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ABSTRACT

The MIT Emissions Prediction and Policy Analysis model is applied to synthetic policies that match key attributes of a set of cap-and-trade proposals being considered by the U.S. Congress in spring 2007. The bills fall into two groups: one specifies emissions reductions of 50% to 80% below 1990 levels by 2050; the other establishes a tightening target for emissions intensity and stipulates a time-path for a "safety valve" limit on the emission price that approximately stabilizes U.S. emissions at the 2008 level. Initial period prices are estimated between $7 and $50 per ton CO2-e with these prices rising by a factor of four by 2050. Welfare costs vary from near zero to less than 0.5% at the start, rising in the most stringent case to near 2% in 2050. If allowances were auctioned these proposals could produce revenue between $100 billion and $500 billion per year depending on the case. Outcomes from U.S. policies depend on mitigation effort abroad, and simulations are provided to illuminate terms-of-trade effects that influence the emissions prices and welfare effects, and even the environmental effectiveness, of U.S. actions. Sensitivity tests also are provided of several of key design features. Finally, the U.S. proposals, and the assumptions about effort elsewhere, are extended to 2100 to allow exploration of the potential role of these bills in the longer-term challenge of reducing climate change risk. Simulations show that the 50% to 80% targets are consistent with global goals of atmospheric stabilization at 450 to 550 ppmv CO2 but only if other nations, including the developing countries, follow suit.

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1. INTRODUCTION

A number of alternative approaches to greenhouse-gas mitigation are under consideration in the United States, but the policy instrument now receiving greatest attention is a national cap-and-trade system. Several bills have been filed in the Congress or are under development. In this report we assess the economic and energy system implications of these proposals, not comparing particular bills in detail but studying synthetic versions that span their main features and illuminate the differences among them. To carry out the economic aspects of the assessment we rely on the MIT Emissions Prediction and Policy Analysis (EPPA) model. The implications of different emissions paths for atmospheric greenhouse gas concentrations and potential climate change are explored using the earth science portions of the MIT Integrated Global System Model (IGSM) of which EPPA is a component.

The term "cap-and-trade" is used to describe a policy that identifies greenhouse-gas-emitting entities covered by the system, sets caps on their emissions and allows trading in the resulting emissions allowances. The "entities" are the points of responsibility for emissions and they may be defined at various levels in the economic system from the coal mine and refinery gate (upstream) to the firm or gasoline station (downstream). At these points the emissions accounting is carried out. Emissions allowances (actually entries in an electronic bookkeeping system) are distributed such that the total is equal to the national cap, and covered entities must surrender allowances equal to their emissions, or the emissions that result when the fuel they supply is burned. Market trading in these allowances establishes a price on emissions that in turn creates economic incentives for cost-effective abatement.[1] It is common practice to distribute allowances to the entities that are the point of regulation, but this procedure is not a requirement of the system. Allowances could be distributed without charge to any persons, firms or other organizations in the economy, or they could be auctioned.

We begin the assessment of current proposals in Section 2 by laying out aspects of system design, and conditions external to the U.S., that influence the performance of cap-and-trade systems. In Section 3 the economic model used in the analysis is described and the assumptions underlying a set of "core" policy cases are identified, including the relative stringency of abatement, the emissions allowance paths, and mitigation undertaken abroad. Section 4 then presents results for the core cases, including price and welfare effects, impacts on energy markets and revenue potential if allowances are auctioned. It is worth noting that, although the focus is on a cap-and-trade system, many of the results are directly applicable to a carbon tax with the same coverage and emissions target.[2] In Section 4 it becomes evident how dependent the results are on

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[1] For a discussion of the history of cap-and-trade systems in the U.S. and analysis of their application to CO_2 see Ellerman *et al*. (2003). A previous U.S. proposal of a cap-and-trade system for greenhouse gases was the Climate Stewardship Act of 2003 (S. 139) introduced in 2003 by Senators McCain and Lieberman. Analyses of this earlier legislation are available in Paltsev *et al.* (2003) and the US EIA (2003).

[2] Tax and quantity instruments have different properties in terms of economic cost and effectiveness under uncertainty, but the scenarios analyzed in this report are simulated in a non-stochastic framework, and in this context tax and quantity constraints are equivalent. Choice between tax and quantity constraints raises important economic issues that deserve attention but are beyond the scope of this analysis.

assumptions about mitigation undertaken in other countries, through terms-of-trade effects, and Section 5 explores this phenomenon in greater detail.

Of necessity the comparison of the core cases requires a common set of system definitions so in Section 6 we investigate various alternative specifications including differences in banking, sectoral coverage, revenue recycling, the provision of a safety valve and international permit trading. One important difference among cases is the role of biofuels, and Section 7 provides a more detailed look at this option and its implications for land use.

The proposals under study specify targets only to 2050, which is too short a period for consideration of the climate impacts. Therefore in Section 8 assumptions are made for the latter half of the century and estimates are provided of the resulting reduction in atmospheric CO_2 concentrations and in projected global temperature change. Section 9 offers some conclusions.

2. ISSUES IN SYSTEM DESIGN AND IMPLEMENTATION

The economic and environmental effects of a cap-and-trade system depend on its features within a particular country, and also on activities in other countries through the influence of trade in energy, non-energy goods and emissions allowances. As background for the assumptions applied in assessing potential U.S. systems, a brief review of these factors is in order. Definitions of terms used in discussing greenhouse gas control policies, especially cap-and-trade systems, are provided in **Appendix A**.

2.1 System Design Features

Cap-and-trade legislation will include a large number of details, and any U.S. system likely will be a negotiated compromise among current proposals. In forming judgments about economic implications of system design a few of these features are of greatest importance.

Stringency of the emissions target. The targeted emissions reduction over the time horizon of the policy is among the most important determinants of policy cost and its climate benefits. Many of the bills considered here state an emissions target for 2050, and that is one way to compare them. However, a better measure of stringency is the sum of national emissions permitted between the start of the policy and mid-century. Such a comparison is used to benchmark the analysis below.

Point of regulation. Current proposals differ in the points in the economic system where the cap is applied (upstream or downstream) and the method of allowance distribution (for free or by auction). The primary effect of this choice of point of regulation is to determine which entities must comply with the regulatory system by monitoring emissions, maintaining records, and submitting allowances. The direct cost of emissions abatement may not be incurred at this stage in the production process. For example, in an upstream system where one point of regulation likely would be at oil refineries, emissions abatement would come mainly from reductions in fuel use downstream. The costs of this abatement would include additional spending for more efficient vehicles, heating equipment and alternative fuels, or the sacrifice of amenities that increase fuel consumption (*e.g.*, larger, more powerful vehicles). Refiners do not directly control abatement (except for emissions in the refinery process itself) but only influence fuel use by passing on the allowance cost to petroleum product consumers.

Similarly, a chemical company will make essentially the same decisions about product line and equipment choices whether it pays a separate natural gas price and surrenders allowances for the emissions released, or simply pays a higher fuel price that includes the allowance cost premium. An upstream allowance system thus assumes that the coal mine, gas gathering point, refinery gate and import terminal will pass through the bulk of the allowance cost to subsequent stages in the economic system and ultimately to goods and services.

How much of the direct mitigation cost is passed forward to consumers is not a choice made by firms but rather depends on the underlying elasticities of supply and demand for the goods and services being produced, and this can be further affected by rate-setting agencies that oversee regulated utilities depending on how the value of allowances are treated in setting rates. The essential point that bears emphasis is that the ultimate distribution of control costs under a cap-and-trade system, especially in unregulated markets, is determined by market forces, not by the choice of upstream or downstream implementation. This fact frees up policy makers to implement such systems at the stage of production where implementation costs are lowest.

Method of allowance distribution and distributional implications. Whether the point of obligation is upstream, downstream or some hybrid, emission allowances are valuable assets and the way they are distributed can have a substantial effect on equity aspects of the system. If allowances are auctioned, then the overall distributional effect depends on what is done with the revenue. If the allocations are distributed on some "grandfathering" principle to firms at the point of regulation, then these firms receive the asset value or scarcity rent.[3] The U.S. sulfur system and the EU Emissions Trading Scheme (EU ETS) are directed toward the point of combustion, and so the firms covered by them are bearing some direct cost of abatement, in spending on improved efficiency, fuel switching, sulfur scrubbing and the like. In trial phase of the EU ETS, however, electricity price changes have appeared to reflect not so much the direct mitigation expenses but the changing marginal cost of permits, even though they were distributed for free. Given that the electricity markets are mostly deregulated in Europe such a pass through of permit price is, or should have been, expected.

In the U.S., on the other hand, where much of the electricity market remains regulated by public utility commissions, rates may not be allowed to rise unless there is an actual cost incurred by the utility. Under that circumstance the value of the allowance asset does not create value for the utility and electricity consumers will benefit relative to the case where rates fully reflected CO_2 prices; *i.e.* rates will not rise as much and utilities will not recover the permit value through higher electricity rates. The downside of this aspect of regulated utility markets is that, because electricity prices will not rise to reflect the full allowance cost, electricity consumers will not have as much of an incentive to reduce their electricity consumption. If the most efficient abatement response involves mostly fuel-switching within the electric sector the inefficiency imposed in such a regulatory setting may be limited. On the other hand, in the refinery example used above very little abatement would occur if fuel prices did not increase to reflect marginal CO_2 prices, and so if concern about rising fuel prices led to some form of price regulation, such as imposition of price controls, it would defeat the purpose of the CO_2 policy.

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[3] In markets under cost-of-service regulation, like some U.S. electric utilities, public authorities may not allow firms to realize scarcity rents in this way.

To summarize, who bears the ultimate burden of the costs of abatement depends on the complex interaction of markets (see, *e.g.*, Fullerton and Metcalf, 2002). In an idealized "neoclassical" model of the economy the burden of the mitigation costs under a cap-and-trade program is independent of the point of regulation. One implication of this principle is that while upstream regulation would create incentives for abatement, the costs of abatement need not be borne upstream. Thus, free distribution of allowances to upstream entities can create an inequitable outcome where they receive a valuable asset but ultimately pass on most of the cost to downstream fuel users. Of course, the actual economy diverges from the way it is represented in idealized economic models, and so the point of regulation can affect outcomes in substantial ways. However, that qualification does not change the conclusion that, to the degree the distributional impacts of the policy are a concern, the focus needs to be on who actually bears the economic burden of the policy, *not* who happens to be given the task of turning in allowances or even who is directly responsible for abating emissions. On equity grounds, the revenue from auctioning permits or the distribution of free allowances could be directed to those who ultimately bear the cost of abatement, whether it is low-income consumers, coal mine owners, coal miners or other groups. To correctly assess the cost implications for different groups requires a detailed representation of the economy, including representation of features such as cost-of-service regulation as in some U.S. electric utilities.

Banking and borrowing of permits. Cap-and-trade systems generally define a set of accounting periods and allocate allowed emissions separately for each period. An important design feature is whether entities under the cap can shift their obligations across periods. If higher costs are expected in the future, firms have an incentive to over-comply early-on and "bank" the excess for use in meeting future obligations. Or they might be allowed to under-comply, "borrowing" from the future by shifting the deficit forward to add to the obligation in subsequent periods. Many cap-and-trade systems allow banking. Provision for borrowing is less common, perhaps because of default risk. In systems that plan for tightening over time, creating the expectation of rising cost, banking is an economic response that will tend to convert any prescribed period-by-period set of targets into a cost-minimizing path with the same total emissions over the policy horizon.

Coverage by sector and greenhouse gas. Cap-and-trade systems are sometimes proposed that include CO_2 only, or CO_2 plus some combination of the other greenhouse gases. A multi-gas implementation then requires some set of exchange rates (Global Warming Potentials or GWPs are used in this study) to allow aggregation of their various effects. Also, systems vary by the number of sectors covered. The EU ETS, for example, covers only electric utilities and heavy industry, and some of the systems assessed below omit households, agriculture, and small entities.

Revenue recycling. If a portion of the allowances is auctioned, or a safety valve provision (discussed next) yields sales proceeds, the system will generate government revenue. One possible application of these funds is the reduction of taxes either on capital (corporate income, dividends or capital gains) or labor (earned income). Existing taxes distort choices in the economy and reducing them may lower this distorting effect and increase economic activity, an effect termed a "double dividend" because the greenhouse gas (GHG) policy would yield not only an environmental dividend but also an economic one. There is a possibility that the efficiency improvements from tax reduction could completely offset the direct cost of the abatement policy, an outcome called a "strong" double dividend. The case where the emission control cost is reduced but not completely offset by revenue recycling has been referred to as a "weak" double dividend. It is also possible if energy is highly taxed that revenue recycling can actually reduce economic activity (see Metcalf *et al*., 2004) but this outcome is unlikely in the U.S. where energy is only lightly taxed.

Provision of a safety valve. When the emissions cap is set there is uncertainty as to how high the emissions price may rise. To guard against price spikes that may threaten excess short-run economic cost (or the survival of the system itself) a price ceiling may be added to the system. Under such a so-called "safety valve" the government offers to sell allowances in unlimited amounts at a fixed price, perhaps at levels rising over time.[4] Whether the safety valve is likely to be triggered can be controlled by joint selection of the number of allowances issued and the safety valve price. The tighter (looser) the cap the higher (lower) the expected allowance price in the absence of the safety valve. If the safety valve price is set relatively high in relation to the expected emissions price then resort to government sales would be less likely. If the safety valve is set relatively low in relation to the expected price then this provision is better thought of as an emissions tax with allocated exemptions.

Note that with a safety valve the original cap is no longer met with certainty. A tight cap with a relatively low safety valve will mean the cap very likely will be exceeded. A loose cap with a relatively high safety valve will make it much more likely that the cap is actually met.

Linkage with non-U.S. systems. The emissions price realized in a U.S. cap-and-trade system could be substantially affected by linkage to outside systems. Relatively low cost emission reductions may be available in projects carried out in other countries (*e.g.*, forest projects) and the admission of such credits can reduce the domestic emissions price and economic cost. If the U.S. is linked to foreign trading systems, a common emissions price will emerge, but whether that result is higher or lower than the autarkic U.S. price would depend on the relative stringency of the before-connection caps in the different systems.

2.2 External Factors

In addition to the features that may be built into cap-and-trade legislation, a number of external factors will influence the economic effects of the system. Two are of particular interest.

Non-U.S. mitigation measures. Estimates of the cost of emissions mitigation in the U.S. will be influenced by emissions control measures being taken elsewhere. Most important, the level of global control will affect the prices of crude oil and other fossil fuels that the U.S. either imports or exports, and the prices of traded quantities of biofuels. Trade in non-energy goods also will be affected, although the effects on the U.S. are generally small in relation to the influence on trade in energy goods. These so-called terms-of-trade effects play an important role in assessment the cost of potential U.S. measures as will be seen below.

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[4] For an analysis of these systems and their relation to banking and borrowing see Jacoby and Ellerman (2004).

Trade restriction. Biofuels offer a relatively low-cost alternative for emission mitigation in the transport sector, and if unrestrained (and depending on emissions targets in other countries) the trade in these fuels could have large effects on land use and related issues of environmental degradation and food prices. In the U.S. biofuels are popularly seen as an abundant domestic resource that could reduce dependence on foreign oil, although imports of ethanol into the U.S. are currently restricted by tariffs.

In the analysis we try to provide insight into many of the issues identified above. However the nature of the model we employ is better suited to examine some of them than others. In the next section we describe the model and some of its limitations.

3. ANALYSIS METHOD

3.1 The Emissions Prediction and Policy Analysis (EPPA) Model

To assess costs and energy system implications of these proposed mitigation measures we apply the MIT Emissions Prediction and Policy Analysis (EPPA) model. The standard version of the EPPA model is a multi-region, multi-sector recursive-dynamic representation of the global economy (Paltsev *et al*., 2005). In a recursive-dynamic solution economic actors are modeled as having “myopic” expectations.[5] This assumption means that current period investment, savings, and consumption decisions are made on the basis of current period prices. This version of the model is applied below.

The level of aggregation of the model is presented in **Table 1**, and model features are further elaborated in **Appendix B**. The model includes representation of abatement of non-CO_2 greenhouse gas emissions (CH_4, N_2O, HFCs, PFCs and SF_6) and the calculations consider both the emissions mitigation that occurs as a byproduct of actions directed at CO_2 and reductions resulting from gas-specific control measures. Targeted control measures include reductions in the emissions of: CO_2 from the combustion of fossil fuels; the industrial gases that replace CFCs controlled by the Montreal Protocol and produced at aluminum smelters; CH_4 from a number of sources, and N_2O from chemical production and improved management of inorganic fertilizer applications. More detail on how abatement costs are represented for these substances is provided in Hyman *et al*. (2003).

Non-energy activities are aggregated to six sectors, as shown in the table. The energy sector, which emits several of the non-CO_2 gases as well as CO_2, is modeled in more detail. The synthetic coal gas industry produces a perfect substitute for natural gas. The oil shale industry produces a perfect substitute for refined oil. All electricity generation technologies produce perfectly substitutable electricity except for Solar and Wind, which is modeled as producing an imperfect substitute, reflecting its intermittent output. Biomass use is included both in transport fuel and electric generation although it does not

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[5] An alternative, forward-looking version of the EPPA model optimizes choices over time where economic actors are said to have “perfect foresight.” Such a forward-looking solution provides a more complete realization of neoclassical economic theory, leading to economic choices that are optimized over time as well as across sectors and regions. In a companion report Gurgel *et al.* (2007) compare the forward-looking EPPA results with those of the recursive model used here for the same core scenarios. They find that the basic behavior of the forward-looking model in terms of abatement and CO_2-e prices is very similar to the recursive model, the main difference being that optimization through time leads to somewhat lower welfare costs as one might expect. They explore additional aspects of policies for which the forward-looking version is particularly appropriate, and results for revenue recycling are summarized below.

penetrate the electric sector in these simulations. There are 16 geographical regions represented explicitly in the model including major countries (the U.S., Japan, Canada, China, India, and Indonesia) and 10 regions that are an aggregation of countries.

When viewing the EPPA model results for emissions prices and welfare costs it is well to remember that in any period the model seeks out the least-cost reductions regardless of which of the six categories of gases is controlled or from which sector they originate, applying the same marginal emissions penalty across all controlled sources. This set of conditions, often referred to as "what" and "where" flexibility, will tend to lead to least-cost abatement. To the degree that cap-and-trade legislation departs from these ideal conditions, costs for any level of greenhouse gas reduction will be higher than computed in a model of this type.

The results also depend on a number of aspects of model structure and particular input assumptions that greatly simplify the representation of economic structure and decision-making. For example, the difficulty of achieving any emissions path is influenced by assumptions about population and productivity growth that underlie the no-policy reference case. The simulations also embody a particular representation of the structure of the economy including the relative ease of substitution among the inputs to production and the behavior of consumers in the face of changing prices of fuels, electricity and other goods and services. Further critical assumptions must be made about the cost and performance of new technologies and what might limit their market penetration. Specifications of alternatives to conventional technologies in the electric sector and in transportation are particularly important. Finally, the EPPA model draws heavily on neoclassical economic theory. While this underpinning is a strength in some regards, the model fails to capture many economic rigidities that could lead to unemployment or misallocation of resources nor does it capture regulatory and policy details that are, as discussed earlier, particularly important in the utility sector.

Given the many assumptions that are necessary to model national and global economic systems, the precise numerical results are not as important as the insights to be gained about the general direction of changes in the economy and components of the energy system and about the approximate magnitude of the price and welfare effects to be expected given alternative features of cap-and-trade design. An uncertainty analysis of these proposals (*e.g.*, Webster *et al*., 2002), a task beyond the scope of this study, would be required to quantify the range about any particular result, although the relative impacts of caps of different stringency likely would be preserved. Policy design inevitably involves a process to reevaluate decisions as new information is gained, rather then deciding once and for all on a long-term policy based on any single numerical analysis.

3.2 Policy Options and Scenario Assumptions for the "Core" Results

In presenting the assessment results we first explore (in Section 4) a set of "core" results applying features that are most common among the proposed cap-and-trade bills. Then, in Section 5, we consider variation in system features over such dimensions as coverage, banking and borrowing, trade restrictions and revenue recycling. We focus the discussion on results that illustrate measures of cost, and effects on energy and agricultural markets. A more complete set of results for each of the scenarios is provided in an appendix to this working paper available at the NBER website. The key features of the set of "core" simulations are the following.

Stringency, coverage, banking and the safety valve. Most of the current proposals specify emissions reductions goals for the period from 2012 to 2050. A selection of these is presented in **Table 2** along with their most prominent features. In several cases a target is stated for 2050 in terms of a percentage reduction below 1990 emissions, providing a firm numerical goal for allowance allocation only in that year. The initial year allowance level is often benchmarked to emissions in the year the bill is passed, or in one case an average of the three years after. The most recent year's emissions inventory available as of this writing is 2005, and so assuming the bill is passed in 2007 or 2008 requires some extrapolation. While some of the bills provide a formula for computing allowances in intervening years others do not, offering targets only for one or two intermediate years. Still other proposals describe emissions allowances that depend on economic growth. For the core cases, we have specified three allowance paths that start in 2012 by returning to 2008 levels, extrapolating 2008 emissions from the 2005 inventory by assuming growth at the recent historical rate of 1% per year as documented in U.S. EPA (2006). We then assume a linear time-path of allowance allocation between this level in 2012 and a 2050 target equal to: (1) 2008 emissions levels, (2) 50% below 1990, and (3) 80% below 1990.

Following the convention noted above, cases are labeled by the cumulative number of allowances that would be made available between 2012 and 2050 in billions of metric tons (bmt), or gigatons, of carbon dioxide equivalent (CO_2-e) greenhouse gas emissions. These amounts are 287 bmt in the case of holding emission flat at 2008 levels, 203 bmt when allowance allocations are cut to 50% below 1990 by 2050, and 167 bmt when allowance allocations are cut to 80% below 1990 by 2050. These allowance paths are plotted in **Figure 1**. Also shown in the figure is our approximation of the allowance paths specified in current bills. In some cases judgments were required to fill in an allowance path that is incompletely specified in the legislation. Also, some of these bills were drafts, or subject to revision, and so readers need to check their status to insure the comparison remains appropriate.

With fixed total allowances over the whole period, and banking, the actual time-path of allowance allocation will not affect the CO_2 prices, energy markets, and other projections simulated by the model in these core runs.[6] It is for this reason that an informative way to compare the bills studied here is by the cumulative allowance allocations under each. This is also a good way to show which of the scenarios we have run is most comparable to specific bills. **Table 3** arranges the bills in the order of stringency, least to most, along with our three core cases. The 287 bmt case is close to the Udall-Petri Bill, the 203 bmt case comes just about at the Feinstein Bill level, and the 167 bmt case is very close to the Sanders-Boxer Bill. Our estimate of total emissions including uncovered sectors for the Lieberman-McCain Bill places it slightly above the 203 bmt case. Kerry-Snowe lies just about halfway between the 167 and 203 bmt cases. On the low side of the 167 bmt case is Waxman and on the high side of the 287 bmt case is Bingaman-Specter, each about 18-19 bmt outside our range. Note that the Bingaman-Specter draft and Udall-Petri include a safety valve feature and so to the extent the safety

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[6] In cases where allowances are auctioned, the time-path affects the auction revenue in each year, and if this revenue is recycled to lower taxes the timing has some effect on the economy and emissions, and potentially affects emissions prices policy cost. The effects of recycling on CO_2-e prices are small, however.

valve is triggered emissions are determined by the price mechanism and are not necessarily fixed.

Throughout the analysis the cap covers the emissions of the six categories of greenhouse gases identified in U.S. policy statements and in the Kyoto Protocol (CO_2, CH_4, N_2O, SF_6, HFSs and PFCs), with the gases aggregated at the 100-year GWP rates used in US EPA (2006). The "core" definition also assumes that the cap applies to all sectors of the economy except emissions of CO_2 from land use, and no credits for CO_2 sequestration by forests or soils are included. It is also important to note that in the core cases nuclear power is assumed to be limited by concerns for safety and siting of new plants, and thus nuclear capacity is not allowed to expand.

The focus of current cap-and-trade legislation on the pre-2050 period leaves open the question of what level of allowances will be available afterward. Extrapolating a linear decline rate would lead eventually to negative allowances.[7] When we extend the policies beyond 2050 in the analysis below we assume that the allowance level in 2050 is simply held constant at that level for the remainder of the century. However, we do not simulate banking into the post-2050 period and so the economic results reported are unaffected by the post-2050 assumptions.

International linkage, non-U.S. mitigation measures and trade restriction. The "core" policy scenarios provide no possibility for crediting reductions achieved in ex-U.S. systems such as the Kyoto-sanctioned Clean Development Mechanism (CDM) or other trading systems such as the EU Emission Trading Scheme. However, it assumed that other regions pursue climate policies as follows: Europe, Japan, Canada, Australia, and New Zealand follow an allowance path that is falling gradually from the simulated Kyoto emissions levels in 2012 to 50% below 1990 in 2050.[8] All other regions adopt a policy beginning in 2025 that returns and holds them at year 2015 emissions levels through 2034, and then returns and maintains them at 2000 emissions levels from 2035 to 2050. We assume no emissions trading among regions, although implicitly a trading system operates within each of the EPPA regions/countries that include, for example, the EU as a single region (see Table 1).

