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Assessment of US GHG cap-and-trade proposals

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In 2007 the US Congress began considering a set of bills to implement a cap-and-trade system to limit the nation's greenhouse gas (GHG) emissions. The MIT Integrated Global System Model (IGSM) – and its economic component, the Emissions Prediction and Policy Analysis (EPPA) model – were used to assess these proposals. In the absence of policy, the EPPA model projects a doubling of US greenhouse gas emissions by 2050. Global emissions, driven by growth in developing countries, are projected to increase even more. Unrestrained, these emissions would lead to an increase in global CO_2 concentration from a current level of 380 ppmv to about 550 ppmv by 2050 and to near 900 ppmv by 2100, resulting in a year 2100 global temperature 3.5–4.5°C above the current level. The more ambitious of the Congressional proposals could limit this increase to around 2°C, but only if other nations, including developing countries, also strongly controlled greenhouse gas emissions. With these more aggressive reductions, the economic cost measured in terms of changes in total welfare in the United States could range from 1.5% to almost 2% by the 2040–2050 period, with 2015 CO_2-equivalent prices between $30 and $55, rising to between $120 and $210 by 2050. This level of cost would not seriously affect US GDP growth but would imply large-scale changes in its energy system.

Keywords: cap-and-trade; climate policy; energy system; economic cost; greenhouse gas emission reductions; United States; US Congress

En 2007 le Congrès des Etats-Unis a commencé à envisager un nombre de projets de lois pour la mise en œuvre d'un système cap-and-trade pour limiter les émissions de gaz à effet de serre (GES) au niveau de la nation. Le modèle pour un système global intégré du MIT (IGSM) – et sa composante économique, le modèle de prédiction des émissions et d'analyse politique (EPPA) – furent employés pour évaluer ces propositions. Le modèle EPPA prédit qu'à défaut de politiques, les émissions de gaz à effet de serre des Etats-Unis doubleraient d'ici 2050. A l'échelle mondiale, les émissions dues à la croissance des pays en développement devraient croître encore plus. Sans mesures de contrôle, ces émissions donneraient lieu à une montée des concentrations globales de CO_2 d'un niveau actuel de 380 ppmv jusqu'à environ 550 ppmv d'ici 2050 et de près de 900 ppmv d'ici 2100, entraînant des températures globales en 2100 de 3.5–4.5°C au-dessus des températures actuelles. Les propositions du Congrès les plus ambitieuses pourraient limiter cette augmentation autour de 2°C, mais seulement si d'autres nations, y compris les pays en développement, eux aussi contrôlent fortement leurs émissions de gaz à effet de serre. Avec des réductions plus appuyées, le coût économique mesuré en fonction du changement de la richesse totale des Etats-Unis pourrait aller de 1.5% jusqu'à presque 2% d'ici la période 2040–2050, avec une montée des prix de l'équivalent CO_2 de 2015 d'entre $30 et $55 à entre $120 et $210 d'ici 2050. Ce niveau de prix n'affecterait pas sérieusement la croissance du PIB américain mais entraînerait des changements de grande échelle dans le système énergétique.

Mots clés: cap-and-trade; Congrès des Etats-Unis; coût économique; Etats-Unis; politique climatique; réductions des gaz à effet de serre; système énergétique

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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.[1] Several bills have been filed in the Congress or are under development. In this article 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.

We begin the assessment of current proposals in Section 2 where 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 3 then presents results for the core cases, including price and welfare effects, and impacts on energy markets.[2] 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.[3] The proposals under study specify targets only to 2050, which is too short a period for consideration of the climate impacts. Therefore in Section 4 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 5 offers some conclusions.

2. Analysis method

2.1. The Emissions Prediction and Policy Analysis (EPPA) model

To assess the 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). The level of aggregation of the model is presented in Table 1. The model includes a representation of an abatement of greenhouse gas emissions (CO_2, 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. 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 Table 1. The energy sector, which emits several of the non-CO_2 gases as well as CO_2, is modelled 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 modelled as producing an imperfect substitute, reflecting its intermittent output. Advanced biomass use is included both in transport fuel and electricity generation although it does not penetrate the electric sector in these simulations (Reilly and Paltsev, 2007). There are 16 geographical regions represented explicitly in the model including major countries (the United States, Japan, Canada, China, India and Indonesia) and 10 regions that are aggregations of countries.

When viewing the EPPA model results for emissions prices and welfare costs it is as 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

TABLE 1 EPPA model details

Countries, regions, and sectors in the MIT EPPA model

Country or region†	Sectors	Factors
Developed	*Non-Energy*	Capital
United States (USA)	Agriculture (AGRI)	Labour
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: NGCC (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).

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.

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 (e.g. Webster et al., 2002) of these proposals, 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 would likely be preserved. Policy design inevitably involves a process to reevaluate decisions as new information is gained, rather than deciding once and for all on a long-term policy based on any single numerical analysis.

2.2. Policy options and scenario assumptions for the 'core' results

In presenting the assessment results we explore (in Section 3) a set of 'core' results applying features that are most common among the proposed cap-and-trade bills. We focus the discussion on results that illustrate measures of cost, and effects on energy markets. A more complete set of results for each of the scenarios and for variation in system features over such dimensions as coverage, banking and borrowing, trade restrictions, revenue recycling and agricultural markets is provided in Paltsev et al. (2007).

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 to an average of the three years after. The most recent emissions inventory as of the time of this analysis is for 2005, and so some extrapolation is required if a bill may not be passed until 2008 or after. 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 estimated 2008 levels, extrapolating 2008 emissions from the 2005 inventory by assuming growth at the recent historical rate of 1% per year as documented in US EPA (2007). 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.

Given the stock nature of the global warming externality, we label the cases 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 judgements 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 ensure the comparison remains appropriate.

