ISSUE BRIEF 2

U.S. CLIMATE MITIGATION IN THE CONTEXT OF GLOBAL STABILIZATION

RICHARD G. NEWELL AND DANIEL S. HALL

U.S. CLIMATE MITIGATION IN THE CONTEXT OF GLOBAL STABILIZATION

Richard G. Newell
and Daniel S. Hall

SUMMARY

This issue brief examines recent studies of long-term scenarios for stabilizing atmospheric concentrations of greenhouse gases (GHGs) to understand whether and how near-term U.S. climate policy can translate into environmentally significant climate outcomes. Specifically, the focus is on modeling analyses that have attempted to quantify the emissions reductions necessary to achieve a defined set of stabilization targets. The scenarios analyzed include information on the path of emissions reductions, changes in technology, and prices for emissions needed to reach different stabilization levels. As such, they provide insight on the near-term actions—particularly with regard to carbon prices and technology developments—that would be consistent with achieving long-term environmental objectives.

The broad picture given by the model scenarios can help inform near-term policy. Although the models differ in their details, several messages emerge.

- Given current estimates of the relationship between GHG concentrations and global temperature change, stabilizing atmospheric concentrations of carbon dioxide (CO_2) at 450–650 parts per million (ppm) by volume significantly reduces the expected change in global average surface temperature and associated impacts relative to baseline projections for increased GHG concentrations.

- Most modeling scenarios for cost-effectively achieving a 550 ppm CO_2 (670 ppm CO_2-e[1]) stabilization target show U.S. and global emissions leveling off over the next several decades, with a slight initial rise in emissions that peaks by 2020–2040, and a declining trajectory thereafter. Stabilizing at lower concentration levels would require that emissions start declining sooner; while a less protective (higher concentration) target would allow for a longer period of continued emissions growth and/or slower decline.

- To cost-effectively stabilize atmospheric CO_2 at about 550 ppm, most models require that global carbon prices rise to \$5–\$30 per metric ton of CO_2 in the next 20 years, increasing to \$20–\$90 per metric ton by 2050, and continuing to rise thereafter. These modeling scenarios assume an idealized, flexible, comprehensive, least-cost approach to reducing emissions. Costs could therefore be significantly higher in the context of real-world policy where countries set different levels and trends of policy stringency, do not cover all sectors, do not include all GHGs, or employ relatively costly policy instruments. For example, limiting mitigation to CO_2 (rather than all GHGs) could roughly double the CO_2 prices needed to achieve a given stabilization goal.

- The more stringent the stabilization target, the higher the CO_2 price required to achieve it and vice versa. Models suggest

1   CO_2 equivalence is a means of measuring the total concentration of all GHGs, not solely CO_2.

that the global carbon price levels needed for stabilization at 450 ppm CO_2 (530 ppm CO_2e) could be 3–14 times higher by 2050 than the price levels needed to stabilize at 550 ppm, assuming emissions reductions are implemented cost-effectively. Likewise, a less stringent 650 ppm CO_2 (830 ppm CO_2e) target could be achieved with CO_2 prices that are 50–75 percent lower than the prices modeled for a 550 ppm target, since considerably less action would be required relative to baseline expectations.

- Although the models show differing degrees of utilization for different technology strategies, all of them indicate that achieving the requisite emissions abatement will necessitate reductions in both overall energy use (through efficiency and conservation) and in the carbon intensity of remaining energy use (through greater reliance on low- or non-carbon resources such as nuclear power, fossil-fuel systems with carbon capture and storage, and renewable electricity and biofuels). Scenarios that assume higher rates of baseline economic growth require pushing harder on each of these technological fronts to achieve a given stabilization goal, with commensurately higher emissions prices.

- Concerted global action including all large emitters will be required in the medium and long term to cost-effectively stabilize atmospheric GHG concentrations. Nonetheless, delaying reductions by developing countries in the near term would not significantly impede the prospects for CO_2 stabilization at levels of about 550 ppm or higher. However, if the stabilization target is close to current levels (450 ppm) flexibility is considerably reduced, and early participation by developing countries becomes essential if much higher costs are to be avoided.

Background on Modeling Efforts

This issue brief focuses on results from two modeling exercises: an analysis of stabilization scenarios developed for the federal government's inter-agency Climate Change Science Program (CCSP) and the Stanford Energy Modeling Forum's EMF-21 study. Although both modeling efforts incorporated non-CO_2 GHGs and included non-CO_2 emissions reductions in their scenarios, we confine the discussion that follows to CO_2 emissions. In all scenarios, CO_2 remains the largest contributor among the GHGs. Further, because it is closely tied to fossil-fuel use, focusing on CO_2 provides insight into how the energy sector might change to achieve alternative stabilization targets.

CCSP Modeling Scenarios

The CCSP study[2] examines different scenarios for stabilizing long-term atmospheric concentrations of the major GHGs: CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6).[3] Computer-based tools known as integrated assessment models were used to examine the GHG emissions trajectories that would be consistent with various stabilization targets and to explore the implications of those emissions trajectories for energy systems globally and in the United States. Working independently, three modeling groups (IGSM, MERGE, and MiniCAM[4]) produced results for the project, providing a range of estimates for emissions trajectories that would achieve different stabilization targets. All modeling teams explored scenarios in which long-term atmospheric GHG concentrations are constrained to the same levels, but the pathways taken to deliver these outcomes vary in terms of the timing and magnitude of emissions reductions, the trajectory of CO_2 prices, and the extent to which various energy technologies are used.

Each modeling team independently produced a baseline scenario representing a world in which there is no climate policy after 2012. They also produced four policy scenarios consistent with achieving four different environmental outcomes. These outcomes were defined in terms of long-term changes in the radiative forcing of the atmosphere[5] relative to pre-industrial times, but they were chosen to be approximately consistent with stabilizing CO_2 concentrations at 450, 550, 650, and 750 ppm by volume.[6] (Taking into account all GHGs based on their CO_2-equivalent contribution to radiative forcing, the corresponding stabilization targets are approximately 530, 670, 830, and 980 ppm CO_2e.[7]) For the policy scenarios, the modeling teams assumed there would be coordinated global action to reduce GHG emissions after 2012, implemented through the imposition of a common global price for GHG emissions. Conceptually, the emissions price can be thought of as arising from a GHG tax, a market-

2 See Clarke, L., J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, and R. Richels. 2006. *Synthesis and Assessment Product 2.1, Part A: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations.* Draft for CCSP Review, December 6, 2006. Our figures are based on the accompanying database of scenario results from November 8, 2006, found at http://www.sc.doe.gov/ober/CPDAC/database_scenarios_information.xls.
3 These are the six GHGs identified in Annex A of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC).
4 The three models are the Integrated Global Systems Model (IGSM) of the Massachusetts Institute of Technology's Joint Program on the Science and Policy of Global Change; the Model for Evaluating the Regional and Global Effects (MERGE) of GHG reduction policies developed jointly at Stanford University and the Electric Power Research Institute; and the MiniCAM Model of the Joint Global Change Research Institute, which is a partnership between the Pacific Northwest National Laboratory and the University of Maryland.
5 Radiative forcing is a measure of the warming effect of the atmosphere; it is typically expressed in watts per square meter.
6 Predicted long-term concentrations of CO_2 varied slightly across the models because the actual long-term stabilization targets used for the analysis were expressed as the additional radiative forcing (or warming effect) from all GHGs—specifically 3.4, 4.7, 5.8, and 6.7 watts per square meter. Since the model outputs for different scenarios showed varying concentrations of non-CO_2 GHGs, final CO_2 concentrations varied slightly around these approximate stabilization targets.
7 We used the following relationship, as published in the IPCC Third Assessment Report, to express radiative forcing (r) in CO_2-equivalent terms: $CO_2e = 280 \exp (r/5.35)$.

based cap-and-trade system, or other policy that imposes a uniform cost per unit of GHG emissions. Results are available for 10-year time steps from 2000 to 2100.

