Energy Security Initiative
at BROOKINGS

EMISSIONS TARGETS IN CAP-AND-TRADE:

CHOOSING REDUCTION GOALS COMPATIBLE WITH GLOBAL CLIMATE STABILIZATION

Bryan K. Mignone

SEPTEMBER 2009
Policy Brief 09-02

Energy Security Initiative
at BROOKINGS





EMISSIONS TARGETS IN CAP-AND-TRADE: CHOOSING REDUCTION GOALS COMPATIBLE WITH GLOBAL CLIMATE STABILIZATION

Bryan K. Mignone

SEPTEMBER 2009
Policy Brief 09-02

About The Brookings Energy Security Initiative

The Energy Security Initiative (ESI) is a cross-program effort by the Brookings Institution designed to foster multidisciplinary research and dialogue on all aspects of energy security today. ESI recognizes that public and private choices related to energy production and use will shape the global economic, environmental and strategic landscape in profound ways and that achieving a more secure future will therefore require a determined effort to understand the likely consequences of these choices and their implications for sound policymaking. The ESI Policy Brief Series is intended to showcase serious and focused scholarship on topical issues in one or more of these broad research areas, with an emphasis on targeted policy recommendations.

Contact for the Energy Security Initiative:

Lea Rosenbohm
Project Manager
(202) 797-6248
lrosenbohm@brookings.edu

EMISSIONS TARGETS IN CAP-AND-TRADE:
CHOOSING REDUCTION GOALS COMPATIBLE WITH GLOBAL CLIMATE STABILIZATION

This paper is the first in a five paper series on US cap-and-trade design

Bryan K. Mignone

Bryan K. Mignone is a fellow and director of research of the Energy Security Initiative at the Brookings Institution. His research focuses on the science, economics and politics of global climate change, with an emphasis on the design and implementation of market-based climate policies.

The author gratefully acknowledges financial support from the Energy Foundation.

Introduction

Among the major environmental threats facing the world today, climate change stands out as both the largest in scope and the most unique in character, in the sense that the atmosphere truly does not recognize national boundaries when it comes to carbon dioxide (CO_2) emissions. Simply put, a ton of CO_2 emitted in the US yields exactly the same global environmental damage as a ton of CO_2 emitted in China, and each country stands to lose from (the damages associated with) what is emitted by the other just as it does from what is emitted within its own borders. Conversely, any nation derives benefits from abatement pursued elsewhere, meaning that individual (national) incentives to abate are greatly undermined by the desire to "free ride" on the actions of others (Hardin, 1968). The upshot is that, without greater explicit coordination among nations, the amount of global abatement realized will almost certainly be undersupplied relative to the true magnitude of the climate change threat.

The history of international environmental politics and its implications for the development of a negotiated agreement are outside the scope of this paper.[1] However, an important starting point for this analysis is the assumption that a consensus climate stabilization target will ultimately emerge as a result of ongoing political discussions. This target will most likely take the form of a number that expresses the maximum acceptable deviation of the global average surface temperature from its preindustrial value. For example, at the most recent G-8 meeting in June 2009, leaders from the industrialized countries committed to limiting the long-term temperature *increase* to 2 degrees Celsius (3.6 degrees Fahrenheit) above its preindustrial value. Although this particular goal has not been endorsed by major developing countries, it does have the virtue of being broadly consistent with scientific developments showing that the risk of dangerous climate impacts, such as the disintegration of polar ice sheets, increases significantly above ~2 degrees C.

Assuming scientific information is successfully coupled with political judgment to yield a consensus target such as the one suggested above, science can be employed once more to translate this goal into a corresponding greenhouse gas concentration target and a global emissions reduction pathway. Although significant uncertainty remains in the climate sensitivity (the relationship between the equilibrium temperature change and the global greenhouse gas concentration), as well as in the abatement potential of non-CO_2 gases (the

[1] For more background on international environmental negotiations and the structure of possible future climate treaty architectures, see, e.g., Aldy and Stavins (2007), Barrett (2003), Benedick (1998), and Mintzer and Leonard (1994).

relationship between the overall greenhouse gas concentration and the CO_2 concentration) and in the response of the carbon cycle (the relationship between the total CO_2 concentration and the CO_2 emissions path), we will show that a 50% global reduction of CO_2 emissions by 2050 relative to 2005 levels, another often stated policy goal, is plausibly consistent with the 2-degree C temperature target. However, this response is on the low end of what might ultimately be required, given the nature of the scientific uncertainties involved.