If total allowances are fixed over the whole period and banking and borrowing are allowed, the actual time path of allowance allocation will not determine the CO_2 prices, energy market developments, and other effects simulated by the model in these core runs. 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-Warner Bill places it slightly below 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 203 bmt case is Bingaman-Specter with estimated total emissions including uncovered sectors being equal to 245 bmt. Note that the Bingaman-Specter draft and Udall-Petri include a safety valve feature and so to the extent the safety valve is triggered emissions are determined by the price mechanism and are not fixed in quantity terms.

Throughout the analysis the cap covers the emissions of the six categories of greenhouse gases identified in US policy statements and in the Kyoto Protocol (CO_2, CH_4, N_2O, SF_6, HFCs and PFCs), with the gases aggregated at the 100-year Global Warming Potential (GWP) rates used in

TABLE 2A Congressional bills, basic features

	Lieberman-Warner 2007	Bingaman-Specter 2007	Kerry-Snowe 2007	Sanders-Boxer 2007	Waxman 2006	Feinstein August 2006	Udall-Petri 2006
Bill number/ name	S.2191; America's Climate Security Act of 2007	S.1766; Low Carbon Economy 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 and trade (HFCs capped separately)	Mandatory, market-based cap on total emissions for all large emitters: cap and trade with safety valve (TAP)	Mandatory, market-based, cap on total emissions for all large emitters: cap and trade	Mandatory, market-based, system to be determined by EPA, allows for cap and trade in one or more sectors	Mandatory, market-based, cap on total emissions for all large emitters: cap and trade	Mandatory, market-based, cap on total emissions for all large emitters: cap and trade	Mandatory, market-based, cap on total emissions for all large emitters: cap and trade with safety valve
Targets	Return emissions to 2005 levels by 2012, then gradually reduce to 70% below 2005 levels by 2050 (set amount of allowances for each year)	Return emissions to 2006 levels by 2020, 1990 levels by 2030, and at least 60% below 2006 levels by 2050 (set amount of allowances for each year up to 2030, then contingent on global effort)	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.

TABLE 2A Congressional bills, basic features *(Cont'd)*

	Lieberman-Warner 2007	Bingaman-Specter 2007	Kerry-Snowe 2007	Sanders-Boxer 2007	Waxman 2006	Feinstein August 2006	Udall-Petri 2006
Allocation of allowances	Table of yearly percent auctioned: starts with 22.5% in 2012, ends with 70.5% 2031–2050, balance allocated free (portions earmarked)	Table of yearly percent auctioned: starts with 24% in 2012, increased to 53% in 2030, and to about 80% by 2050, balance allocated free (portions earmarked)	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	• Upstream • Covered entities produce over 80% of national emissions • Covered entities are those that emit, produce or import products that emit over 10,000 metric tons of GHGs per year	• Upstream • Technology Accelerator Payment (TAP) (i.e. safety valve): instead of submitting allowances can pay TAP price: \$12/mt CO_2, escalates	• Total GHGs less than 450 ppmv • Banking • Provisions to track, report, verify emissions • Non-compliance penalties	• Less than 3.6°F (2°C) temperature increase, and total GHGs less than 450 ppmv • Suggests declining emissions cap with technology-	• Less than 3.6°F (2°C) temperature increase, and total GHGs less than 450 ppmv • Banking • Provisions to track, report, verify emissions	• Keep temperature increase to 1 or 2°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

• Separate quantity of emission allowances (Emission Allowance Account) for each year from 2012 to 2050 • Banking • Borrowing (up to 15% per yr) • Non-compliance penalties	annually at 5% real • Banking • President can exempt entities and extend to uncovered entities • Provisions to track, report, verify emissions • Non-compliance penalties		indexed stop price • Provisions to track, report, verify emissions	• Non-compliance penalties		Secretary of State certify that other countries are controlling their emissions

TABLE 2B Congressional bills, additional details and features *(Cont'd)*

	Lieberman-Warner 2007	Bingaman-Specter 2007	Kerry-Snowe 2007	Sanders-Boxer 2007	Waxman 2006	Feinstein August 2006	Udall-Petri 2006
Provisions related to foreign reductions	• Acceptance of foreign allowances (up to 15%) • 2.5% of yearly allowances for reducing tropical deforestation in other nations • Help develop and fund adaptation plans in and deploy technology to least developed nations • Review of other nations: if major emitting nations do not take comparable action within 8 yrs, President can require importers to submit allowances for emission-intensive	• 5-yr reviews of 5 largest trading partners: if taking comparable action, President recommends emission reductions of at least 60% below 2006 by 2050, also decisions about foreign credits and international offset projects • If other nations do not take comparable action, President can require importers to submit allowances for emission-intensive products from such nations		• 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

	products from such nations	• International technology development programme					
Credit Provisions	• Credits from sequestration for facilities that do not use coal (for coal-using facilities sequestration reduces their allowance submission), emissions that are destroyed or used as feedstocks, offsets (up to 15%) from non-covered entities	• Credits from sequestration, the use of fuels as feedstocks, the export of covered fuel or other GHGs, hydrofluorocarbon destruction, and offset projects that reduce uncovered GHGs, and perhaps international offset projects	• Credits from sequestration	• Credits from sequestration • Renewable energy credit programme		• Credits from sequestration, non-covered entities, international projects, and responsible land use	• Credits from sequestration