The models used in the CCSP study had several common characteristics: all were global in scale, represented multiple geographic regions, could produce emissions trajectories and totals for the major GHGs, incorporated technology in sufficient detail to report which sources of primary energy were being used, were economics-based and thus could simulate the macroeconomic costs of stabilization, and looked forward until at least the end of the 21st century. The models also all used a least-cost approach to reducing emissions. This least-cost assumption is sometimes referred to as *where*, *when*, and *what* flexibility. That is, reductions are taken in all locations (*where*), during the entire time period (*when*), and across all GHGs (*what*) such that the total cost of achieving the target is minimized. This flexibility lowers the overall cost of stabilization by equalizing the marginal costs of mitigation across space, time, and type of GHG. In practice, however, the ability to implement policies that achieve least-cost reductions on a global scale may be compromised, for reasons discussed in the final section.

EMF-21 Modeling Scenarios

The EMF-21 modeling project[8] was similar to the CCSP scenario analysis but included many more models. Nineteen modeling teams, including the three CCSP teams, evaluated atmospheric stabilization under two strategies: a CO_2-only mitigation strategy, and a multi-gas mitigation strategy (where the multi-gas strategy included the other major GHGs). The radiative forcing target selected for this project was close to that of the second CCSP policy scenario, so the multi-gas strategy results are comparable to stabilization at 550 ppm CO_2 (650 CO_2e).[9] EMF-21 modeling teams produced a baseline scenario and a policy scenario that achieved long-term stabilization. As in the CCSP scenarios, the participating EMF-21 models assumed global participation and *where-when-what* flexibility in terms of implementing least-cost emissions reductions, although they differed in the exact approach used to model this flexibility. Results are available for 25-year time steps from 2000 to 2100.

550 ppm CO_2 Stabilization Scenarios

In the next five sections, we discuss results from the CCSP and EMF-21 modeling analyses for a long-term stabilization target of approximately 550 ppm CO_2 (670 ppm CO_2e). We focus on

8 See Multi-Greenhouse Gas Mitigation and Climate Policy, F. C. de la Chesnaye, and J. P. Weyant, eds. *The Energy Journal,* Special Issue (2006).
9 As with CCSP, the actual target was expressed in terms of increased radiative forcing relative to pre-industrial times—specifically, 4.5 watts per square meter.

Scenarios that model a 550 ppm CO_2 stabilization target typically show U.S. (and global) emissions leveling off over the next several decades—with a slight initial rise in emissions that peaks by 2020–2040, and declining emissions thereafter.
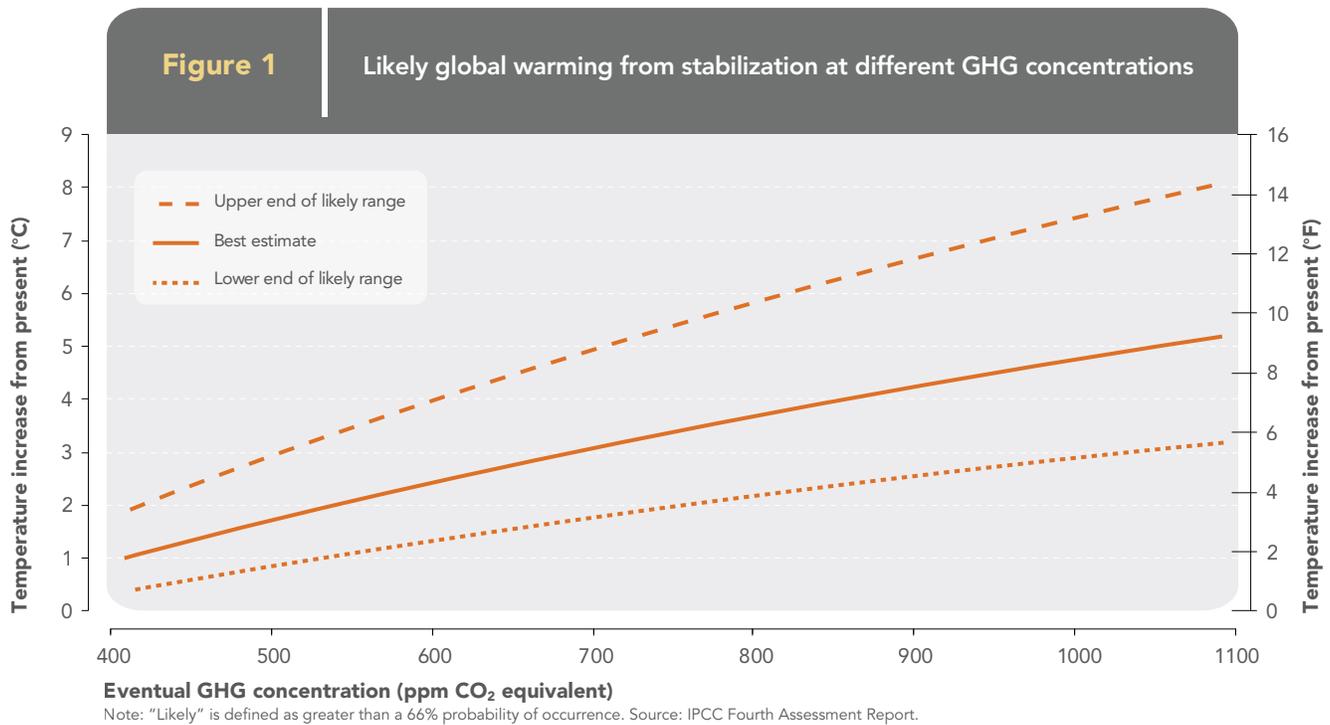
the 550 ppm CO_2 target level because it has received much attention in the literature. Any stabilization target, or indeed even the choice of an ultimate objective for climate policy—be it based on atmospheric GHG concentrations, emissions price, risk management, technology development, or some other objective—is ultimately a sociopolitical decision.

There are several reasons we focus our discussion on CO_2. First, it is the most important GHG: as a result, no model achieves stabilization without reducing CO_2 emissions. Second, the strong link between CO_2 and energy use implies that any effective climate policy must produce fundamental changes to the energy system. Finally, the modeling results we use provide technological detail about the character of CO_2 reductions that is not present for the non-CO_2 gases. For example, the models report whether CO_2 reductions are achieved through expanded use of nuclear power or from carbon capture and storage, but they do not report whether methane reductions come from landfills or pig farms.