In light of the many known uncertainties associated with the climate system response, policymakers may wish to revise the global emissions path in order to improve the likelihood of attaining the 2-degree temperature target, or they may decide to adopt a different target altogether. In either case, when considering the implications for the design of a US cap-and-trade system, we will take the 50% reduction in CO_2 emissions by 2050 relative to 2005 levels as the basic policy goal to be explored in this paper. Assuming that this target is widely recognized and shared among the "major emitters" (a group that typically refers to those countries who participate in the US-led "major emitters forum"), a potentially more difficult problem involves dividing up the implied abatement burden among nations whose historical responsibility, vulnerability to climate change, adaptation capacity and economic resources to devote to environmental improvement vary considerably.[2]

In order to examine the sensitivity of US policy choices to international action, we consider several possible approaches for determining what might constitute "comparable effort" or an "equitable distribution" of burden. Combining basic scientific information with a set of plausible burden sharing rules allows us to define a range of US targets broadly consistent with global climate stabilization. An important conclusion from this analysis is that the specification of US targets is relatively insensitive to the choice of comparability metric, at least in the near-term, provided that the notion of "common-but-differentiated" responsibilities envisioned by the UN Framework Convention on Climate Change (UNFCCC) is incorporated in some way.[3]

In addition, we find that the amount of new technology needed to satisfy US emissions targets generally falls within the range of plausibility, given current information about the pace of future technological deployment. This implies that uncertainty related to future technology is probably not sufficient to warrant *ex ante* revision of the emissions targets derived from a top-down analysis, as some have suggested. Rather, to hedge against worst case outcomes, cap-and-trade policy could be designed flexibly, in a way that would allow targets to be adjusted *ex post* if technology deployment turned out to be much weaker (and the associated costs much higher) than anticipated. Such flexibility could be directly incorporated into the design of policy through explicit cost containment provisions, a subject that is discussed at greater length in a related paper (Mignone, 2009).

In this paper, we consider each of these issues in greater detail. Section 2 examines possible global temperature and concentration goals, making use of the guidance provided by the UNFCCC and subsequent technical and political judgments about the meaning of "dangerous interference" with the climate system. Section 3 discusses how available scientific information could be used to translate any such concentration or temperature

[2] For more on the Major Emitters Meetings, see <http://www.state.gov/g/oes/climate/mem>.
[3] The concept of "common but differentiated" responsibilities was first introduced in Article 3 of the Framework Convention on Climate Change. For full text of the Convention, see: <http://unfccc.int/resource/docs/convkp/conveng.pdf>.

target into a single global emissions reduction pathway. Section 4 considers various proposals for dividing up the global abatement burden, given different notions of "comparability," and discusses what this implies for the design of emissions reduction targets in the US. Section 5 considers the implications of these emissions reduction targets for the transformation of the US energy system and examines whether top-down emissions goals derived from a global disaggregation of abatement are consistent with bottom-up technological constraints on the future energy system. Section 6 concludes with a recap of the major issues and with appropriate policy recommendations.

Consensus Climate Targets

Article 2 of the UNFCCC states that the ultimate objective of global climate policy is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference (DAI) with the climate system."[4] While seventeen years have passed since the drafting of the Convention at the 1992 Rio Earth Summit, and while 192 countries have now ratified this agreement, prospects for greater political consensus about the meaning of DAI have only recently improved. One such interpretation appears in the most recent G-8 position statement on climate change, adopted at the June 2009 leaders' summit in L'Aquila, Italy, where industrialized nations committed to limiting the rise in global average temperature to 2 degrees C above its pre-industrial value. In so doing, the G-8 indicated a desire to "avoid the risk of serious economic consequences and irreversible damage to the environment and the climatic system," thereby echoing the language of the original Framework Convention.[5]

A comprehensive analysis of all the anticipated impacts of climate change and what these might imply for the choice of a global temperature target is beyond the scope of this paper. Instead we will largely take the above temperature target as given and focus on the implications of this choice for global greenhouse gas concentration and emissions targets. It is worth noting, however, that one need only consider a small subset of impacts in order to gain basic intuition about plausible targets and to see that a 2-degree threshold is at least consistent with common sense interpretations of the word "dangerous."