TABLE 2C Congressional bills, additional details and features *(Cont'd)*

	Lieberman-Warner 2007	Bingaman-Specter 2007	Kerry-Snowe 2007	Sanders-Boxer 2007	Waxman 2006	Feinstein August 2006	Udall-Petri 2006
Other features	• Carbon Market Efficiency Board: monitors economy and allowance trading market, can provide relief (more borrowing, lower loans, loosened cap for a given year, etc.) to avoid significant harm to the economy, as long as cumulative emissions reductions over the long term remain unchanged • Climate Change Credit Corporation: proceeds from allowance auctions and trading activities,	• Proceeds from auction go to Energy Technology Deployment Fund (which also gets all proceeds from TAP payments), Adaptation Fund, and Energy Assistance Fund • Incentives to produce fuel from cellulosic biomass	• Climate Reinvestment Fund: proceeds from auctions, civil penalties, and interest, used to further Act and for transition assistance • National Climate Change Vulnerability and Resilience Programme • 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	• 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	• 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 • Biodiesel and E-85 fuel pump expansion • Plans to extend California-style green-technology programmes 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

	deposited into multiple funds (6 new) covering technology R&D, transition assistance, wildlife and ecosystem restoration, climate adaptation and security, and firefighting • Energy efficiency standards • Incentives to produce fuel from cellulosic biomass		• E-85 fuel pump expansion • Consumer tax credits for energy efficient motor vehicles	and final standards for all units, regardless of when they were built, by 2030 • Motor vehicle emission standard

Notes: The Lieberman-Warner Climate Security Act (S. 2191) is analysed in Appendix D of Paltsev et al. (2007). Feinstein Bill is based on San Francisco Chronicle article (Hall and Kay, 2006).

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

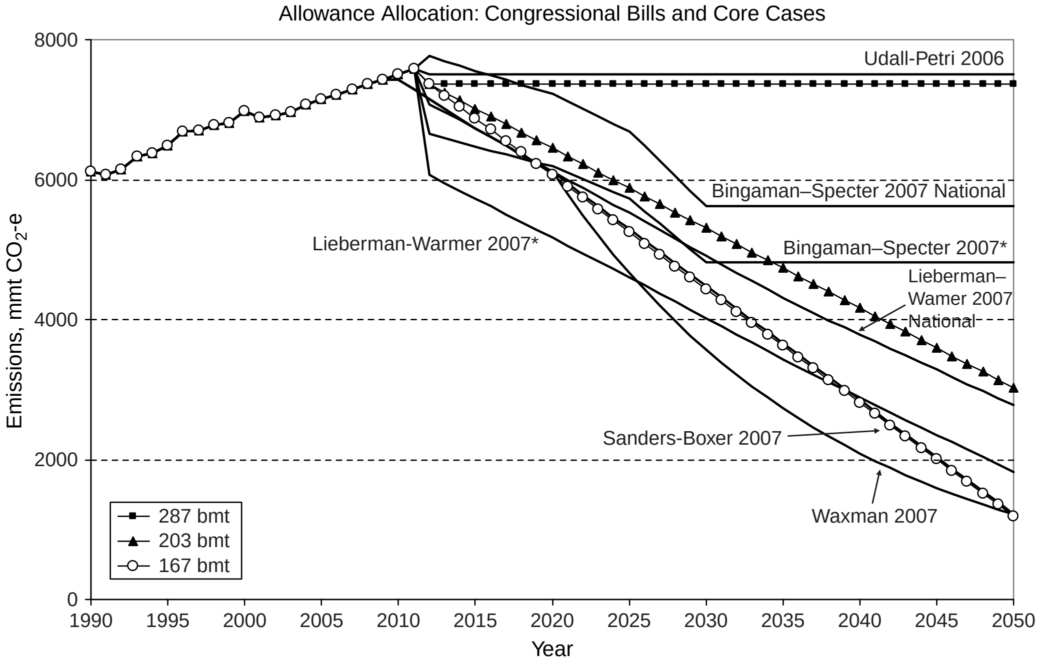


FIGURE 1 Scenarios of allowance allocation over time.

*For Lieberman-Warner and Bingaman-Specter, these are the allowance paths for covered sectors only.
The estimated total national emissions are shown separately and labelled as 'National' for the corresponding bills.

TABLE 3 GHG cumulative allowances available from 2012 to 2050

Allowance path	Cumulative allowances 2012–2050, bmt CO_2e
Udall-Petri 2006	293
287 bmt	287
Bingaman-Specter 2007	245 (210)[a]
203 bmt	203
Feinstein August 2006	195
Lieberman-Warner 2007	190 (153)[b]
Kerry-Snowe 2007	179
Sanders-Boxer 2007	167
167 bmt	167
Waxman 2007	148

[a] 210 are the allowances for covered sectors; 245 is the estimate of total emissions including uncovered sectors. The actual national emissions depend on growth in uncovered sectors. The allowances for covered sectors for 2030–2050 are kept constant as specified in the Bill. An additional provision can change these allowances based on actions at the international level.
[b] 153 are the allowances for covered sectors; 190 is the estimate of total emissions including uncovered sectors. The actual national emissions depend on growth in uncovered sectors. The Bill also has a provision for an increase in allowances for domestic projects and purchases from foreign trading systems, each limited to 15% of total covered emissions.

US EPA (2007). 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. We relax this assumption in Section 3.

The 'core' policy scenarios provide no possibility for crediting reductions achieved in ex-US systems such as the Kyoto-sanctioned Clean Development Mechanism (CDM) or other trading systems such as the EU Emission Trading Scheme (ETS). However, it assumes 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. All other regions adopt a policy beginning in 2025 that returns emissions to their 2015 levels by 2034, and then further reduces them to their 2000 levels by 2035 and holds emissions at that level to 2050. We assume no emissions trading among regions, although implicitly a trading system operates within each of the EPPA regions/countries which include, for example, the EU as a single region (see Table 1). Availability of CDM projects and emissions trading have a potential to reduce policy costs, however, Paltsev et al. (2007) estimate that international emissions trading does not lead to substantial economic efficiency gains unless the US policy is much more stringent than that in other regions.

3. Core results

Given the assumptions discussed in the previous section, we can now model our three policies. We begin by discussing economy-wide impacts and then focus attention on particular industries. In all cases we identify policy impacts by comparing the core cases with a reference scenario that assumes a business-as-usual or no-policy future.

