.21%. And all of the estimated impacts are small—less than 1% of GDP, 20 years from now.

What should we conclude from these wide disparities? All models are wrong, in the sense that no model can perfectly predict the future. But they are wrong in different ways, and those differences can teach us a great deal. Some models draw on a vast array of historical data to estimate economic relationships. Others include fine-grained models of the electric power sector to reflect the full array of generating technologies and to account for subtle but important factors such as "vintage effects" associated with infrastructure built at different points in time. Still others incorporate sophisticated land use modules, used to assess the potential for storing carbon in forests and farms. But no model does everything well—which means that all models have blind spots. The important thing is to keep their limitations in mind, and use them the way they were intended: as tools to inform policy making, rather than as reliable snapshots of the future.

Any economic model makes a host of assumptions about how the world works, and understanding these assumptions is critical to evaluating the model's forecasts. Responsible modelers advertise their assumptions, and defend their reasons for making them; if the assumptions are not (a) clear, and (b) explained, caveat emptor.

As an aid to interpreting the results of economic models, Table A-1 provides a checklist of seven key modeling assumptions that help to shape model forecasts. These are not the only assumptions that matter, of course—but they are among the most important.[39] The remainder of this Appendix explains these assumptions in greater detail.

One caveat: Any discussion of assumptions runs the

Figure A-1: Variation in estimated impacts of an international climate change agreement on U.S. GDP.

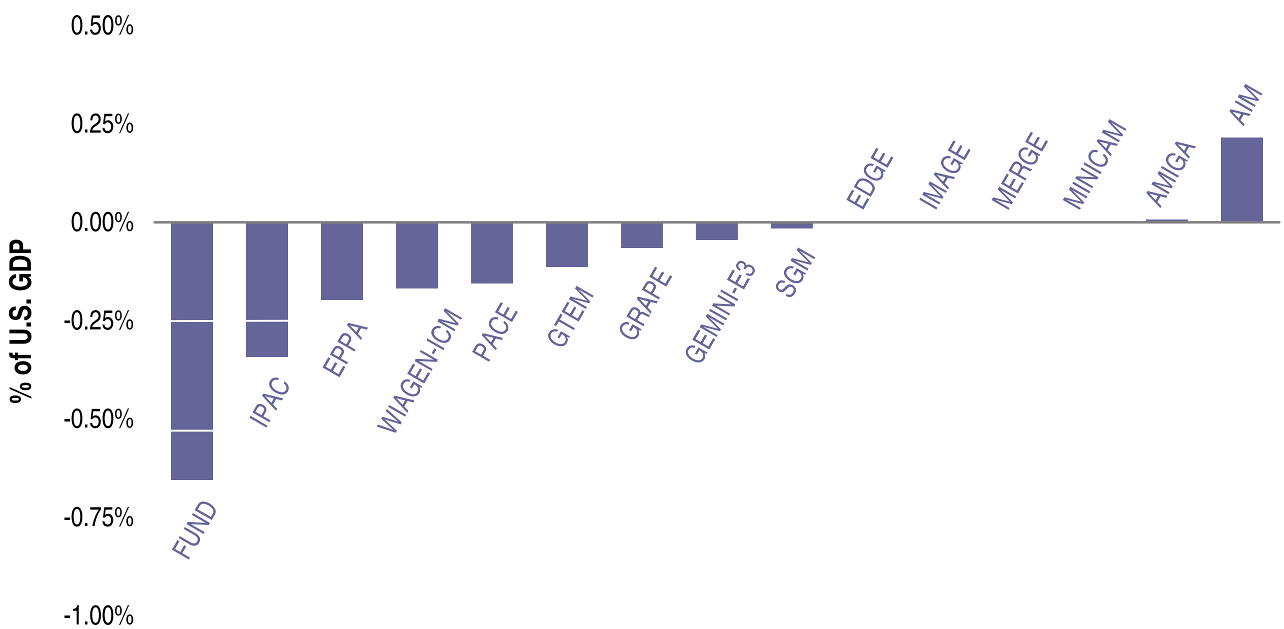


Figure A-1 presents the projected impacts of a global climate agreement on U.S. GDP in the year 2030, according to fifteen models that participated in Energy Modeling Forum-21. (Source: Data from De la Chesnaye and Weyant, eds.,"Multi-Greenhouse Gas Mitigation and Climate Policy," Energy Journal, Special Issue, November 2006.)

risk of overgeneralization. That applies with special force to any attempt (as in this Appendix) to reduce the many shades of nuance and subtlety to binary distinctions. There is of course a great deal of variation among models within the same category, and the specific choices a modeler makes can matter as much as the broader category in which the model ends up.

1. How fast do emissions rise under business as usual?

Economic models vary greatly in their expectations about what will happen to emissions in the absence of greenhouse gas controls. Figure A-2 illustrates this point. It shows the "reference scenarios" for the 15 Energy Modeling Forum models considered above—all meant to reflect business as usual. While projected emissions rise very slowly under the most "optimistic" models, they more than double under alternative sets of assumptions.

As the figure makes clear, what a particular model predicts to be business as usual depends on myriad assumptions. For example, models must make assumptions about future prices of fossil fuels: the lower the price, the more rapidly are emissions expected to rise. And they must determine the rate of energy efficiency improvements: the faster the rate of improvement, the slower the growth in emissions. No single one of these assumptions is necessarily more valid than another—nobody has a crystal ball. But they sum up to dramatic differences.