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[7] A negative allowance allocation is not impossible. If, for example, international emissions trading were in effect developed countries could receive a negative allowance allocation, and they would be required to purchase allowances from developing countries to make up for this negative allocation in addition to any emissions they have. Or some have discussed the possibility of using biomass as a feedstock for hydrogen, stripping out the carbon and storing it underground, or stripping carbon out of the air and storing it. Were these technologies considered realistically feasible at large-scale, a global net allocation could eventually be negative and atmospheric concentrations would then reverse and decline.

[8] To provide an allowance path that falls gradually at first, accelerating as 2050 is approached, we fit a simple quadratic function, solving the equation:

$$X_{2050} - X_{2012} = b_{\text{target}} * t^2 ,$$

for the coefficient b_{target} where t is time (2012 = 0; 2050 =38) and X_{2012} and X_{2050} are emissions targets for the year 2012 and 2050 respectively. With X_{2012} set to the 2008 emission level as estimated above and the X_{2050} target given above we can solve the equation for b_{target} (target = 10, 30, 50, 70, 80) when t = 50 – 12 = 38. We can then use the equation below to solve for all other years (X_{YEAR}):

$$X_{\text{YEAR}} = b_{\text{target}} * t^2 + X_{2012} .$$

The EPPA model solves only every 5-years, and so the first year for which we simulate policy costs is the year 2015.

Allowance allocation and revenue recycling. Allowances are assumed to be distributed for free. The distributional implications of abatement and allowance allocation were discussed Section 2.1. In a model like EPPA, however, with a single representative agent that owns all resources (*i.e.* labor, capital, other assets), all costs necessarily fall on that single agent and there is no difference if allowances are dispensed for free in a lump sum manner, or allowances are auctioned and the revenue is distributed in a lump sum manner. Thus, we are not able to deal with the variety of distributional issues raised in Section 2.1.

Distributional effects will vary depending on who owns what resources and how the costs of different goods change. For example, if lower income people spend a larger percentage of their income on energy, the impact of rising energy prices will have a disproportionately large effect on them. Similarly, if energy costs are higher because of heating requirements in Northern States or for air conditioning in the South, people there may be disproportionately affected compared to the Pacific States where the climate is relatively mild. If the point of regulation is midstream— *e.g.*, electric utilities, industrial emitters and refiners—and allowances are given to them freely, this new asset will represent increased value for these firms and their shareholders to the extent product prices reflect the marginal CO_2 prices. Meanwhile, asset values and employment at upstream coal companies could decline. If, on the other hand, allowances were auctioned and the revenue distributed in a lump sum manner (*e.g.*, equally to every citizen, every adult citizen, or every taxpayer), the distributional effects would change substantially.

4. CORE RESULTS

The estimates presented in this section are dependent on assumptions in Section 3.2 about how U.S. policy is implemented and on emissions controls assumed to be imposed in other countries. The core assumptions are designed to set a context for assessment of these proposals but many factors come into play and other assumptions are also plausible. Moreover, the bills include different features, some of which may or may not be exercised, are incompletely specified, or may change. For example, linkage with emissions trading with other countries is authorized or anticipated in some of the bills, but may depend on a later judgment by the Administration that the foreign system is sound. Also, several of the bills include regulatory measures (*e.g.*, tightening of auto design regulations), renewable portfolio standards, and specific expenditure programs (*e.g.*, R&D and technology subsidies) that we do not model. Thus, this section is a starting point for exploration of the costs and other impacts of the proposed legislation. Section 4 addresses the sensitivity of these results to several of the core assumptions.

4.1 Emissions, Greenhouse Gas Prices and Welfare Cost

All three emissions reductions paths show net banking, with GHG emissions below the allocations in early years and exceeding them in later ones (**Figure 2**). Thus, for example, projected emissions in 2050 in the 167 bmt case (allowances in 2050 at 80% below 1990) are only about 50% below 1990. Similarly, for the 203 bmt case emissions in 2050 are a little over 40% below 1990 even though allowances allocated in 2050 are 50% below 1990. The 287 bmt case has emissions in 2050 about 5.5% above the allowance allocation in that year.

The bump-up in emissions in 2035 is due to assumptions about policies abroad and the resulting effects on international fuel markets, as the developing countries ramp down their emissions in 2035. Their emissions reductions result in lower demand for fossil fuels, especially petroleum, reducing their prices. The U.S., with the banking provision, takes advantage of this effect by consuming relatively more petroleum products when the fuel price falls. Since the U.S. must meet its overall cap over the period to 2050 these added emissions must be made up for with greater reductions (and banking) in earlier periods. Other assumptions about policies abroad could smooth out or eliminate this effect, but the U.S. would still likely exhibit net banking.

The core scenarios assume all-greenhouse-gas policies with emissions trading among gases at their Global Warming Potential (GWP) values. All prices are thus CO_2-equivalent prices (noted CO_2-e) and that is the case throughout this report. CO_2-e prices for the 287, 203, and 167 bmt cases in the initial projection year (2015) are \$18, \$41, and \$53 per ton CO_2-e (all in 2005 prices) as graphed in **Figure 3a** and shown in **Table 4**. The design of the scenarios ensures that prices rise at the real interest rate, assumed constant at 4% per annum. With banking allowance, holders decide whether to bank or not by comparing the expected rate of return on abatement (and banking of allowances) to returns on other financial instruments and alter their banking behavior until these returns are equalized. The result is that by 2050 carbon prices reach \$70, \$161, and \$210 per ton CO_2-e for the 287, 203, and 167 bmt cases. (Solutions where banking is not allowed are explored in Section 6.1.)

Recognizing that there is uncertainty in emissions growth and abatement cost means it is highly unlikely that the price path would follow this smooth increase because market participants might start with one set of expectations only to have them change as new information was revealed.

As discussed in Appendix B the version of the EPPA model used here incorporates endogenous labor supply, allowing employment to respond to changes in the market economy. Under this formulation the welfare measure includes not only changes in aggregate market consumption but also effects on leisure time. The main measure of overall economic cost we report is change in welfare that, following standard economic theory, is measured as equivalent variation.[9] The results for the three core scenarios are graphed in Figure 3b and shown in Table 4. Other macroeconomic measures (macro-economic market consumption, GDP) are provided in Appendix C. The initial (2015) levels of welfare effects are quite small at 0.01, –0.04%, and –0.08%, ending at –0.18, –1.45, and –1.79% in 2050 for the 287, 203, and 167 bmt cases, respectively.[10]

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[9] The general equilibrium modeling convention is based on economic theory whereby workers willingly choose to work or not, and when they choose not to work they value their non-work time at the marginal wage rate. Carbon dioxide mitigation tends to increase the cost of consuming market goods and thus workers have a tendency to choose to work less, and thus have more non-work time. As a result, the percentage welfare changes in Figure 3b and Table 4 combine a loss of market consumption that is partly offset by a gain in leisure. Moreover, the denominator is larger by the amount of leisure accounted for in the model, which for our accounting increases the denominator by about 17%. How much non-work time to account is somewhat arbitrary and so the denominator in this calculation can be made larger or smaller depending on how much time is accounted. For the model used here we assume a reasonable number of potential labor hours rather than accounting all waking hours of people of all ages. For a discussion, see Matus *et al.* (2007).

[10] If the endpoint percentage below 1990 is the same but the reduction path is more gradual following the quadratic path we have specified for other countries (see footnote 8) more cumulative allowances are available and the overall policy cost is less. We simulated the model in such cases for endpoints 50% and 80% below 1990. Cumulative emissions in these two cases are 230 and 206 bmt compared with 203 and

Given the smooth rise in the CO_2-e price a similarly smooth increase in the welfare cost might be expected. Instead the percentage loss increases through 2030, drops back in 2035, and then increases again. This pattern results because there are two components of the welfare change. One is the direct cost of abatement that can be calculated as the area under a marginal abatement curve. A second stems from general equilibrium interactions, and in this case it is mostly the effect of terms-of-trade impacts on the U.S. resulting from climate policy abroad. Thus, as with the emissions path shown in Figure 2, this pattern is driven by assumptions about policy in the rest of the world, especially the tightening of policies in developing countries in 2035.[11]

Because of the importance of these terms-of-trade effects it is useful to recall the core assumptions about international actions. These cases vary the stringency of the policy in the U.S. but leave unchanged the mitigation efforts of the rest of the world. In the 203 bmt case the U.S. takes on reduction targets similar to other developed countries with the developing countries following later. Whereas the U.S. and developed country allowance allocation is 50% below 1990 in 2050, developing countries are still at their 2000 levels. Although the developing country targets are less stringent relative to 1990 emissions levels, this policy nevertheless represents quite stringent reductions for rapidly growing developing countries. In the 167 bmt case the U.S. mitigation efforts are more stringent than other developed countries in terms of abatement relative to 1990 emissions levels, while in the 287 bmt case the U.S. lags behind them. In this less ambitious case the U.S. effort eventually falls behind that of developing countries, even while the U.S. benefits from terms-of-trade effects.

In viewing these results it is well to keep in mind the political realism of the more- and less-stringent cases, where the U.S. makes a stronger or weaker effort in relation to others. For our purpose a common assumption about external conditions provides a point of departure for comparing different U.S. effort levels. We alter the level of effort assumed abroad in sensitivity analysis discussed below to help isolate the terms-of-trade effects from the costs directly associated with abatement in the U.S. The importance of assumptions about mitigation efforts abroad in assessment of U.S. domestic proposals is further emphasized in Section 5 where we explore alternative scenarios of rest-of-world effort. Together these core and alternative scenarios highlight the strategic implications of cooperative and non-cooperative mitigation that arise through terms-of-trade effects, further complicating policy coordination among countries with different impressions of climate impacts and with incentives to “free ride” on abatement efforts elsewhere.

4.2 The Role of the Non-CO_2 Gases

Inclusion of non-CO_2 greenhouse gases in the policy can be important in reducing the policy cost. Recall that the reduction scenarios are defined in terms of CO_2 equivalents (CO_2-e) with the non-CO_2 gases weighted in terms of their GWPs. Initial levels of

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167 bmt with a linear decline, and thus they obviously lead to higher emissions. Consequently the CO_2-e prices are lower—initially \$35 and \$42 compared with \$41 and \$53 for the linear paths, rising to \$140 and \$165 by 2050, and the welfare losses are lower, 1.08 and 1.48 in 2050 compared with the 1.45 and 1.79 with the linear assumption.

[11] In the forward-looking version of EPPA (Gurgel *et al.*, 2007) consumption changes are smoothed over time as is expected when agents can look ahead and shift present consumptions and savings decisions when they anticipate a future shock.

reduction of several of these gases can be achieved at low cost relative to CO_2, so they are a natural early target for control efforts. Their relative role, period by period, is illustrated in **Figure 4**, using the 203 bmt case as an example. Note that in 2015 these gases represent roughly one-third of CO_2-e reductions, their fraction falling to a quarter in 2020 and to one-fifth in 2025. After that time the reductions to be achieved from controlling these gases is pretty much exhausted, so the absolute level of abatement increases very little, and their contribution relative to total CO_2-e abatement falls to around a tenth in 2050.

The same pattern holds in the other cases. In general, at lower CO_2-e prices the non-CO_2 gases play a larger relative role and can forestall the need for rapid adjustment in the energy sector while contributing, especially in the case of methane, near-term climate benefits. While beyond the scope of this analysis, Reilly *et al*. (2006) provide an evaluation of the cost-effectiveness and climate effects of including non-CO_2 GHGs in a control regime. These findings suggest that even though their relative importance falls over time in policies aimed at substantial reductions in greenhouse gases, their overall role in a cost-effective strategy should not be overlooked.

4.3 Energy Market Effects

The proposed policies have substantial effects on fuels and electricity markets, both in terms of prices and quantities consumed. In reviewing these results it is important to distinguish between the price of fuels themselves and the cost of using them, where the consumer expenditure includes the fuel price and the emissions charge. The carbon contents of fuels are relatively stable, so the price inclusive of the emissions charge can be calculated by adding the appropriate CO_2 penalty for a gallon, barrel, ton, or tcf of the fuel. **Table 5** shows the added cost resulting from a $27 per ton CO_2-e price for a variety of fuels and the percentage increase this implies relative to the average price for these fuels for 2001-2005 (excluding Federal and State excise taxes). In an upstream system the CO_2-e price will be embedded in the fuel price while in a downstream system the fuel user will pay separately for the fuel and for the allowance. Mixed systems will have the carbon charge embedded in some fuel prices and separate from others. We follow the convention of reporting the fuel prices, exclusive of any carbon charge, and electricity prices inclusive of carbon charges because the effect of carbon prices on the electricity price depends on the mix of fuels, and the degree of capture and sequestration, among other things, which change across scenarios.

The percentage price increases for fuels will vary from these estimates as the CO_2-e price varies, and also with changes in the fuel price. The EPPA model projects fuel price changes in the reference, and also that these prices will further change as a result of mitigation policy. In addition, the base price and price projection for any particular year is most appropriately viewed as a five-year average because the model simulates the economy in 5-year time steps. The results for the reference and core cases are shown in **Figure 5**. For a sense of the actual fuel prices projected in these scenarios the index values in the figure can be multiplied by the base prices in Table 5.

The fuel price effects of mitigation policies can be summarized as follows. There are reductions in petroleum product prices relative to the reference projection due to reductions in the crude oil price. This result reflects the fact that there is significant rent in the crude oil price, and the global policy to restrict carbon emissions reduces oil consumption, acting in effect like a monopsony buyer that extracts some of the producer rent. The reduction in overall world demand for oil has a strong effect, relative to the reference, in all cases. The relatively smaller difference among the policy cases occurs because only the stringency of the U.S. policy is varying. We also see the effect of strengthening of the policy in developing countries in 2035, which causes oil prices to fall relative to the reference. Across the core policy cases, then, petroleum product prices rise by about 25% in contrast to more than doubling in the no-policy reference.

Natural gas markets in EPPA are modeled such that international prices do not fully equalize, and so changes in domestic demand can have a larger effect on domestic prices. Whether this result accurately describes emerging global gas markets depends on how fast LNG infrastructure can be developed, especially whether terminals in the U.S. will be built to keep pace with demand, and LNG production facilities abroad can expand. Many analysts see a single world gas market emerging soon, and so the EPPA model structure may underestimate the potential role of natural gas and overestimate the rise in domestic prices. However, with a global policy other regions also change their demand for gas, and exert strong pressure on prices even with a world market. Under emissions mitigation U.S. gas prices approximately follow the reference level for the first 10 years, rising above the reference through 2030 or 2040 depending on the policy case, and then again falling below the reference price. This price pattern reflects the changing role of gas under CO_2 policy. Depending on the CO_2 and fuel prices, gas can be a relatively low-carbon fuel for electricity generation where it substitutes for coal. However, at higher carbon prices coal generation with CO_2 capture and storage (CCS) is even less CO_2 intensive and more economic. In other end uses for natural gas, such as in space heating, a CO_2 price spurs increased efficiency or a switch to electricity thereby reducing the demand for gas. Thus, the rise in the price of gas in middle years occurs when the increase in demand for gas for electricity generation is strong and offsets decreased demand elsewhere in the economy. As carbon prices rise further, coal with CCS displaces natural gas generation and the demand for gas, and its price, falls relative to the reference. How fast this transition occurs depends on the stringency of the policy.

There is relatively little rent in coal prices, so the model results show less adjustment in the price (and more in the quantity of coal consumed). The rents are mostly eliminated by 2030, but thereafter coal generation with CCS enters and coal demand and prices recover. The electricity price is inclusive of the carbon charge and emissions mitigation increases prices relative to the reference. The EPPA model includes increasing adjustment costs when technologies expand rapidly, and these policies involve a rapid transformation of electricity generation. This feature of the sector results in electricity prices overshooting the long-run level as this adjustment occurs, and then falling from that level by 2040, especially in the more stringent 167 and 203 bmt cases. By that time, the electricity sector is substantially de-carbonized. The difference between the electricity price in the policy cases and the reference is the marginal cost of adding capture and sequestration, plus any difference in the carbon dioxide price, times any remaining emissions. Since we assume a capture efficiency of 90% and upwards, differences in the carbon dioxide price across scenarios have a minimal effect on electricity prices.

Table 5 and Figure 5 can be used together with CO_2-e prices in Table 4 to estimate the projected user cost of fuel. Table 5 provides 5-year average prices for 2002-2006. (Ideally the 2003-2007 period would be used as a basis for comparison, as it is centered on 2005, but 2007 data are not yet available.) Thus, for example, the petroleum product price index in the 167 bmt case is at 1.45 in 2025, and multiplying this result by the 5-year average gasoline price in Table 5 of $1.40 (the $0.42 from federal and state excise taxes must be subtracted from $1.82 so that the tax is not multiplied) gives a projected gasoline price (excluding the carbon charge and excise taxes) of about $2.03. Adding the excise tax back on gives a projected gasoline price of $2.45. The CO_2-e price in 2025 for the 167 bmt case is $79 per ton CO_2-e or about 2.92 times the $27 CO_2-e ($0.26 per gallon) benchmark in Table 5. The carbon charge per gallon then is 2.92 times $0.26, or $0.76. Adding this premium to the gasoline price gives a total user cost of gasoline of $3.21. (If the cap-and-trade implementation was upstream this would be the price consumers would see at the pump.) Absent the policy, the EPPA model projects a 2025 reference price for petroleum products of 1.69 times the 2005 level, which is $2.79 (including the excise tax). This means that the incidence of the $0.76 CO_2 cost per gallon for the 167 bmt policy is projected to be split such that $0.42 (the difference between the policy and reference gasoline prices) is passed through to the consumer and the remaining $0.34 is passed back to producers mainly affecting returns to crude oil. Note, however, that cost incidence is strongly affected by the assumption that the world pursues a carbon policy. If the policy were only implemented in the U.S., then the effect on world oil prices is smaller, and much more of the carbon tax burden would fall on U.S. consumers.

As presented in **Figure 6**, all three core policy cases show substantial reductions in primary energy use compared to the reference case, an increase in the use of natural gas through about 2030 that parallels a significant absolute reduction in the use of coal, and growth in the use of coal again after 2030. Shale oil production begins to take market share in the 2040-2045 period in the reference but it does not appear in any of the policy cases. The return of coal is a result of the economic viability of coal power generation with carbon capture and storage (CCS).

In many respects the three core policy cases are similar in their effects on primary energy use. The main difference among them is that the more stringent cases accelerate the shift in the power sector first to gas and then to coal with CCS, and generate greater reductions in overall energy use. The other major energy market change is the substantial growth in biofuel liquids to replace petroleum products in the 203 and 167 bmt cases.[12] In these cases, petroleum product use falls by 32% to over 40% from the present level of use, whereas in the reference case petroleum product use rises by about 87%. In the 287 bmt case only small amounts of biofuel liquids enter the market, and the CO_2-e price is not sufficient to induce much of a reduction in petroleum product use.

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[12] At this point it is worth recalling the dependence of results on EPPA model structure and input assumptions. It is assumed that biofuels will be allowed to compete for market share on an economic basis, without constraints because of environmental or other side effects. The implications of this assumption are explored in Section 7. The same assumption applies to CO_2 capture and storage. Relaxation of these assumptions about competition on an economic basis would raise the estimated emissions price and welfare cost of each of the cap-and-trade cases. On the other hand, the reference scenario does not fully address environmental issues associated with shale oil development and continued expansion of fuel use and associated pollutant emissions. Adding environmental constraints on these could change technological choices in the reference and reduce fossil fuel use from what we project thus leaving less reduction needed to meet a given greenhouse gas target.

The CO_2-e price has a substantial impact on the price of gasoline, especially in the more stringent cases. The CO_2-e price alone would add over $2.00 to the price of a gallon in the 167 bmt case and nearly $0.70 in the 287 bmt case. But because the reduction of fuel demand depresses petroleum product prices by $0.30 to over $1.00 per gallon in later periods, the incentive effects on gasoline consumption are reduced, especially in the less stringent cases. Thus, while the effects of the policy on the world market for petroleum and petroleum product prices convey a terms-of-trade advantage for the U.S., they at the same time lead to relatively smaller incentives for reducing petroleum product use.

A striking aspect of the 203 bmt case is that biofuels enter in 2025 and 2030, then shrink in 2035 only to again take market share toward the end of the study period. This again is a result that comes from the tightening of the policy in developing countries, which reduces the oil price but increases the price of liquids from biofuels as developing countries use them to meet their CO_2 obligations. Biofuels are modeled as a perfect substitute for refined oil products in EPPA and so the clearing price for biofuels is the refined oil price plus the CO_2 charge, which they do not bear, and so that margin goes to biofuels producers. An analysis limited to the U.S. might indicate biofuel entry into the U.S. market at lower net gasoline prices, and would not show the drop in 2035 in the 203 bmt case even as CO_2-e prices rise.

The broader lesson to be drawn from these results is not the specific timing of biofuel use in the U.S. but the importance of considering international competition for biofuels especially with strong CO_2 policies abroad. We examine some of the implications of expanded biofuel use in Section 7, but one result relevant to this behavior of U.S. biofuel use is that the fluctuation in the 203 bmt case is primarily a U.S. consumption effect: we do not see a drop in global production of biomass fuel in 2035. Thus, the reduction in biofuel use in the U.S. does not reflect a threat to the viability of a biofuel industry; quite the contrary, it results from increased demand for biofuels abroad. With flex-fuel vehicles it is not so hard to imagine that the fuel mix in the U.S. could change substantially from year to year as relative prices change.

It is important to note that the large demand for biofuel is a result of it being the main alternative to fossil-based transportation fuel in the EPPA model. If the model included relatively low cost vehicles that could be run in total or in part on electricity—an option requiring improvements in battery technology—then the demand for biofuels could be substantially reduced, to be replaced by demand for electricity. The basic determinant of which technology wins in an economic model, presuming an equal quality of service delivered, is which is less expensive. Where there are close technology competitors then small changes in estimated cost, well within ranges of uncertainty about where breakthroughs may occur, can lead to a different technology choice and mix of energy inputs. Section 6.3 considers nuclear and carbon capture and storage as alternatives in the electric, but a similar sensitivity analysis could well be applied to transportation alternatives.

4.4 Potential Revenue from an Allowance Auction or a Greenhouse Gas tax

As noted previously, there are various ways to administer a policy designed to create price incentives for reducing GHG emissions. In a cap-and-trade system the allowances can be given away or they can be auctioned. Or the emissions penalty could be set directly by a CO_2 tax. In the case of the tax or allowance auction a stream of revenue is generated. The CO_2-e price times the number of tons of allowances distributed in any period gives the total value of the allowances distributed, or alternatively the amount of auction or tax revenue that could have been collected. Options for use of the revenue include lump-sum distribution to households, reducing labor or capital taxes, or spending the funds for other purposes (*e.g.*, R&D or low-income fuel assistance). In Section 6.4 we explore the potential effects of revenue recycling. Here our interest is in the gross amount of potential revenue generated, or alternatively the size of the asset transfer involved in a lump sum distribution.

As can be seen from **Table 6** the potential revenue streams are substantial, ranging in just the first period of the policy from $130 billion in the 287 bmt case to $366 billion in the 167 bmt case. Potential revenue rises most rapidly in the 287 bmt case; the annual allowances distributed are the same in each year and the allowance price rises at 4% and so revenue necessarily rises at 4%. While the allowance prices are also rising at 4% in the 203 and 167 bmt cases, the number of allowances distributed each year is falling, thus revenue necessarily rises at less than 4% per year. In the 167 bmt case, revenue peaks around 2030 and declines by about 40% from this peak by 2050, ending up almost 32% below the 2015 level, and at about one-half the 2050 level of the other two cases. Table 6 also shows the potential tax disbursement to a family-of-four household each year. For this purpose we have simply divided the population by 4 as if the population were divided into four-person households and then divided the total revenue by this artificially constructed number of households. The amount ranges from about $1630 to $4560 in 2015, and ranges from about $2520 to $5190 in 2050.

To further illustrate the fiscal potential of an allowance auction or equivalent emissions tax we also include in Table 6 the CO_2-e auction proceeds as a percentage of Federal tax revenue.[13] The potential auction revenue is substantial—about 10-15% of total Federal tax revenue in many periods across the three cases but ranging from a low of 5% to nearly 20%. Thus if the revenue were used to cut taxes evenly across different income groups and income sources, this would be approximately the percentage reduction in the Federal tax bill that taxpayers could expect to see. If, as we discuss in Section 6.4, the tax cuts were directed either toward labor or capital taxes then the rate cuts would be higher and the changes in individual tax bills would depend on the degree to which their income was from labor or from investment returns.

5. EXPLORATION OF TERMS-OF-TRADE EFFECTS

The core cases assume that the U.S. adopts a cap-and-trade measure that is not linked to policies in the rest of world and that, across alternative U.S. policy cases, the mitigation effort remains unchanged elsewhere. As shown above, policies abroad can influence the U.S. through a terms-of-trade effect even without linking emissions trading systems.

Recall that in the core cases developed countries pursue a gradual cut to 50% below 1990 by 2050, and that developing countries begin mitigating in 2025 by cutting emissions back to 2015 levels, returning to 2000 levels in 2035 and holding at this level through 2050. We do not simulate banking in countries abroad, nor do we allow international emissions trading among regions. To test alternatives to this scenario we

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[13] Tax rates in EPPA are based on combined Federal, State and local taxes. For purposes of estimating the Federal share, we have assumed that it grows at the rate of GDP and that remaining tax revenue is State and local taxes.

consider two cases: (1) only the U.S. and other developed countries take mitigation action (noted US+DEV), and (2) mitigation policy is only pursued in the U.S. (noted US only). These are extreme assumptions—it would not make much sense for the U.S. to pursue these policies if no other country followed suit, and given the importance of developing countries it may even be unlikely that the developed countries including the U.S. would pursue these paths through 2050 if others failed to follow. While less extreme cases could be simulated, the cases examined here allow us to identify the terms-of-trade effects of policies adopted abroad.