3.1. Emissions, GHG prices and welfare cost

All three emission reductions paths show net banking,[4] 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 emissions. 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% above the allowance allocation in that year.

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

The core scenarios assume that the United States adopts an all-greenhouse-gas policy with emissions trading among gases at their GWP values. All prices are reported in CO_2-equivalent units (noted 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 Panel a of Figure 3 and shown in Table 4. Bankable allowances are financial assets. As such, arbitrage in finance markets

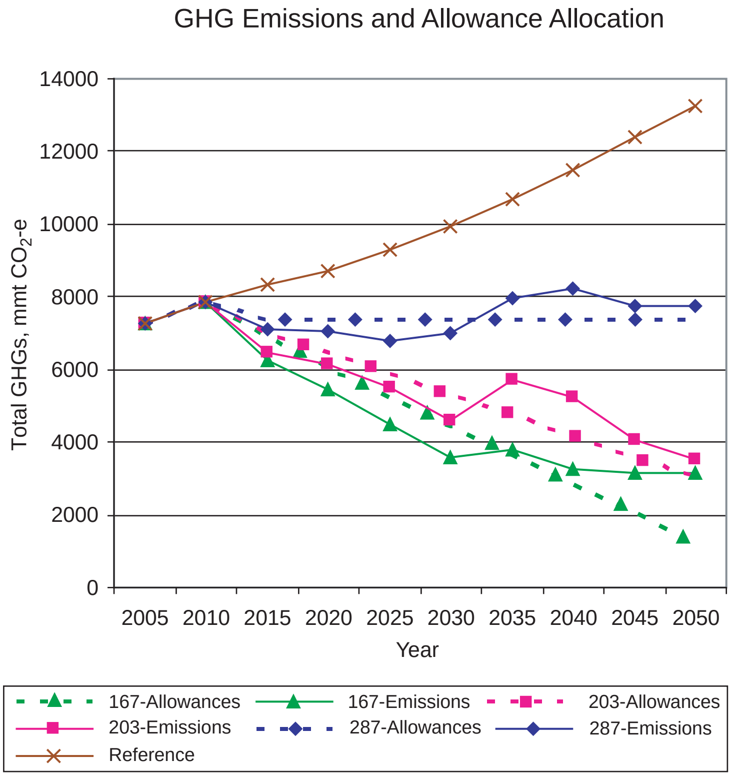


FIGURE 2 Total GHG emissions and associated allowance allocation path

ensures that they will earn the same rate of return as other financial assets, here assumed constant at 4% per annum. The return on an allowance is simply the increase in the price of the allowance. Thus, in the case of free banking and borrowing of allowances, permit prices must grow at an

Panel a. CO_2-e prices

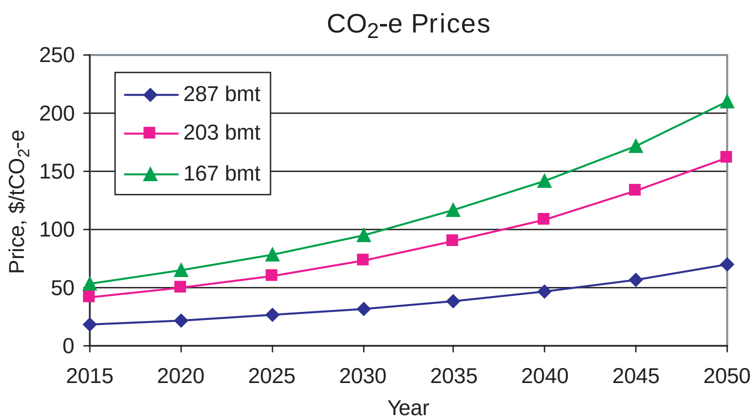


FIGURE 3 CO_2-e prices and welfare effects in the core scenarios

Panel b. Welfare effects

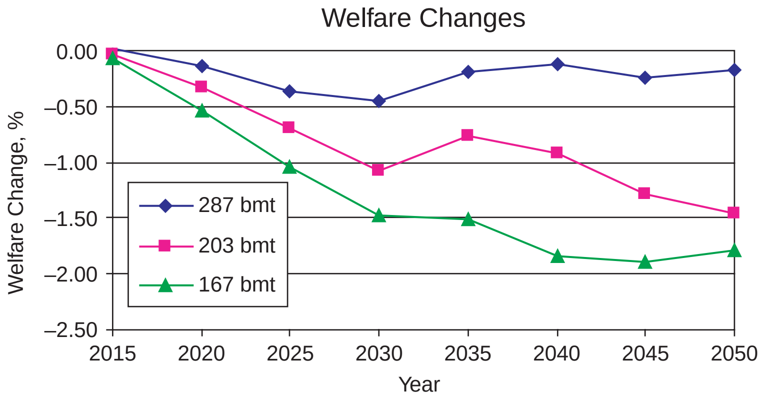


FIGURE 3 CO_2-e prices and welfare effects in the core scenarios *(cont'd)*

annual rate equal to the return on other financial assets. 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.

Following standard economic theory, we calculate and report the overall economic cost of the policy scenarios using a dollar-based measure of the change in welfare for the representative agent in the United States. In technical terms, welfare is measured as equivalent variation and it reflects a change in aggregate market consumption and leisure activity. The results for the three core scenarios are graphed in Panel b of Figure 3 and shown in Table 4. Other welfare measures (macroeconomic market consumption and GDP) are provided in Paltsev et al. (2007). The initial (2015) levels of welfare effects are small: at 0.01, –0.04% and –0.08%; they rise to –0.18, –1.45 and –1.79% in 2050 for the 287, 203 and 167 bmt cases respectively.

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 the welfare cost is driven not only by US policy but

TABLE 4 Core price and welfare results: US + World Policy

	CO_2-e Price (\$/tCO_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

also by activity in the rest of the world. The increase in emissions mitigation by developing countries in 2035 affects domestic welfare through terms-of-trade effects, predominantly through changes in oil prices.