A good example of such an impact is the sea-level rise that would result from the partial disintegration of polar ice sheets. While the processes governing the stability of ice sheets are currently not well understood (in terms of yielding accurate quantitative projections), it is generally agreed that the mechanisms by which ice sheets lose mass are qualitatively different from the mechanisms by which they gain mass. More specifically, their growth involves a steady accumulation of precipitation over thousands of years, whereas disintegration appears to occur on considerably shorter timescales, perhaps a result of melt water

[4] See footnote 3 for link to full text of the Framework Convention. Since ratification of the Convention, a good deal of effort has been devoted to the interpretation of the concept of "dangerous interference." For example, see Hansen (2005), O'Neill and Oppenheimer (2002), Oppenheimer (2005), Oppenheimer and Petsonk (2005).

[5] The G-8 position statement on climate change can be found at: <http://www.g8italia2009.it/static/G8_Allegato/Fact%20Sheet%20-%20Climate%20Change%20(ENG).pdf>.

lubricating the base of the sheet and allowing it to more easily slide off the land on which it sits.

The complete disintegration of the Greenland or West Antarctic ice sheets is not likely to occur in this century, but the threshold at which these outcomes become effectively inevitable could be crossed much sooner, perhaps within a period of decades if emissions are allowed to increase unabated. According to the Intergovernmental Panel on Climate Change (IPCC), there is "medium confidence that at least partial deglaciation of the Greenland ice sheet, and possibly the West Antarctic ice sheet, would occur over a period of time ranging from centuries to millennia for a global average temperature increase of 1-4 degrees C, relative to 1990-2000."[6] Such temperature thresholds could clearly be exceeded in this century, thus committing the world to 7 meters (m) of global sea level rise (in the case of Greenland) and 5 m of global sea level rise (in the case of Antarctica). Since the resulting impacts on coastal settlement would be considered "dangerous" by any ordinary definition of that word, one may view the 2-degree target as a reasonable, albeit subjective, attempt to mitigate the risks associated with this particular threat. Of course, it would be advisable to consider the full range of human and natural system impacts when formulating a global policy target such as the one discussed above.[7]

In order to understand the quantitative relevance of the 2-degree target for decision-making, it is necessary to first review some of the basic mechanisms that drive human-induced climate warming. To begin, one should recall that the presence of carbon dioxide in the atmosphere heats the Earth's surface by trapping infrared radiation that would otherwise escape to space, redirecting that radiation back toward the surface of the Earth. Importantly, this "greenhouse effect" existed well before humans emitted large amounts of fossil fuel-derived CO_2 into the atmosphere, leading to warming of the surface sufficient to support the existence of liquid water and to conditions generally favorable to the evolution of life itself.

In using the term "greenhouse effect" to describe recent (and future) human-induced climate change, one is actually referring to an *enhancement* of the natural greenhouse effect, a simplifying convention we will also adopt here for convenience. In order to formulate policy, one must know something about how this modern greenhouse effect, measured in terms of its contribution to the equilibrium temperature change, varies with the amount of carbon dioxide added to the atmosphere. Since radiation is absorbed by CO_2 at discrete frequencies, this absorptive ability actually diminishes as the relevant frequency bands become saturated, as more CO_2 is added to the atmosphere. For our purposes, this means that if one examined the relationship between the increase in the atmospheric greenhouse gas concentration and the increase in temperature, it would not be a straight line but a curve that flattened out as the concentration increased, as shown in **Figure 1**.

Quantitatively, this figure suggests that a policy target of 2 degrees C warming relative to preindustrial values would require the greenhouse gas concentration to level off at about 450 parts per million CO_2e (see blue square in **Figure 1**).[8] Taken literally, this figure also suggests that the relationship between the greenhouse gas concentration

[6] See p. 17 of IPCC (2007). Text of the Summary for Policymakers is available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg2/ar4-wg2-spm.pdf>.

[7] Interested readers should consult the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007), which devotes an entire volume to issues related to impacts and adaptation. For a link to the Summary for Policymakers, see footnote 6.