Figure 7 illustrates the effects of the different assumptions on the CO_2-equivalent price in the U.S. for the 203 bmt case, and **Figure 8** reports the U.S. welfare effects for all three cases.[14] As can be seen in Figure 7, the more aggressive the mitigation action taken abroad the higher the required CO_2-e price in the U.S. Consistently across all three of the U.S. policy variants the CO_2-e price is highest if all countries mitigate (here, represented by the assumed reductions underlying the core 203 bmt case). U.S. prices are somewhat lower if only the developed countries reduce (US+DEV) and lower still if only the U.S. mitigates (US only). Two factors contribute to this result. As previously noted, mitigation policy abroad reduces the world oil price, so that achieving the same reduction of oil use at this lower price requires a higher CO_2-e price in the U.S.; in effect the U.S. emissions price needs to make up for the drop in the world oil price. Second, more stringent mitigation policy abroad leads to greater global biofuel use, and the resulting higher biofuel prices require higher U.S. CO_2-e prices to achieve the needed reductions.

Moving to the welfare costs in Figure 8, lower CO_2-e prices generally result in lower *direct*[15] mitigation cost, which is one part of the measured welfare change. Terms-of-trade effects, potentially through all markets but more importantly through oil and agricultural markets, also influence the results. Agricultural markets are strongly affected by competition for land from biomass energy production. Because of the different factors operating in each scenario, we need to take these one by one to understand the results.

In the 287 bmt cases the carbon price is somewhat lower with less mitigation abroad, and this lower direct cost of the policy tends to drive the results in early years. Few biofuels are used by the U.S in this scenario. However, after 2035 in the core cases, when the policy is tightened in developing countries, two important positive terms-of-trade benefits accrue to the U.S. First, world oil prices are lower and since the U.S. is a big oil importer this is beneficial. And second, demand for biofuels increases abroad, and even though the U.S. uses little in this case, this change raises agricultural prices through land-market impacts. Since the U.S. is a net agricultural exporter this effect also results in a terms-of-trade benefit. Thus, the welfare costs fall in the U.S. after 2035 compared with earlier years, even though the direct cost is growing. Reducing or eliminating mitigation

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[14] For the CO_2-e price, the 167 bmt and 287 bmt cases show a pattern similar to that shown for 203 bmt and are omitted to simplify the figure. The data for these other two cases is provided in Appendix C.

[15] It is useful again to distinguish between the *direct* abatement cost and additional economic impacts that stem from interactions with the rest of the economy—*general equilibrium (GE) effects*. The *direct* cost is a measure that can be obtained by integrating under a marginal abatement cost curve, or can be approximated as the triangle area under the abatement curve equal to 0.5 × CO_2-e price × quantity abated. GE effects can stem from interactions with pre-existing distortions (*e.g.*, taxes) from externally induced terms-of-trade effects, from the fact that the domestic policy itself creates terms-of-trade effects, and from other rigidities in the economy. Many aspects of model structure produce GE effects that are not easy to separately measure because of the inherent interactions in the economy.

abroad eliminates these positive terms-of-trade effects and a smoother pattern of costs emerges over time, as we would expect given the CO_2-e price path in the U.S.

The 203 bmt cases show the strongest effects on U.S. CO_2-e prices from changes in the mitigation policy abroad, and thus the direct cost of the policy is lower with less mitigation effort abroad compared to the core cases. This is the dominant effect in the near term and is responsible for the lower welfare cost through 2030 when less is done abroad. Without the strengthening of the developing country policy in 2035, we do not see the significant terms-of-trade benefit from lower oil prices at that point, and so the welfare loss continues to increase in these scenarios. By 2050, however, the added direct cost in the core case is beginning to cancel out the terms-of-trade benefit, and so the welfare cost in all three cases are similar. In large part this result is due to the biofuels market. Recall that in the 203 bmt core case biofuels enter strongly in U.S. energy consumption in 2025, and 2030, and then shrink in 2035, reappearing later. Biofuel is mostly imported in these scenarios, and so its increasing price due to a stronger mitigation effort abroad creates a further terms-of-trade loss, but not if there are few imports as in 2035 in the core case. Since the mitigation level required in the U.S. can be achieved without biomass consumption in 2035, oil imports are considerably larger than in the preceding or following years, and the terms-of-trade benefit is that much greater. This sharp reduction in biofuels use does not occur in the cases with less mitigation abroad, and thus we see a smoother pattern of welfare change over time.

The 167 bmt cases show the smallest difference in the U.S. CO_2-e price and welfare effects among cases. In large part, this policy requires fairly drastic emissions reductions in the U.S. Thus, oil consumption is much lower in these cases so the flexibility to increase it when the price falls in 2035 is severely limited and the terms-of-trade benefit is less. When the U.S. is mitigating alone there is less pressure on biofuels markets, lowering the cost of substituting biofuels for petroleum products and reducing the terms-of-trade loss in the biofuels market. The bioenergy market and land-use implications of biofuels use are discussed in greater detail in Section 7.

One way to isolate the terms-of-trade effects that arise from policies outside the U.S. is to consider the difference in the welfare cost in the U.S. with and without action in the rest of the world. We make that calculation in **Table 7**. Also, because banking is redistributing the effects through time it is useful to look at the net difference over the whole period. For this purpose we calculate the discounted (Net Present Value) loss in percentage terms. If the net terms-of-trade effects originating from policy abroad are positive, then the NPV difference will be positive and *vice ver*sa. As shown in the table, the terms-of-trade calculation in the 287 bmt case is positive, reflecting the strong effect of lower world oil prices. The U.S. consumes very little biofuel in this scenario and so the potentially negative effect on the terms of trade from that source is not relevant. In the 203 and 167 bmt cases there are net terms-of-trade losses as discussed above because the CO_2 constraints greatly limit U.S. oil consumption and thus the terms-of trade benefits from this source. Imported biofuels become an important source of terms-of-trade losses.

6. ALTERNATIVE DESIGN FEATURES AND EXTERNAL CONDITIONS

We next turn to a set of scenarios that consider alternative design features, exploring aspects of the scenarios that affect the estimated cost and highlighting other aspects of the results. In this part of the assessment a limited set of results is presented. More complete results for all scenarios, including welfare, consumption, GDP, energy market, greenhouse gas emissions by gas, fuels used in electricity generation, and biofuels and agricultural trade are presented in Appendix C.

6.1 The Effects of Banking

Many of the current proposals allow banking of allowances. As discussed above and shown in Figure 2, banking results in a reallocation of the abatement effort toward the near term so that less stringent reductions are needed in later years. In **Figure 9** we report the effect on CO_2-e prices (Panel a) and welfare (Panel b) of cases with No Banking (NB) compared with the results for core cases that include banking. We expect the CO_2-e prices to start out lower and end up higher in the no banking (NB) cases, and that is the pattern that emerges. The initial (2015) NB prices are \$6, \$10 and \$17 per ton CO_2-e compared with \$18, \$41, and \$53 for the 287, 203, and 167 bmt cases, respectively. They rise to \$77, \$262, and \$2559 by 2050 in the NB cases compared with \$70, \$161, and \$210 per ton CO_2-e for the 287, 203, and 167 bmt cases. The increase in CO_2-e prices in 2050 under the 203 bmt case and 2045 in the 167 bmt case (off the scale in Figure 9) result from the difficulties of reducing emissions in transportation. More details on this result are discussed below in Section 7 where we address biofuels and land-use implications.

Not surprisingly the welfare effects show a similar pattern, and losses rise to nearly 5% in the 167 bmt case. Note that without banking a target of 80% below 1990 emissions yields emissions 91% below the reference, and thus we are simulating an economy that is operating with less than 10% of reference emissions. Put another way, the economy of 2050 is more than three times the size of the current economy and population has increased by nearly one-third and yet the U.S. is emitting only about 15% of the GHGs of today. The EPPA model assumes substantial improvement in efficiencies throughout the economy, and price increases in transportation and other parts of the economy stimulate further technological substitution. Thus, even to achieve the results shown here considerable advance in technology is needed, but to achieve an economy that is nearly GHG-free at reasonable cost will require technological advances beyond those we have modeled.

We would expect the banking cases to show a lower Net Present Value welfare cost over the study period even considering that the higher costs in later years under No Banking are discounted at the 4% economy-wide interest rate. That result does hold for the 287 and 167 bmt cases but the difference is not very large. In the 287 bmt case, the NPV loss rounds to only 0.08% with banking and 0.07% without banking. Looking at more (and not necessarily meaningful) significant digits shows just how small the difference is—loss is 0.077% in the 287 bmt case and 0.074% in the NB case. The NPV loss for 167 bmt is 0.41% in the banking case and 0.42% in the NB case.

The 203 bmt case shows a slight advantage for the NB case (0.24% compared with 0.26%), an unexpected result. The likely reason is that there are extra-fuel-market influences, such as terms-of-trade effects that are not fully reflected in the allowance banking decision, and this may also reflect incomplete reallocation through time in the recursive-dynamic structure that does not fully optimize through time. While the banking-NB comparison shows very small differences in our scenarios in terms of NPV, banking provisions provide flexibility in the face of uncertainty that we have not modeled, and so the numerical result here should not be interpreted as suggesting that banking is not a useful policy design feature.

6.2 Limited Sectoral Coverage

Some of the proposals that focus on a downstream emissions cap exempt entities below some annual emissions level such as 10,000 tons of CO_2. One rationale is that monitoring small emitters would be too costly. In principle, such a provision would exclude the transportation sector with its many individual vehicles, but existing bills include it by moving the cap upstream to refiners who then must carry allowances for emissions that will result from the transportation fuel they sell. To represent this feature, we simulated a policy that exempts agriculture, households (*i.e.* natural gas and heating oil), and the service sector. Included under the cap are energy-intensive industry, other manufacturing, electric utilities, refineries, and transportation fuels. (The exempted sectors are not unaffected by the mitigation policy: inclusion of electric utilities under the cap means that their electricity prices will rise.) The limitation on coverage means that 77% of emissions as of 2005 are under the cap, and to simulate this policy we simply scale economy-wide allowances down by this amount over the whole period. It turns out in the EPPA reference that emissions from the covered sectors are growing somewhat more rapidly than the exempt sectors, and so by 2050 the covered sectors account for 83% of economy-wide emissions in the reference.

The CO_2-e prices are somewhat lower with sector exemptions compared with the economy-wide policy results (**Table 8**). Since the allowance allocation is proportionally scaled as a first approximation one might expect little difference. To the extent a difference exists it is because abatement is relatively easier or more difficult in the covered and exempted sectors, and over time there is differential growth between the two. Since emissions of the covered sectors are growing slightly more rapidly than the exempt ones, proportionally scaling down the allowances based on the share of emissions in the covered sectors in 2005 would, by itself, tend to lead to somewhat higher prices. Likely offsetting this effect is the inclusion of electric power under the cap where the availability of a variety of low carbon technologies usually results in this sector abating more than proportionally to other sectors. Additionally, the non-CO_2 GHGs are inexpensive to abate, especially those from non-agriculture sources, and they are included in the covered sectors. With fewer sectors competing for allowances released by abatement in the electric sector and from non-CO_2 GHG abatement, CO_2-e prices are lower compared with the economy-wide cases.

As shown in **Table 9** the welfare costs are lower with these sectors exempted than for the economy-wide cap. With sectors exempted the abatement required is proportionally less, and so as a first approximation we would expect the cost to be proportionally less as well. Costs are also lower because the CO_2-e price is somewhat lower. Once past the first few years, the sector welfare costs are about 70% of the economy-wide cost. In early years when the CO_2-e price is low much of the abatement is from non-CO_2 GHGs as shown in Figure 4 and even more so for the exemption case, lowering the welfare cost to about one-half that of the economy-wide policy.

Of course, the lower cost is associated with a less environmentally effective policy because of the higher emissions (**Figure 10**). One concern would be a widening gap in emissions between economy-wide implementation and implementation with sector exemptions, which would occur if the exempt sector emissions were growing rapidly.

This result might reflect leakage because the mitigation policy led to shifts of production among sectors. Leakage of CO_2—increases in emissions in the non-covered sectors compared to the reference emissions from these sectors— are 0.7, 1.0, and 1.1 bmt over the 38-year horizon of the policy in the 287, 203, and 167 bmt cases, respectively, relatively small compared with the total emissions allowed in these cases.

6.3 Nuclear Power and Carbon Capture and Storage

In the core cases we limited nuclear electricity generation to that possible with current capacity on the basis that safety and siting concerns would prevent additional construction. With strong greenhouse gas policy such concerns may be overcome, especially if other major technologies such as carbon capture and storage can not be successfully developed, run into their own set of regulatory concerns, or turn out to be very expensive. To explore the possible outcome we relax the limitation on nuclear expansion, and assume that new generation plants become available that can produce delivered power at a 25% mark-up over coal generated electricity without CCS.[16] The coal CCS generation technology is assumed to have a mark-up of about 20% above coal without CCS.

Figure 11 shows the penetration of nuclear power and coal generation with and without CCS in the 203 bmt core case. The 25% mark-up on nuclear with a 20% mark-up on CCS is just about the level needed to make nuclear competitive with CCS given that CCS bears some cost associated with CO_2 emissions that are not captured and stored, and given the changing fuel and other prices simulated in the model. With removal of non-economic limitations nuclear penetrates strongly beginning in 2020, reaching 20 EJ by 2050, over six times current production (Figure 11a). The fate of CCS is the mirror image. With nuclear limited, CCS expands beginning in 2020 to about 18 EJ in 2050. When nuclear is allowed to compete on economic terms, some CCS is viable but it begins losing out to nuclear after 2040, when the CO_2-e price has risen substantially. Coal generation without CCS disappears in either case.

These relatively detailed results help illustrate the scale of effort required to meet these policy constraints. There are just over 100 nuclear reactors in the U.S. today, and so a six-fold increase in nuclear generation would require the construction of on the order of 500 additional reactors. If nuclear cannot penetrate the market the scale issue is not avoided but instead is transferred to CCS, requiring siting and construction of about the same number of new CCS plants. The need to phase out coal without CCS indicates the potential value of a CCS technology that could be used to retrofit existing generation plants, extending the life of existing investment and limiting the number of completely new plants that were needed. The capital intensity of these technologies are a concern as we find that the investment demand needed for such expansions crowds out investment in other areas of the economy, and thus increases the welfare cost of the policy.

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[16] The mark-up is relative to the cost of electricity including transmissions and distribution (T&D) charges. Engineering estimates typically compare costs at the busbar, and in such comparison the mark-up would be higher because T&D costs are the same regardless of the generation technology.

6.4 Revenue Recycling

A large body of economic analysis shows economic gains from auctioning allowances and using the revenue to lower existing taxes on labor and capital. The recursive dynamic structure of the standard EPPA model is not well-suited to evaluating these potential benefits. Gurgel *et al*. (2007) have developed a fully dynamic version of EPPA that results in very similar the abatement levels and CO_2-e prices as in the standard EPPA but is solved as a fully dynamic model where agents have perfect foresight. They use this version of EPPA to investigate revenue recycling and other issues, simulating the same 287, 203, and 167 bmt policies. It is not possible to completely investigate the many issues involved in revenue recycling here, but given the general interest in this topic it is useful to give some general indication of the magnitude of benefits revenue recycling could achieve.

Gurgel *et al*. (2007) find a 15% to as much as 70% reduction in the welfare cost when allowance auction revenue is used to lower capital taxes and a 5% to 20% reduction in cost when labor taxes are reduced. This result is consistent with other research that generally shows a greater benefit from capital tax recycling. The percentage reduction in cost is largest for the 287 bmt case and smallest for the 167 bmt case. One reason for this difference across cases lies in the fact that the denominator in this calculation—the welfare cost of the policy without recycling—is higher in the 167 bmt case. Another is that any benefit from revenue recycling depends first on how much revenue there is. Recall from Table 6 that while potential revenue starts out much higher in the 167 bmt case because of the high initial CO_2-e price, it actually falls off substantially by the end of the period because so few permits are available for auction when the policy becomes very tight. In the 287 bmt case, the revenue stream starts low but grows substantially over the period. Thus, the tax rate cut is not very different across the cases because they yield similar flows of revenue, so the numerator in the calculation—the recycling benefit—is not that different across the cases.[17] An important insight to be gained, then, is that a very tight policy that auctions very few permits will generate very little revenue. Stabilization ultimately requires very low emissions and so revenue recycling benefits are a transitory feature in stabilizations policies.

6.5 Provision of a Safety Valve

At various points in the discussion we have pointed out the similarities between a cap-and-trade system and an emissions tax. Another option introduced in Section 2.1 is a hybrid consisting of cap-and-trade system with a safety valve. In such a regime provisions are included that cap the CO_2-e price. This idea was prominently part of a report by a National Commission on Energy Policy (NCEP, 2004), and the level of the price cap identified in one of the proposals summarized in Table 2 follows the recommendations of that report. Usually the proposed price caps follow a time-path that rises at an estimated (real) rate of interest. Such a price path approximates an efficient allocation of abatement over time by keeping the net present value emissions price

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[17] An important aspect to consider is that the welfare costs of the policy in forward-looking model are considerably lower than in the recursive model because it is optimizing over time as well as among sectors. Thus, applying these percentage cost reductions to results from the recursive model may overstate the potential revenue recycling benefits.

constant, and this approach is consistent with the price path we derive for a cap-and-trade system with banking.

The term “safety valve” comes from the notion that the price cap would be set substantially above expected prices under the cap to prevent the price from spiking in extreme circumstances. Recall from Section 2.1 that “high” is relative to the stringency of the cap and the expected emission price. A low level in relation to the stringency of the cap can assure that the safety operates frequently which, as noted above, would work much like a CO_2 tax with allocated exemptions. If the safety valve is likely to always be triggered, the level of allowances distributed for free regulates how much revenue the government receives. If the cap is high enough so that the safety valve is only rarely triggered the policy becomes equivalent to a pure cap-and-trade system.

The analysis we conduct can provide only limited insights with regard to the value of the safety valve in policy design. In particular, the above discussion highlights the fact that the motivation for a safety valve is to limit cost *given uncertainty*. To capture the value of the safety valve we would need to stochastically simulate the EPPA model, a task that is beyond the scope of this effort. As long as we are simulating EPPA in a non-stochastic mode, however, for every quantity constraint there is a price path that will deliver that same amount of abatement. And *vice versa*: the amount of abatement generated by a price path can be observed and the policy instead specified as a quantity constraint. Thus, the policy cases as simulated above can be interpreted as a cap-and-trade system, as a tax system in which the tax level is set at the prices observed in our simulations, or as a cap-and-trade system with a safety valve set at the price level we simulate.

For example, the 203 bmt case could be interpreted instead as a CO_2 tax policy with the tax rising from $41 to $161 per ton CO_2-e. Or that price level can be interpreted as a safety valve price path as long as allowance allocation was no more than the 203 bmt. If, for example, the cap was set at one-half of the 203 bmt and the allowance path was just cut in half each year, the only effect would be to reduce tax revenue by one-half. No other aspects of the scenario are changed by this reinterpretation. The only case where differences will appear is if tax or auction revenue is used to cut taxes as in Section 6.4. Cutting the revenue in half by distributing half of the allowances for free would mean that the capital tax rate could not be cut as far, and any tax recycling benefits would be reduced.

It is also useful to note that, in the world of certainty that we are simulating, if the safety valve price rises at an economy-wide rate of interest and that is the same rate at which banking decisions are made, then either the safety valve is always triggered or it is never triggered. This result follows from simple algebra—both the banking price and the safety valve price rise at the same rate, and so if one is higher than the other at any point it is higher at all points. Of course, the safety valve need not rise at the rate of interest—it could be fixed at a flat level—or the legislatively prescribed rate of increase might not match the actual rate that traders are using in their banking decisions.[18] The inter-

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[18] A difference between the rate of increase in the safety valve and the banking rate would tend, in a “certain” world, to generate two periods—one where the safety valve is triggered and one where it is not. Which comes first depends on whether the banking rate is higher or lower than the prescribed rate of increase in the safety valve. The U.S. Energy Information Administration (US EIA, 2007) used a banking

relationship of banking behavior and the safety valve should not be surprising. They are competing policy features that are both intended to smooth out short-term variations in the prices that might come about because economic activity and emissions can vary from a long-term trend. If both are included in a policy, one of them will likely dominate the other depending on the safety valve level and increase compared with the banking rate.

Finally, it is worth pointing out that setting the level of a safety valve to limit cost must consider whether it will achieve the desired level of abatement or not. Legislation that prescribes either a safety valve price or a cap is inevitably subject to review as to the adequacy of the policy and its cost, and such reviews are written into the various legislative proposals. The popular view of a price/safety valve policy instrument is that it provides certainty in the policy cost while creating uncertainty in how much abatement will be achieved, while a cap-and-trade instrument creates certainty in environmental effectiveness but leaves uncertainty in the cost. This stark characterization of the difference is only valid in a world where the policies are never revised. A cap that turns out more expensive than anticipated could be revised and loosened. A safety valve path that is not achieving significant reductions might be revised upward. Changing evidence of the threat of climate change could also lead to revisions, in either direction, of a price or quantity instrument. There is thus likely to be less difference between these instruments over the long-term where over-arching goals of the policy are shaped by improved understanding of the science and economics of the problem, and prices and quantities are revised to be consistent with that improving knowledge.

Applying these concepts we construct a policy case with a price path similar to the one proposed in the National Energy Commissions report (NCEP, 2004) that begins at \$6 per ton CO_2-e and rises to about \$39 per ton CO_2-e by 2050.[19] Then to explore the potential costs and effectiveness of the safety valve we conduct four simulations reported in Figure 12: (1) the safety valve (SV) case in the U.S. with the standard assumptions in the core cases about mitigation efforts abroad (US+ROW), (2) the SV case in the U.S. and no mitigation action abroad (US only), (3) no action in the U.S., and the standard assumptions about effort abroad (ROW only), and (4) the SV case in the U.S. with the safety valve price being revised upward in 2030 and standard assumptions about action abroad (SV Revised 2030). The SV Revised 2030 case is an artificial construction to illustrate the possibility that events may unfold in ways that lead to a revision some time before 2050. If we knew now what these events were we would reshape the overall price path to start higher and rise at 5%, without a sudden revision.

Figure 12a shows the standard safety valve price path and the path when the price is revised in 2030. In the revised path, the price is doubled in 2030 and then continues to grow at 5% per year. Figure 12b shows the welfare effects. Here, as in the 287 bmt revenue recycling case, the U.S. welfare change is small initially and then welfare actually improves relative to the no-policy reference case; that is, the policy appears to be beneficial to the economy. The US Only and ROW Only simulations confirm that the welfare benefit in the US+ROW case is a terms-of-trade effect. In the US Only case there is always a welfare cost and it rises over time as the CO_2-e price rises. The ROW Only

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rate of 8% with a safety valve rising at 5%. As a result the cap was binding in early years and the banking price rose at 8% eventually catching up to and triggering the safety valve.

[19] This level has also been adopted in the Bingaman-Specter draft legislation and analyzed by the EIA (US EIA, 2007).

case shows even larger benefits for the U.S. than the US+ROW case. Thus, relative to that case the addition of a policy in the U.S. reduces welfare.

The plausibility of the rest of the world pursuing a fairly stringent policy while the U.S. is pursuing a relatively weaker one can be questioned. In that regard, one way to motivate the SV Revised 2030 case is that with developing countries joining in 2025, the U.S. might then see reason to intensify its efforts by revising upward the safety valve price in 2030, with this leadership move then bringing a further commitment of developing countries in 2035. As the SV Revised 2030 case shows in Figure 12b, the upward revision of the safety valve basically eliminates the net terms-of-trade gain from the ROW policy, leaving the U.S. better off with the revision than if it had pursued the safety valve without the rest of the world. Obviously, such a scenario of international cooperation is fairly simple-minded speculation on our part, but it does illustrate the degree to which decisions about the level of U.S. effort over an extended period depends on what other countries do, and whether or not U.S. leadership generates a following.

In cap-and-trade cases total emissions must be less than the cap. With a price instrument the price is certain but the level of emissions is uncertain. While we do not represent many of the inevitable uncertainties in economic projections the different assumptions about international policy can be seen as one of the uncertain aspects of the future. And, as shown in Figure 12c, what the rest world does in terms of mitigation strongly affects U.S. emissions and the effectiveness of a price instrument. Here we also plot the reference level of emissions when there is no policy in the U.S. or the rest of the world. First, note that the U.S. emissions drop about 1800 mmt of CO_2-e below the reference in the US+ROW case by 2025, and then do not drop much more below the reference for most of the rest of the period even though the CO_2-e price is escalating at 5% per year. However, it can be seen from the ROW Only case that U.S. emissions without a policy would have risen above the reference, reflecting leakage from the ROW policy into the U.S. The main source of this leakage in the EPPA model is lower world oil prices that then lead to greater petroleum product use. Compared, then, to the ROW Only case the escalating CO_2-e price gradually increases the level of abatement. Somewhat more surprising is that in the US Only case, the policy with the specified safety valve becomes very effective toward the end of the period. Recall that the EPPA model reference petroleum product prices rise substantially if the world is not taking action, as shown previously in Figure 5. Thus with mitigation only by the U.S., biofuels become economically competitive with refined oil, lowering emissions at the safety valve-determined emissions price.