This divergence has a big impact, since the effort needed to reach a given stabilization target depends on what is assumed to happen in the absence of a climate policy. The greater emissions are assumed to be in the absence of policy, the more they need

TABLE A-1: Assumptions matter: Economic greenhouse gas model checklist

This table lists a set of key assumptions embedded in economic models of climate policy. The columns on the right describe the contrasting approaches used in different models, according to whether they are generally associated with higher or lower predicted costs of cutting greenhouse gas (GHG) emissions. Of course, these are complex assumptions, and boiling them down to "higher or lower cost" necessarily entails a number of important simplifications. See text for more detailed discussion.

ECONOMIC GHG MODEL CHECKLIST

Assumption	Lower cost	Higher cost
1. How fast do emissions rise under business as usual?	SLOW RISE	FAST RISE
2. How are market interactions modeled?	COMPUTABLE GENERAL EQUILIBRIUM	MACRO-ECONOMIC
3. How does the model treat technological change?	INDUCED TECH. CHANGE	EXOGENOUS TECH. CHANGE
4. How does the model represent available technologies?	BOTTOM-UP	TOP-DOWN
5. What is the potential for expanding electricity generation from renewable sources?	EXTENSIVE AND PRICE SENSITIVE	LIMITED, PRICE INSENSITIVE
6. How much substitution is allowed across sectors and regions?	MORE SECTORS	FEWER SECTORS
7. Which greenhouse gases are considered?	MULTIPLE GHGs	CO_2 ONLY

Figure A-2: Projected global CO2 emissions under "business as usual" for fifteen models.

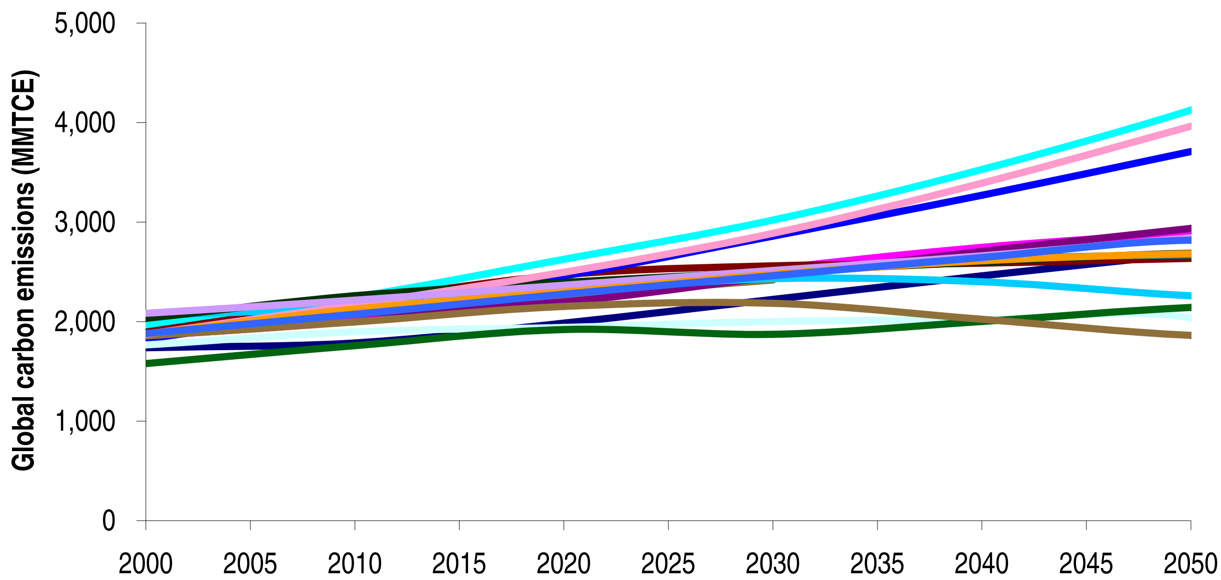


Figure A-2 shows the projections of global CO2 emissions made by the fifteen models in the Energy Modeling Forum in their reference scenarios. All projections correspond to "business as usual"; the wide variation demonstrates the disparities in underlying assumptions about economic growth, energy efficiency, and so on. (Source: Data from De la Chesnaye and Weyant, eds.,"Multi-Greenhouse Gas Mitigation and Climate Policy," Energy Journal, Special Issue, November 2006.)

to be cut—and thus the higher the absolute costs are predicted to be.

All else being equal, models that project rapidly rising emissions under business as usual tend to find reducing emissions is more costly in absolute terms.

2. How are market interactions modeled?

A model seeks to reflect the complex interactions of an entire economy. For example, how do the internal dynamics of models ensure that the demand for energy equals the supply? There are two widely used approaches to represent these interactions.

The first approach, called a computable general equilibrium (CGE) model, assumes that markets allocate resources and "clear" efficiently across sectors. This assumption allows CGE modelers to represent dynamic market interactions as a set of mathematical equations. The virtue of this approach is flexibility: Economic agents (firms and consumers) adjust to new circumstances, taking each other's responses into account, just as in real markets. A disadvantage is that it assumes a degree of market efficiency that is seldom present in the real world.

The second approach, used by "macroeconomic" models, relies on sophisticated statistical analysis to estimate relationships among market forces and sectors using historical data. The model then extrapolates these relationships into the future. The advantage of this "econometric" approach is that by drawing on a deep reservoir of data, the model incorporates historically tested costs and interactions into predictions of market behavior. This is especially attractive for short-term projections.

For longer time horizons, however, the econometric approach is overly constraining: It spins out fixed historical relationships, rather than reflecting new market interactions.

> The projected costs of combating global warming are typically lower in CGE models, which assume high levels of market efficiency.