[8] Co_2e, or CO_2-equivalent, is a unit of concentration benchmarked to the radiative forcing impact of CO_2. It provides a useful way to measure the concentration of all greenhouse gases simultaneously in a familiar currency.

and the implied temperature increase is known precisely. While it is true that there will be a unique temperature response to a given increase in the greenhouse gas concentration in the real world, this relationship is not known with certainty *a priori*. The parameter that expresses the sensitivity of the average surface temperature increase to a sustained doubling of the greenhouse gas concentration is called the *climate sensitivity*, and it is generally believed to be bounded between 2 and 4.5 degrees C per doubling of the CO_2-equivalent concentration. For simplicity, the relationship in **Figure 1** assumes that the climate sensitivity is equal to its central case estimate of 3 degrees C per doubling CO_2e.[9]

Before considering what this result implies for future climate stabilization, it is helpful to briefly revisit the atmospheric conditions that prevailed in the past as well as those that exist today. In the centuries prior to industrialization, the atmospheric CO_2 concentration remained steady at about 280 parts per million. Today the concentration is about 390 parts per million (and rising), and the global surface temperature has increased by about 0.5 degrees C since preindustrial times.[10] It is important to note that the difference between the present concentration and the target concentration (~60 ppm) is roughly half the difference between the preindustrial concentration and the present concentration (~110 ppm). This difference gives some sense of how little room there is left to maneuver if relatively low temperature thresholds are to be avoided.

In fact, the picture is somewhat worse than it first appears, because the accounting above considered only carbon dioxide. In reality, methane and nitrous oxide contribute approximately another 50 ppm CO_2e to the atmospheric concentration today, meaning that, in CO_2e terms, it is virtually impossible that the total atmospheric concentration of greenhouse gases will remain below 450 ppm, since we are already on the cusp of that limit today. Holding the concentration of CO_2 below 450 ppm might still be consistent with a long-term 2-degree target, but only if non-CO_2 gases are controlled in coming decades in a way that allows the total greenhouse gas concentration to converge to the CO_2-only concentration.

In light of these considerations, there are two ways to think about CO_2 stabilization at 450 ppm. In a world in which abatement of non-CO_2 gases is very aggressive (and in which the climate sensitivity is limited to 3 degrees C), the long-term equilibrium temperature response will be approximately 2 degrees C. On the other hand, if abatement of non-CO_2 gases does not proceed as quickly or as aggressively (or if the climate sensitivity is greater than 3 degrees C), then the implied equilibrium temperature increase will be larger than 2 degrees C. For example, if we assume that the contribution of non-CO_2 gases grows to approximately 100 ppm CO_2e, then stabilization at 450 ppm CO_2, would lead to a total greenhouse gas concentration of ~550 ppm CO_2e, which would yield approximately 3 degrees of warming, assuming the same climate sensitivity as above (see the grey triangle in **Figure 1**).[11]

Of course, things could also turn out better than anticipated. For example, the climate sensitivity could be less than 3 degrees C. However, for simplicity, we will assume that stabilization of CO_2 at 450 ppm is the primary policy goal. While this is

[9] See p. 65 of IPCC (2007b). Complete text of the Technical Summary is available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-ts.pdf>.

[10] This 0.5 degree C is the transient temperature increase measurable today, not to be confused with the equilibrium temperature change that would result if the CO_2 concentration were fixed at 390 ppm for a long period of time. The equilibrium temperature change will always be higher than a transient change measured prior to equilibrium.

[11] For comparison see Table SPM.6 in the Synthesis Report Summary for Policymakers of the IPCC Fourth Assessment Report, available at: <http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf>.

consistent with the 2-degree C temperature target under the particular assumptions discussed above, the reader may consider other possible implications of this trajectory, by revisiting the main assumptions about the climate sensitivity and the emissions of non-CO_2 gases.

A Global Emissions Reduction Path for CO_2

The next step in establishing a coherent global policy response involves translating a particular concentration goal into a global emissions reduction path. This, in turn, requires a deeper understanding of the *carbon cycle*. Toward this end, it is helpful to explicitly define the differences between emissions of greenhouse gases and the resulting atmospheric concentration. The atmospheric *concentration* of CO_2 effectively measures the "stock" or accumulated pool of anthropogenic carbon in the atmosphere, while the *emissions* of CO_2 measures the annual contribution to this total pool. Without any "sinks" to remove carbon from the atmosphere, the concentration at any given moment would simply be the sum of emissions over all previous periods.