Nonetheless, it is worth noting that the role of the non-CO_2 GHGs, while smaller, is important in these models. In the CCSP modeling, for example, non-CO_2 gases make up 25–30 percent of the total baseline radiative forcing in 2050, while reductions in non-CO_2 gases by 2050 account for 20–40 percent of the overall change in radiative forcing needed to

Figure 1 — Likely global warming from stabilization at different GHG concentrations

Temperature increase from present (°C) / Temperature increase from present (°F)

- – – Upper end of likely range
- —— Best estimate
- ⋯⋯ Lower end of likely range

Eventual GHG concentration (ppm CO_2 equivalent)

Note: "Likely" is defined as greater than a 66% probability of occurrence. Source: IPCC Fourth Assessment Report.

limit warming to a level consistent with stabilization at 550 ppm CO_2. We discuss the importance of other GHGs in the context of cost-effective stabilization further in the final section.

We also focus on results up until mid-century. A 2050 timeframe is near enough to provide some confidence that the model outputs are realistic, yet sufficiently long term to be informative and relevant for exploring how near-term policy and technology decisions could influence the achievement of long-term goals.[10] Modeled projections of carbon prices, emissions trajectories, and energy and technology developments can provide useful insight into the policy interventions that could be necessary to achieve different stabilization paths.

In the final section, we explore other mitigation scenarios. How do results change if a different stabilization target is chosen? If actual policies as implemented do not resemble the least-cost approach used for modeling, how might costs change? What if the technological options are broader or more constrained than assumed?

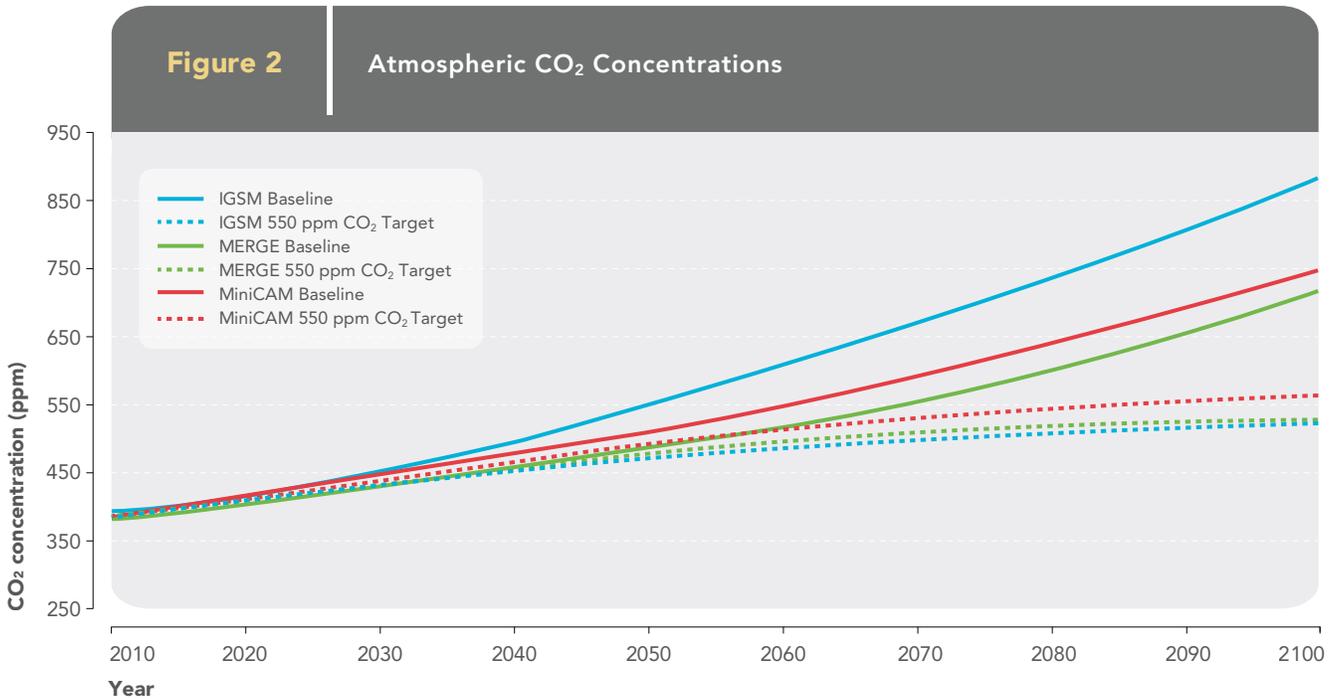## Atmospheric Concentrations and Temperature Change

The pre-industrial concentration of CO_2 in the atmosphere was 280 ppm; the current level is 380 ppm CO_2. Other major GHGs contribute approximately 70 ppm CO_2e to present GHG concentrations, bringing existing concentrations of the six main GHGs in the atmosphere to about 450 ppm CO_2e. Other anthropogenic activities (including aerosol emissions and land-use changes) have a net cooling effect (negative radiative forcing) such that the current net forcing effect from anthropogenic sources is approximately equal to 380 ppm CO_2e.[11] About 2–3 ppm CO_2e are currently added to the atmosphere each year, and this amount has been growing. The temperature response to a change in atmospheric GHG concentrations is called climate sensitivity. The recently released Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[12] states,

> The equilibrium climate sensitivity is a measure of the climate system response to sustained radiative forcing. It is not a projection but is defined as the

11 See Figure SPM.2 (p. 4) of IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Summary for Policymakers.* Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva: IPCC.
12 Ibid., p. 12.

10 Issue Brief #3, focusing only on economic impacts, only looks out to 2030 where there is greater confidence in those estimated impacts.

Figure 2 Atmospheric CO_2 Concentrations

Legend:
- IGSM Baseline
- IGSM 550 ppm CO_2 Target
- MERGE Baseline
- MERGE 550 ppm CO_2 Target
- MiniCAM Baseline
- MiniCAM 550 ppm CO_2 Target

Y-axis: CO_2 concentration (ppm)
X-axis: Year

global average surface warming following a doubling of carbon dioxide concentrations. It is *likely* to be in the range 2 to 4.5°C with a best estimate of about 3°C, and is very *unlikely* to be less than 1.5°C.[13]

Figure 1 shows the range of long-term warming (in degrees Celsius and Fahrenheit) that would be expected at different GHG stabilization levels based on the IPCC's current estimate of likely climate sensitivity. Changes in global average surface temperature are relative to present conditions; thus, the range of warming impacts shown is additional to the approximately 0.8°C (1.4°F) of warming that is estimated to have already occurred relative to pre-industrial conditions.

Figure 2 shows baseline CCSP projections for atmospheric CO_2 concentrations, along with concentrations for scenarios that achieve stabilization at about 550 ppm CO_2. It also shows that baseline projections from the CCSP reach atmospheric concentrations of 710–880 ppm CO_2 (930–1390 ppm CO_2e) by 2100, depending on the model. Moreover, because the baseline case assumes no effort to achieve stabilization, concentrations would continue rising beyond 2100 in these

scenarios. Looking back to Figure 1, a concentration of 900 ppm CO_2e would likely produce an eventual temperature increase of about 2.5°–7°C (5°–12°F). At 1100 ppm CO_2e, the likely temperature increase would be about 3°–8°C (6°–14.5°F), relative to current temperatures. Warming would continue beyond these ranges in the baseline scenarios until stabilization is achieved. Stabilization around 550 ppm CO_2 (670 ppm CO_2e) would likely result in 2°–5 °C (3°–9°F) of warming, with a best estimate of 3°C (5.5°F).