The SV Revised 2030 case can be further motivated by the observed pattern of emissions with and without policy in the rest of the world. One can imagine that a broad goal of the safety valve policy is to hold U.S. emissions flat over the longer term and that is being roughly accomplished in the US Only case. However, that goal is not being met by 2030/2035 in the US+ROW policy. Our doubling of the safety valve price in 2030 gets the U.S. back on track to hold emissions more or less flat, and that revision can be seen as an adjustment in the safety valve price to keep the U.S. headed toward a quantity target, retaining the safety valve instrument to protect against short-term price spikes but unwilling to live with the long-term implications for emissions if it is not adjusted.

6.6 International Allowance Trading

We turn next to the potential implications of international emissions trading. As shown above, banking reallocates abatement and cost through time making it difficult to sort out the impact of other design features. To isolate the effects of emissions trading, therefore, we simulate scenarios without banking. Note also that in the core scenarios there is no trading among regions. Here we create a scenario where all world regions except the U.S. trade among themselves. This further allows a focus on just the implications for the U.S. of joining an international emissions trading system.[20]

Pre-trade and trading prices for the 203 bmt and 167 bmt cases are shown in **Figure 13**.[21] Panel (a) shows pre-trade prices and panel (b) contrasts the world trading price with the pre-trade prices in the rest of the world (ROW). Note that the ROW pre-trade prices are affected by the policy in the U.S. The factors producing this effect are the same as those behind the influence of ROW actions on U.S. domestic prices: under more stringent U.S. controls, reduced U.S. demand for oil and higher demand for biofuels combine to widen the gap between fossil and non-fossil alternatives thus requiring a higher CO_2-e price abroad to meet the assumed emissions cap.

Figure 13a shows that the pre-trade price differences are relatively small in the 203 bmt case up to 2045, with the U.S. pre-trade price higher than the world price so the U.S. would be a net buyer of allowances if it joined the international trading system. The 167 bmt case has U.S. pre-trade prices further above those in the ROW, and so this is a case where the U.S. would be a strong net purchaser of allowances after 2035. Figure 13b compares the world trading price and the ROW pre-trade price (note the difference in vertical scale). The effect on the world price of the U.S. joining the emissions trading system is moderate in the 203 bmt case (an increase of about a little less than \$10 per ton CO_2-e) in later years, and somewhat greater (around \$20 per ton CO_2-e) in the 167 bmt case. It is noteworthy that the indirect effects on the world price through terms of trade and international price changes are at least as great as the direct effect of the U.S. entering the trading system.

Regarding the welfare effects of trading, shown in **Table 10**, we find the conventional result that emissions trading improves welfare for the U.S. in the 167 and 287 bmt cases. The improvement is substantial in the 167 bmt case because the pre-trade prices in the U.S. were quite large by the end of period, generating substantial direct mitigation policy costs. The U.S. is a small net seller of allowances in almost all years in the 287 bmt case, and this generates no change or small welfare gains in all years. The 203 bmt case shows emissions trading to be welfare worsening for the U.S. This perverse outcome can be produced by interactions with existing distortions in the economy or through terms-of-trade effects (Babiker *et al*., 2004; Paltsev *et al*., 2007). In this case, it is likely that terms-of-trade effects are driving this result. As Webster *et al*. (2006) show, if the direct gains from trade are relatively small (because the pre-trade price difference is small) then indirect effects through changes in the terms of trade can dominate the direct trading benefits. Here the likely dominating terms-of-trade effects occur because by entering the

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[20] Going from no trading to trading abroad has some effects on the U.S. through terms-of-trade changes but these are relatively minor.

[21] The U.S. pre-trade price in the 287 bmt case is very similar to the ROW pre-trade price, and thus there is little incentive for trade. To simplify the figure this case is omitted.

permit market the U.S. forces more abatement abroad. A main avenue of abatement is the use of biofuels, and this drives up the world price of this fuel, which the U.S. imports. This effect worsens the terms of trade.

More broadly, in many policy-design discussions allowance credits from outside the U.S. trading system are seen as a means to lower the cost of the greenhouse gas policy in the U.S. But this argument assumes that there is a low-cost supply of credits for which there is little competition—*i.e.* that the U.S. is the only significant country pursuing a stringent mitigation policy. If other developed countries are pursuing a policy of similar stringency, the CO_2-e price in these regions will be similar to that in the U.S. and so they will not be a source of low-cost allowances.

Before the developing countries take on a policy they may be a source of credits through the Clean Development Mechanism (CDM) of the Kyoto Protocol, but the evidence suggests that because of the project-based nature of such credits only a relatively small percentage of the potential reductions in developing countries can actually be formulated as projects that would meet CDM criteria. Thus, the U.S. and other developed countries will compete for a relatively limited supply, with some but limited savings in the U.S. If the developing countries take on a real cap sometime in the next decade or so, and given their relatively rapidly growing emissions, the prices they would see are not that different from those obtained in the U.S. in our model simulations (under the 203 bmt case) and so there is little potential U.S. benefit. It is only when the U.S. agrees to bear a substantial share of the reduction burden by accepting a much tighter policy than other countries that emissions trading brings significant benefits.

Emissions trading probably ought to be seen, therefore, mainly as an instrument by which the U.S. and perhaps other developed countries might accept a large share of the cost burden, either on the basis that this is "fair" or to induce developing countries to take on at least some commitment by implicitly agreeing to pay for their reductions by awarding allowances that we will purchase from them. If instead U.S. policy is designed so that the U.S. mitigation effort is comparable to that of other regions (*i.e.* the CO_2-e price is likely to be within 50% or so of other regions) then there is a substantial chance that trading will have little benefit for the U.S., or may be welfare worsening.

Another aspect of these scenarios is the likely role of biofuels as a substitute for international allowance trading. To the extent biofuels are providing abatement at the margin, and this is especially true in the 203 bmt case, the common global biofuel price will tend to equalize CO_2-e prices among regions: regions with relatively tight constraints will import more biofuels causing the CO_2-e price to be lower than it would otherwise, whereas regions with relatively looser constraints will not compete as effectively for biofuels and their CO_2-e price will not be as low as it would be if the biofuel price had not been bid-up by countries with tighter constraints.[22]

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[22] The possibility of the domestic prices of a non-traded good or factor input (in this case the CO_2-e allowance price) to equalize across countries is consistent with basic economic theory as expressed in the well-known factor price equalization theorem that predicts equalization of wages and returns to capital even in the presence of restrictions on capital and labor mobility. An important element of the theorem is perfect substitution of foreign and domestic goods, which we have represented in the case of biofuels. Imperfect substitution of other goods, and limits on mobility of labor and capital mean that CO_2-e prices actually diverge among regions in EPPA simulations. Relaxing these assumptions could tend to result in greater convergence in CO_2-e prices among regions even without emissions trading. One implication of this argument is that, if some regions are not capped, the CO_2-e price could approach zero because production

7. BIOFUELS AND LAND USE

As already discussed in several sections, biofuel liquids play an important role in the mitigation scenarios, as they are the main non-carbon alternative to petroleum products that we represent in the EPPA model. Corn-based ethanol production has grown rapidly in the U.S. in the past few years, but even with that growth total ethanol production in the U.S. is a very small percentage of total gasoline consumption (about 2%). Brazil is one of the major producers internationally, and while production there is substantial relative to Brazil's domestic gasoline consumption, total Brazilian ethanol production is about equal to that in the U.S. This comparison simply highlights the fact that U.S. petroleum consumption is very large relative to existing ethanol production. It is also important to realize that the principal motivation for using ethanol in fuels in the U.S. currently is as an oxygenating additive. This source of demand (and the production needed to supply it) is not explicitly represented in the EPPA model, but is part of aggregated agriculture and industry sectors in the EPPA database.

For biofuels to make a substantial contribution to CO_2 abatement in the U.S. their supply would need to expand considerably beyond its role as a fuel additive. In addition, how ethanol is produced would need to change. Current ethanol production processes in the U.S. actually emit a fair amount of CO_2 because fossil fuels are used in the distillation process, and to a lesser extent in growing the corn. Further, the expansion of corn-based ethanol production is limited—if the entire U.S. corn crop were turned to ethanol one estimate is that it would supply less than 10% of U.S. gasoline demand. Focus has therefore shifted to production of biofuels from cellulosic plant material, which while not yet commercialized is highly promising. Cellulosic conversion utilizes much more of the energy in the biomass, and a broader range of crops can be used.

Biofuel liquids in the EPPA model are based on the assumption that cellulosic conversion processes are successfully commercialized and that the energy needed in the conversion/ distillation process is also supplied by biomass so that there is no net CO_2 release. A source of biomass process energy could actually be the lignin in biomass, which cellulosic conversion processes closest to commercialization cannot convert to liquid fuels. While other processes are under development that would break down the lignin as well, if heat energy is required in the processing of ethanol anyway then the lignin by-product can be used directly for that purpose, without a further costly conversion. If not, some other, relatively expensive non-fossil source of energy would be required, or the process would need to include carbon capture and sequestration. The EPPA model assumptions about the cost and efficiency of ethanol production are in line with engineering estimates, once scale economies are realized and experience is gained with initial demonstration plants (see Paltsev *et al*., 2005).

Before focusing attention on the EPPA results, the magnitude of the potential land pressure from biomass can be illustrated using some simple calculations presented in **Table 11**. On the assumptions detailed above and in the table, if all U.S. cropland, grassland, and forestland were used to produce biomass liquids, total U.S. production could reach about 81 exajoules (EJ). Coincidentally, this quantity would just cover the 78 EJ of petroleum product consumption in the U.S. in 2050 in our reference projection.

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and consumption activities would shift to the uncapped regions—leakage from the policy would be complete.

Needless to say, converting every bit of grassland, forestland and cropland to biomass production would have massive implications for land use, and would leave no land left for food, forest, and fiber production—thus it is a purely hypothetical calculation. From this simple calculation it should be evident that biofuels production, even at levels that would offset 10 or 15% of petroleum product use, would have substantial effects on agricultural markets and on land use.

Some popular estimates of U.S. biomass potential suggest greater possibilities but often they involve a comparison of total biomass energy, failing to consider conversion losses or assuming some other source is available for process energy. Or studies compare U.S. biomass energy to just U.S. oil imports or current gasoline consumption, failing to consider the likelihood that demand for fuels will increase. Others further assume that greater efficiency in vehicles, without increased miles driven, will actually reduce fuel demand over time. The EPPA model projects continuing increase in vehicle fuel efficiency even in the reference case, where vehicle efficiency improves by nearly 60% by 2050 in vehicles of all types (*i.e.* including commercial transport) compared to the fleet average today. Thus, the 78 EJ of petroleum product use in the U.S. already includes assumptions about aggressive improvement in vehicle efficiency.

The EPPA model results for biofuels are presented in **Figure 14** with two assumptions: as in earlier simulations with free trade in biofuels, and in a set of cases where there is no biofuel trade (noted NobioTR). We find that with free trade, biofuel use is substantial in the 203 bmt and 167 bmt cases, rising to 34 to 36 EJ in the core cases, as shown in Figure 14a. The 287 bmt case results in very little U.S. biofuels consumption—less than 1 EJ in any year, and so we do not show it in the figure. World liquid biofuel use is substantial in all three cases (Figure 14b), reaching 92 to 127 EJ, because the rest of the world is pursuing the same strong greenhouse gas policy in all cases. Thus, the main difference is the changes in biofuel use in the U.S. The 287 bmt case, if the U.S. pursued the policy alone, would lead to substantial biofuels use in the U.S., but demand from the rest of the world prices the U.S. out of the market, with other mitigation options able to more cheaply meet the U.S. cap. As the estimates in Table 11 suggest, if produced domestically, the amounts used in the U.S. would require on the order of 40% of U.S. cropland, forestland, and grassland (about 700 million acres). To produce the world total ethanol production of 127 EJ would require about 2.5 billion acres (or about 1 billion hectares).

The EPPA model projects, however, that virtually all of the U.S. biofuels would be imported. Some U.S. domestic production (less than 0.8 EJ) finally occurs in 2050 in the 203 bmt and 167 bmt case. Interest in biofuels use in the U.S. is often heightened by the belief that we would be able to rely on a domestic resource. In that regard, the EPPA model may not ideally represent differential productivity of biofuels across the world. However, it is notable that the U.S. currently restricts biofuels imports to support the domestic industry. Might the U.S. rely on its domestic biofuels production capability? To examine this possibility we also show a case where trade in biofuels is restricted, requiring that any use in the U.S. (or in any region) be domestically produced within that region. Biofuel use in these cases is shown in Figure 14 as well, noted NobioTR. As might be expected, the restriction leads to lower biofuels use in the U.S. and in the total for the world, but biofuel use, and hence production, in the U.S. is substantial, rising into the 25 to 30 EJ range by the end of the period as compared to the 30 to 35 EJ under free trade. This quantity of biofuel would still require about 30% of all U.S. crop, grass, and forestland or over 500 million acres of land.

Figure 15 illustrates one of the important implications of a substantial biofuels industry for the 167 bmt case. The U.S. now is a substantial net agricultural exporter, and under the EPPA reference without greenhouse gas policy this pattern is projected to continue. In the core cases, U.S. net agricultural exports are projected to more than double compared with the reference. As other regions expand biofuel production, they import more agricultural goods and thus U.S. net exports grow. The significant effect of barring biofuels imports into the U.S. under a stringent climate policy is that domestic production of biofuels significantly reduces agricultural production, and instead of the U.S. being a significant net exporter of agricultural products we become a large net importer. Whereas net exports today are on the order of $20 billion, the U.S. grows to be a net importer of over $80 billion of agricultural commodities. The agricultural sector in the EPPA model is highly aggregated—a single sector includes crops, livestock, and forestry. As a result, one should not put too much stock in the absolute value of net exports in the reference—it could be higher or lower depending on how agricultural productivity advances in the U.S. relative to other regions of the world. However, if on the order 25 EJ of ethanol must be produced in the U.S., requiring on the order of 500 million acres of land, it is nearly inevitable that this would lead to the U.S. becoming a substantial agricultural importer.

Several other critical aspects of this level of biofuels production are worth pointing out. In keeping with U.S. proposals as well as with policy developments abroad such the EU ETS or the Kyoto Protocol (see Reilly and Asadoorian, 2007), we have not extended the cap-and-trade system to cover land-use emissions. If included at all, land use is often covered under a crediting system. However, as shown by McCarl and Reilly (2006), except for quite low CO_2-e prices the economics of biofuels tends to dominate the economics of carbon sequestration in soils. The implication is that, at the level of biofuels demand simulated here, there would be scant incentive to protect carbon in soils and vegetation through a credit system. Landowners would instead tend to convert land to biofuels or more intense cropping.

Whether the biofuels themselves are produced on existing cropland or not, the overall need for cropland would require significant conversion of land from less intensively managed grass and forestland. This initial disruption would lead to significant CO_2 release from soils and vegetation. If mature forests are converted it can take decades of biofuels production to make up for the initial carbon loss. Whether the land is located in the U.S. or abroad its conversion is likely to contribute substantial carbon emissions, substantially negating the savings from reduced fossil energy use. Thus, one of the most serious issues raised in this analysis is the need to expand a cap-and-trade system to include land-use change emissions, and to be doubly concerned about leakage from reductions in the U.S., through biofuels imports, unless mitigation policies abroad *that include land-use emissions* are in place.

8. CENTURY SCALE EMISSIONS AND CLIMATE RESULTS

The policy time-horizon of 2050 in the current congressional proposals is long relative to the planning horizon for government efforts that may extend no more than a few years to a decade, but as described in the recent IPCC report (IPCC, 2007) the world is already committed to a substantial amount of warming through 2050, even if atmospheric greenhouse gas concentrations were stabilized at today's levels. Moreover, stabilization of concentrations at today's levels would require that the entire world immediately reduce emissions to very low levels, a feat that would be politically difficult and economically costly. To begin to assess the adequacy of proposed policies in the face of goals such as stabilization of greenhouse gases in the atmosphere, or of holding total warming below a target such as 2°C, requires a time horizon of at least 100 years and simulation of the emissions projections from human activities that result from these policy scenarios through an earth system model.

To explore climate response we use the MIT Integrated Global System Model (IGSM), described in detail in Sokolov *et al*. (2005), and we extend the emissions scenarios studied above through the year 2100. One advantage of the IGSM is its flexibility to vary key parameters of climate response to represent uncertainty or to allow it to reproduce the response of a full range of three-dimensional atmosphere-ocean general circulation models (AO GCMs) that would, themselves, require several months of computer time to produce a single 100-year simulation. For purposes of this report we developed parameterizations of the IGSM that represent each of three major U.S. AO GCM models—those of the Goddard Institute for Space Studies (GISS-SB), the Geophysical Fluid Dynamics Laboratory (GFDL-2.1), and the National Center for Atmospheric Research (CCSM3). These models show somewhat different climate responses to the same anthropogenic forcing and thereby illustrate some of the uncertainties in translating an emissions trajectory into an estimate of climate change.

We simulate the climate effects of six different climate policy scenarios through 2100 (see **Figure 16**). The first is a reference emissions forecast that includes no specific climate policy (Reference). Then three global participation scenarios include the international policy in our core policy scenarios in the 167, 203, and 287 bmt cases. We extend these three cases through 2100 by holding annual emissions allowances at their 2050 level through the end of the century. (Recall that in the 203 bmt case, the U.S., Europe, Japan, Canada, Australia, New Zealand are 50% below 1990 levels in 2050; all other countries are at their 2000 levels. In the 167 bmt case the U.S. is 80% below 1990 levels and in the 287 bmt case U.S. emissions are held at 2008 levels.) To examine the climate implications of the global versus partial participation, the fifth case assumes abatement efforts in developing countries are delayed until 2050, at which point mitigation efforts return them to 2000 levels where they remain through 2100 (Developing Countries Delayed). The sixth case assumes developing countries take no abatement action through 2100 (Developed Only). Abatement in the developed countries remains unchanged in these latter two cases and the U.S. policy is set at the 203 bmt level.

Assumption of such abrupt changes in policy, such as developing countries suddenly returning to 2000 levels in 2050, is not very realistic but what matters for a long-term goal such as stabilization are cumulative emissions and so more realistic time-paths with the same level of cumulative emissions over the century can be imagined. Similarly, since we are not focusing on abatement cost after 2050, one can imagine different ways in which the abatement effort is shared among countries post 2050, and as long as cumulative global emissions are the same the long-term climate consequences will be little affected.

The scenarios include all greenhouse gases and policies to abate them. The EPPA model also projects aerosols and tropospheric ozone precursors, and while the GHG policies simulated here do not include targets for these substances, to the extent policy affects the level of combustion of fossil fuels and other activities that generate emissions, it affects these other greenhouse substances as well. The emissions levels projected by EPPA of these substances, as they change among GHG policy scenarios, are simulated through the IGSM and contribute to the projected changes in climate. We focus on the CO_2 concentrations (which are only indirectly affected by the level of other substances) and the global mean surface temperature change (which is affected by the level of GHGs and all other radiatively active substances). Concentrations of other gases such as methane, nitrous oxide, and of aerosols and ozone also change but are not shown here.

As shown in Figure 16, the CO_2 concentrations reach 880 ppmv by 2100 in the Reference, rising at an accelerating rate. The results show the importance of developing country participation in the determination of long-term CO_2 concentrations. In the Developed Only case the growth in atmospheric concentrations is slowed but it still reaches 750 ppmv. In the cases where developing countries participate, however, even when effort is delayed to 2050 concentration growth is restrained considerably and the CO_2 level is at 560 ppmv in 2100. A 450 ppmv goal is sometimes advanced as a desirable target. The most stringent policy we have simulated here, Global Participation with the U.S. at 167 bmt, is not sufficient to meet a 450 ppmv target: by 2050 concentrations are already at 460 ppmv.

The different U.S. policies have relatively small effects on the CO_2 concentration if other regions do not follow the U.S. lead. This result further highlights the need for significant international participation. The expectation of those supporting tighter targets in the U.S. may well be that it would lead other developed countries along the same more stringent path, and perhaps accelerate mitigation efforts in the developing countries, or that recognizing that developing countries may delay participation the U.S. would take stronger measures to make up for this delay. In that regard, the concentration difference in 2100 between the 167 and 287 bmt case is just about the concentration difference between cases where the developing countries join in 2025 versus delaying their participation until 2050. Thus, the 167 bmt case can be viewed as the U.S. making up for delayed developing country participation, with the 287 bmt case achieving approximately the same concentration result if developing country participation can be achieved earlier. In that regard, the policies we assumed to occur abroad are only a few highly stylized possibilities, but they, rather than differences in the U.S. policy, drive the climate results.

As far as atmospheric concentrations are concerned, it is not important where emissions are cut, and achieving any of the atmospheric targets now under discussion raises the question of how much more other developed countries and developing countries would be willing to do. Our extension of the policies beyond 2050 is obviously arbitrary. If the world pursued the Global Participation path the growth trajectory of CO_2 emissions would be altered significantly, but a goal of stabilization would require still further cuts.

As noted above, what matters most for long-term concentration goals are cumulative emissions over the century, so a useful way to understand how these policies contribute to stabilization goals is to compare cumulative emissions under these scenarios to those that would be consistent with particular stabilization levels. In that regard, the MIT IGSM was recently employed in development of stabilization scenarios as part of a U.S. Climate Change Science Program exercise (US CCSP, 2006). An idealized cap-and-trade system was implemented beginning in 2015 in which the whole world participated. The price path of the emissions constraint over the whole period (2015-2100) was constrained to rise at a 4% rate to simulate banking and cost-effective allocation of abatement over time.

We show in **Table 12** the cumulative emissions from 2012-2050 and from 2012-2100 for the U.S. and the world in the reference case and in the four stabilization levels of the CCSP study.[23] Also shown are the Global Participation, Delayed Developing, and Developed Only scenarios developed here. In the table we list the stabilization levels in the CCSP study in terms of CO_2 concentration levels, 450 through 750 ppmv, although that analysis formulated the targets as radiative forcing levels that allowed some additional increase in other greenhouse gases. Some policy discussions have been framed in terms of stabilization of CO_2-equivalent. Obviously, a 450 ppmv CO_2 target that allows additional increases in other gases is a looser target than a 450 ppmv CO_2-e target. To illustrate this difference for the CCSP targets we have calculated the CO_2-e target equivalent to the radiative forcing levels set out in the CCSP study. Thus, as shown in Table 12, the 450 CO_2 target, considering the additional radiative forcing from other greenhouse gases, is equivalent to a 523 CO_2-e target, and the 550 CO_2 target is equivalent to a 675 CO_2-e target.[24] Cumulative emissions in the table are GWP-weighted CO_2-e emissions.

Comparing the policy scenarios examined here to the CCSP results, a first observation is that U.S. emissions through 2050 (203 bmt) and through 2100 (363 bmt) are below emissions of the U.S. in the CCSP 450 ppmv case. Thus, if the emissions allowances in the 203 bmt case were assigned to the U.S. under an overall global target consistent with 450 ppmv as in the CCSP case, and with global emissions trading, then the U.S. would take on some of the cost of abatement in other countries by purchasing allowances from them. In that sense, the 203 bmt case is consistent with 450 ppmv, but the policy in the rest of the world in the Global Participation scenario is too loose. The 167 bmt of emissions in that tighter U.S. case (which would lead to 236 bmt for 2012-2100 if extended by holding at 80% below 1990 from 2050 through 2100) would transfer even more of the cost burden to the U.S. The core case with 287 bmt is very close to the 282 bmt of U.S. emissions in the 550 ppmv CCSP scenario, but it would mean that the U.S. would not take any responsibility for costs of abatement in other regions. If emissions in the U.S. remained at the 2008 level through 2100, cumulative U.S. emissions would be 662 bmt, somewhat above the CCSP 550 ppmv cumulative emissions total of 539 bmt. Thus, even under the assumption that the U.S. took responsibility only for its own emissions it would need to further cut its emissions after 2050 to meet a 550 ppmv goal unless other countries took on some of that responsibility.

Looking at the global totals, in the Developing Delayed scenario the world still is within striking distance of the 550 ppmv goal if the post-2050 targets were tightened a little. However, this delay puts the 450 ppmv goal essentially out of reach because to achieve it would require that virtually no more emissions be allowed after 2050. We saw

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[23] The results are from the MIT contribution to the CCSP study, which also involved two other models.

[24] CO_2-e levels are calculated as the concentrations of CO_2 that would generate the same combined radiative forcing coming from CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6.

this in Figure 16 where 450 ppmv is already exceeded in these cases by 2050.[25] In the Developed Only case emissions through 2100 are more than 850 bmt above the cumulative emissions in the 750 ppmv CCSP stabilization scenario. Concentrations are rapidly approaching 750 ppmv in this case in 2100, and so only with draconian measures implemented in 2100 to cut global emissions to near zero would 750 ppmv be possible. The CCSP scenarios have concentrations in 2100 still well below 750 ppmv recognizing that further emissions would occur after 2100 as the world continued cutting toward levels that would eventually stabilize at 750 ppmv. There are, of course, uncertainties in uptake that would lead to either higher or lower concentrations for these emissions paths—one estimate is that an emissions path consistent with a 550 ppmv target might result in actual concentrations ±50 ppmv from the target given (Webster *et al.*, 2003). Putting those uncertainties aside, Table 12 provides a useful way to think about how much more effort would be required to meet specific goals, and opens the way for discussions about which countries take up that effort and whether it is taken on sooner or later.