To develop a more conceptual understanding of the carbon cycle, one might imagine using a faucet to fill up a bathtub. If the drain is closed (and perfectly tight), then the amount of water in the tub at any given point in time is simply the total amount of water released from the faucet between the time it was first turned on and the time at which the amount in the tub is measured. One may complicate this picture slightly by opening the drain at the bottom of the tub. If the drain removes water slowly, while the faucet adds water quickly, then the total amount of water in the tub would still rise, but it would do so at a rate lower than it would if the drain remained tightly closed.

Qualitatively, the real carbon cycle resembles this second picture. Sinks in the land and ocean (the "drain") take up a fraction of the carbon released by human activities (the "faucet") in each year and sequester this carbon from the atmosphere, thus lowering the concentration of atmospheric CO_2 relative to what it otherwise would be. As a result, accurate conversion between a global CO_2 concentration trajectory and the global CO_2 emissions path compatible with that trajectory requires a quantitative understanding of the future response of these sinks to increases in the atmospheric CO_2 concentration.

While there are significant quantitative uncertainties related to both land and ocean sinks, and while projecting the response of either involves understanding complex physical, chemical and biological processes, the future behavior of the ocean sink is more tightly constrained than the land sink due to a better understanding of the underlying ocean mechanisms. Even the sign of the land sink (i.e. whether it will be a net source or a net sink in the future) remains uncertain. For this reason, we focus more of our attention on the ocean, which is expected to absorb anthropogenic carbon steadily for many decades to come.

Fundamentally, ocean uptake is driven by the CO_2 gradient that exists between the atmosphere and the surface ocean, a gradient that is enhanced by the addition of fossil fuel-derived CO_2 into the atmosphere. Based on its sheer size, the ocean has great potential to absorb "excess" CO_2. In fact, if concentrations of CO_2 were well-mixed across all layers of the ocean, from top to bottom, then the oceanic reservoir would provide an almost infinite sink for anthropogenic carbon, one that could be approximated by simply assigning a characteristic lifetime (or equivalently, a single decay rate) to atmospheric CO_2. While this approach is popular in some policy applications, where the effective lifetime is often estimated to be between 100-200 years, it is a rather unsatisfactory approximation to use when quantitatively relating CO_2 emissions to atmospheric concentrations, or vice versa.

There are several reasons why this approach is not appropriate for any but the most conceptual purposes. First, the ocean is actually not well-mixed from top to bottom but is quite strongly stratified, with a steep gradient separating a well-defined surface "mixed layer" (approximately the top 100 meters) from the abyssal region that is largely out of contact with the surface on the timescales relevant to the uptake of anthropogenic CO_2. Since the communication between these regions is relatively weak, the surface ocean (and the carbon it contains) only slowly equilibrates with the abyssal ocean, meaning that the effective size of the oceanic reservoir available for exchange with the atmosphere is actually much smaller than it might appear, at least on relatively short timescales.

Secondly, the surface reservoir exhibits complex chemistry that alters the concentration of CO_2 available for exchange with the atmosphere. Just as the capacity of the atmosphere to absorb infrared radiation diminishes as more CO_2 is added (as discussed in Section 2), the effectiveness with which the ocean absorbs CO_2 from the atmosphere diminishes with the addition of CO_2. As a result of these complex physical and chemical processes, the relationship between the atmospheric concentration and a given emissions path cannot be modeled by assuming that CO_2 simply accumulates in the atmosphere as it would if the sink were turned off or that it is characterized by a single lifetime that would result from an infinite oceanic sink. The truth is somewhere in between.

To further illustrate this, panel (a) of **Figure 2** shows the future atmospheric concentration trajectory that results from the "no sink" approximation together with the trajectory that results from a more accurate specification of the future ocean sink. The CO_2 emissions source used in calculating these concentration trajectories is provided in panel (b) of **Figure 2**. In this particular example, emissions decline by 50% relative to 2005 levels by 2050 and then continue to fall by 2% per year thereafter.