U.S. CO_2 Reductions

Scenarios that model a 550 ppm CO_2 stabilization target typically show U.S. (and global) emissions leveling off over the next several decades—with a slight initial rise in emissions that peaks by 2020–2040, and declining emissions thereafter (Figures 3 and 4). The three CCSP models follow this pattern, with projected emissions in the MERGE model peaking higher and earlier and emissions in the other two models being relatively flat (the IGSM emissions path falls slightly, then rises slightly, then falls slightly again but essentially remains constant). Also note the significant divergence in projected baseline emissions—we return to this point below. There is a wider spread of trajectories among the 16 models in the EMF-21 study. Figure 4 shows that the median EMF-21 result

13 "Likely" is defined in the IPCC report (p. 4) as corresponding to a greater than 66 percent probability of occurrence, while "very unlikely" corresponds to a less than 10 percent probability of occurrence.
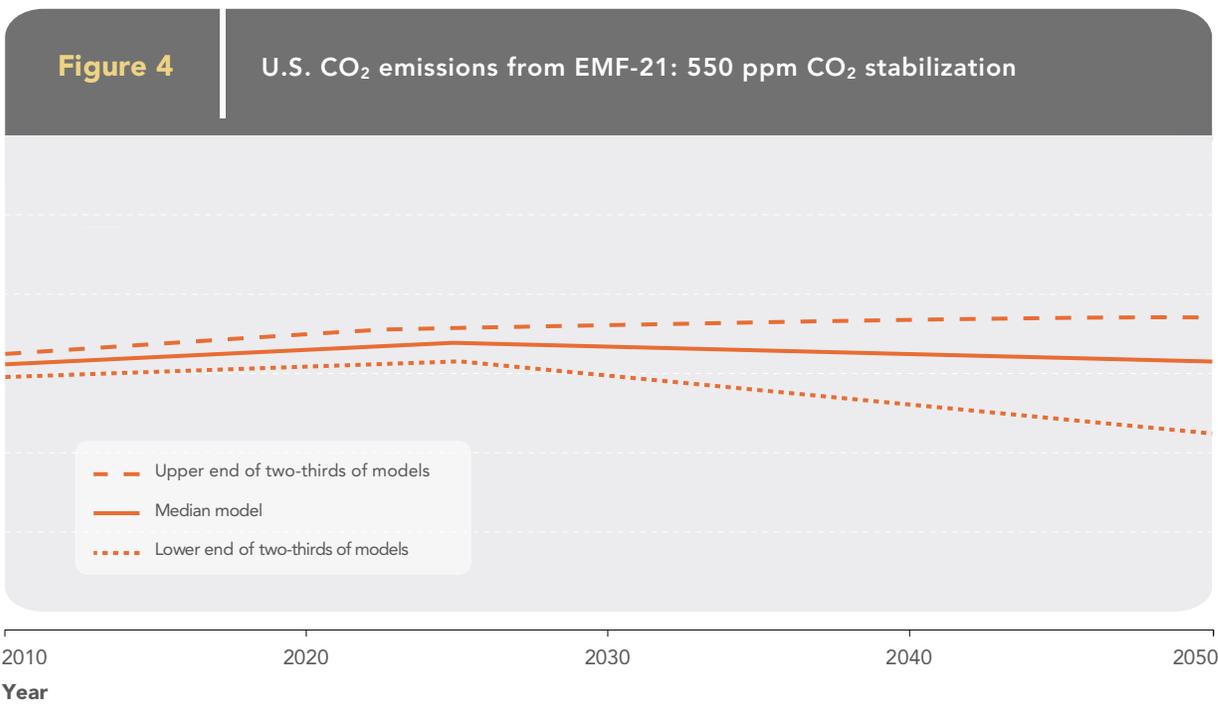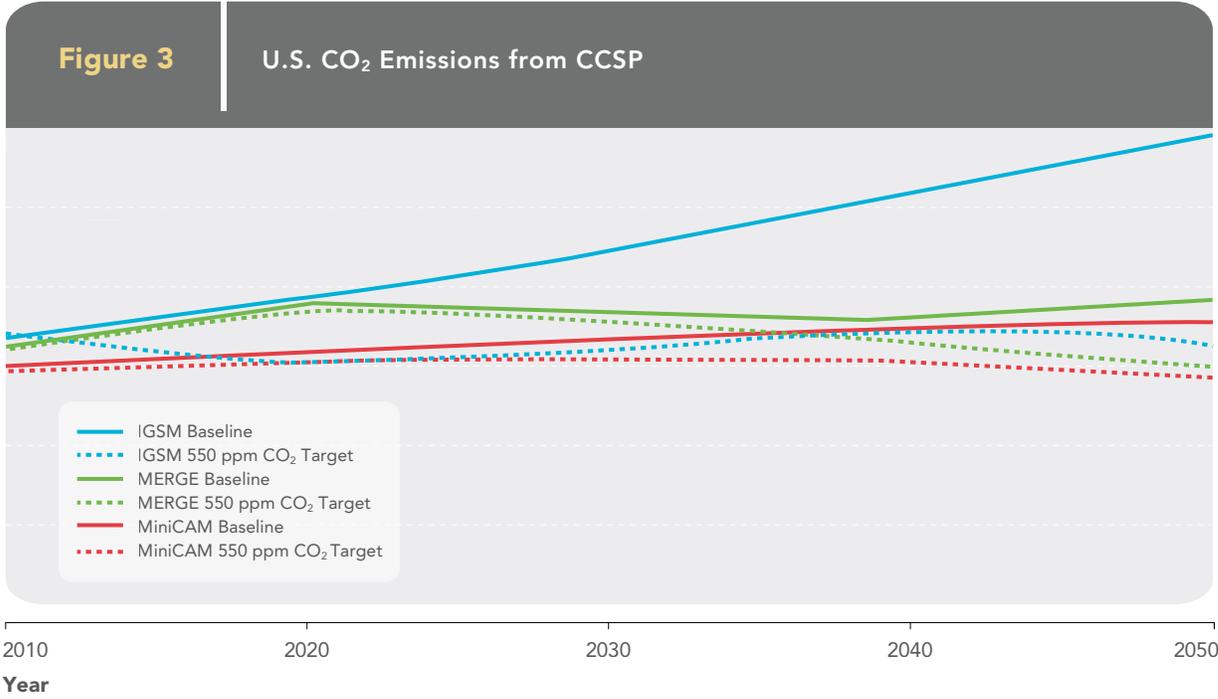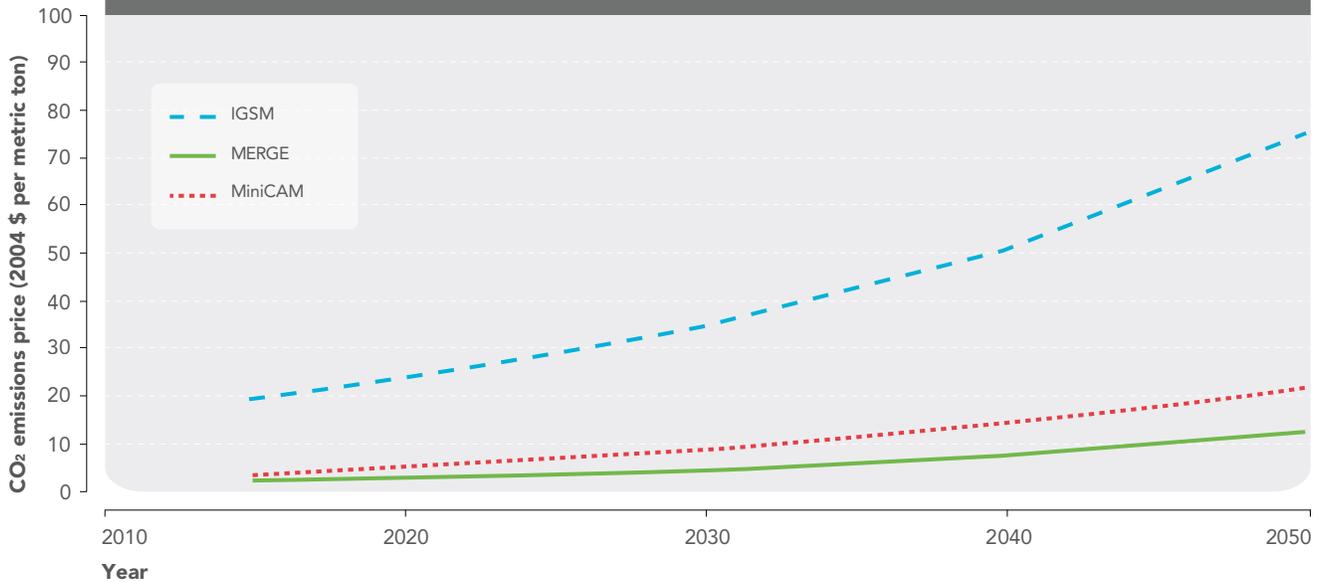
Figure 3 | U.S. CO$_2$ Emissions from CCSP