Turning to the climate effects of these scenarios, **Figure 17** shows the increase in the global mean surface temperature from 2000 for our replication of the three U.S. GCMs. In the Reference the temperature rise by 2100 is about 3.5, 4.0 and 4.5 °C for the GFDL 2.1, CCSM3, and GISS_SB models, respectively. The Global Participation and Developing Countries Delayed scenarios restrain the increase to be in the range of 1.7 to 2.4 °C above year 2000. Since the year 2000 temperature was already approximately 0.8 °C above the pre-industrial level, even these assumed mitigation policies would yield a 2100 temperature 0.5 to 1.2 °C above the 2 °C goal identified by the EU. The Developed Only scenario cuts only about 0.5 °C of the warming from the reference, again illustrating the importance of developing country participation. As the CO_2 concentration results foreshadow, the differences in the global mean surface temperature increase among the three U.S. policy scenarios are relatively small, and thus a primary motivation for the U.S. to choose a tighter policy is to stimulate more stringent policies abroad.

Compared with previous proposals, many of the bills now in Congress propose much deeper cuts, and have specified a policy over a longer horizon. Thus, it is possible to begin to assess their implications for future climate, making some crucial but at least plausible assumptions about actions in the rest of the world. On the one hand, if U.S. measures can help bring along the world, then reduction in warming from what might occur without any mitigation action is substantial. On the other hand, even with the very substantial measures proposed, and the whole world eventually falling in line, we could expect to see additional warming of twice to three times that we have seen over the last century, if these AO GCMs reasonably represent the response of the earth system to increasing greenhouse gas concentrations. Failure to take any action, or failure to substantially involve the developing countries would, according to these estimates, lead to very substantial warming over the century.

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[25] The approximate nature of the cumulative emissions comes into play here—if cumulative emissions could be exactly related to concentrations then they should be below 450 ppmv in 2050. However, if the emissions occur over a shorter period of time the ocean is not able to take the CO_2 up as fast, and so there is some difference if the cumulative emissions are over 50 years or 100 years—in this case about 10 ppmv.

9. CONCLUSIONS

There is a wide range of proposals in the U.S. Congress that would impose mandatory controls on U.S. greenhouse gas emissions, yielding substantial reductions in U.S. greenhouse gas emissions relative to a projected reference growth. The scenarios explored here span the range of stringency of these bills. Not all of the proposals have specified the mechanisms by which they would achieve their reduction targets. We implemented them as pure cap-and-trade systems with one alternative where we specified a price path.

It is probably useful to identify two groups of Congressional proposals. One set seeks dramatic reductions in U.S. greenhouse gas emissions, setting targets for 2050 that are as much as 80% below U.S. emissions in 1990. Several of these proposals have been crafted with a goal of putting the U.S. on a path toward targets like 450 ppmv CO_2 stabilization or 2 °C temperature increase from the pre-industrial level, assuming that the rest of the world takes substantial mitigation measures as well. This group includes the McCain-Lieberman, Boxer-Sanders, Feinstein, Waxman, and Kerr-Snowe bills. Another set of proposals have more modest reduction goals, deflecting U.S. emissions growth or possibly stabilizing U.S. emissions, and include a safety valve feature to limit the cost increase. This set includes the Bingaman-Specter and Udall-Petri proposals.

Table 13 summarizes these Bills and indicates their approximate costs by identifying the case we simulated that seems closest in terms of the overall cap or CO_2 price. The table reports the CO_2-e price in 2015 and 2050 and the welfare cost in 2020 and 2050. Apart from the many limitations of any modeling effort of this type, an important caveat to these cost estimates is that the scenarios we simulated represent pure economic-incentive based policies with banking undertaken on the assumption that the policies are expected to be implemented as designed to 2050. The actual Congressional proposals all include other provisions, from funds for R&D to other requirements such as a renewable portfolio standards or efficiency standards. In other cases the actual form of the policy that would achieve these quantitative targets is incompletely specified or left up to the executive agency that would implement the policy. Most also include provisions that would allow revision of the goals with changing evidence of the threat of climate change, and necessary provision, but one that adds uncertainty to the level of the cap or the price.

Those proposals with goals of substantially cutting U.S. emissions between now and 2050 would likely generate prices in the range of \$30 to \$55 per ton of CO_2-e in 2015, rising to the range of \$120 to over \$200 by 2050: economic welfare losses from the mitigation policy are estimated to rise to 1.1% to almost 2% by 2050. If economic decision-makers were less than confident that measures would be imposed without relaxation to 2050 then there might be somewhat lower levels of banking, leading to lower prices and costs in early periods and higher prices and costs later, as suggested by Figure 9. Banking also depends critically on expectations about future technology, and the market may assess those prospects very differently from how we have specified them. Optimism about future technology would reduce banking and near-term abatement and CO_2-e prices. Greater pessimism on future technology or abatement potential would drive near term prices and abatement higher. No assessment was carried out of the economic effects of climate change avoided or ancillary benefits of emissions mitigation, but of course these benefits would provide at least a partial offset to the mitigation cost. However, because of the long-lived nature of greenhouse gases and the moderating influence of the ocean, much of the climate benefit of reductions through 2050 would accrue beyond the horizon of this analysis.

Those proposals that would slow or stop the rise in emissions but not substantially cut them from today's levels have somewhat lower costs. A policy that froze emissions at 2008 levels would generate a price of $18 per ton of CO_2-e in 2015, rising to around $70 by 2050. Related proposals specify a safety valve of $6 per ton of CO_2-e rising to $39 by 2050. If the U.S. pursued this target alone it would essentially freeze emissions at 2008 levels and have welfare costs that rose to just above 0.4%, but the effectiveness and cost of this proposal depends highly on assumptions about policy abroad, as well as other uncertainties that we have not explored.

More important than these specific numbers are some broad insights that may help shape U.S. greenhouse gas mitigation policy:

- The cost of policy in the U.S. is greatly affected by policies in the rest of the world. A stringent policy elsewhere reduces oil prices and confers a terms-of-trade advantage to the U.S. On the other hand, such a policy abroad raises the cost of biomass energy, conferring a substantial terms-of-trade loss when the U.S. has a strong mitigation policy. Together these two changes widen the gap between petroleum product and biofuels prices with a tighter target abroad. The implication is that a higher CO_2-e price in the U.S. is required to meet the same emissions target. If a price instrument is used instead, then the effectiveness of U.S. abatement depends on efforts elsewhere. With a less stringent U.S. policy, terms-of-trade benefits from reductions in the world oil price can lead to an improvement in welfare in the U.S. compared to the case where there was not mitigation policy anywhere.

- International emissions trading does not lead to substantial economic efficiency gains unless the U.S. policy is much more stringent than the policy in other regions. If the U.S. policy is similar in stringency (comparing pre-trade CO_2-e prices) trade can be welfare worsening because of terms-of-trade effects. One reason emissions trading is less important is that trade in biofuels tends to close the gap between pre-trade emissions prices so that this energy-trade substitutes for trading in emissions allowances.

- Cutting emissions in the U.S. and world implies a transition to carbon-free transportation fuels. One of the more technology-ready options is biofuels. However, at a scale to contribute substantially to abatement it would require hundreds of millions of acres of land in the U.S. and perhaps 1 billion hectares (2.5 billion acres) worldwide. This level of production would require conversion of land to bioenergy crops and in the process could release carbon stored in vegetation and soils. We were not able to investigate the magnitude of this effect, but given the area of land involved it would be large. To avoid reductions in carbon dioxide emissions from fuel use being offset by land use emissions, it will be necessary to price land-use emissions similarly to emissions from fossil fuel.

Ideally, land-use emissions would be part of the same cap-and-trade system as fuel emissions, or would be subject to the same CO_2-e tax or price incentive.

- With no restrictions on biomass trade we find that the U.S. would mainly be an importer of biofuels when there is a stringent domestic mitigation policy. Rather than going to biofuels production, U.S. farmland would be used to produce food for export; regions abroad would devote more of their agricultural land to biomass and import agricultural products from the U.S. If we restrict U.S. biofuels use to domestically produced feedstock, on the order of 500 million acres of U.S. land would be required, more than the total of all current U.S. cropland. In this case, the U.S. would become a large importer of food, fiber, and forest products, rather than the net exporter of these products as is currently the case.
- Potential revenue from allowance sales or a CO_2-e tax (or windfall gain to those to whom allowances were freely distributed) are substantial under the emissions limits we examined, ranging from about \$130 to \$370 billion per year in 2015 to \$250 to \$515 billion per year in 2050. In more stringent policies revenue falls off in later years because the number allowances falls off faster than the CO_2-e price rises. If distributed to households, the annual distribution would be on the order of \$1600 to \$4900 per family-of-four household. The CO_2-e revenue is on the order of 10 to 15% of estimated future total Federal tax revenue, ranging across scenarios and over time from 5 to nearly 20%.
- One use of auction or tax revenue is to cut existing taxes, for example on labor and capital. Capital tax reductions would likely reduce costs more than use of revenue to reduce labor taxes. Potential revenue under more stringent bills consistent with stabilization of concentrations falls because so few allowances are available for auction and this can ultimately limit the benefits of revenue recycling.

The purpose of U.S. mitigation measures is to substantially reduce the amount of climate change we would otherwise experience. Absent controls on greenhouse gas emissions, global temperatures could rise by 3.5 to 4.5 °C by 2100 given our reference emissions and reflecting a climate response to greenhouse gas emissions like that of the models of the three major U.S. climate modeling centers. Our results confirm the well-known fact of global climate change: to meet temperature or concentration goals requires concerted efforts from much of the world over a substantial period of time. With rapid growth in developing countries, failure to control their emissions could lead to a substantial increase in global temperature even if the U.S. and other developed countries pursue stringent policies.

It is useful to evaluate the global costs and global benefits of achieving such targets, as difficult as that is to do. However, it is not possible to connect specific U.S. policy targets with a particular global concentration or temperature target, and therefore the avoided damages, because any climate gains depend on efforts in the rest of the world. And unfortunately, absent a global agreement a country’s best strategy in terms of its own self-interest is to do little and free-ride on the actions of others. Of course, if all behave in this way very little mitigation will be achieved. If a cooperative solution is at all possible, therefore, a major strategic consideration in setting U.S. policy targets should be their value in leading other major countries to take on similar efforts.

Also at issue is the equitable sharing of the cost burden of emissions reduction. Such equity concerns are inextricably linked to the strategic objective of getting other countries to mitigate their own greenhouse gas emissions. Poorer countries see a U.S. and developed world that has freely emitted CO_2 over the history of fossil use, and are thus responsible for the level of concentrations we see today. And they see economies with far higher incomes that are in a better position to afford the burden of mitigation. Thus, a perception of the U.S. taking on an equitable share of the burden of abatement is probably essential if the U.S. policy is going to serve the strategic goal of moving climate policy forward elsewhere. These issues are well beyond the scope of this analysis but consideration of them is essential in determining the best policy for the U.S.

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APPENDIX A: Some Useful Terms Defined

Cap and trade system: a system that identifies emitting entities, sets a cap on total emissions, distributes emissions allowances to covered entities that in total equal the cap, requires entities to turn in allowances equal to their emissions in each period (*e.g.*, year), and allows trade (purchasing and selling) so that a market for and a price of emissions allowances is established.

GHG or CO_2 tax: a tax per unit of greenhouse gas (GHG) or CO_2 whose level is set by a public entity, requiring covered entities to pay the tax for every ton of GHG or CO_2 emitted. The desire to avoid paying the tax provides an economic incentive to reduce emissions.

Covered entity: used here to refer to organizations or individuals who are covered by a cap and trade system (or a GHG/CO_2 tax) and therefore must surrender allowances or pay the tax to cover emissions for which they are deemed responsible.

Safety valve: A feature of a cap and trade system where the public entity managing the system announces a maximum price for allowances, and stands ready to sell as many additional allowances beyond the cap level that entities are willing to purchase at the set price.

Allowances: Certificates (more likely electronic entries) covered entities acquire and must surrender to cover there emissions, typically designated in tons of CO_2 or CO_2-equivalent.

Credits: If allowed under a cap and trade system, these are certificates that can be used in place of allowances. They are generated from activities of entities not covered by the cap and trade system. Entities hoping to sell into the system would need to have credits approved and certified on a project-by-project basis by the public entity overseeing the crediting activity. Approval and certification is meant to assure that the number of credits granted is consistent with the requirements spelled out in the policy. Usually this means that the entities reduced emissions from a baseline (that must be established and approved) by the amount of the credits they are claiming.

Opt in: A provision in a cap and trade system that would allow a non-covered entity to opt into the system and become a covered entity. This would typically involve establishing an allowance level for the entity and adding this level of allowances to the total cap for the whole system. Generally, the allowance level would be given freely to the entity thus providing an incentive to opt in: if the entity can reduce emissions at less than the going allowance price, they can then sell extra allowances into the system for a profit.

Revenue recycling: Using the revenue from a carbon tax or that obtained from auctioning allowances to reduce other taxes in the economy such as those on earned income or on capital.

Lump sum distribution of allowances (or allowance or tax revenue): Lump sum refers to a distribution mechanism that does not affect relative choices among goods or the relatively profitability of different activities. [Failure to insure lump sum distribution can undermine the efficiency of a cap and trade system. Basing distribution on some historical data (*e.g.*, historical emissions) that cannot be affected is a lump sum mechanism. However, if a program established the expectation allowance allocation in the future would be based on emissions in the future (*e.g.*, allocations in 2020 based on emissions in 2015) then entities would have an incentive to have high emissions in 2015 to ensure a larger allocation of allowances in 2020, and this would work counter to incentives to abate emissions in 2015. Distributing allowance revenue or revenue from a CO_2 tax to those who spent the most on energy could also undermine the system by creating an incentive to use more energy to get a bigger share of the revenue that would counter the intended goal of the tax or cap system to use less energy and emit less CO_2.]

Auctioning of allowances: in a cap and trade system, specifying that the allowances would be auctioned off to the highest bidders and the revenue from the auction collected by the public agency responsible for the system.

Grandfathering/free distribution of allowances: in a cap and trade system, specifying that the allowances would be distributed at no cost to those receiving them. Such allowances could be given to anyone or any regardless of whether they are a covered entity. If not covered, the presumption is that they would sell allowances into the market. In trading systems developed to date, the practice has been to distribute allowances to covered entities usually in some ratio that approximated how many they would "need" to cover their emissions, proportionally reduced to meet the overall cap. Grandfathering refers to one specific approach, using an historic year's emissions level as the basis for free allowance distribution.

Banking & borrowing: Banking refers to abating below the level of allowances available in a period and using the extra allowances to offset emission in future years. Borrowing is the reverse, using allowances from the future against emissions today.

Carbon and CO_2: Carbon dioxide (CO_2) is the gaseous combustion product that is the main greenhouse gas related to human activities. By some conventions, only the carbon is measured and reported. The difference is the molecular weight of carbon dioxide (44) to that of carbon dioxide (12). Different reporting conventions thus can lead to values that differ by the factor of 3.667—one ton of carbon is equivalent to 3.667 tons of CO_2 and a $100/ton carbon is equal to (approximately) $27/ton CO_2.

Greenhouse Gases (GHGs): Gaseous substances that are transparent to incoming short wave radiation (*i.e.* light) but reflect back long wave energy (*i.e.* heat) radiated from the earth's surface. This heat-trapping ability leads to warming of the troposphere (including air temperature at the earth's surface). Nearly all proposed GHG policies have focused on carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6). Ozone (O_3) and chlorofluorcarbons are also important greenhouse gases. In addition, aerosol particles affect the radiative balance of the atmosphere, some cooling and some warming the troposphere.

CO_2-equivalent (CO_2-eq.) emissions and prices: Denotes that non-CO_2 gases are included and converted to a CO_2-equivalent amount (See Global Warming Potentials).

Global Warming Potentials (GWP). Indices that take into account the radiative properties and lifetimes of different greenhouse gases to describe their radiative effect relative to CO_2.

Market-based approaches: Emissions policies that achieve reductions by creating economic incentives for abatement. Either cap and trade or an emission tax are generally considered to be “market-based” in that they do not mandate a specific technology that must be used or a specific emissions limit for individual entities that must be met. Covered entities have the option of buying permits or paying the tax if that appears to be less costly than abating. However, complying with the rules is mandatory.

Emissions trading: a cap and trade system and/or the process of buying and selling emissions allowances under such a system.

International linkage: allowing a domestic cap and trade system to be linked to a cap and trade system in another country, requiring that each country honor the allowances issued by the other.

Covered entities: Those entities covered under a cap and trade system and who must surrender allowances to cover their emissions (or emissions for which they are deemed responsible), or equivalently for a tax system those entities who must pay the tax.

Upstream and downstream regulation: The point in the fuel production, refining, conversion, distribution, and combustion chain where emissions are regulated. Downstream refers to regulation of the final fuel users who burn the fuel and release the emissions. Upstream refers to fossil fuel producers (importers) deemed responsible for emissions equal to the carbon content of the fuel sold. There are possibilities of midstream regulation as well, for example, gasoline retailers, petroleum refiners, or natural gas utilities could be required to surrender allowances (or pay a CO_2 tax) for the carbon content of the fuel they sold.

Incidence of a tax or GHG abatement cost: Who bears the final cost of a tax or abatement taking into account the ability of those directly paying the tax or abating to pass along the cost either downstream to consumers by raising prices of goods or upstream to owners of production inputs (*e.g.*, capital, labor, energy resource assets) through lower wages or payments for capital or resource inputs.

APPENDIX B: EPPA Model Details

The EPPA model is multi-regional CGE model of the world economy (Babiker *et al.*, 2001; Paltsev *et al.*, 2005), which is built on the economic and energy data from the GTAP dataset (Dimaranan and McDougall, 2002; Hertel, 1997) and additional data for the greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and urban gas emissions (CO, VOC, NOX, SO_2, BC, OC, NH_3) (Mayer *et al.*, 2001) based on United States EPA inventory data and projects (US EPA 2001a-c, 2002a,b), including endogenous costing of the abatement of non-CO_2 GHGs (Hyman *et al.*, 2003). It has been used extensively for the study of climate policy (Jacoby *et al.*, 1997; Babiker *et al.*, 2000, 2003; Paltsev *et al.*, 2003; Reilly *et al.*, 2003; McFarland *et al.*, 2004; Jacoby *et al.*, 2006), climate interactions and impacts (Reilly *et al.*, 1999; Felzer *et al.*, 2005; Sarofim *et al.*, 2005; Reilly *et al.*, 2007; Matus *et al.*, 2007), and to study uncertainty in emissions and climate projections for climate models (Webster *et al.*, 2002, 2003). The current level of disaggregation of the standard EPPA version is provided in Table 1 in the text.

Several improvements have been incorporated in the model from the version documented by Paltsev *et al.* (2005) that are important for the analysis in this report. In the standard version of EPPA labor supply is exogenous and investment is set equal to savings. We have improved the representation of taxes. Tax levels are recalculated from the GTAP tax data as described in Gurgel *et al.* (2007). Regarding labor supply we have followed a standard approach of introducing a labor-leisure trade-off as was done for an earlier EPPA version (Babiker *et al.*, 2002). We followed an approach of Bovenberg *et al.* (2005) applied in a static setting in the recursive model, separately representing investment in the market economy and in households (*i.e.* investment in owner-occupied housing). As shown in Babiker *et al.* (2001), the values for elasticity of substitution (used in the EPPA model) are related to supply elasticities and shares as:

$$\eta^S = \sigma \frac{1-a}{a},$$

where η^S is an own-price elasticity of supply, σ is the elasticity of substitution, and a is the value share (in our case, a share of labor or market investment).

Table B1. Parameter Values.

Labor Share[a]	0.8
Investment Share[b]	0.77
Labor Supply Elasticity[c]	0.25
Capital Supply Elasticity[d]	0.3

[a] A share of labor in the total value of labor and leisure.

[b] A share of non-residential investment in the total value of residential investment and the other investment.

[c] Based on Babiker *et al.* (2002).

[d] Based on Chirinko *et al.* (2004).

Reference Case (Ref)										
	2005	*2010*	*2015*	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
ECONOMY WIDE INDICATORS										
Population (million)	296	309	321	334	347	359	369	379	388	397
GDP (billion 2005$)	11981	14339	16921	19773	22846	26459	30534	34929	39530	44210
% Change GDP from Reference	--	--	--	--	--	--	--	--	--	--
Market Consumption (billion 2005$)	8217	9858	11533	13384	15364	17761	20467	23392	26456	29567
% Change Consumption from Reference	--	--	--	--	--	--	--	--	--	--
Welfare (billion 2005$)	9656	11773	13933	16342	18948	22016	25414	29032	32780	36553
% Change Welfare from Reference(EV)	--	--	--	--	--	--	--	--	--	--
CO$_2$-E Price (2005\$/tCO$_2$-e)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
***PRICES** (index, 2005=1.00)*										
Petroleum Product	1.00	1.15	1.30	1.48	1.69	1.87	1.97	2.09	2.19	2.25
Natural Gas	1.00	1.11	1.27	1.48	1.66	1.95	2.31	2.73	3.12	3.55
Coal	1.00	1.04	1.07	1.09	1.13	1.16	1.20	1.24	1.28	1.32
Electricity	1.00	1.11	1.19	1.27	1.35	1.38	1.42	1.42	1.42	1.41
***TRADE & PRODUCTION** (selected indicators)*										
Bio Liquids Production in US (EJ)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Bio Liquids Imports (EJ)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Net Bio Liquids Imports (billion 2005$)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Net Crude Oil Imports (billion 2005$)	77.40	85.21	93.97	102.60	110.94	126.11	149.39	170.99	159.14	144.83
Net Agriculture Exports (billion 2005$)	25.64	25.53	20.40	19.29	14.24	12.35	11.48	10.92	11.61	14.99
***GHG EMISSIONS** (mmt CO$_2$-e)*										
GHG Emissions	7091.9	7680.1	8201.5	8595.6	9219.3	9884.8	10711.0	11507.3	12433.3	13283.3
CO$_2$ Emissions	5984.3	6517.4	6995.2	7357.3	7915.4	8518.8	9283.0	10012.9	10871.0	11655.9
CH$_4$ Emissions	583.4	602.0	611.6	617.1	630.5	643.1	652.2	663.6	676.5	683.1
N$_2$O Emissions	385.2	387.9	381.3	372.4	366.5	365.6	372.8	380.8	391.0	407.3
Fluorinated Gases Emissions	140.0	173.8	214.4	250.0	308.1	358.5	404.3	451.3	496.2	538.5
***PRIMARY ENERGY USE** (EJ)*										
Coal	22.6	24.3	25.8	26.6	30.9	35.0	39.9	44.8	49.6	53.3
Total Petroleum Products	42.0	46.0	49.6	52.6	55.2	58.8	63.9	68.8	73.6	78.5
Including Shale Oil	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.7	19.6
Natural Gas	22.5	24.7	26.8	28.9	28.4	28.3	27.7	26.8	25.8	25.1
Nuclear (primary energy eq)	9.3	9.0	8.8	8.7	8.6	8.5	8.4	8.4	8.3	8.3
Hydro (primary energy eq)	2.9	2.8	2.8	2.8	2.8	2.9	2.9	3.0	3.1	3.2
Renewable Elec. (primary energy eq)	0.6	0.7	0.8	1.0	0.9	1.2	1.1	1.4	1.5	1.6
Biomass Liquids	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Primary Energy Use	99.8	107.6	114.6	120.5	126.8	134.6	143.9	153.1	161.9	170.0
Reduced Use from Reference	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
***ELECTRICITY PRODUCTION** (EJ)*										
Coal w/o CCS	6.9	7.6	8.3	8.6	10.2	11.7	13.4	15.2	17.0	18.5
Oil w/o CCS	0.3	0.3	0.3	0.3	0.4	0.4	0.4	0.5	0.5	0.6
Gas w/o CCS	2.1	2.5	3.1	3.9	3.3	3.1	2.9	2.7	2.4	2.3
Nuclear	3.0	3.0	3.0	3.0	3.0	3.1	3.1	3.1	3.1	3.1
Hydro	0.9	1.0	1.0	1.0	1.0	1.0	1.1	1.1	1.1	1.2
Other Renewables	0.2	0.2	0.3	0.3	0.3	0.4	0.4	0.5	0.6	0.6
Gas with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Coal with CCS	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total Electricity Production	13.4	14.6	15.9	17.1	18.2	19.7	21.3	23.1	24.7	26.2

Full results from other runs are available as Appendix C at
http://mit.edu/globalchange/www/MITJPSPGC_Rpt146_AppendixC.pdf.