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 US but leave unchanged the mitigation efforts of the rest of the world. In the 203 bmt case the United States takes on reduction targets similar to other developed countries with the developing countries following later. Whereas the US and developed country allowance allocations are 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 very stringent reductions (in comparison to their reference emissions) for rapidly growing developing countries. In the 167 bmt case the US 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 United States lags behind them. In this less ambitious case the US effort eventually falls behind that of developing countries, even while the United States 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 United States 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 US 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 United States. The importance of assumptions about mitigation efforts abroad in the assessment of US domestic proposals is further emphasized in Paltsev et al. (2007). 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 an incentive to ‘free ride’ on abatement efforts elsewhere.

3.2. Energy market effects

The proposed policies have substantial effects on fuels and electricity markets, both in terms of prices and quantities consumed. The EPPA model projects fuel price changes in the no-policy Reference case, and also shows how these prices will further change as a result of mitigation policy. The energy price effects of mitigation policies are discussed in detail in Paltsev et al. (2007).

As presented in Figure 4, 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 show similar patterns of change in 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. 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.

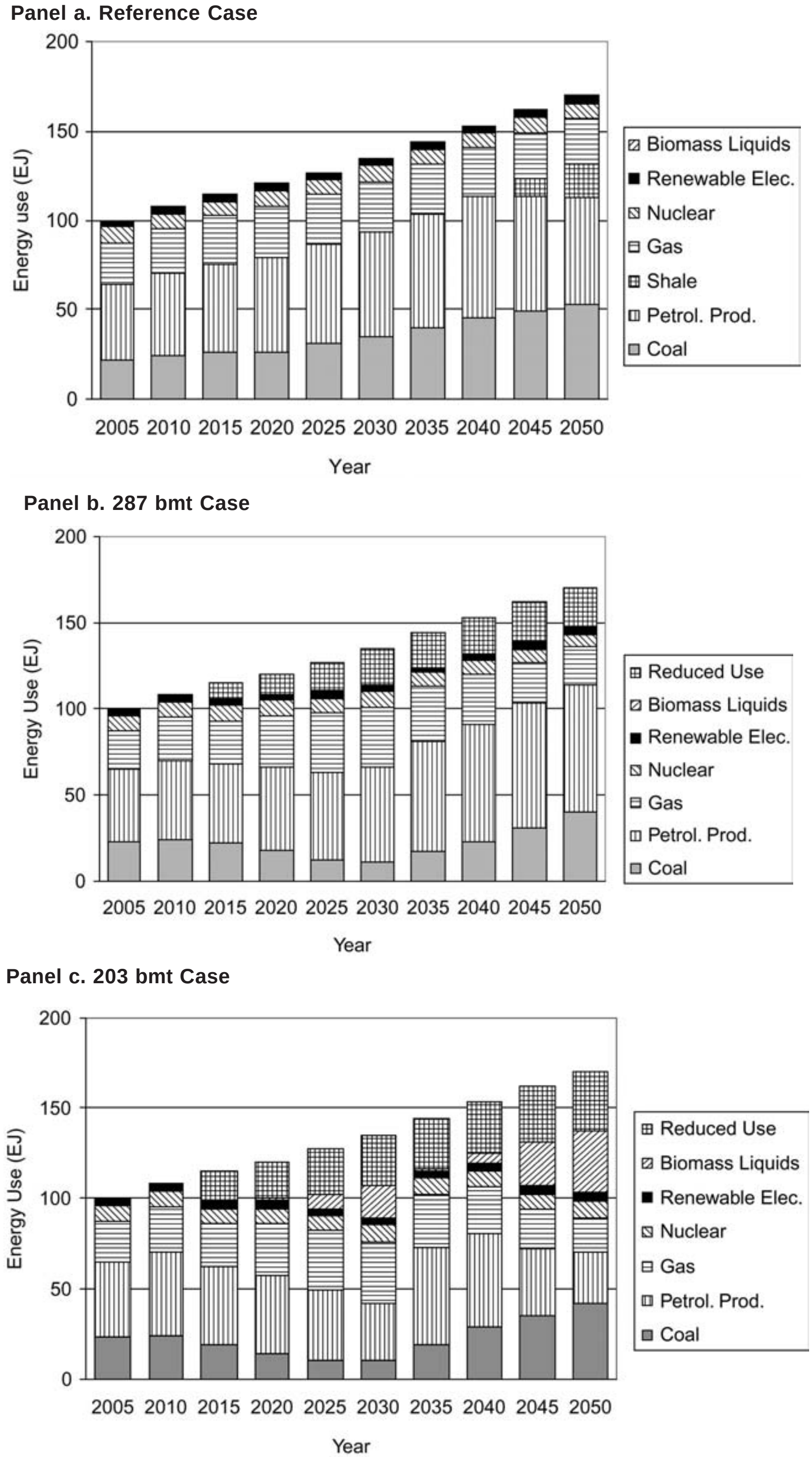


FIGURE 4 Primary energy use in the reference and core scenarios

Panel d. 167 bmt Case

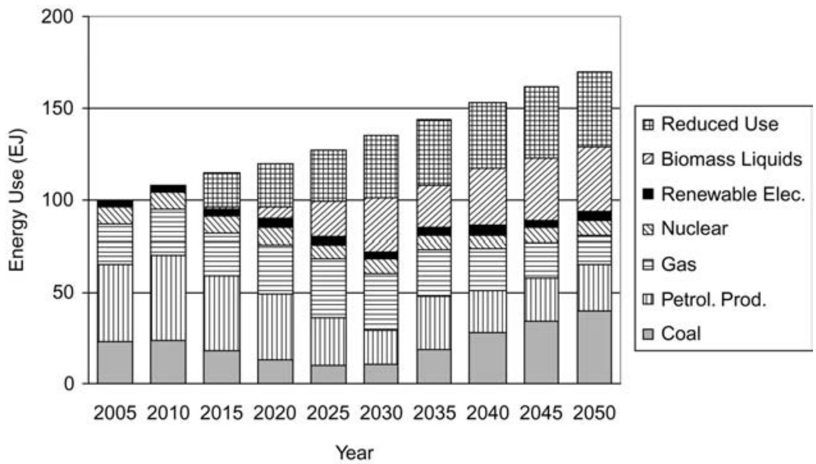


FIGURE 4 Primary energy use in the reference and core scenarios *(cont'd)*

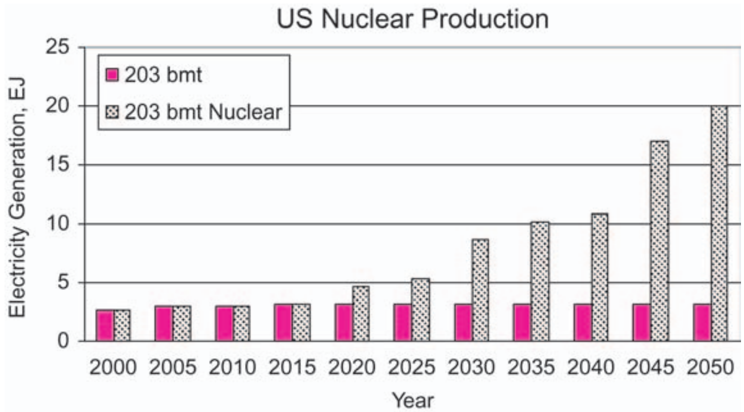