Billion metric tons of CO$_2$ per year

- IGSM Baseline
- IGSM 550 ppm CO$_2$ Target
- MERGE Baseline
- MERGE 550 ppm CO$_2$ Target
- MiniCAM Baseline
- MiniCAM 550 ppm CO$_2$ Target

Year

Figure 4 | U.S. CO$_2$ emissions from EMF-21: 550 ppm CO$_2$ stabilization

Billion metric tons of CO$_2$ per year

- Upper end of two-thirds of models
- Median model
- Lower end of two-thirds of models

Year

Figure 5 — CO$_2$ emissions price from CCSP: 550 ppm CO$_2$ stabilization

has U.S. emissions rising slowly for the next two decades and falling slowly thereafter to achieve the 550 ppm CO$_2$ target. The figure also shows U.S. emissions trajectories for the upper and lower ends of two-thirds of the EMF-21 modeling results (the top line omits the 17% of results that show higher emissions, while the bottom line omits the lower 17% of model results, for a total of one-third).

Prices for CO$_2$ Emissions

Most model projections for stabilizing CO$_2$ show CO$_2$ prices rising gradually through mid-century and beyond. To achieve stabilization at about 550 ppm, most models project that CO$_2$ prices will need to rise to $5–$30 per metric ton by 2025, increasing to $20–$90 per metric ton by 2050, and continuing to rise thereafter. However, a few models predict prices outside these ranges for cost-effective stabilization at 550 ppm CO$_2$ (see Figures 5 and 6 below).[14]

Shifts in Energy Technologies

Here we describe the changes in energy technology projected to be necessary, based on the CCSP results, to achieve CO$_2$

stabilization at 550 ppm. Model projections include changes in both the type and amount of fuels used and the energy technologies deployed. The stabilization scenarios show a trend toward lower overall energy use, reduced use of fossil fuels, and increased use of renewable electricity and biofuels, nuclear energy, and fossil-fuel-based electricity production with carbon capture and storage. Figure 7 summarizes projected changes in U.S. primary energy use in 2050. Changes are shown for a 550 ppm CO$_2$ climate policy relative to baseline projections across all major energy technologies in both absolute and percentage terms (for example, according to the IGSM results, commercial biomass production in 2050 is 250 percent higher in the stabilization case than in the baseline forecast).

One of the major changes projected in the 550 ppm stabilization scenarios is a downward shift in total energy use relative to the baseline.[15] The models project that overall energy consumption will be approximately 5–20 percent lower under a climate policy designed to achieve stabilization at 550 ppm, with larger reductions anticipated from models (such as IGSM) that project higher baseline energy use (see Figure

14 Note that the model with higher prices in Figure 5, IGSM, is also the model with the highest baseline emission level in Figure 3. The consistency of this relationship is discussed in Issue Brief #3 concerning mitigation costs.

15 This shift is depicted on the positive side of the ledger in Figure 7, where it is reported as an "energy reduction." The rationale is that reductions in the use of carbon-intensive energy sources must be matched by increased use of lower-carbon technologies, reduced energy use, or some combination of both.