The difference in concentration outcomes between these projections is significant. Under the "no sink" approximation (black curve), emissions simply accumulate in each period, leading the atmospheric concentration to rise quickly, ultimately stabilizing near 610 ppm in 2200, when emissions finally drop to zero. Under the more realistic representation of the sink (blue curve), the concentration reaches a maximum of ~450 ppm around 2075 and declines slowly thereafter. It is clear from inspection of this figure that the ocean sink provides an important environmental service by attenuating the accumulation of CO_2 in the atmosphere.

Assuming the net land sink (total uptake by land minus emissions from deforestation) grows to about 2 Pg CO_2 per year by 2050, the scenarios above suggest that a global emissions reduction of approximately 50% by 2050 relative to 2005 levels (as in panel b of **Figure 2**) would be sufficient to hold the CO_2 concentration below 450 ppm.[12] These results are relatively insensitive to the future emissions decline rate after 2050, varying between 447 and 457 ppm for decline rates between 1% and 4% per year, respectively. They are somewhat more sensitive to assumptions about the land sink, yielding atmospheric CO_2 concentrations between 442 and 461 ppm when the net land sink varies between 0 and 4 Pg CO_2 per year. Finally, the results are weakly dependent on the shape of the future emissions path. If the emissions path is concave (as in the scenarios described in the following section) rather than linear between now and 2050, the peak atmospheric concentration increases by ~10 ppm.

It is reasonable to ask what happens to the atmospheric CO_2 concentration if abatement is more aggressive and emissions drop below 50% by 2050. Using a realistic approximation of future carbon uptake, we find that, in the limit where emissions drop to zero by 2050, the concentration drops to only ~425 ppm, because the time at which the emissions source exactly balances the total sink (i.e. the time at which the peak concentration is achieved) advances by only a few years.[13] An important lesson from this is that reductions in emissions yield diminishing marginal returns once the 2050 target reaches about 50%. In the remainder of this paper, we take this 50% reduction as the primary policy target and focus on the sensitivity of US policy choices to assumptions about international burden sharing.

[12] A variety of assumptions are possible about the future land sink. For example, in a recent comparison of integrated assessment models used to evaluate scenarios like the ones here, the estimated net land sink in 2050 varied between 0 and ~7 Pg CO_2 per year (Clarke et al., 2007). Complete text of this report is available at: <http://www.climatescience.gov/Library/sap/sap2-1/finalreport/default.htm>. Note also that 1 Pg $CO_2 = 1 \times 10^{15}$ g CO_2.

[13] For a deeper discussion of the atmospheric implications of different emissions trajectories, see Mignone et al. (2008) and references therein.

Comparability in National Emissions Reduction Targets

The 17 nations that take part in the Major Emitters Forum discussed earlier are responsible for approximately 80% of global greenhouse gas emissions today. In considering the possible distribution of future abatement responsibilities, we will further restrict our analysis to four regions responsible for about 60% of total CO_2 emissions, namely the United States, the European Union, China and India. In so doing, we will attempt to shed light on ways in which the global burden might be shared among all nations, using this smaller subset to develop useful intuition. While this analysis can be used to inform international policymaking, our primary purpose here is not to propose a new structure for an international agreement, but rather to understand the sensitivity of US policy choices to a range of possible assumptions about future international action.

The fundamental challenge in designing an equitable agreement can be illustrated with a simple example. Start with a proposal that calls for global CO_2 emissions to be reduced by 50% relative to 2005 levels by 2050, as discussed above. Arguably, the simplest way to meet this obligation would be to require all nations to simply reduce their emissions by 50% relative to 2005 levels by 2050. However, because emissions in China and India are projected to roughly triple over this period, while emissions in the US and EU are expected to remain relatively flat, this policy would require emissions in non-OECD countries to be reduced by far more than emissions in OECD countries *relative to what they otherwise would have been*. Countries like China and India are likely to balk at such proposals on the grounds that they effectively get penalized for successful future development.

An alternative to this approach would be to determine the relative reduction from the global "business-as-usual" (BAU) path that would be required to reach the same global emissions target in 2050 and then apply this reduction to all regions individually. This reduction turns out to be ~72% if growth trends continue along current trajectories. From a distributional point of view, this arrangement implies that developing countries would reduce their emissions by a smaller amount (less than 50%) relative to 2005 levels by 2050, while developed countries would reduce their emissions by a larger amount (more than 50%) relative to 2005 levels by 2050. This asymmetric burden-sharing rule is one plausible interpretation of the "common but differentiated" responsibilities envisioned by the UNFCCC.