A striking aspect of the 203 bmt case is that biofuels enter in 2025 and 2030, then shrink in 2035 only to again take market share towards the end of the study period. This again is a result that comes from the tightening of the policy in developing countries, which reduces the oil price but increases the price of liquids from biofuels as developing countries use them to meet their CO_2 obligations. Biofuels are modelled 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 United States might indicate biofuel entry into the US 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 United States but the importance of considering international competition for biofuels, especially with strong CO_2 policies abroad. Some of the implications of expanded biofuel use are examined in Reilly and Paltsev (2007).

3.3. Nuclear power and carbon capture and storage

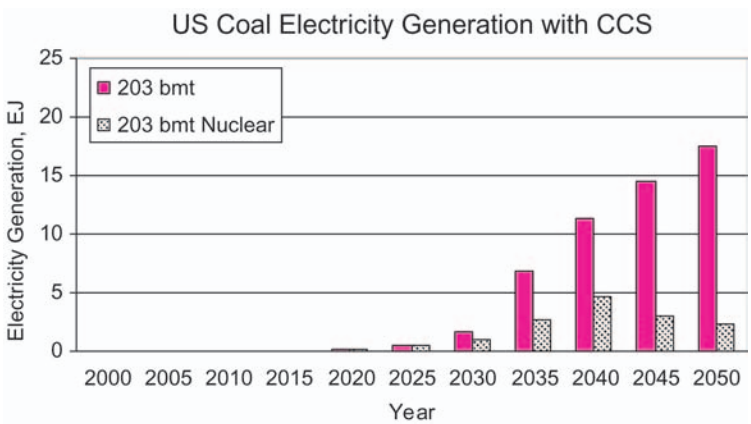
In the core cases we limited nuclear electricity generation to that possible with current capacity on the basis that safety and siting concerns would prevent additional construction. With strong greenhouse gas policy such concerns may be overcome, especially if other major technologies such as carbon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

Figure 5 shows the penetration of nuclear power and coal generation with and without CCS in the 203 bmt core case. The 25% markup on nuclear with a 20% markup on CCS is just about the level needed to make nuclear competitive with CCS given that CCS bears some cost associated with a fraction of CO_2 emissions that is not captured plus the effects of changes in fuel and other prices simulated in the model. With the removal of non-economic limitations nuclear penetrates

Panel a. Nuclear generation



Panel b. Coal generation with CCS



Panel c. Coal generation without CCS

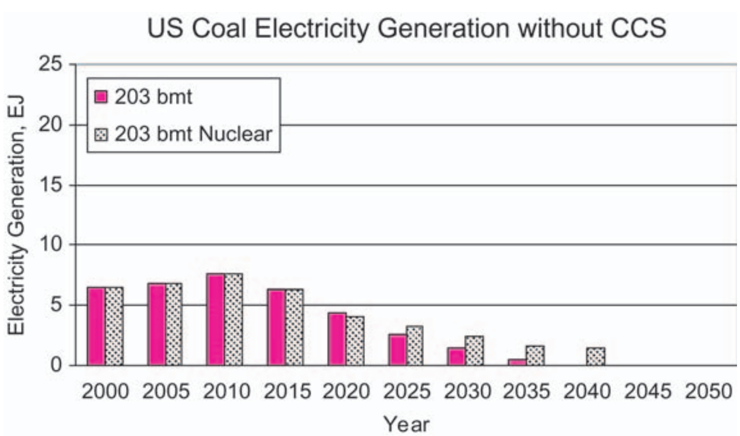


FIGURE 5 US electricity generation in the expanded nuclear case and the core 203 bmt case

strongly beginning in 2020, reaching 20 Exajoules (EJ) by 2050, over six times current production (Panel a, Figure 5). The fate of CCS is the mirror image. With nuclear limited, it 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. Without CCS coal generation disappears in either case.

These relatively detailed results help to illustrate the scale of effort required to meet the policy targets in the three core cases. There are just over 100 nuclear reactors in the United States 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 is 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.