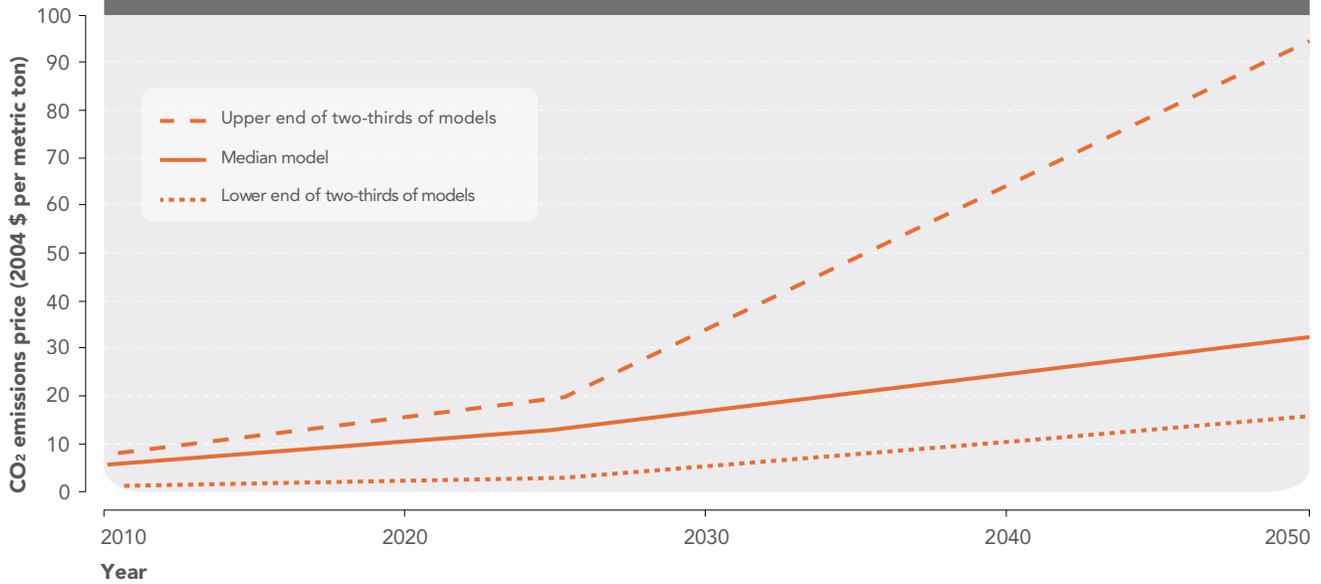## Figure 6 — CO₂ emissions price from EMF-21: 550 ppm CO₂ stabilization
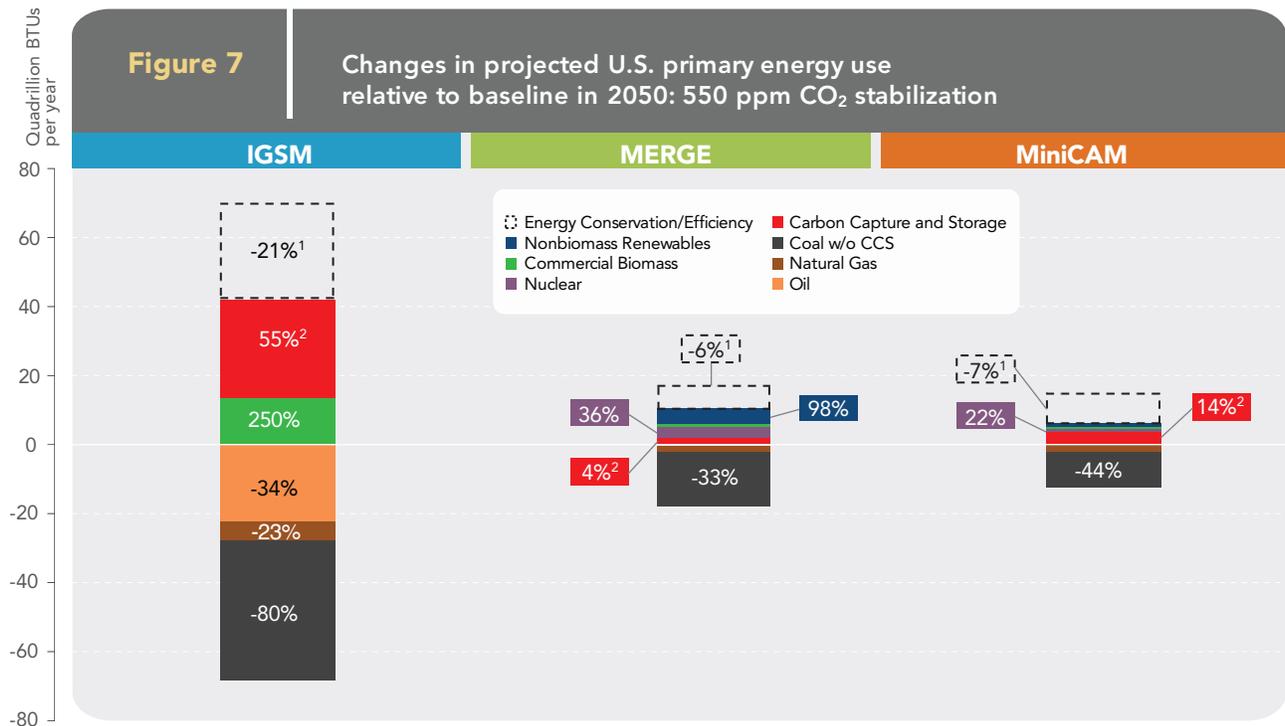

Figure 7 — Changes in projected U.S. primary energy use relative to baseline in 2050: 550 ppm CO₂ stabilization

Percentage changes are relative to baseline projections for each technology, except as noted.

[1] Percentage change in total primary energy use relative to baseline projection.   [2] Percentage increase in CCS relative to projected total coal use in baseline scenario.

4). Baseline projections of energy use are primarily driven by assumptions about economic growth. For example, the IGSM model assumes an average annual GDP growth rate of about 2.7 percent from 2010 to 2050, while MERGE and MiniCAM assume growth rates of 1.6–1.7 percent per year. The IGSM baseline projection for U.S. GDP in 2050 is therefore about 50 percent higher than the MERGE or MiniCAM projection.

Stabilization also implies significant changes to the remaining energy mix. Conventional coal use in the United States is significantly lower under the 550 ppm stabilization scenario than in the baseline in all three CCSP models. Note that the projected reduction in total coal use (both with and without carbon capture and storage) is similar across the three models—around 25–30 percent or 10–15 quadrillion Btus (quads), relative to baseline projections. All models shift some of this coal into plants with carbon capture and storage. The IGSM model projects the largest shift, with a major drop in conventional coal use and a large increase in carbon capture and storage. Specifically, the IGSM projection for 2050 shows the equivalent of about 800 coal-fired power plants using capture and storage, each with 500 megawatts (MW) net capacity (see Table 1). The other two models project much more modest increases in carbon capture and storage, equivalent to 50–100 new plants with this technology.

One of the major changes projected in the 550 ppm stabilization scenarios is a downward shift in total energy use relative to the baseline. The models project that overall energy consumption will be approximately 5–20 percent lower under a climate policy designed to achieve stabilization at 550 ppm.

Table 1	Number of facilities for each 1 quadrillion Btu (quads) per year of primary energy input (based on representative facility capacity)	
Type of facility	Facility capacity	Facilities per quad
Coal-fired power plant	500 megawatts	28
Natural gas base load power plant[1]	100 megawatts	142
Nuclear power plant	1,000 megawatts	12
Wind farm	100 megawatts	380
Ethanol plant	100 million gallons/year	150
Oil refinery	100,000 barrels/day	5

[1]Note that natural gas has many uses as a primary fuel apart from electricity generation

The MERGE and MiniCAM models project very little change in oil use, relative to the baseline, in the 550 ppm stabilization scenario, whereas the IGSM model shows a significant reduction in oil use (projected consumption is 33 percent below the baseline case, implying a reduction equal to about half of current U.S. oil use). There is significant substitution of biofuels for oil in the IGSM model: much of the "commercial biomass" reported in Figure 7 for IGSM consists of biomass-based liquid fuels for use in the transportation sector (i.e., biofuels). Assuming, for purposes of illustration, that the biofuels contribution is all ethanol, this implies a 30-fold increase in ethanol production from current levels, to more than 160 billion gallons per year.[16]

The MERGE and MiniCAM models project significant growth in electricity production using non-fossil technologies in the 550 ppm scenario, whereas IGSM does not. Specifically, both models project an increase in nuclear generation that equates to about 20–40 additional 1,000 MW nuclear power plants. MERGE also projects that electricity production from non-biomass renewable resources (e.g., wind, solar, geothermal) will double by 2050 under a 550 ppm stabilization policy, relative to the baseline forecast. The model does not make projections concerning the specific mix of renewable technologies used to supply this increase, but if wind generation is assumed to account for most of it, these results imply approximately 1,500 new wind sites at 100 MW capacity each.