3. How does the model treat technological change?

A cap-and-trade program for greenhouse gases will put a price on carbon, creating a powerful driver for investment and innovation in areas such as energy efficiency and renewable energy generation. A central challenge is how to represent this complex, volatile and poorly understood process of "induced technological change" in an economic model.

Because this challenge has not been fully mastered, most models assume that technological change is "exogenous"—that is, unresponsive to prices and policies. A typical approach is to assume that technological improvement will take place at a predetermined rate—often chosen to match historical improvements in productivity. Another device is to introduce a "backstop technology"—an externally assumed technological development (for example, large amounts of solar energy generation at a constant cost) as a general marker for overall technological innovation. Assuming that such a technology will become available brings down the estimated cost of meeting a given stabilization target. The crudeness of these "shortcuts" reflects both the primitive status of the ability of models to incorporate technological change and the imperative to "introduce" some sort of surrogate for this very powerful force.

Some models have begun incorporating induced technological change by assuming feedback loops between the price of carbon allowances and the pace of technological improvements. But these efforts are still in their early stages.

> Representing technological change and how it responds to economic drivers is one of the most difficult challenges modelers face. Models with "induced technological change" tend to predict more rapid deployment of new technologies, bringing down the cost of carbon mitigation.

4. How does the model represent available technologies and their adoption by firms?

Models can take one of two approaches to incorporating the adoption of available technologies by firms and consumers. "Bottom-up" models take explicit account of the suite of technologies available. For example, a bottom-up model of residential electricity demand would specify an array of specific energy-saving technologies that households could adopt, along with the carbon allowance prices that would make them attractive.

In contrast, "top-down" models incorporate technology choice implicitly, by drawing on past experience and observations about how consumers behave. A top-down model would forecast electricity demand by starting with information about how consumers (in the aggregate) have responded to past changes in electricity prices, and extrapolating that to the price changes that might occur under climate policy. Some models, such as the NEMS model maintained by the U.S. Energy Information Administration, take a hybrid approach—marrying a bottom-up model of a specific sector (e.g. the electric power sector) with a top-down model of the economy as a whole.

In principle, a top-down approach does not necessarily have to lead to higher predicted costs than a bottom-up structure. In practice, however, bottom-up models tend to predict more rapid technology adoption in response to the economic incentives created by a cap on greenhouse gas emissions. As a consequence, such models tend to predict lower costs associated with climate policy.

> Bottom-up models, which explicitly incorporate the suite of available technologies in a given sector, typically predict lower costs for capping carbon.

5. What is the potential for expanding electricity generation from renewable sources?

Because carbon constraints will have a direct impact on the price and consumption of fossil fuels, the share of electricity that can be generated from renewable sources will be a crucial factor in determining the cost of reducing greenhouse gas emissions. Hence the assumptions a model makes about the availability and cost of renewable energy sources are critical, even though they often are buried in a morass of technical detail.

Renewable energy sources have grown dramatically in the United States over the past decade, fueled by rising prices of natural gas as well as by government policies such as state-level "renewable portfolio standards." Whether that trend will continue to pick up steam, and how responsive it will be to global warming policies, are crucial questions.

As it turns out, different models answer these questions in dramatically different fashion. Figure A-3 shows the expected paths of renewable energy generation under three different models discussed in the main body of the report: MIT, RTI, and EIA. The figure compares the models' projections for the share of electricity generated from renewable sources under "business as usual" and climate policy. For MIT, we use projections from the most stringent climate policy, which would reduce emissions by 80% below 1990 levels. For RTI, we use the Lieberman-Warner projections; these are higher than for the "bounding analysis" done by RTI, because RTI revised its representation of the electricity sector in the interim. The EIA model refers to the Lieberman-McCain legislation; as a result, it depicts the *least* stringent policy scenario among the three analyses shown.

In the MIT model, the share of electricity from renewable energy under business as usual is constant over the next several decades, hovering around 8%. Even more striking is the lack of response to climate policy: for the year 2030, for example, the model projects that renewable sources will account for 7% of electricity generation under business as usual, but just 10% under a very ambitious climate policy. This lack of a response to policy stems from two features of the MIT model. First, like most models, MIT's EPPA model is calibrated to a single base year. In MIT's case, that year is 1997—meaning that key parameters in the model must be chosen to replicate the energy sector (and the rest of the economy) in that year. As a result, MIT's figures do not even reflect *current* renewable electricity generation. The second contributing feature of the MIT model is a technical assumption about the *elasticity of substitution* between renewable generation and electricity produced from conventional sources—that is, how readily electricity generated from wind and solar sources can replace electricity from fossil fuel and nuclear energy. The MIT model assumes a low value for this parameter, as a crude way of reflecting the intermittency of wind power, the dependence of solar power on sunlight, and so on.

In contrast, the other two models project more growth in renewables under climate policy. RTI estimates generation of 14% and 17% from renewables in the years 2020 and 2030, respectively—relative to just 10% under business as usual. (The RTI model has a similar structure as MIT, but assumes a somewhat higher value for the elasticity, and is calibrated to a base year of 2001.) The EIA model is even more optimistic. While it anticipates a similar growth in renewable energy sources under business as usual, it projects a much more robust response to a carbon cap like the one contained in the Lieberman-McCain bill (S. 280). Indeed, as Figure A-3 shows, under the EIA model's assumptions, renewable elec-

Figure A-3: Projected share of electricity generation from non-hydro renewable sources