Tables and Figures

Table 1. EPPA Model Details

Country or Region[†]	Sectors	Factors
Developed	***Non-Energy***	Capital
United States (USA)	Agriculture (AGRI)	Labor
Canada (CAN)	Services (SERV)	Crude Oil Resources
Japan (JPN)	Energy-Intensive Products (EINT)	Natural Gas Resources
European Union+ (EUR)	Other Industries Products (OTHR)	Coal Resources
Australia & New Zealand (ANZ)	Industrial Transportation (TRAN)	Shale Oil Resources
Former Soviet Union (FSU)	Household Transportation (HTRN)	Nuclear Resources
Eastern Europe (EET)	***Energy***	Hydro Resources
Developing	Coal (COAL)	Wind/Solar Resources
India (IND)	Crude Oil (OIL)	Land
China (CHN)	Refined Oil (ROIL)	
Indonesia (IDZ)	Natural Gas (GAS)	
Higher Income East Asia (ASI)	Electric: Fossil (ELEC)	
Mexico (MEX)	Electric: Hydro (HYDR)	
Central & South America (LAM)	Electric: Nuclear (NUCL)	
Middle East (MES)	Electric: Solar and Wind (SOLW)	
Africa (AFR)	Electric: Biomass (BIOM)	
Rest of World (ROW)	Electric: Natural Gas Combined Cycle (NGCC)	
	Electric: Coal with CCS (IGCAP)	
	Electric: Gas with CCS (NGCAP)	
	Oil from Shale (SYNO)	
	Synthetic Gas (SYNG)	
	Liquids from Biomass (B-OIL)	

[†] Specific detail on regional groupings is provided in Paltsev *et al.* (2005).

Table 2a. Congressional Bills, Basic Features

	Lieberman-McCain 2007	**Bingaman-Specter Draft 2007**	**Kerry-Snowe 2007**	**Sanders-Boxer 2007**	**Waxman 2006**	**Feinstein August 2006**	**Udall-Petri 2006**
Bill Number/ Name	S.280; Climate Stewardship and Innovation Act of 2007		S.485; Global Warming Reduction Act of 2007	S.309; Global Warming Pollution Reduction Act of 2007	H.R.5642; The Safe Climate Act of 2006 (companion bill to Boxer-Sanders)		H.R.5049; Keep America Competitive Global Warming Policy Act of 2006
Basic Framework	Mandatory, market-based, cap on total emissions for all large emitters: cap & trade	Mandatory, market-based, cap on GHG "intensity" (emissions per $ GDP): cap & trade with safety valve	Mandatory, market-based, cap on total emissions for all large emitters: cap & trade	Mandatory, market-based, system to be determined by EPA, allows for cap & trade in 1 or more sectors	Mandatory, market-based, cap on total emissions for all large emitters: cap & trade	Mandatory, market-based, cap on total emissions for all large emitters: cap & trade	Mandatory, market-based, cap on total emissions for all large emitters: cap & trade with safety valve
Targets	Return emissions to 2004 levels by 2012, to 1990 levels by 2020, and to 60% below 1990 levels by 2050. Target emissions are (in mmt of CO$_2$): 2012-2019 = 6,130; 2020-2029 = 5,239; 2030-2049 = 4,100; and 2050 on = 2,096.	Targeted reduction in GHG intensity is 2.6% annually between 2012 and 2021, then 3.0% per year beginning in 2022.	Freeze emissions in 2010, and gradually reduce to 65% below 2000 levels by 2050. Reduce to 1990 levels by 2020, then 2.5% per year between 2020 and 2029, and 3.5% per year between 2030 and 2050.	Freeze emissions in 2010, achieve 1990 levels by 2020, reduce by 1/3 of 80% below 1990 levels by 2030, by 2/3 of 80% below 1990 levels by 2040, and 80% below 1990 levels by 2050.	Freeze emissions in 2010, reduce by 2% per year starting in 2011 to reach 1990 levels by 2020, then by 5% per year starting in 2021 to reach 80% below 1990 levels by 2050.	Cut emissions to 70% below 1990 levels by 2050.	Cap for emissions set prospectively at emission levels three years after the enactment of the legislation.
Allocation of Allowances	Undetermined percent auctioned, balance allocated free	10% auctioned, 55% free (but gradually phased out), 29% to states, 5% for ag. sequestration, 1% early reduction	Undetermined percent auctioned, balance allocated free	Undetermined allocation, any allowances not allocated to covered entities should be given to non-covered entities	Undetermined percent auctioned, balance allocated free	Undetermined auctioning and allocation	20% free, 20% to states (reduced yearly), remaining 60% to Treasury, Energy Department, and State Department
Additional Details	• Covered sectors produce about 85% of national emissions; • Covered entities emit, or produce or import products that emit, over 10,000 metric tons of GHGs per year • Banking • Borrowing (up to 25%) • Provisions to track, report, verify emissions • Non-compliance penalties	• Regulated at upstream • Safety valve: if traded allowances hit safety valve price, gov. issues more allowances at that price: $7/metric ton of CO$_2$ (escalates annually at 5% real) • Banking • Non-compliance penalties • Emissions can increase if GDP grows faster than intensity reductions, and can exceed cap if safety valve is used	• Total GHGs less than 450 ppmv • Banking • Provisions to track, report, verify emissions • Non-compliance penalties	• Less then 3.6^{o}F (2^{o}C) temperature increase, and total GHGs less than 450 ppmv • Suggests declining emissions cap with technology-indexed stop price • Provisions to track, report, verify emissions	• Less then 3.6^{o}F (2^{o}C) temperature increase, and total GHGs less than 450 ppmv • Banking • Provisions to track, report, verify emissions • Non-compliance penalties	• Keep temperature increase to 1 or 2^{o}C	• Regulated at upstream • Safety valve: $25 per ton of carbon (just under $7 per ton of CO$_2$), price can only increase if the President and Sec. of State certify that other countries are controlling their emissions

Table 2b. Congressional Bills, Additional Details and Features

	Lieberman-McCain 2007	Bingaman-Specter Draft 2007	Kerry-Snowe 2007	Sanders-Boxer 2007	Waxman 2006	Feinstein August 2006	Udall-Petri 2006
Provisions Related to Foreign Reductions	• Credits for approved projects in developing countries (e.g. CDM) • Acceptance of foreign allowances	• Every 5 yrs review of trading partners, and Congress can change US cap or safety valve • Credits for approved projects in developing countries (e.g. CDM) • Acceptance of foreign allowances		• Task Force on International Clean, Low Carbon Energy Cooperation to increase clean technology use and access in developing countries		• Credits for protecting rain forests in developing countries • Proposed acceptance of foreign allowances	• 10% of allowances to the State Department for spending on zero-carbon and low-carbon projects in developing nations
Credit Provisions	• Limited use of credits from sequestration, non-covered entities, and international projects (can offset up to 30%) • Farmers and foresters, can earn credits to sell through sequestration	• Use of credits from sequestration, non-covered entities, the use of fuels as feedstocks, the export of covered fuel or other GHGs, and international projects • Farmers and foresters, can earn credits to sell through sequestration	• Credits from sequestration	• Credits from sequestration • Renewable energy credit program		• Use of credits from sequestration, non-covered entities, international projects, and responsible land use • Farmers and foresters, can earn credits to sell through sequestration	• Credits from sequestration
Other Features	• Climate Change Credit Corporation: proceeds from allowance auctions and trading activities, used for transition assistance, habitat restoration, and technology R&D	• Climate Change Trust Fund: proceeds from allowance auctions and safety-valve payments, used for technology R&D. Fund capped at $50 billion (excess goes to U.S. Treasury)	• Climate Reinvestment Fund: proceeds from auctions, civil penalties, and interest, used to further Act and for transition assistance • National Climate Change Vulnerability and Resilience Program • EPA to carry out R&D • Renewable and energy efficiency portfolios: 20% of electricity must be renewable by 2020 • Motor vehicle emission standard • Renewable fuel required in gasoline • E-85 fuel pumps • Consumer tax credits for energy efficient motor vehicles	• EPA to carry out R&D • Sense of Senate to increase federal funds for R&D 100% each year for 10 years • Transition assistance • Renewable and energy efficiency portfolios: 20% of electricity must be renewable by 2020 • Mandatory emissions standards for all electric generation units built after 2012 and final standards for all units, regardless of when they were built, by 2030 • Motor vehicle emission standard	• Climate Reinvestment Fund: proceeds from allowance auctions and civil penalties, used to further Act and for transition assistance • Renewable and energy efficiency portfolios: 20% of electricity must be renewable by 2020 • Motor vehicle emission standard	• Climate Action Fund: proceeds from allowance auctions and interest, used for technology R&D, wildlife restoration, and natural resource protection • Renewable portfolio for utilities; • Carmakers must improve mileage by 10 mpg by 2017 • Emission standards for power producers • Increase availability of biodiesel and E-85 fuel pumps; • Plans to extend California-style green-technology programs nationwide	• Advanced Research Projects Agency-Energy: 25% of allowances for new Energy Department technology program • 25% of allowances to the Secretary of the Treasury, who deposits proceeds from selling the allowances into the Treasury

*** *Feinstein Bill:*** Based on a San Francisco Chronicle article (Hall and Kay, 2006). Implementation is now expected to be proposed through 5 separate bills to be introduced in 2007.

*** *Olver-Gilchrist*:** HR-620, the Climate Stewardship Act of 2007, is similar to McCain-Lieberman 2007 above.

Sources: US House of Representatives, 2006a,b; US Senate, 2007a,b,c,d

Table 3. Cumulative allowances available from 2012 to 2050

Allowance Path	*Cumulative Allowances 2012-2050, bmt*
Bingaman-Specter Draft 2007	306
Udall-Petri 2006	293
287 bmt	287
Lieberman-McCain 2007	216 (186)*
203 bmt	203
Feinstein August 2006	195
Kerry-Snowe 2007	179
Sanders-Boxer 2007	167
167 bmt	167
Waxman 2007	148

* 186 are the actual allowances for covered sectors; 216 is the estimate of total emissions including uncovered sectors from WRI (2007). The actual national emissions depend on growth in uncovered sectors.

Table 4. Core price and welfare results: US + World Policy

	CO_2-e Price ($/t$CO_2$-e)			*Change in Welfare (%)*		
	287 bmt	***203 bmt***	***167 bmt***	***287 bmt***	***203 bmt***	***167 bmt***
2015	18	41	53	0.01	-0.04	-0.07
2020	22	50	65	-0.13	-0.32	-0.55
2025	26	61	79	-0.36	-0.69	-1.05
2030	32	74	96	-0.45	-1.08	-1.47
2035	39	90	117	-0.19	-0.77	-1.51
2040	47	109	142	-0.12	-0.92	-1.84
2045	57	133	172	-0.24	-1.28	-1.90
2050	70	161	210	-0.18	-1.45	-1.79

Table 5. Relationship between ~ $27 per ton CO_2-e price and recent average fuel prices (Note: No adjustments for the effects of the policy on the producer price.)

Fuel	**Base Price Ave. 2002-2006 (2005$)**	**Added Cost ($)**	**Added Cost (%)**
Crude Oil ($/bbl)	$40.00	$12.20	30%
Regular Gasoline ($/gal)	$1.82	$0.26	14%
Heating Oil ($/gal)	$1.35	$0.29	21%
Wellhead Natural Gas ($/tcf)	$5.40	$1.49	28%
Residential Natural Gas ($/tcf)	$11.05	$1.50	14%
Utility Coal ($/short ton)	$26.70	$55.30	207%

Source: U.S. average prices for 2002-2006 computed from DOE EIA price data. Base cost price is the 5-year average price, except coal (2001-2005). To the gasoline price we have added $0.42 to include the federal and an average of state gasoline excise taxes.

Table 6. Potential CO_2-e auction or tax revenue

	2015	2020	2025	2030	2035	2040	2045	2050
Total Potential Auction/Tax Revenue (billions $/yr)								
287 bmt	130	159	193	235	286	348	423	515
203 bmt	287	321	356	391	425	455	477	489
167 bmt	366	392	413	425	423	399	346	250
US Pop.	321	334	347	359	369	379	388	397
Potential Tax disbursement/family of 4 ($/yr)*								
287 bmt	1,630	1,900	2,230	2,620	3,100	3,670	4,360	5,190
203 bmt	3,580	3,850	4,100	4,360	4,600	4,800	4,920	4,920
167 bmt	4,560	4,700	4,760	4,740	4,580	4,210	3,560	2,520
CO_2 Revenue as a Percentage of Non-CO_2 Federal Tax Revenue (%)								
287 bmt	7	7	7	8	8	9	9	10
203 bmt	15	14	14	13	12	11	11	10
167 bmt	19	17	16	14	12	10	8	5

*Rounded to nearest $10.

Table 7. Isolating terms of trade effects on US welfare (% change from reference)

	Welfare in the Core Cases Minus Welfare for US Alone		
Year	***287 bmt***	***203 bmt***	***167 bmt***
2015-2050 NPV	0.09	-0.01	-0.12
2015	0.00	-0.05	-0.02
2020	-0.05	-0.17	-0.14
2025	-0.05	-0.25	-0.06
2030	-0.13	-0.35	-0.03
2035	0.12	0.35	0.08
2040	0.21	0.39	-0.23
2045	0.30	0.12	-0.28
2050	0.34	-0.10	-0.24

Table 8. CO_2-e prices with small emitting sectors exempted, banking case

Year	Economy-Wide Cap			Agricultural, Households, Services Excluded from Cap		
	287 bmt	203 bmt	167 bmt	287 bmt SEC	203 bmt SEC	167 bmt SEC
2015	18	41	53	14	31	41
2020	22	50	65	17	37	50
2025	26	61	79	20	45	61
2030	32	74	96	25	55	74
2035	39	90	117	30	67	90
2040	47	109	142	37	82	109
2045	57	133	172	44	99	133
2050	70	161	210	54	121	161

Table 9. Welfare effects with small emitting sectors exempted, banking case

Year	Economy-Wide Cap			Agricultural, Households, Services Excluded from Cap		
	287 bmt	203 bmt	167 bmt	287 bmt SEC	203 bmt SEC	167 bmt SEC
2015	0.01	-0.04	-0.07	0.01	-0.02	-0.04
2020	-0.13	-0.32	-0.55	-0.10	-0.23	-0.32
2025	-0.36	-0.69	-1.05	-0.34	-0.52	-0.74
2030	-0.45	-1.08	-1.47	-0.33	-0.82	-1.19
2035	-0.19	-0.77	-1.51	-0.14	-0.72	-1.11
2040	-0.12	-0.92	-1.84	-0.10	-0.80	-1.42
2045	-0.24	-1.28	-1.90	-0.17	-0.99	-1.41
2050	-0.18	-1.45	-1.79	-0.27	-1.11	-1.30

Table 10. US welfare effects of emissions trading in the no banking cases

	287 bmt No TR	287 bmt TR	203 bmt No TR	203 bmt TR	167 bmt No TR	167 bmt TR	ROW only, No TR	ROW only, TR
2015	0.01	**0.00**	0.01	**0.00**	0.01	**0.00**	0.00	**0.01**
2020	-0.06	**0.00**	-0.13	**-0.01**	-0.20	**-0.02**	-0.01	**-0.01**
2025	-0.22	**-0.14**	-0.43	**-0.24**	-0.64	**-0.33**	0.04	**0.02**
2030	-0.31	**-0.23**	-0.76	**-0.47**	-1.08	**-0.62**	0.09	**0.09**
2035	-0.23	**-0.12**	-0.93	**-0.83**	-1.48	**-1.32**	0.36	**0.37**
2040	-0.30	**-0.26**	-1.28	**-1.27**	-1.91	**-1.91**	0.46	**0.46**
2045	-0.39	**-0.40**	-1.54	**-1.65**	-2.62	**-2.45**	0.52	**0.52**
2050	-0.46	**-0.41**	-1.68	**-1.88**	-4.86	**-2.81**	0.62	**0.65**

Table 11. Continental US hypothetical maximum biomass energy potential

Continental US, current land uses	Hectares (millions)	Acres (millions)	Maximum dry biomass (EJ)	Maximum liquid fuel (EJ)
Cropland	176	442	53	21
Grassland	235	587	70	28
Forest	260	651	78	31
Parks, etc	119	297	NA	NA
Urban	24	60	NA	NA
Desert, wetland, etc	91	228	NA	NA
US Total	906	2265	202	81

Source: Land area is from USDA (2006). Dry biomass production is based on production of 15 oven dry tons per hectare per year = 300 GJ/ha/yr (IPCC, 2001). Maximum assumes all land of that type is used for biomass production, and total assumes parks/preserves and urban land would not be used and that desert, wetland, etc. would not be used and/or would not be productive. Maximum liquid fuel assumes that 40% of the energy in the biomass is converted to liquid, and the remaining is used for process energy or remains in other by-products.

Table 12. Global and US Cumulative Emissions

Policy/ Target		***Global 2012-2050, bmt CO_2-e***	***Global 2012-2100, bmt CO_2-e***	***US 2012-2050, bmt CO2-e***	***US 2012-2100, bmt CO2-e***
Reference		2,461	7,408	419	1,278
Global and US emissions for a globally optimized time path to meet stabilization targets*					
CO_2	***CO_2-e*****				
750	***925***	2,031	4,924	364	888
650	***812***	1,842	4,082	344	741
550	***675***	1,530	3,033	282	539
450	***523***	1,145	2,168	229	399
Global and US emissions in long-term scenarios simulated in this report					
Global participation 287 bmt		1,577	3,133	287	662
Global participation 203 bmt		1,494	2,834	203	363
Global participation 167 bmt		1,456	2,710	167	236
Developing Delayed***		2,132	3,475	203	363
Developed only***		2,132	5,789	203	363

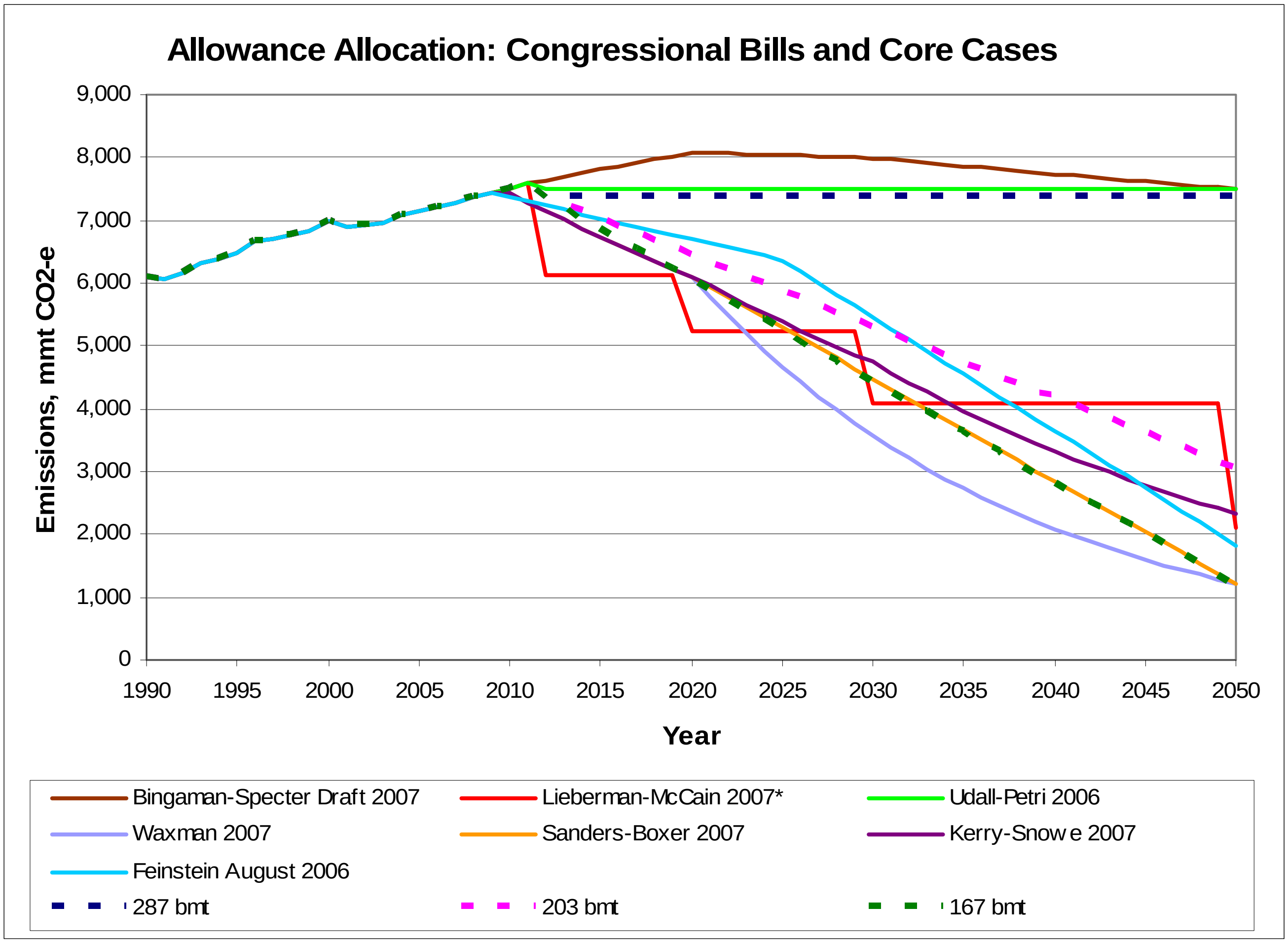
*From US CCSP (2006) as simulated by the MIT IGSM

**CO_2-e levels are calculated by estimating the concentrations of CO_2 that would generate the same radiative forcing that comes from CO_2, CH_4, N_2O, PFCs, HFCs, and SF_6 in the CCSP scenarios.

***Developing Delayed and Developed Only cases are based on the 203 bmt core case

Table 13. Congressional Proposal Summary

Allowance Path	***Nearest Case***	***CO_2-e Price, $/T***		***Welfare cost %***		***Comments***
		2015	2050	2020	2050	
Bingaman-Specter Draft 2007	SV USA only SV USA+ROW	7	39	-0.06 -0.07	-0.46 +0.45	Gains in USA+ROW stem from terms-of-trade effects
Udall-Petri 2006		Similar to Bingaman-Specter				
Lieberman-McCain 2007	203 bmt SEC	31	121	-0.23	-1.11	National emissions allowed estimated at 216 bmt, costs would thus be slightly lower.
Feinstein August 2006	203 bmt	41	161	-0.32	-1.45	National emissions allowed is 195bmt, costs would be slightly higher. Policies and measures rather than a pure cap and trade.
Kerry-Snowe 2007	Between 203 and 167 bmt	~47	~141	~-0.28	~-1.62	Calculated as halfway between these two cases. Includes additional efficiency standards and other features.
Sanders-Boxer 2007	167 bmt	53	210	-0.55	-1.79	Many other features of the Bill—e.g. efficiency standards, renewable portfolio requirements—are not included.
Waxman 2007	At 148 bmt, somewhat tighter than Sanders-Boxer, and so costs would be higher					



* For Lieberman-McCain, this is the allowance path for covered sectors only.