4. Century-scale emissions and climate results

The target 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 the 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 the response of the climate system to projected emissions 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 US 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. The first is an extension of the Reference emissions forecast applied above 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 United States, Europe, Japan, Canada, Australia and New Zealand are 50% below 1990 levels in 2050; all other countries are at their 2000 levels. In the 167 bmt case the United States is 80% below 1990 levels and in the 287 bmt case US emissions are held at 2008 levels.) To examine the climate implications of global versus partial participation as well as the timing of developing countries 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 US 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 atmospheric stabilization are cumulative emissions over the study period. Modelling more realistic time paths of emission reductions for the developing countries with the same level of cumulative emissions over the century would not lead to appreciably different results. Similarly, since we are not focusing on abatement costs 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, a policy to manage the target gases affects these other greenhouse substances as well. Emissions of these substances projected by EPPA, 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 reported here.

As shown in Figure 6, the CO_2 concentrations reach 880 ppmv by 2100 in the Reference case, 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 United States at 167 bmt, is not sufficient to meet a 450 ppmv target: by 2050 concentrations are already at 460 ppmv.

Not shown on the figure, the 450 ppmv CO_2 goal is only achievable if all developing countries (including China and India) achieve reductions from their reference emissions similar to those in the United States in the 167 bmt or 203 bmt cases. Considering the current state of climate policy negotiations, this seems an unlikely outcome. Some policy discussions have been framed in terms of stabilization of CO_2-equivalent of all GHG gases. The 450 CO_2 target, considering the additional radiative forcing from other greenhouse gases, is equivalent to 523 CO_2-e target (Paltsev et al., 2007).

The three different US policy scenarios yield relatively small variation in the global CO_2 concentration if other regions do not follow the US lead. This result further highlights the need for significant international participation. The expectation of those supporting a tighter target in the United States may well be that US effort would lead other developed countries along

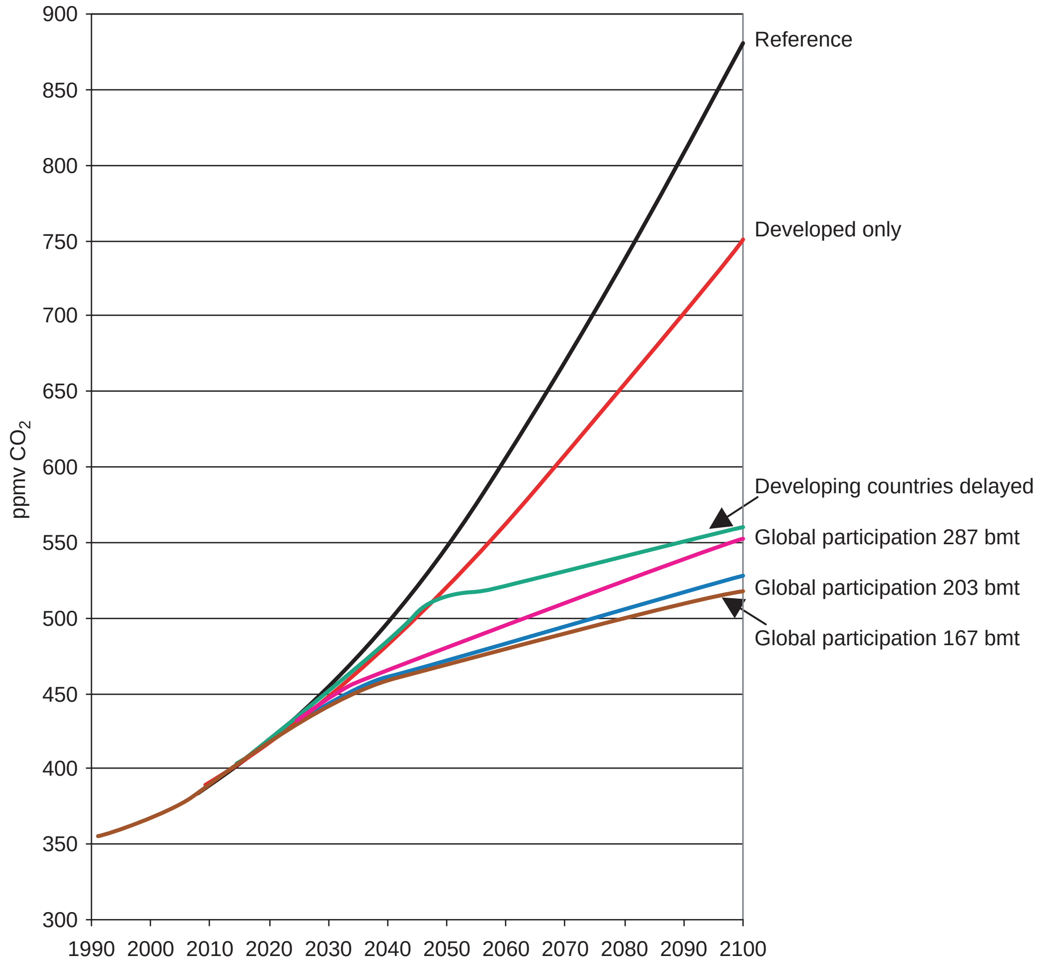
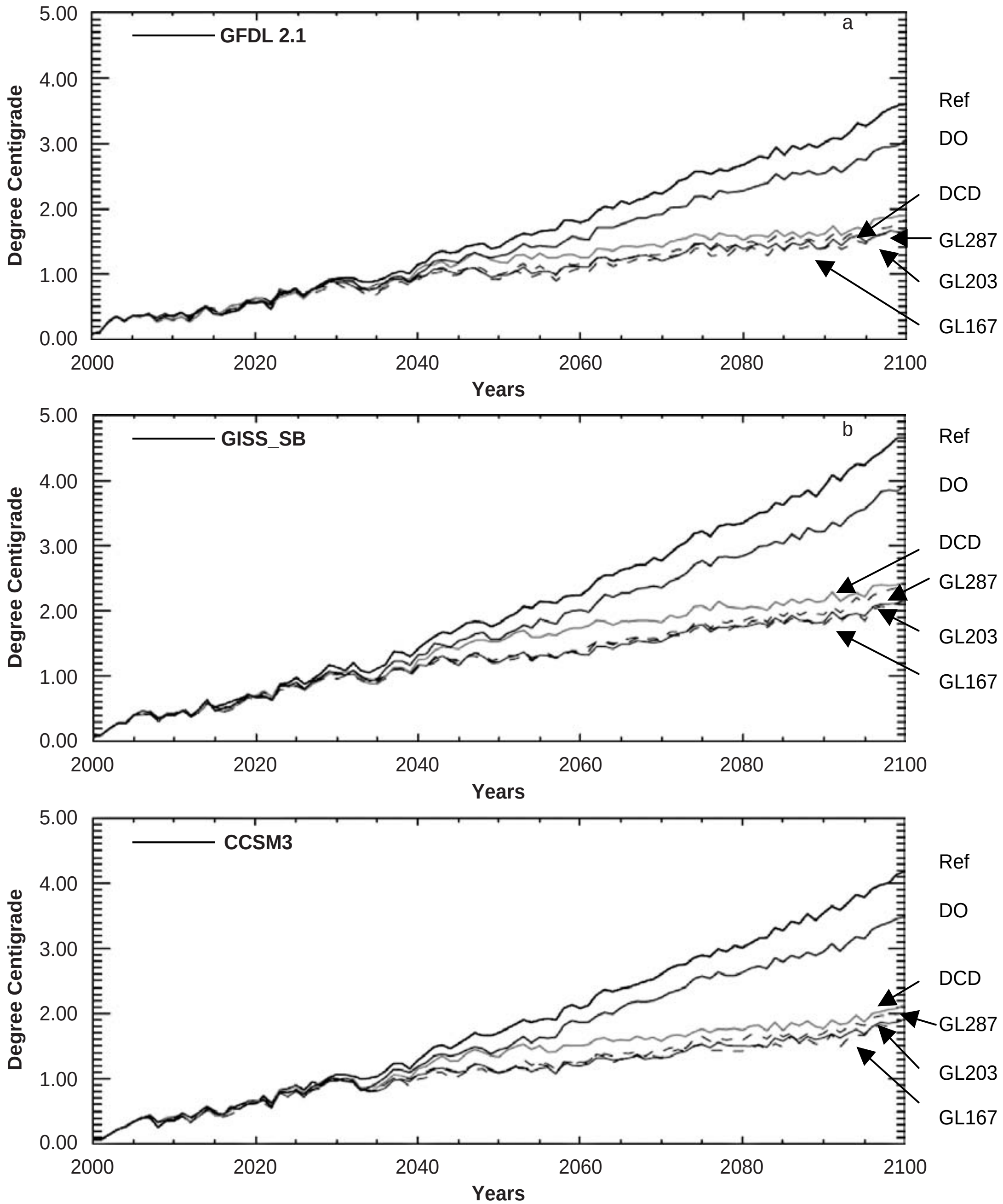