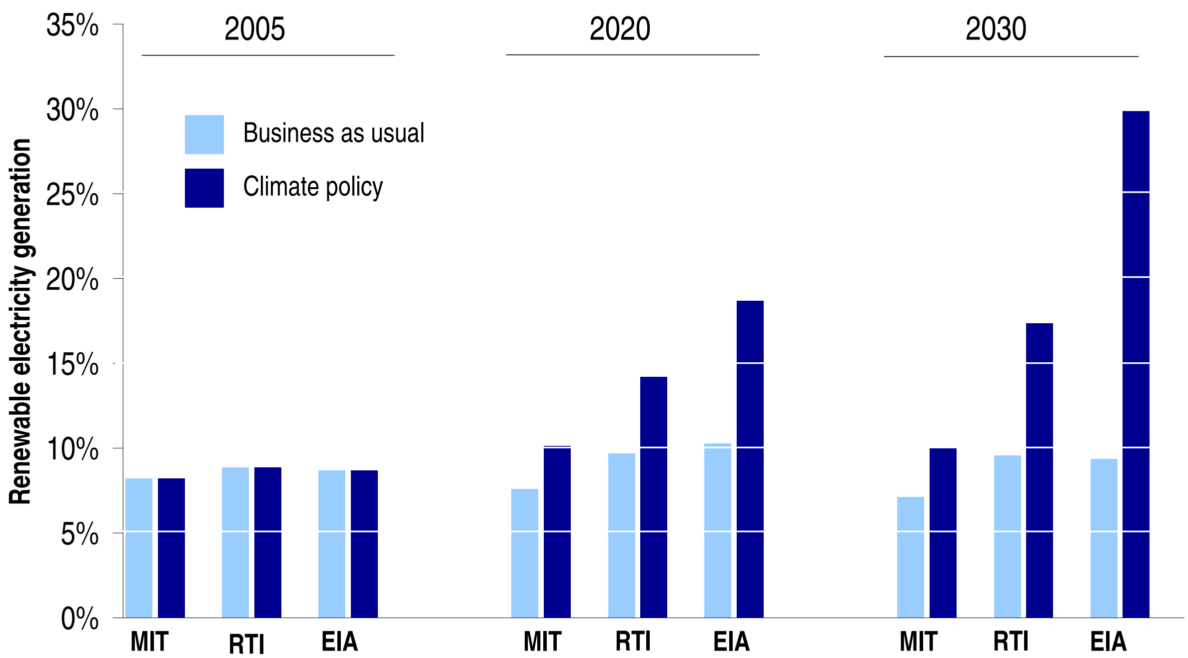


Figure A-3 shows the projected share of electricity generation in the United States from non-hydropower renewable sources (wind, solar, biomass), under business as usual and climate policy, according to analyses by EIA, RTI, and MIT. (Source: Results for MIT for reductions of 80% below 1990 by 2050; RTI results from its analysis of Lieberman-Warner for EPA; EIA data from its analysis of Lieberman-McCain bill. See text for details.)

tricity generation by the year 2030 is nearly three times as large with a cap on greenhouse gases than without it.

> The greater the potential for growth in renewable energy generation, the lower the costs of meeting a given climate stabilization target.

6. How much interaction does the model allow across economic sectors?

Some models have separate components for many different industries, allowing them to reflect interactions among multiple parts of the economy. Others lump industries together into just a few sectors, or even treat the economy as a single unit.

> Larger and wider markets can draw on more varied opportunities to reduce emissions, relative to smaller, more isolated markets. This raises the efficiency gains from trading carbon allowances and lowers the estimated costs of abatement for the economy as a whole.

7. Which greenhouse gases are considered?

Although carbon dioxide (CO2) receives the lion's share of attention for its contribution to global warming, other pollutants—such as methane and nitrous oxide—do more damage on a pound-for-pound basis. Bringing these gases into the system—

by crediting emissions reductions on a "CO2-equivalent" basis—expands the avenues for low-cost emissions reductions, especially in the short term.

> Models that incorporate greenhouse gases other than CO2 into an emissions trading program predict lower costs for slowing and stopping global warming.

ECONOMIC GHG MODEL CHECKLIST

Below we show how the models discussed in the text stack up against this checklist. Of course, any binary ("red/green") representation is necessarily a simplification, and several of the models defy easy categorization. Nonetheless, the checklist presents a visual signal of the variation across models in the key assumptions identified above. A red square indicates that the model's approach is generally associated with higher predicted costs of climate policy; a green square indicates an assumption that typically leads to lower costs. A blank square indicates insufficient information.

		Emissions BAU 1	Market interactions 2	Technological Change 3	Technology detail 4	Renewable sources 5	Sectors 6	GHGs 7
IN TEXT	EIA	green	red	green	green	green	red	green
	IGEM	green	green	red	red	red	red	green
	RTI	green	green	red	red	red	green	green
	PNNL	red	green	red	red	red	green	green
	MIT	red	green	red	red	red	green	green
OTHERS (EMF-21)	AIM	green	green	red	red	red	green	green
	AMIGA	red	green	green	green	green	green	green
	EDGE	green	green		red	red	red	green
	FUND	red	green	red	red	red	red	green
	GEMINI-E3	red	green	red	red	red	green	green
	GRAPE	green	red	red			red	green
	GTEM	red	green	green	red		green	green
	IMAGE	green	red	green	green	green	red	green
	IPAC	green	green	red	green	green	green	green
	MERGE	green	green	green	green		red	green
	MINICAM	green	red	red	green	green	red	green
	PACE	green	green		red			green
	WIAGEN-ICM	red	green	green	red		green	green