Figure 7 presents primary energy consumption in quads per year. Table 1 below indicates how many facilities are implied by each additional quad of primary energy input, assuming

16 In reality, not all commercial biomass use will consist of biofuels and even the biofuels component will likely include a mix of fuels besides ethanol, such as biodiesel. Although the CCSP analysis does not provide a detailed breakdown of these results, this simple illustration provides some sense of the potential scale of biofuels production under a stabilization policy.
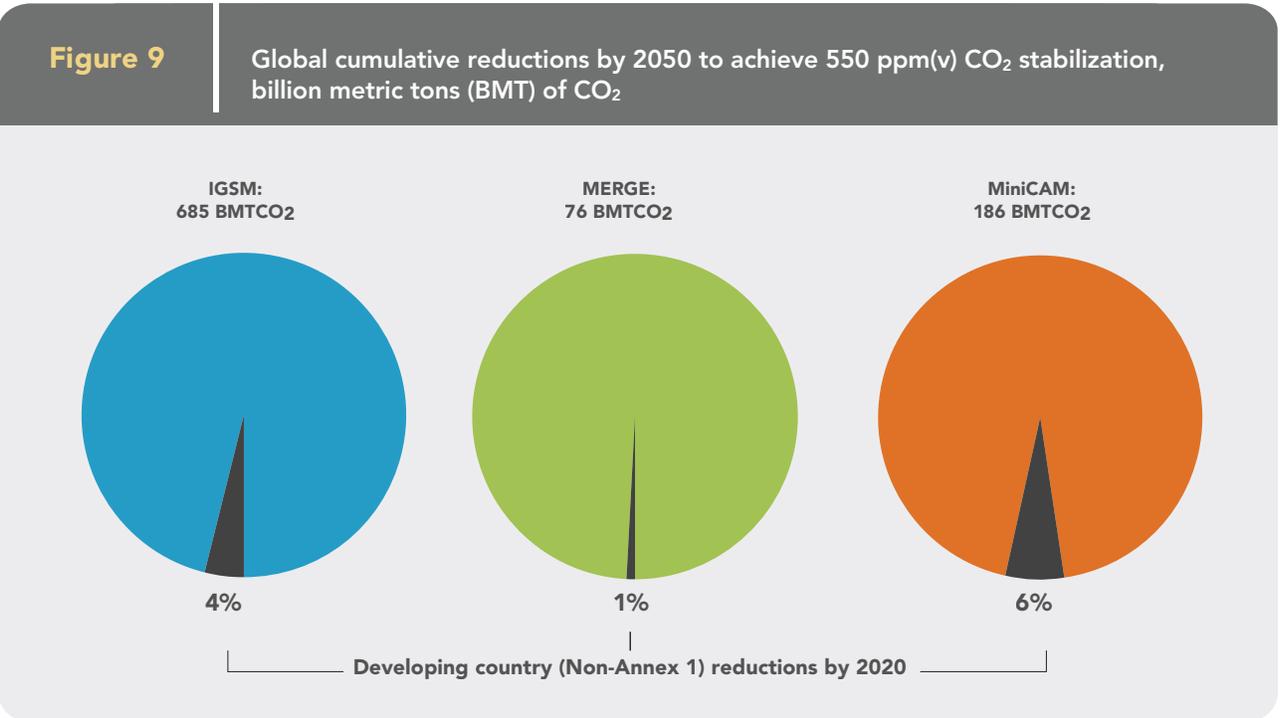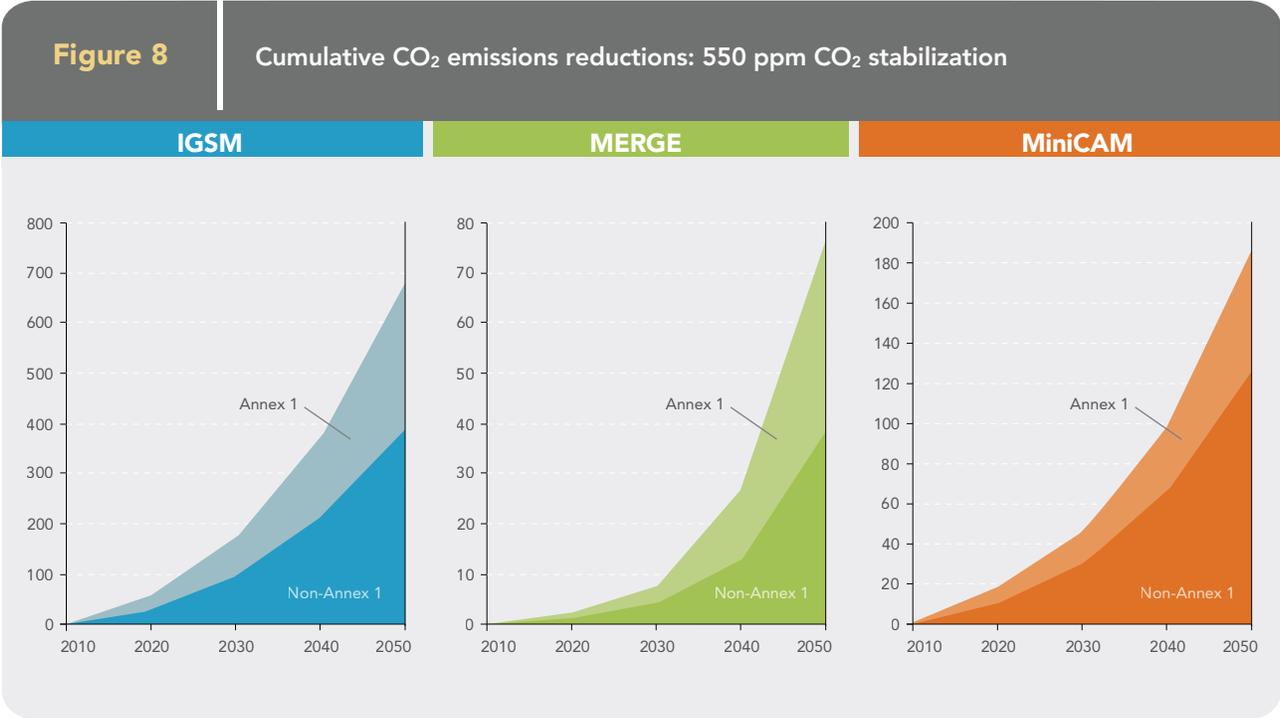
Figure 8 — Cumulative CO$_2$ emissions reductions: 550 ppm CO$_2$ stabilization

IGSM	MERGE	MiniCAM

Figure 9 — Global cumulative reductions by 2050 to achieve 550 ppm(v) CO$_2$ stabilization, billion metric tons (BMT) of CO$_2$

IGSM: 685 BMTCO2   MERGE: 76 BMTCO2   MiniCAM: 186 BMTCO2

4%   1%   6%

Developing country (Non-Annex 1) reductions by 2020

Table 2	Comparison of carbon prices under alternative modeling scenarios		
Modeling study	Scenario	Price in 2025 ($/metric ton CO_2)	Price in 2050 ($/metric ton CO_2)
CCSP[1]	450 CO_2 (530 CO_2e)	40-95	140-250
	550 CO_2 (670 CO_2e)	5-30	10-75
	650 CO_2 (830 CO_2e)	1-10	5-30
EMF-21[2]	All 6 GHGs	13 (3-20)	30 (15-95)
	CO_2 reductions only	26 (6-37)	55 (25-150)

1   Ranges shown are based on the results from three models.
2   Median results for the 550 ppm CO_2 (650 ppm CO_2e) case are shown with the upper and lower two-thirds of model results in parentheses.

representative facility sizes and capacity utilization factors.[17] For example, a 1-quad increase in the use of nuclear power translates into roughly 12 new 1,000-MW nuclear power plants. Values for coal-fired power plants apply to plants with carbon capture and storage if one interprets the facility capacity as net output, after accounting for the energy penalty associated with carbon capture. Finally, 1 quad of oil use per year equals about 0.47 million barrels of oil per day.