Figure 1. Scenarios of allowance allocation over time

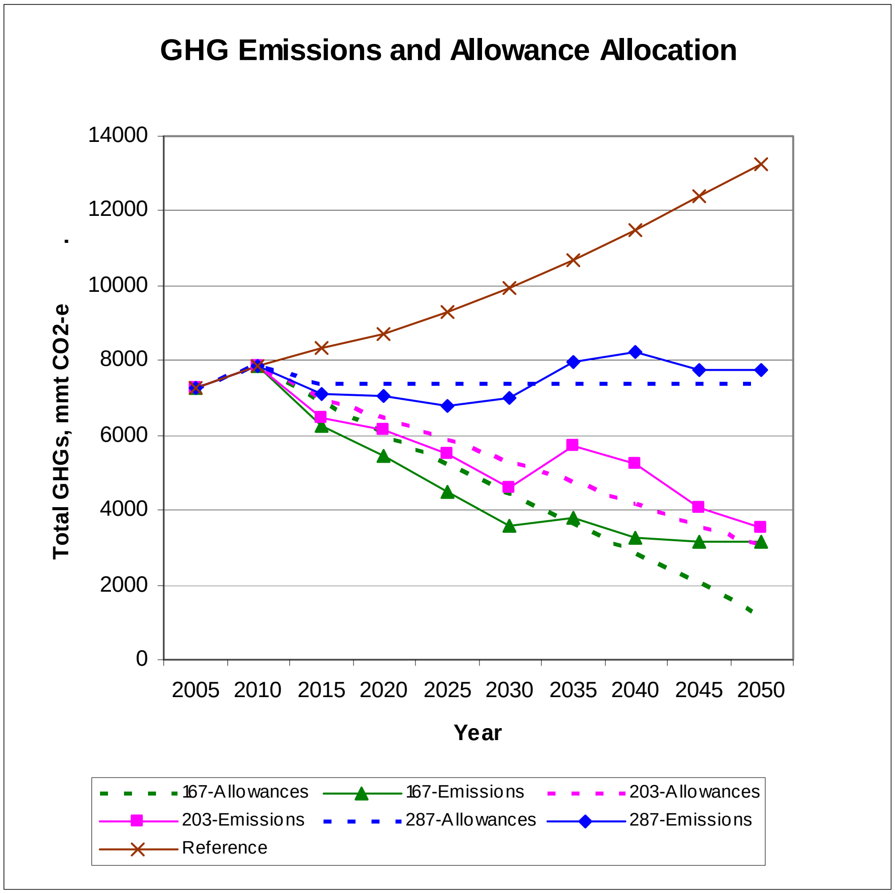
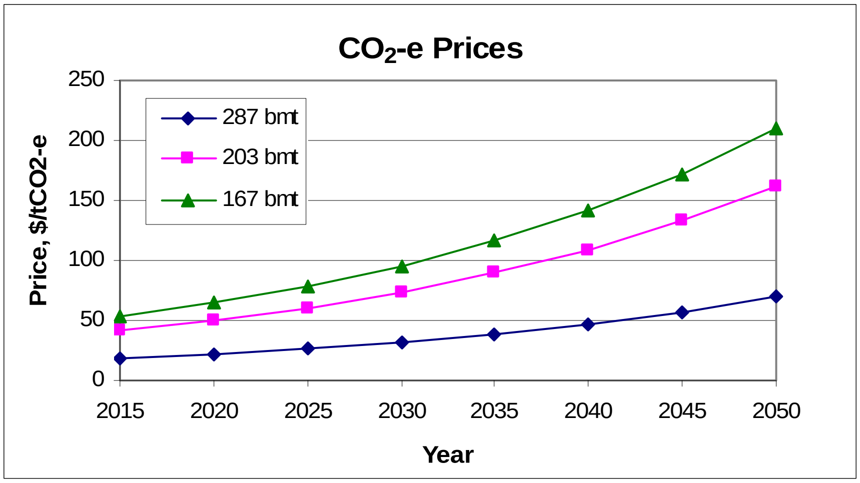


Figure 2. Total GHG emissions and associated allowance allocation path

Panel a. CO$_2$-e Prices



Panel b. Welfare Effects

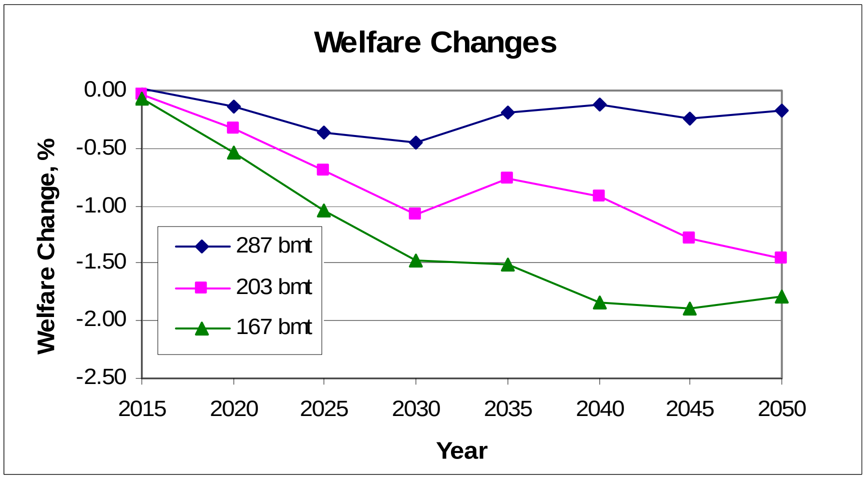


Figure 3. CO$_2$-e prices and welfare effects in the core scenarios

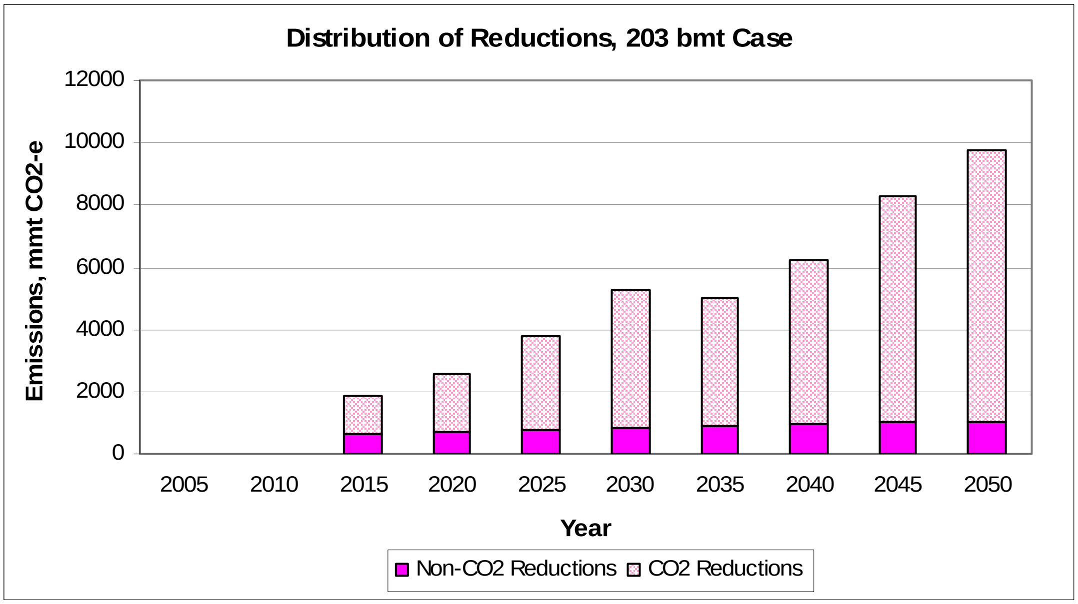
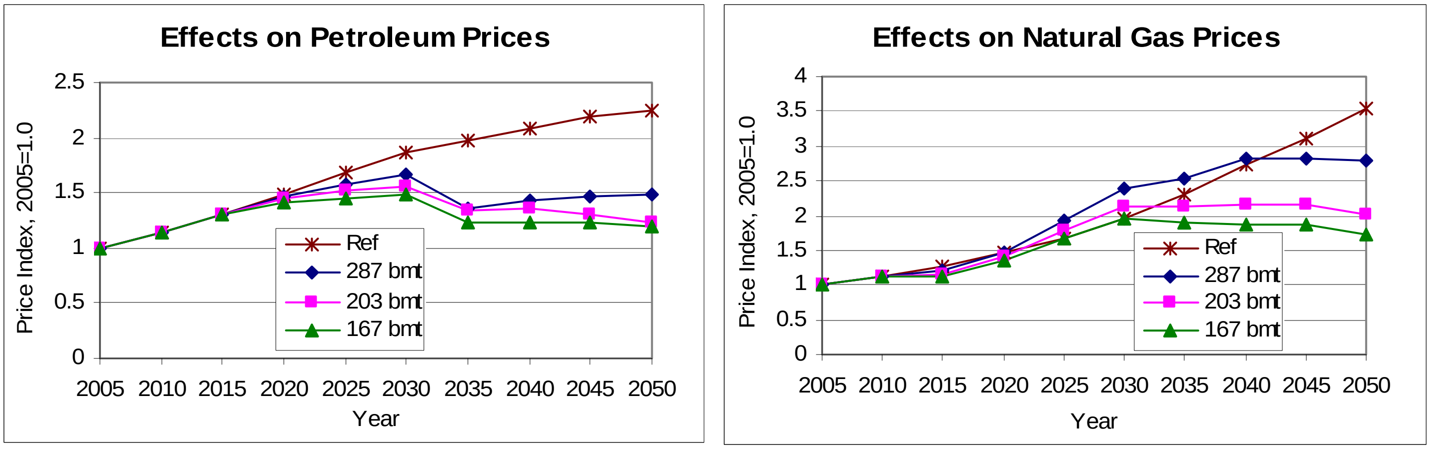


Figure 4. Distribution of emissions reductions, 203 bmt case

Panel a. Petroleum Product Prices **Panel b. Natural Gas Prices**



Panel c. Coal Prices **Panel d. Electricity Prices**

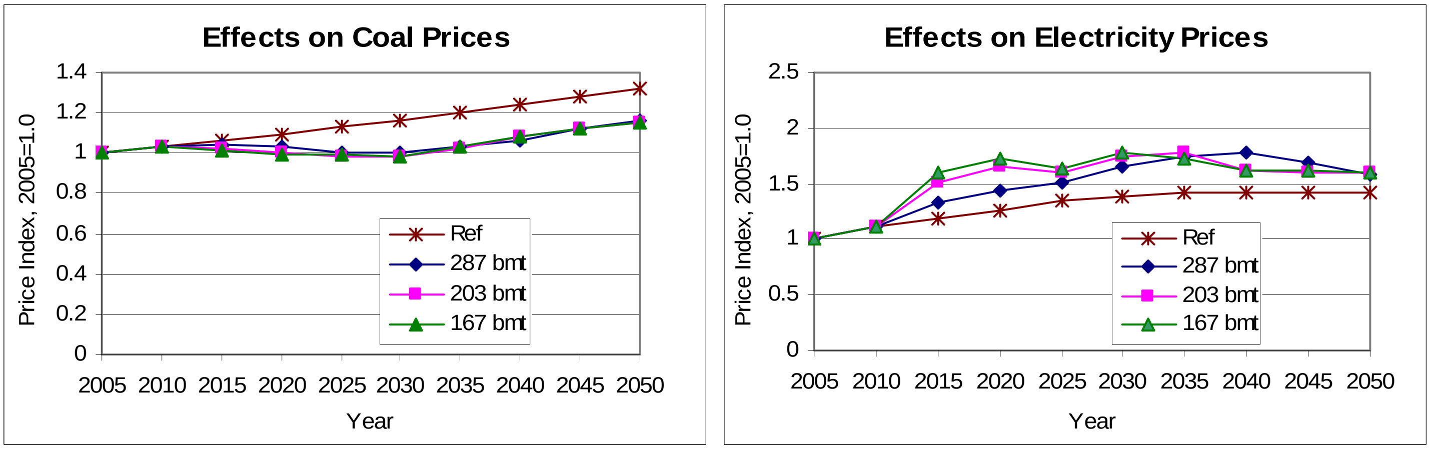
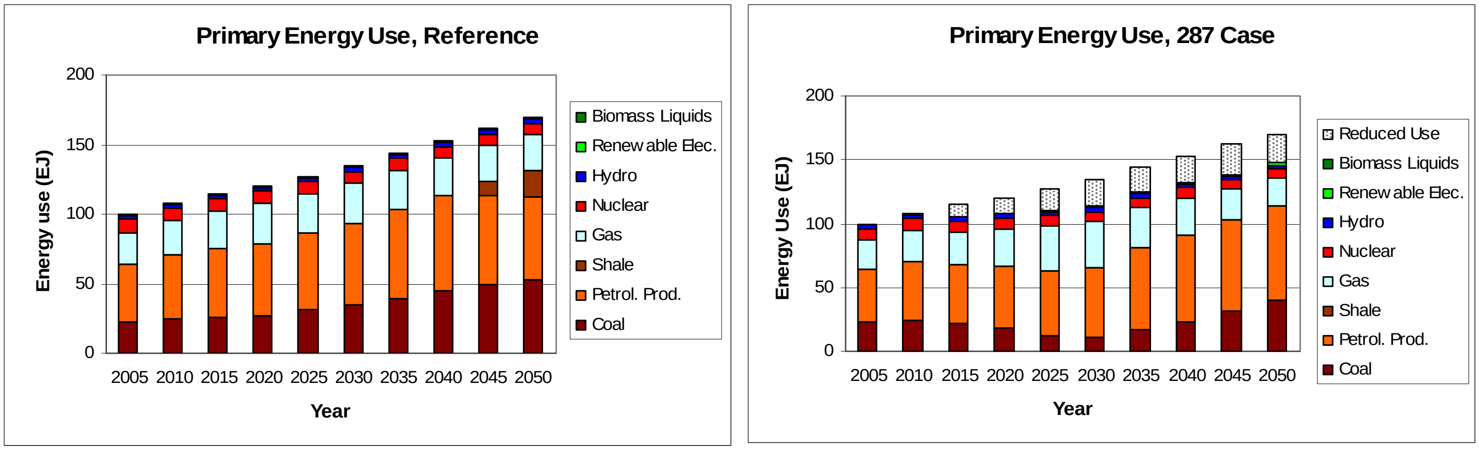


Figure 5. Fuel prices in the reference and core scenarios

Panel a. Reference Case

Panel b. 287 bmt Case



Panel c. 203 bmt Case

Panel d. 167 bmt Case

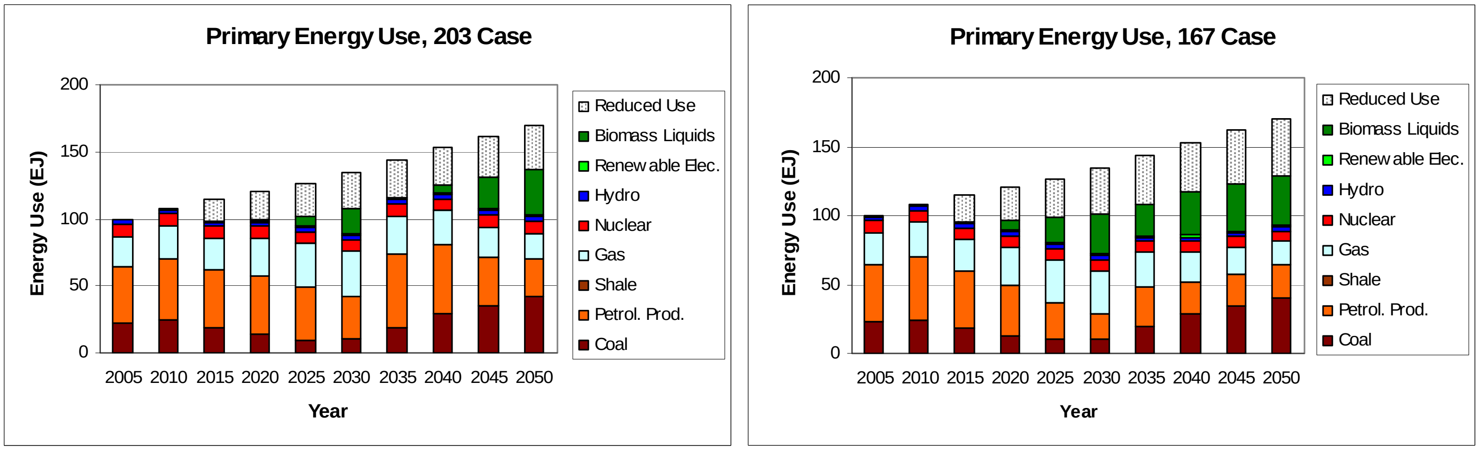


Figure 6. Primary energy use in the reference and core scenarios

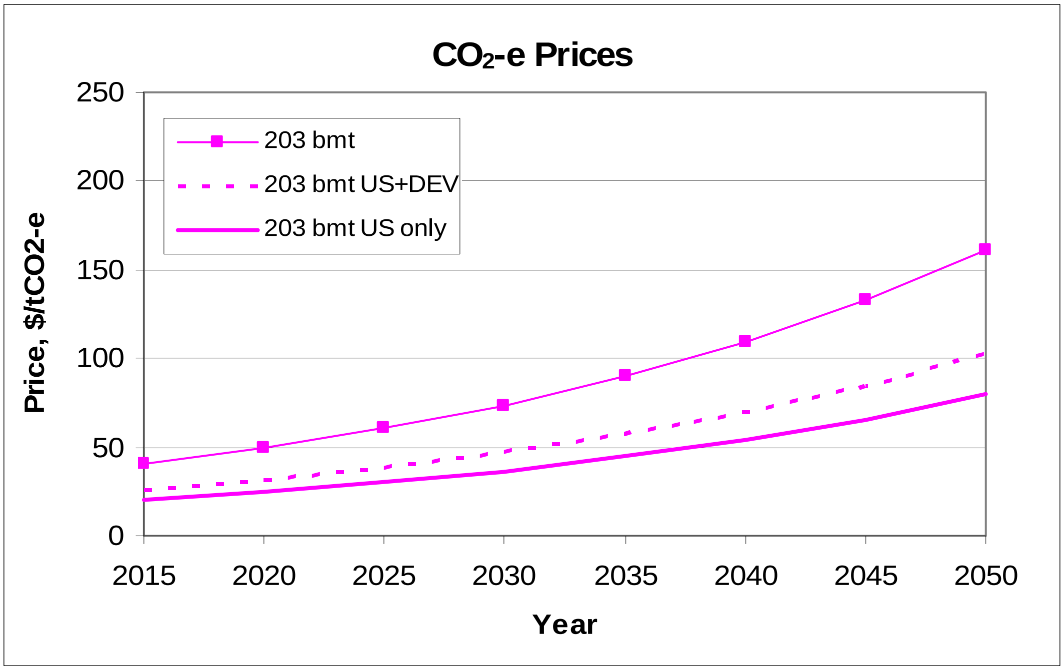
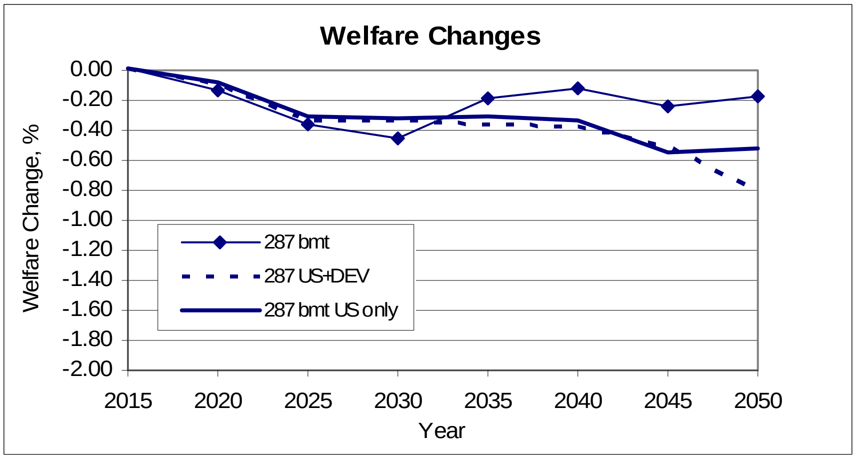
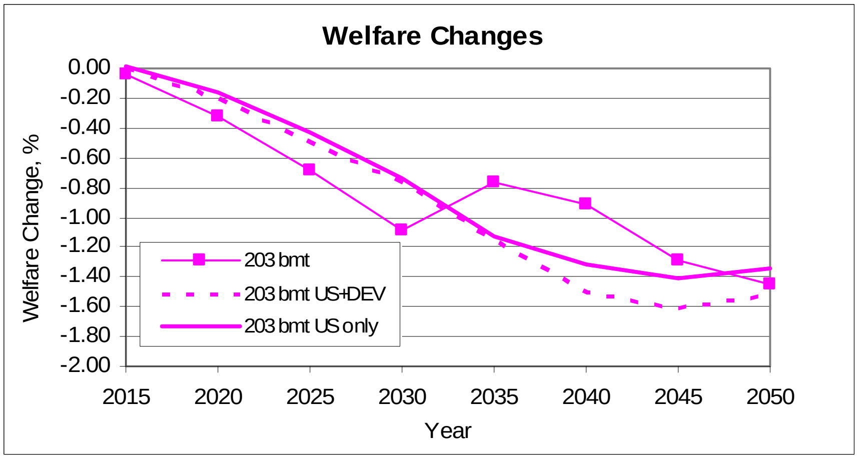


Figure 7. Effects of alternative policies abroad on US CO_2-e prices, no allowance trading

Panel a. 287 bmt Case



Panel b. 203 bmt Case



Panel c. 167 bmt Case

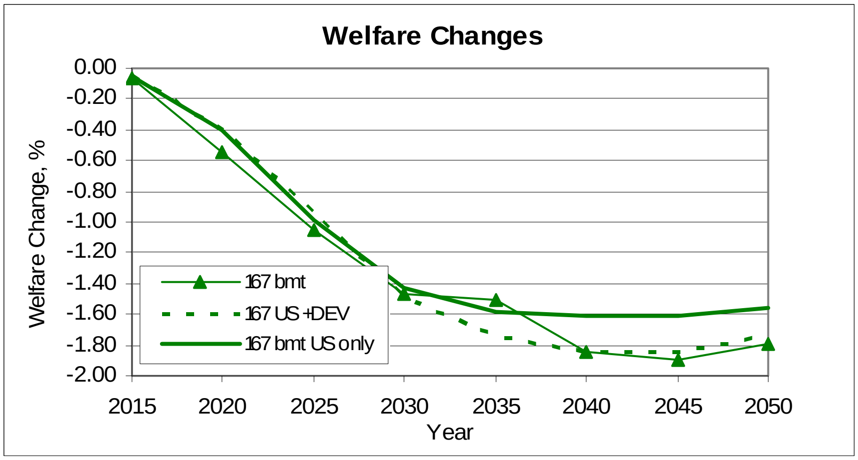
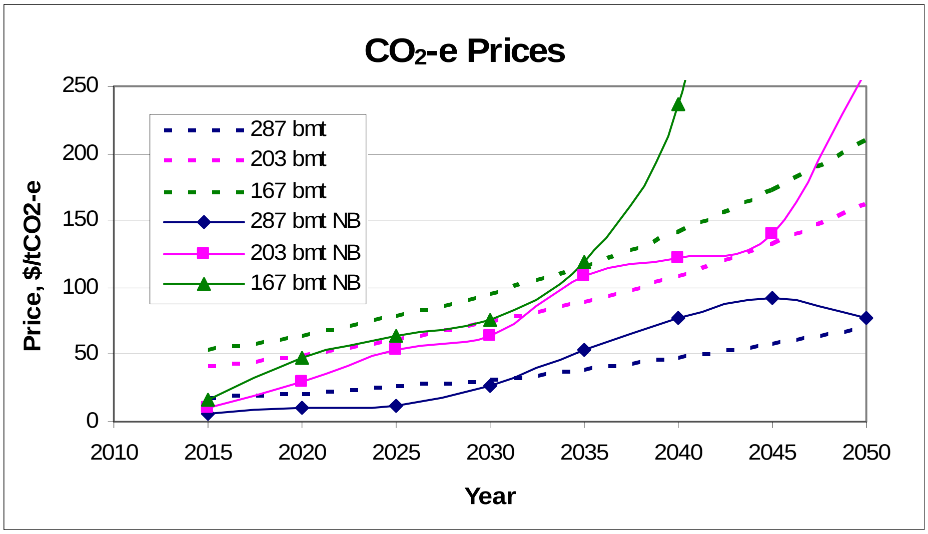


Figure 8. Effects of alternative policies abroad on US welfare, no trading

Panel a. CO_2-e Prices



Panel b. Welfare Changes

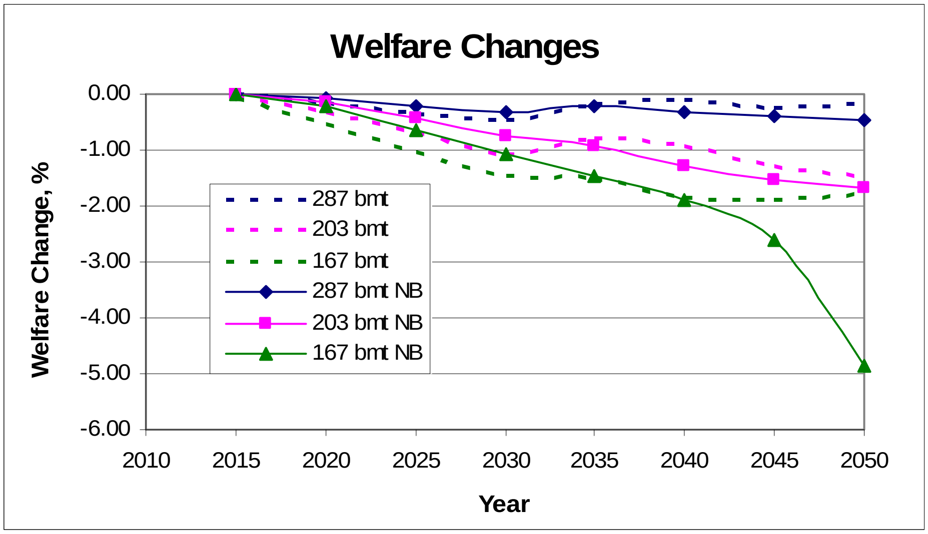


Figure 9. Effects of banking: no banking (NB) and core cases (dashed lines)