(1) For EMF21: Based on the all-greenhouse-gas emission projections. We used the median emission projections as the reference to classify the models. Some flexibility was introduced to take into account the relevant differences in greenhouse gas emissions reported for 2000 and the different pathways. In cases where emissions were very close to median emissions, emissions in the years 2030 and 2050 were the determining factors.
(2) We have shaded red models such as MINICAM that are partial rather than general equilibrium models.
(3) Only learning-by-doing and R&D are considered induced technological change (ITC). Price-induced technological substitution is not considered to be ITC.
(4) The key criterion here is technology detail in the energy sector. Some models that often are classified as "top-down" are shaded green here because they include very detailed bottom-up energy sectors; examples are AMIGA and NEMS.
(5) For many of the models, this information can be inferred from the detail presented for the power sector.
(7) Although all the models presented incorporate greenhouse gases other than CO_2, it is important to realize that this is a recent development in the technology of the models themselves; indeed, the express purpose of EMF-21 was to compare estimated economic impacts with and without non-CO_2 mitigation. Moreover, the models themselves vary in the number of other gases they consider; at a minimum, they consider nitrous oxide (N_2O) and methane (CH_4) as well as CO_2, but some (e.g., MIT's EPPA model) also incorporate other gases such as HFCs, PFC, and SF_6.

Notes

1. Each of the solid lines in Figure 1 corresponds to cumulative greenhouse gas emissions of 3,700 metric gigatons (GT) CO2-equivalent over the period 1990-2100. That cumulative total carbon budget is consistent with avoiding prolonged warming above 2°C mean global temperature relative to the preindustrial period; this corresponds to avoiding prolonged atmospheric greenhouse gas concentrations above 450 ppm CO2-equivalent. The carbon budget was calculated with version 4.1 of the MAGICC climate model developed by Tom Wigley of the National Center for Atmospheric Research, using the "most likely values" of climate parameters according to the Intergovernmental Panel on Climate Change Fourth Assessment Report. The pathways are merely illustrative and are constructed as follows: Each pathway assumes that emissions follow the business as usual (BAU) pathway (derived from IPCC scenario B2, 2007) until the starting year of the policy. A ten-year transition period follows during which emissions growth slows and then reverses. The rate of emissions reduction is held constant from the end of this transition period through the year 2100.

2. Productivity and efficiency improvements in the economy tend to produce a small, annual "natural" reductions in carbon emissions.

3. One can also express the nature of the challenge in terms of emissions intensity—that is, tons of greenhouse gas emissions per dollar of GDP. If (as forecast by the U.S. Energy Information Administration) the world economy grows at an annual rate of 4.1%, meeting the 450 ppm goal starting in the year 2030 would require reducing emissions intensity by 99% over the following 50 years.

4. This argument has been given more formal underpinnings by Harvard economics professor Martin Weitzman, who has demonstrated that conventional expected utility analysis can break down in the presence of even small amounts of structural uncertainty about long-run economic growth, along with a "thick tail" of events with low probability but catastrophic damages. Both preconditions are characteristic of global warming. See Martin Weitzman, "The Stern Review of the Economics of Climate Change," *Journal of Economic Literature* 45(3): 703-24 (September 2007).

5. In order to focus only on objective analyses from academic and government sources, we have chosen *not* to include three analyses of the Lieberman-Warner bill that have been released by advocates on both sides of the climate policy debate: CRA International; the American Council for Capital Formation, in conjunction with the National Association of Manufacturers; and the Clean Air Task Force. (We do refer to the CATF study later in the text, but only to illustrate the importance of modeling assumptions in the context of energy efficiency).

6. The EPA analysis is available online at http://www.epa.gov/climatechange/downloads/s2191_EPA_Analysis.pdf; the complete results are available at http://www.epa.gov/climatechange/downloads/DataAnnex-S.2191.zip. We use the results for the "Alternative Reference" scenario. The EPA's other reference scenario (the "Core" scenario) was based on the EIA's Annual Energy Outlook 2006, which did not take into account the energy bill passed in 2007. The "Alternative Reference" scenario we rely on assumes earlier adoption of energy efficient technologies under business as usual; as a result, according to the EPA, this scenario is more consistent with current law, and is in line with the revisions EPA expects to make to its reference case in the coming months. (See page 6 of the EPA's report.) When the "Core" reference scenario is used as a baseline, the estimated impacts of the Lieberman-Warner bill increase, though not dramatically.

7. Sergey Paltsev, John M. Reilly, Henry D. Jacoby, Angelo C. Gurgel, Gilbert E. Metcalf, Andrei P. Sokolov, and Jennifer F. Holak, "Assessment of U.S. Cap-and-Trade Proposals, Appendix D: Analysis of the Cap and Trade Features of the Lieberman-Warner Climate Security Act (S.2191)," an appendix to MIT Joint Program on the Science and Policy of Global Change Report No. 146; available online at http://mit.edu/globalchange/www/MITJPSPGC_Rpt146_AppendixD.pdf. This analysis of Lieberman-Warner should be viewed as somewhat preliminary; the MIT researchers did not model several key aspects of the legislation, in particular the provision allowing for the use of international credits, which would reduce the costs of achieving the emissions reduction targets.

8. The output data from the MIT analysis were circulated in a working paper: Sergey Paltsev, John M. Reilly, Henry D. Jacoby, Angelo C. Gurgel, Gilbert E. Metcalf, Andrei P. Sokolov, and Jennifer F. Holak, "Assessment of U.S. Cap-and-Trade Proposals," MIT Joint Program on the Science and Policy of Global Change Report No. 146 (April 2007), 66 pp. Detailed data are available online at http://mit.edu/globalchange/www/MITJPSPGC_Rpt146_AppendixC.pdf. Output from the RTI and PNNL models was prepared for a conference convened by the Nicholas Institute of Environmental Policy, held July 17-19, 2007, in Washington, D.C.; the data were made available by the modelers themselves. We thank Martin Ross (of RTI) and Ron Sands (of PNNL) for sharing their results, and Brian Murray of the Nicholas Institute for facilitating that process.