The Importance of Global Participation

The model scenarios described in this paper assume cost-effective global efforts to reduce GHG emissions starting in 2012, whereas—in reality—political constraints may delay action in some countries. Particular concern has been expressed that developing countries—the "non-Annex I" countries[18]—do not have commitments under the Kyoto Protocol. As shown in Figure 8, it is clear from the CCSP modeling that concerted global action including all large emitters will be required in the medium and long term to cost-effectively stabilize GHG concentrations (note also the wide range of required reductions, depending on estimated baseline emissions). In fact, emissions reductions (relative to baseline) in non-Annex I countries account for

17 The capacity utilization factor for a given plant or facility is the ratio of actual output to maximum rated output. The capacity factors assumed in Table 1 are as follows: 0.8 for coal, 0.8 for natural gas base-load, 0.9 for nuclear, 0.3 for wind, 0.8 for ethanol, and 0.9 for oil.
18 The term "Annex I" originates from the U.N. Framework Convention on Climate Change, which called for the countries listed in Annex I to take initial responsibility for limiting GHG emissions. Annex I is limited to the world's more developed countries, including Australia, Austria, Belarus, Belgium, Bulgaria, Canada, Croatia, Czech Republic, Denmark, European Economic Community, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Latvia, Liechtenstein, Lithuania, Luxembourg, Monaco, Netherlands, New Zealand, Norway, Poland, Portugal, Romania, Russian Federation, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, Ukraine, United Kingdom of Great Britain and Northern Ireland, and the United States of America. When the Kyoto Protocol was negotiated, all the countries that agreed to emissions reduction targets (listed in Annex B of the Protocol) were Annex I countries. The only Annex I countries that did not agree to targets were Belarus and Turkey. Two Annex I countries, the United States and Australia, agreed to targets but have not ratified the Protocol.

more than half of total reductions by 2050 under cost-effective stabilization. Results from the three models also indicate, however, that near-term reductions by non-Annex I countries—that is, reductions that occur by 2020—account for only 1–6 percent of the cumulative reductions needed through 2050 to achieve the 550 ppm CO_2 stabilization target (see Figure 9). This suggests that it would be feasible to make up for near-term delays in reducing emissions from some countries—as long as those countries eventually participate. Note also that there is a distinction between where reductions occur and *who pays* for those reductions.

Sensitivity of Results to Alternative Mitigation Scenarios

As discussed previously, these modeling exercises assume that emissions reductions are achieved in a least-cost manner. For a variety of reasons, however, the ability to achieve this ideal may be compromised. If mitigation efforts are not comprehensive, whether in terms of country participation or the GHGs and sectors covered, the cost of achieving a given stabilization target increases. Models also have to make assumptions about the availability of low-carbon alternatives and the pace of technology development in the future. If carbon-reducing technologies advance more quickly than modeled, the costs of mitigation will be lower; conversely, if technology advances more slowly, costs will be higher. This section briefly explores the sensitivity of the modeling results to different assumptions concerning the choice of stabilization targets, policy coverage, and technology availability.

First, the CCSP modeling also included, in addition to the 550 ppm CO_2 stabilization scenarios discussed earlier, scenarios that that achieved stabilization at around 450 ppm CO_2 (530 ppm CO_2e) and 650 ppm CO_2 (830 ppm CO_2e). In Table 2, we compare CO_2 prices in these scenarios to the results for the 550 ppm scenarios. Note that modeled CO_2 prices are 3–14 times higher in the 450 ppm scenarios than in the 550 ppm scenarios. By contrast, carbon prices are 50–75 percent lower in the less stringent 650 ppm scenarios. The EMF-21 modeling exercise compared the costs of a climate policy that included all six major GHGs, as discussed earlier, to the costs of a policy that achieved the same reductions in radiative forcing by reducing CO_2 emissions alone. The results provide insight on the value of flexibility in a multi-gas strategy. As shown in Table 2, the carbon prices needed to achieve stabilization at 550 ppm CO_2 in the EMF-21 scenarios roughly double if non-CO_2 gases are not included in the mitigation strategy.

Flexibility—in terms of where reductions take place, when reductions are taken, what gases are included, and which technologies are available for mitigation—is an important determinant of cost.

Other modeling studies have investigated scenarios that make different assumptions concerning technology development, policy effectiveness, and country participation. For example, the MERGE model was recently used to evaluate the costs of mitigation under scenarios in which there is not global participation and with alternative technology assumptions.[19] For the technology scenarios, researchers examined scenarios where nuclear power and carbon capture and storage were not available to mitigate GHG emissions in the future. They found that this would not have a large impact on CO_2 prices in the near term (over the next 20 years), but that medium- and long-term CO_2 prices would have to more than double to achieve stabilization if these technologies were unavailable.

The same study also examined the impacts of country participation and policy design by exploring scenarios in which non-Annex I countries do not participate in GHG mitigation efforts until 2050 while Annex I countries set annual reduction targets. In the parlance defined earlier, these alternative scenarios constrain *where* and *when* flexibility by confining reductions to developed (Annex I) countries and by imposing, in those countries, constant annual percent reduction targets that cannot be traded across time. Results from these scenarios suggest that if a relatively stringent stabilization target is chosen (equivalent to the 450 ppm CO_2 target from CCSP), the key to controlling costs is to include all countries in the policy. Achieving the more stringent target without the participation of non-Annex I countries

becomes much more expensive. On the other hand, delaying reductions from developing countries to 2050 had a smaller impact on the CO_2 prices if a less stringent stabilization target (equivalent to the 550 ppm CO_2 target from CCSP or EMF-21) was chosen. The primary driver of CO_2 prices in scenarios with less stringent stabilization targets was whether countries had binding annual reduction targets. Without flexibility to trade reductions across time, the near term prices necessary to achieve stabilization rose dramatically. This happens because the cost-effective profile of emissions reduction opportunities falls by an accelerating amount over time, rather than declining by a constant annual amount (note the curvature in Figure 8, reflecting an acceleration in reductions); this acceleration is particularly strong in the MERGE model.

More generally these studies show that flexibility—in terms of where reductions take place, when reductions are taken, what gases are included, and which technologies are available for mitigation—is an important determinant of cost.

19 Richels, R., T. Rutherford, G. Blanford, L. Clarke. 2007. *Managing the Transition to Climate Stabilization* Working Paper 07-01, AEI-Brookings Joint Center for Regulatory Studies.