FIGURE 6 CO_2 concentrations in six scenarios using MIT IGSM; see text for details

a similarly stringent path, and perhaps accelerate mitigation efforts in the developing countries. It is noteworthy that 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 United States 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 assume to occur abroad drive the climate results more than the differences among the three US policy scenarios modelled here.

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.



Ref – Reference (solid line)
DO – Developed only (solid line)
DCD – Developing countries delayed (solid line)
GL287 – Global participation, 287 bmt (dashed line)
GL203 – Global participation, 203 bmt (solid line)
GL167 – Global participation, 167 bmt (dashed line)

FIGURE 7 Global mean surface temperature increase in six scenarios using MIT IGSM

Turning to the climate effects of these scenarios, Figure 7 shows the increase in the global mean surface temperature from 2000 for our replication of the three US GCMs. In the Reference scenario 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 1.7–2.4°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 0.5–1.2°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 US policy scenarios are relatively small, and thus a primary motivation for the US 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 strong measures in developed countries 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 two to three times what we have seen over the last century if these AO GCMs reasonably represent the response of the earth system to increasing GHG 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.

5. Conclusions

A wide range of proposals have been put forward in the US Congress that would impose mandatory controls on US greenhouse gas emissions, yielding substantial reductions in US GHG 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 banking.

With their objective of substantially cutting US emissions between now and 2050, these proposals would be likely to generate prices in the range of $30–55 per ton of CO_2-e in 2015, rising to the range of $120 to over $200 by 2050. Economic welfare losses from these mitigation policies are estimated to range between 1.5 and just under 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. Banking also depends critically on expectations about future technology, and the market may assess those prospects very differently than the way 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. Because of the long-lived nature of greenhouse gases and the moderating influence of the ocean, however, 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.

The purpose of US 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 3.5–4.5°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 US climate modelling centres. 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 United States and other developed countries pursue stringent policies.

While it is useful to evaluate the global costs and benefits of achieving such targets from the perspective of an individual country, even one as large as the United States, the benefits of abatement depend critically on whether or not other countries follow along. If a cooperative solution is at all possible, therefore, a major strategic consideration in setting US 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 GHGs. While these issues are beyond the scope of this analysis consideration of them is essential in determining the best policy for the US. Our hope is that the results of this analysis can contribute to that discussion.

Notes

1. For a discussion of the history of cap-and-trade systems in the US and analysis of their application to CO_2 see Ellerman et al. (2003). A previous US 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. Sensitivity analysis regarding the assumptions made for the 'core' cases can be found in Paltsev et al. (2007).
3. Tax and quantity instruments have different properties in terms of economic cost and effectiveness under uncertainty, but the scenarios analysed 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.
4. As the proposals become ever more stringent toward 2050 and costs are rising over time, the tendency is to bank emissions permits rather than to borrow them, but it should be noted that borrowing is an important component of a climate policy design as it provides additional flexibility to smooth over time potential short-time shocks to abatement costs.

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