9. As noted in the text, the Senate bills would cover 75 to 85

percent of U.S. greenhouse gas emissions. In contrast, the generic "bounding analyses" apply the percentage emissions reduction target to all U.S. greenhouse gas emissions. In effect, they assume a truly economy-wide program, covering not only all CO2 emissions from fossil fuel combustion but also non-CO2 greenhouse gas emissions from agriculture, land use, landfills and so on. Moreover, unlike the Senate legislation, the "bounding analyses" do not allow for the use of international offset credits, which further raises the reductions that must be made within the United States.

10. While an imperfect measure of welfare, GDP is the most commonly cited single number in public discussions about the economic impacts of climate policy; we focus on it because of that salience. Most models also estimate impacts on consumption; we consider those in Section 6, in the context of households. The MIT model, unlike the others, presents its main results in terms of social welfare (although it also provides forecasts for GDP). The predicted impact of climate policy on welfare is greater (in percentage terms) than the impact on GDP, but smaller than the impact on consumption.

11. We compute the present value in the year 2010, using a discount rate of 3%.

12. From low to high impact, the model projections for that year are as follows: EIA L-M, 0.34%; MIT 80% below 1990, 0.36%; MIT L-W, 0.37%; MIT 50% below 1990, 0.56%; RTI L-W, 0.60%; RTI 50% below 1990, 1.26%; IGEM L-W, 3.61%. Note that in some cases GDP increases with deeper reductions (e.g., compare among the MIT models); this is because the more ambitious targets spur greater investment.

13. The EIA reports residential electricity price, total residential electricity demand, and the total number of households. We first compute the number of households using electricity by multiplying EIA's forecast for total households by the share of households using electricity in 2001, according to the 2001 Residential Energy Consumption Survey. Dividing total residential electricity demand by the number of households yields household consumption; multiplying by price yields expenditures. The dollar figure given in the text represents a simple, undiscounted average. At a discount rate of 3%, the average present value of the monthly increase would be around $2.40.

14. Electricity prices are taken from EIA data, available online. Household expenditures in 1990 are from the EIA's Residential Energy Consumption Survey, which reported average annual household spending on electricity of $761 in nominal terms. Dividing by twelve and applying the Consumer Price Index yields monthly spending of $94.76 in 2005 dollars. The RECS is not yet available for 1995; however, multiplying the EIA's average residential electricity price for 2005 by average household consumption yields a figure of $94.80 per month, also in 2005 dollars. As a point of comparison, the Consumer Expenditure Survey—an entirely separate survey conducted annually by the Bureau of Economic Analysis—reported almost identical monthly electricity expenditures of $94.40 and $96.25 per month (both expressed in 2005 dollars) for 1990 and 2005, respectively.

15. The CATF analysis uses the same reference or "business-as-usual" scenario as EIA used in its analysis of the Lieberman-McCain legislation. To reflect the bill's provisions for stimulating technology development and deployment (using revenue raised from the auction of greenhouse gas allowances), CATF used EIA's Residential and Commercial Best Available Technology case. We thank Joe Chaisson of the Clean Air Task Force for generously sharing the results of the study with us.

16. The IGEM model, which does not include a detailed electricity sector module, does not report projections of residential energy prices.

17. The estimates given in the text are based on the implied long-run price elasticity for residential electricity demand of -0.49 implied by the EIA NEMS model. (See Steven H. Wade, "Price Responsiveness in the *AEO2003* NEMS Residential and Commercial Buildings Sector Models," Energy Information Administration Analysis Report, downloaded from www.eia.doe.gov/oiaf/analysispaper/elasticity/pdf/buildings.pdf) That figure is determined from simulations of a price doubling between 2005 and 2025, and therefore is appropriate to apply to the nonmarginal changes considered here.

    In the analyses by RTI, PNNL, and EIA, the projected increase in the cost of electricity generation under climate policy in the year 2030 (relative to business as usual) ranges from 14% for the MIT analysis of Lieberman-Warner, to 50-60% for the more stringent bounding analyses. Multiplying these percentage price increases by -0.49 yields the implied difference in consumption; multiplying price by quantity then yields the percentage increases in expenditure given in the text. The variation in the dollar amounts is larger than the variation in the percentage increases, because the models differ in their projections of electricity prices under business as usual.

18. The RTI, PNNL, and MIT models all generate forecasts at five-year intervals. We estimate "chained" values for consumption by computing the percentage price change between each interval within a policy scenario (i.e. business as usual or climate policy), multiplying it by price elasticity to get the associated percentage change in quantity, and applying that to the estimated quantity in the prior period. All quantities and prices are expressed as an index with the value in 2005 set to unity.

For this exercise we use -0.65 as our elasticity. This is the average intermediate-run price elasticity of residential electricity demand reported by Dahl, whose survey remains the standard reference in the literature. We use the *intermediate-run* elasticity because we are considering five-year changes in prices in the context of a permanent policy shift. Since price elasticity is greater in the long run, our approach is conservative. Using Dahl's long-run estimate of -0.9, or even the median value of -0.8 from a recent survey by Espey and Espey, would imply that total household expenditures would *decrease* under climate policy in most models, relative to business as usual. See C. Dahl, "A Survey of Energy Demand Elasticities in Support of the Development of the NEMS," Contract No. DE-AP01-93EI23499 (Washington, DC, October 1993).); and James A. Espey and Molly Epsey, "Turning on the Lights: A Meta-Analysis of Residential Electricity Demand Estimates", *Journal of Agricultural and Applied Economics* 36(1): 65-81 (2004).