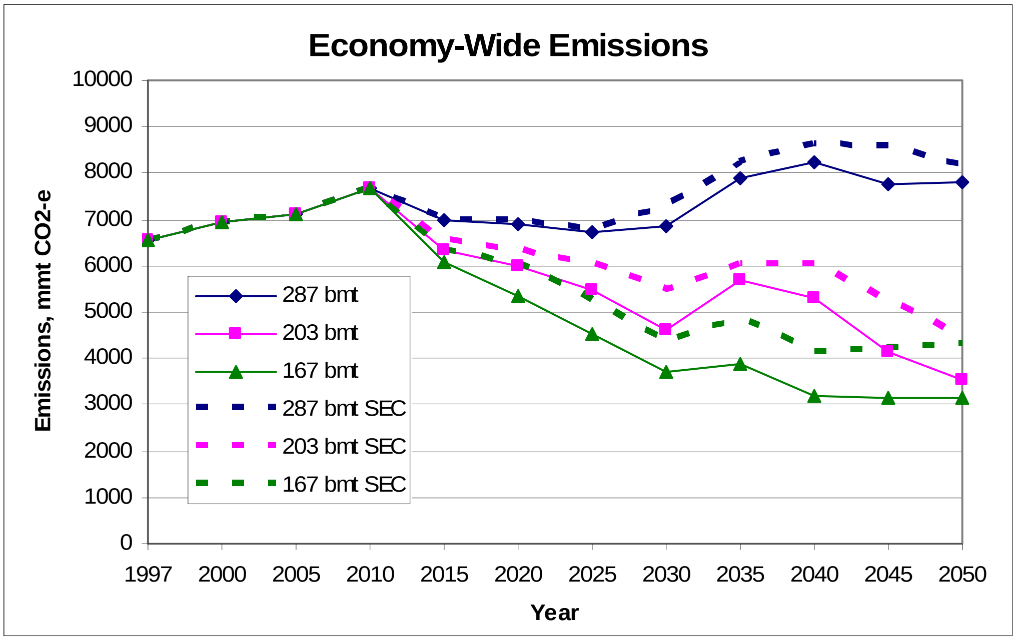
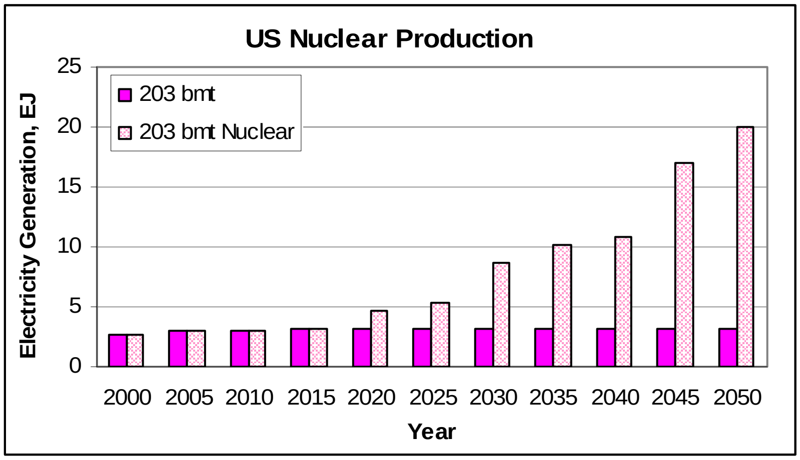
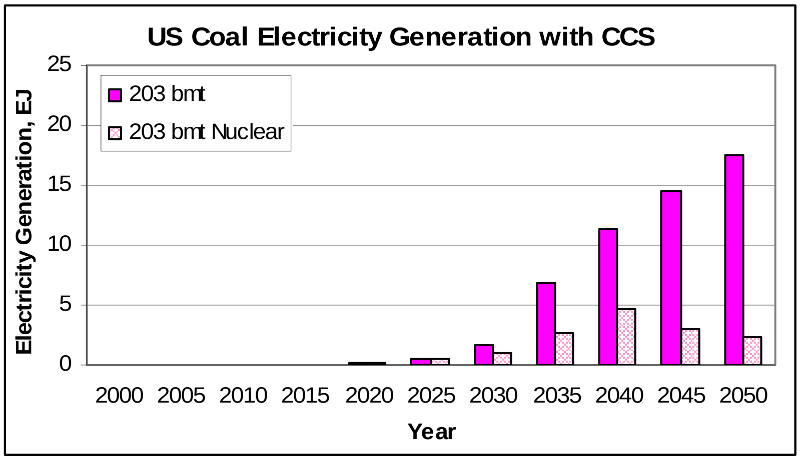


Figure 10. Economy-wide emissions with sectoral policies (SEC) compared with the core scenarios with banking

Panel a. Nuclear Generation



Panel b. Coal Generation with CCS



Panel c. Coal Generation without CCS

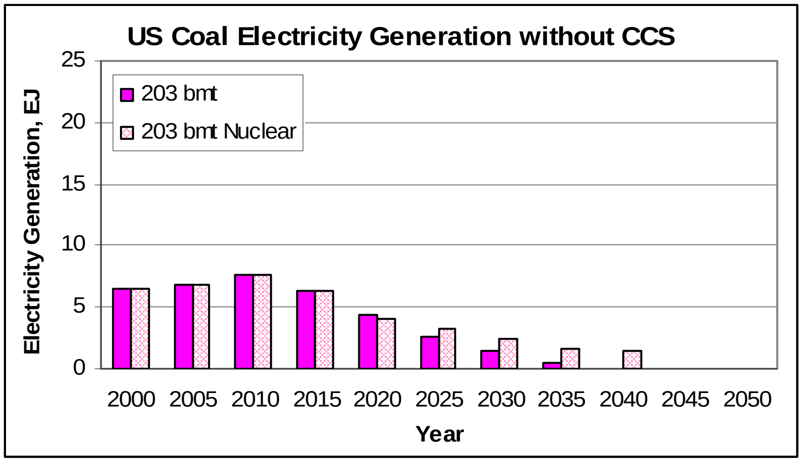
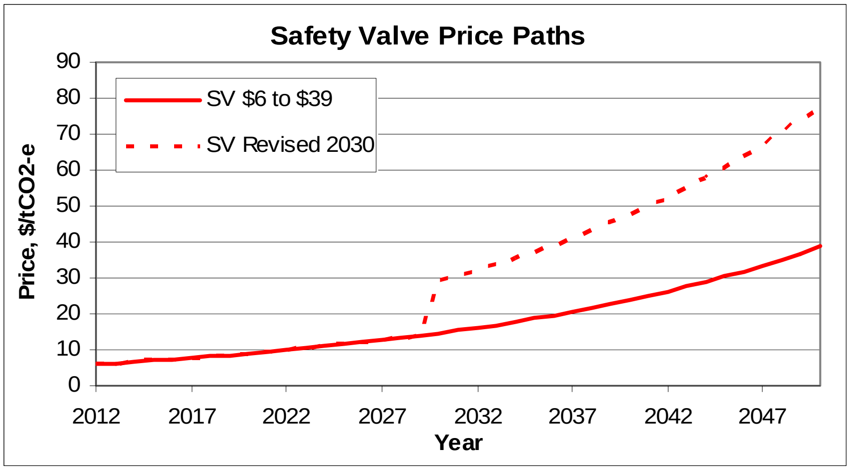
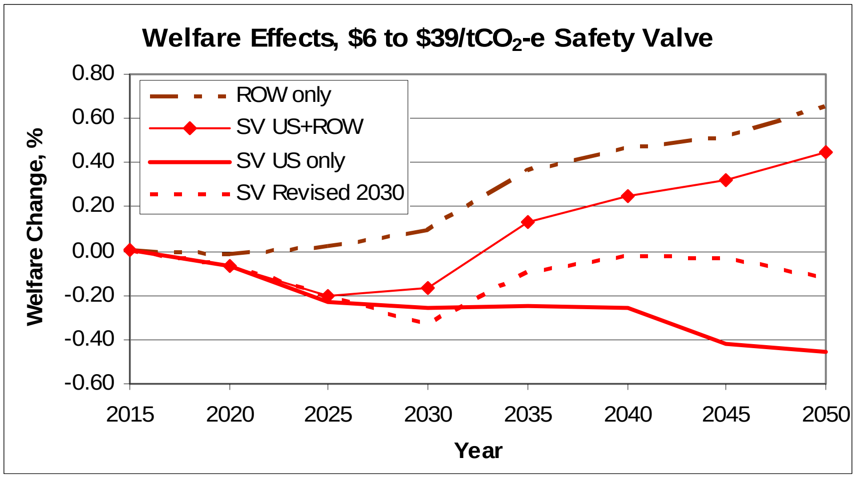


Figure 11. US electricity generation in the expanded nuclear case and the core 203 bmt case

Panel a. Safety Valve Price Paths



Panel b. Welfare effect



Panel c. US Emissions

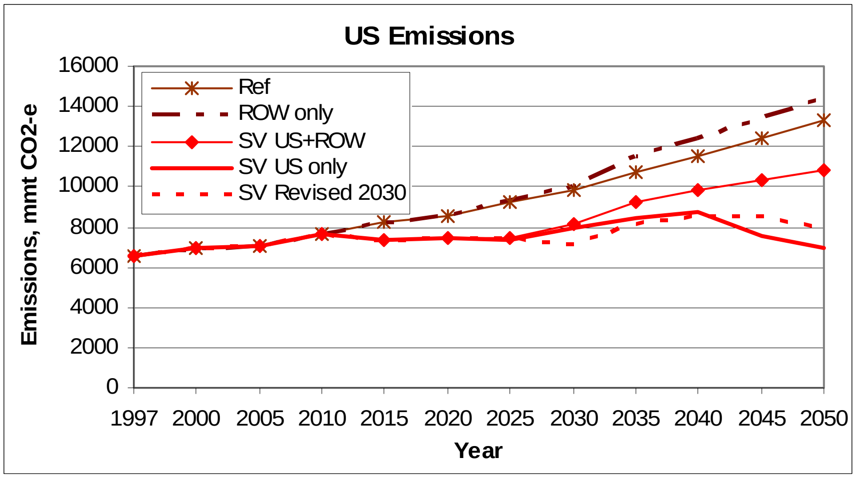
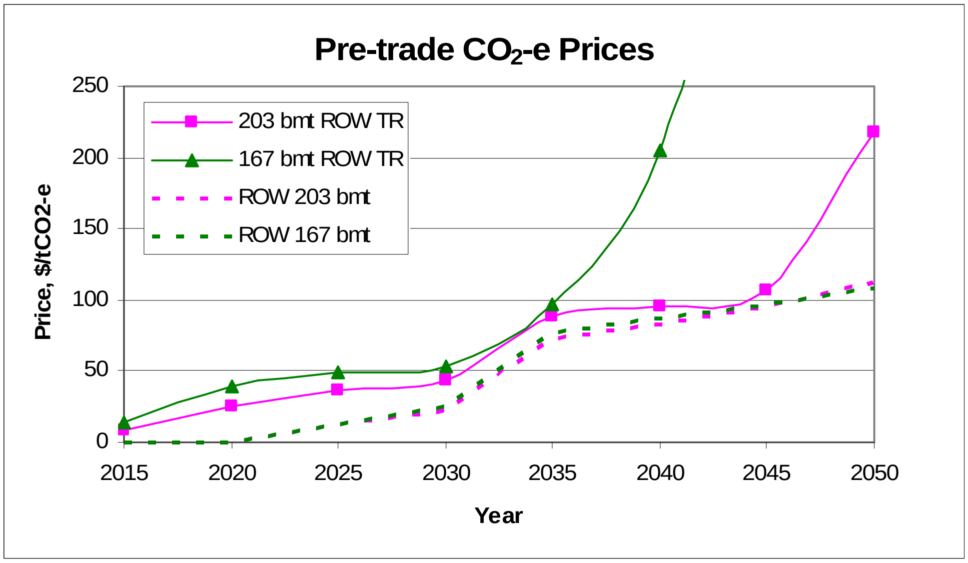


Figure 12. Effects of a "safety valve" at $6 in 2012 rising to $39/tCO$_2$-e in 2050

Panel a. Pre-trade prices, US and ROW, with trade among ROW regions



Panel b. World prices with US trading, ROW pre-trade

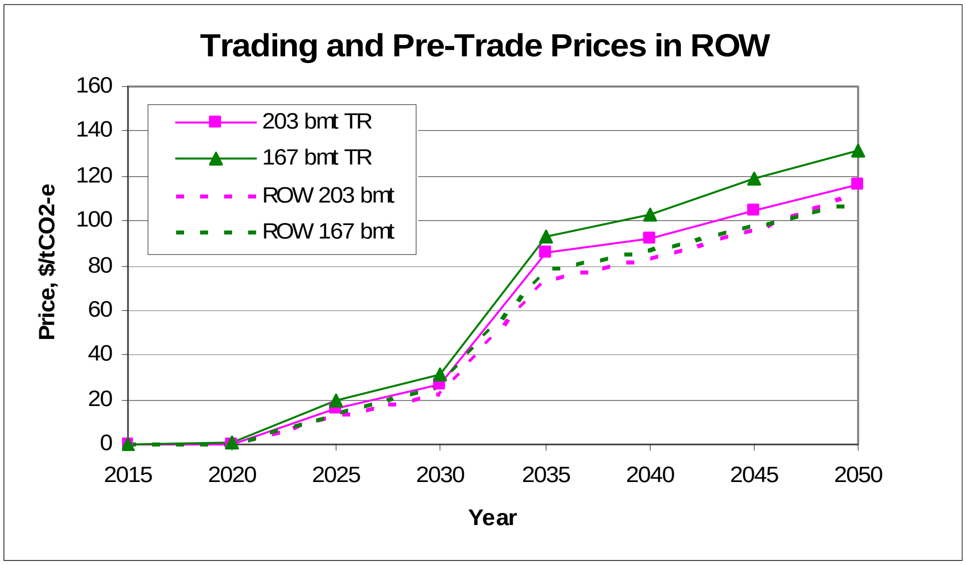
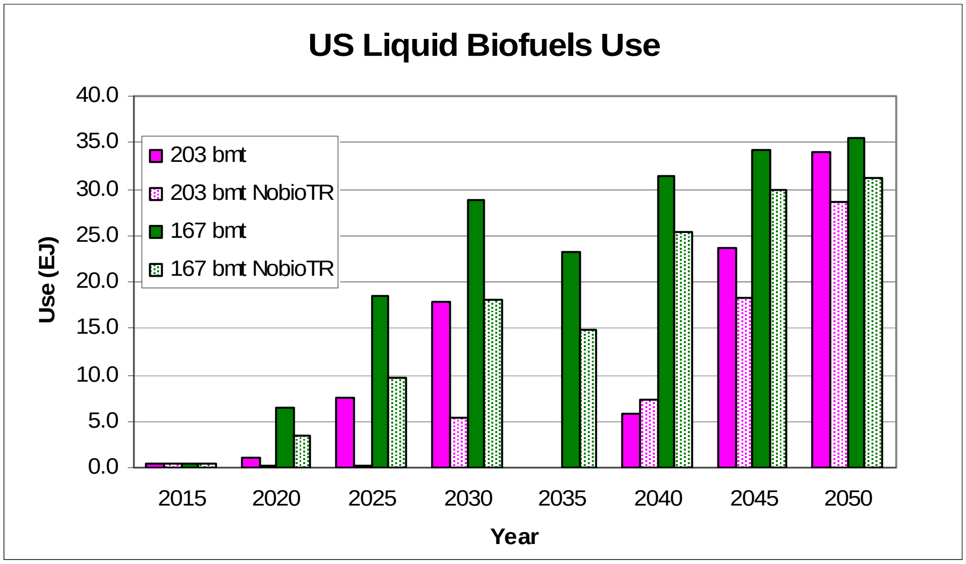


Figure 13. CO_2-e prices and emissions trading

Panel a. US



Panel b. World Total

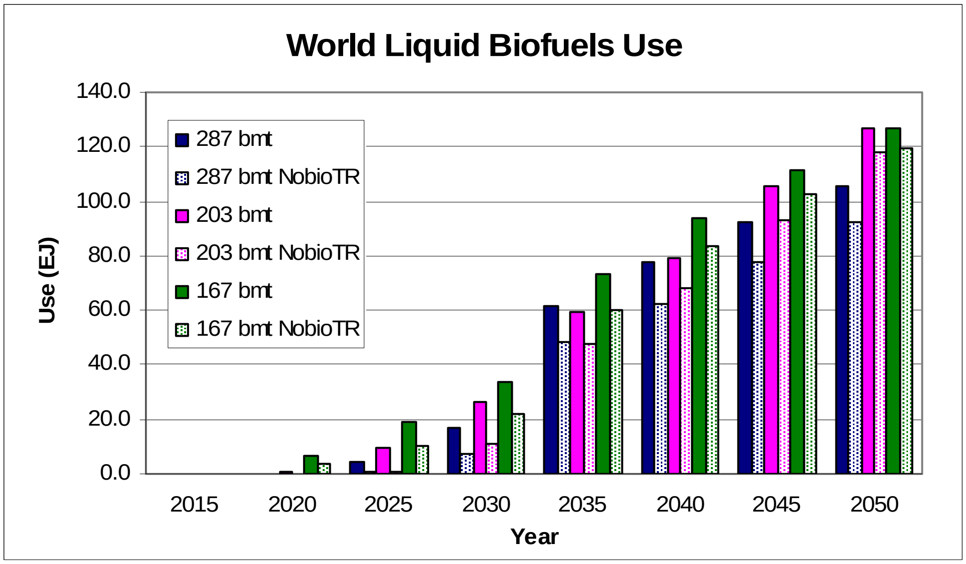


Figure 14. Liquid biofuel use, with and without international trade in biofuels

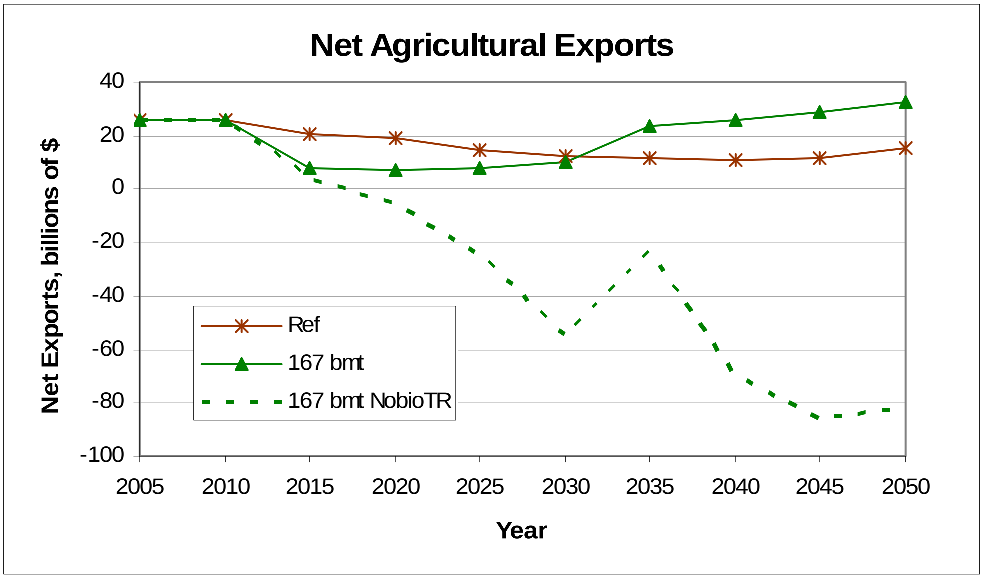


Figure 15. Net agricultural exports in the 167 bmt case, with and without biofuels trading

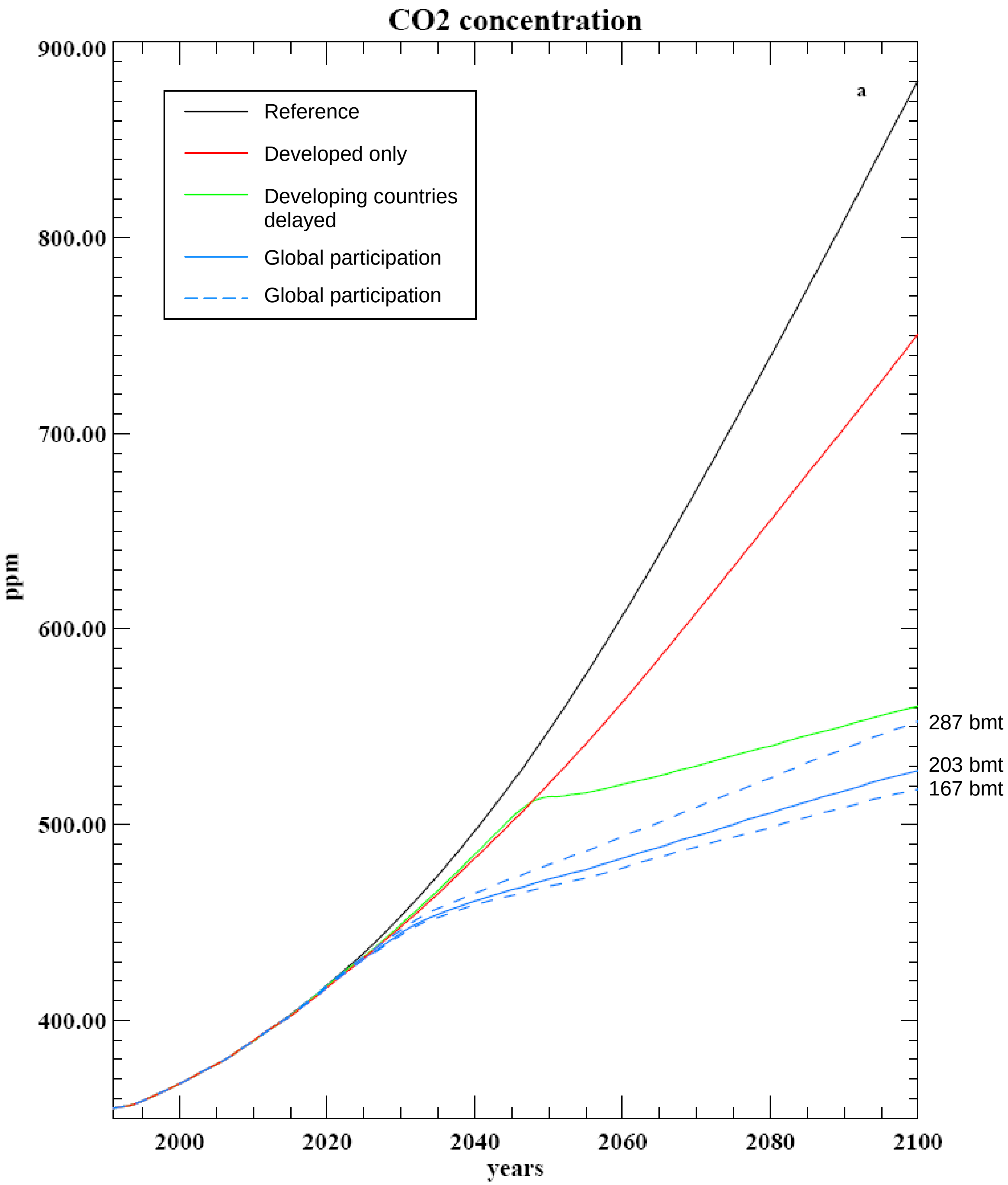


Figure 16. CO$_2$ concentrations in six scenarios using MIT IGSM; see text for details

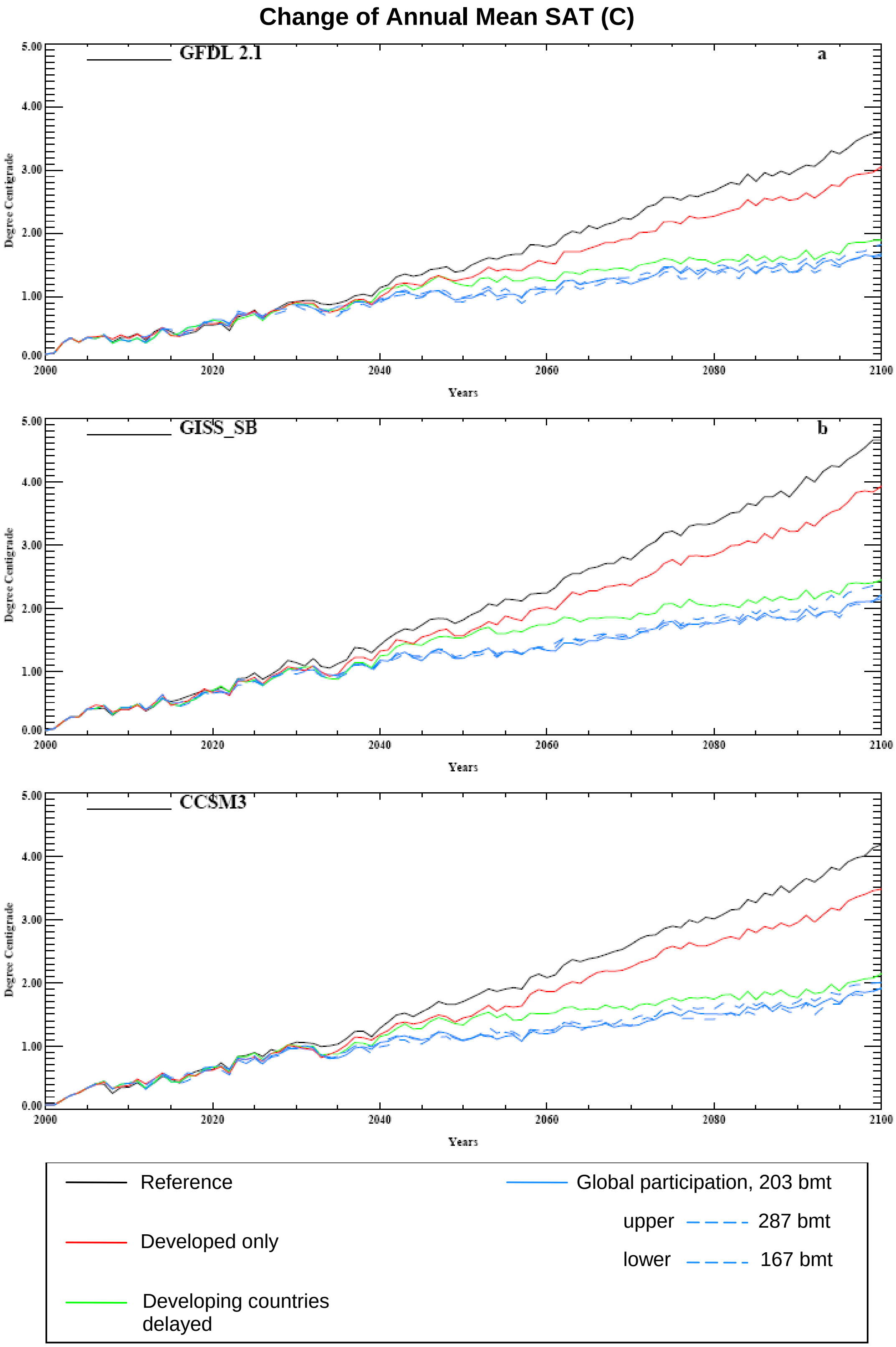


Figure 17. Global mean surface temperature increase in six scenarios using MIT IGSM