19. For the years 1990-2005, we used EIA time series data on energy prices available on the EIA website, computed annual averages, and applied the CPI to convert to constant 2005 dollars. To estimate expenditures, we multiplied these prices times the reported average household energy consumption for 1993, 1997, and 2001 from the periodic Residential Energy Consumption Surveys conducted by the EIA, along with the 2005 estimate for average household energy consumption used by the EIA in the Lieberman-McCain analysis.

    See notes 13 and 18 for explanation of how we computed budget forecasts for the years 2005-2030.

    The two RTI analyses—the assessment of Lieberman-Warner and the "bounding analysis"—used markedly different reference cases for natural gas prices. The percentage increases in energy bills implied by the two analyses were similar. To avoid confusion, we have depicted only the analysis of the Lieberman-Warner bill.

20. From the point of view of economic efficiency, there are merits to such broader coverage. First, the overall economic costs are likely to be lower as more sources of emissions are included. Second, not including households under the cap would distort household decision making in the long runŨ– by making natural gas and heating oil look "cheap" relative to electricity, because the true social costs of carbon were left out.

21. These estimates are based on EIA's estimated long-run demand elasticities of -0.41 for natural gas and -0.6 for heating oil (Wade, op. cit.). The numbers reported for heating oil are for the MIT model only; RTI and PNNL do not forecast heating oil prices. See note 17 for an explanation of our calculations.

22. We use an estimate of -0.7 for price elasticity, which is the average long-run estimate for residential natural gas demand reported by Dahl (1993, op. cit.); no intermediate-run estimate is given for natural gas. See note 18 for an explanation of our methodology.

23. All gasoline prices correspond to the sales-weighted average retail price of gasoline, for all grades across the United States, including federal and local taxes. The historical data represents monthly average retail prices from the EIA's *February 2008 Monthly Energy Review.*

24. See David Bird, "Low Stocks of Gasoline Drive Prices to Record," *Wall Street Journal*, May 19, 2007, Section B, p. 3.

25. The shaded area (corresponding to a 90% confidence interval) is constructed as follows. We started with the assumption (standard for energy prices) that gasoline prices follow a random walk with drift, and hence that deviations from the long-term trend are normally distributed. Using annual time-series data from the EIA for the period 1973-2005, we then estimated the drift and variance of retail gasoline prices. (The use of annual price data matches the granularity of the EIA projections, which are also on an annual basis.) The shaded area in the figure represents 1.64 times the estimated standard deviation, above and below the projected price path.

26. This is the message that emerges from a recent report by the Congressional Budget Office. Although the report emphasizes the potential disparities in the impact of emissions reductions across households of different income levels, it also finds that the overall impact on the economy would be small—between 0.15% and 0.34% reduction in GDP, relative to business as usual, for a 15% cut in total emissions. This is comparable to the numbers we present in this report for somewhat larger reductions. See Terry Dinan, "Trade-Offs in Allocating Allowances for CO_2 Emissions," Congressional Budget Office Economic and Budget Issue Brief (April 25, 2007); and the longer report on which that brief was based, Terry Dinan and Diane Rogers, "Who Gains and Who Pays Under Carbon-Allowance Trading? The Distributional Effects of Alternative Policy Designs" (June 2000); both are available at www.cbo.gov.

    Similarly, the Center on Budget and Policy Priorities estimates that just 14% of the value of emissions allowances would be sufficient to fully offset the impact of higher energy prices on the poorest one-fifth of American households and partially offset the costs for middle-class households. The CBPP also suggests the range of policies mentioned in the text. See Robert Greenstein, Sharon Parrott, and Arloc Sherman, "Designing Climate-Change Legislation that Shields Low-Income Household from Increased Poverty and Hardship," available at http://www.cbpp.org/10-25-07climate.pdf.

27. For example, Gib Metcalf of Tufts University has calculated that a $15 carbon tax—comparable to the EIA's estimate of the initial carbon allowance price under Lieberman-McCain—would raise prices of most goods and services by less than 1%, although prices of energy would rise by a good deal more.

28. Consumer expenditure data comes from the National Economic Accounts maintained by the Bureau of Economic Analysis; we used figures for 2005 from Table 501 of the System of National Accounts data for the purposes of spending categories. Data are available at http://www.bea.gov/national/xls/tab501.xls. Federal government expenditure is taken from the National Income and Product Accounts tables maintained by the Bureau of Economic Analysis. State and local government expenditure comes from U.S. Census Bureau statistics, available at http://www.census.gov/govs/www/estimate05.html. Finally, to allocate household tax payments to government services, we drew on two sources: Congressional Budget Office, "Historical Effective Tax Rates: 1979 to 2004" (December 2006), available at http://www.cbo.gov/ftpdocs/77xx/doc7718/ Effective-TaxRates.pdf; Robert S. McIntyre, Robert Denk, Norton Francis, Matthew Gardner, Will Gomaa, Fiona Hsu, and Richard Sims, "Who Pays? A Distributional Analysis of the Tax Systems in All 50 States," 2nd ed. (Washington, D.C.: Institute on Taxation and Economic Policy, January 2003). All expenditure figures are for 2005.

29. Note that these numbers do not represent the total spent on such services, but rather the average amount contributed by households, either through direct consumption or through tax dollars. Since governments also collect tax revenue from other sources (e.g. corporate profits and commercial real estate), the fraction of household income spent on government services is smaller than the fraction of GDP. To take one example: households contribute about 4 cents to national defense out of every dollar of income, but total spending on national defense amounts to nearly 5% of GDP.)

30. See David Brauer, "What Accounts for the Decline in Manufacturing Employment?" Congressional Budget Office Economic and Budget Issue Brief (February 2004).

31. Lucias Foster, John Haltiwanger, and Namsuk Kim, "Gross Job Flows for the U.S. Manufacturing Sector: Measurement from the Longitudinal Research Database," U.S. Census Bureau, Center for Economic Studies Working Paper 06-30 (June 2006), 41 pp.; available at http://www.econ.umd.edu/~haltiwan/ download/gflows_112906.pdf. For more on job creation and destruction, see also Stephen J. Davis and John Haltiwanger, "Gross Job Flows," Chapter 41 in Orley Ashenfelter and David Card, eds., *Handbook of Labor Economics*, Volume 3 (Amsterdam: Elsevier Science, 1999), pp. 2711-2805; and Stephen J. Davis, R. Jason Faberman, and John Haltiwanger, "The Flow Approach to Labor Markets: New Data Sources and Micro-Macro Links," *Journal of Economic Perspectives*, 20(3): 3-26 (Summer 2006).

32. Annual flows are smaller than the cumulative total of quarterly flows because the former exclude jobs created and then lost (or vice versa) within a calendar year. Hence annual flows reflect more persistent job losses and gains, while quarterly flows better convey the short-term volatility. Annual figures are from John R. Baldwin, "Productivity growth, plant turnover, and restructuring in the Canadian manufacturing sector," in David G. Mayes, ed., *Sources of Productivity Growth* (Cambridge, UK: Cambridge University Press, 1996); cited in Davis and Haltiwanger (op cit.).

33. The data provided by Foster *et al.* (see note 31) are presented as quarterly rates, calculated as the ratio of the change in employment to the average of current and previous period's employment. To translate those into absolute numbers, we computed a rolling two-quarter average of manufacturing employment using data from the Bureau of Labor Statistics, and multiplied it by the quarterly rates provided by Foster *et al.*

34. Arthur M. Bueche, "Synthetic Rubber in World War II," *Science*, 191(4231): 1007 (March 12, 1976); Vernon Herbert and Attilio Bisio, *Synthetic Rubber: A Project that Had to Succeed* (Westport, CT: Greenwood Press, 1985); Paul Wendt, "The Control of Rubbert in World War II," *Southern Economic Journal* 13(3): 203-227 (January 1947).

35. Frederic C. Lane, *Ships for Victory: A History of Shipbuilding Under the U.S. Maritime Commission in World War II* (Baltimore: Johns Hopkins Press, 1951); John Gorley Bunker, *Liberty Ships: The Ugly Ducklings of World War II* (Annapolis, MD: Naval Institute Press, 1972).

36. This principle is famously illustrated by the race to solve one of the most pressing technological challenges of the 17th and 18th centuries—namely, how to determine a ship's location on the open ocean. Latitude could be easily determined by the sun's passage, but longitude was much more difficult. In the hopes of spurring the discovery of a solution, Parliament in 1714 offered a prize of £20,000 to the first person to demonstrate a reliable method of fixing longitude. The scientific grandees of the day were sure that the answer lay in the stars, and they set about tracking the minute movements of the moon and amassing enormous catalogs of constellations so that a ship captain could fix his position by tracking the movement of the heavens. A better answer, however, turned out to be the construction of a better clock—one that could keep accurate time far away from shore, despite the pitch and yaw of the open ocean and the warping effects of tropical humidity. For a fascinating

account of this story, see Dava Sobel, *Longitude: The True Story of a Lone Genius Who Solved the Greatest Scientific Problem of His Time* (New York: Penguin, 1996).

37. See Donella H. Meadows, Dennis L. Meadows, Jörgen Randers, and William W. Behrens III, *The Limits to Growth* (New York: Universe Books, 1972); and William D. Nordhaus, "Lethal Model 2: The Limits to Growth Revisited," *Brookings Papers on Economic Activity* 2:1-43 (1992).

38. See Francisco de la Chesnaye and John Weyant, eds., "Multi-Greenhouse Gas Mitigation and Climate Policy," *Energy Journal*, Special Issue, November 2006. Eighteen models participate in the EMF; we consider only the 15 that model the U.S. economy. Note that the policy scenario assumed participation by all countries and regions starting in 2013, and sought the least-cost reductions. These assumptions dampen the estimated impact on the U.S. economy, relative to the more realistic assumption that the United States and other developed countries will act to reduce emissions before the rest of the world does so.

39. Some of these assumptions have been highlighted in previous analyses, but others—in particular the role of renewables—have been largely overlooked. For previous studies of the assumptions that drive model results, see Robert Repetto and Duncan Austin, *The Costs of Climate Protection: A Guide for the Perplexed* (Washington, DC: World Resources Institute, 1997), 56 pp.; Terry Barker, Mahvash Saeed Qureshi, and Jonathan Köhler, "The Costs of Greenhouse Gas Mitigation with Induced Technological Change: A Meta-Analysis of Estimates in the Literature," Tyndall Centre for Climate Change Research Working Paper 89, University of Cambridge (July 2006), 63pp; and Carolyn Fischer and Richard D. Morgenstern, "Carbon Abatement Costs: Why the Wide Range of Estimates?," Resources for the Future Discussion Paper RFF DP 03-42 REV (November 2005), 21 pp.