The second large row of boxes in **Table 1** (containing the two clusters labeled 'POL-1' and 'POL-2') shows how these two scenarios compare quantitatively. Consider first the policy in which all nations reduce their emissions by 50% relative to 2005 levels (POL-1). While the reductions in 2050 are identical relative to 2005 levels in all regions (see the second column of numbers shaded in gray), there is a noticeable difference in the 2020 reductions between regions (first column). This is due to the fact that the deflection from BAU is assumed to be gradual in all cases. Thus, while emissions in the OECD decrease in 2020 (relative to 2005), emissions in the non-OECD actually *increase* over this period, before eventually declining to meet the 2050 target. This is an important point to emphasize because it means that near-term emissions increases in the non-OECD can be consistent with aggressive global abatement goals.[14]

The next two columns (in the POL-1 cluster) show how emissions change relative to BAU in 2020 and 2050, respectively. In the OECD regions, the reductions relative to BAU in 2050 are not much different than the respective reductions relative to 2005 (i.e. close to 50%), because the BAU path in the OECD is relatively flat. On the other hand, the implied reductions relative to BAU in the non-OECD are closer to 80% in 2050. This result illustrates the equity perception problem mentioned above.

As an alternative, consider the policy in which all nations agree to reduce their emissions *relative to projected BAU emissions* by the same amount (72%) in 2050, as indicated by the gray shading under POL-2. In this case, emissions in the US and EU decrease by considerably more than 50% relative to 2005 levels by 2050, while emissions in China and India decrease by significantly less than 50% relative to 2005 levels by 2050. Equating reductions relative to projected BAU in 2050 is thus one way to realize "comparability," that is, to incorporate expected future economic growth into the design of emissions reduction targets. Others possible paths to "comparability" include: (a) equalizing emissions per unit of GDP by 2050 and (b) equalizing emissions per capita by 2050. Of course, these approaches by no means exhaust the set of possible equity metrics or burden sharing rules that one might devise to realize the intent of Article 3 of the UNFCCC.[15]

In any case, the two alternative scenarios are presented in the bottom row of boxes in **Table 1**. In order to meet the global 50% reduction relative to 2005 by 2050, emissions per GDP must converge to ~72 tons CO_2 per million USD (POL-3), while emissions per capita must converge to ~1.4 tons CO_2 per person (POL-4). Using the former metric, the EU and China face emissions constraints similar to those encountered under POL-1, while the US faces constraints similar to POL-2 and India fares considerably better than it would under either POL-1 or POL-2. In the equal emissions per capita case, the US, EU and China all face greater emissions constraints than they do under any of the other policies, while India faces far more lenient constraints. In fact, Indian emissions under POL-4 increase over the entire 2005-2050 horizon.

Several additional insights are revealed in **Figure 3**, which shows the implied emissions trajectories in each region under the four different policies considered above. First, note that within any region, the spread in emissions between scenarios is relatively small in 2020 and considerably larger in 2050. This feature is an artifact of the design of the scenarios themselves and the fact that they all follow a smooth transition path away from BAU. An important implication is that if national targets are constrained on the one hand by an ambitious global emission target and on the other hand by the rate at which emissions can diverge from BAU,

[14] BAU trajectories are taken from EIA's International Energy Outlook 2009 (EIA, 2009). Values beyond 2030 are extrapolated using the EIA's projected trends through 2030. The complete report is available at: <http://www.eia.doe.gov/oiaf/ieo/index.html>.
[15] For a recent example of a more complex burden-sharing rule, see Chakravarty et al. (2009).

then the range of feasible targets is actually quite limited, at least in the near term. For example, if one discards the first scenario (POL-1) as largely inconsistent with the notion of "common but differentiated" responsibilities, then required US emissions reductions vary between 16% and 21% relative to 2005 levels in 2020 and between 65% and 90% relative to 2005 levels in 2050. These targets are broadly consistent with those included in the most recent version of the Waxman-Markey climate change bill (sometimes referred to by the acronym ACESA).[16]

The second noteworthy feature of this figure is the clear difference between the shape of the OECD trajectories and the shape of the non-OECD trajectories. In the OECD, a gradual deflection from BAU is consistent with an immediate downturn in emissions (because BAU is relatively flat), while in the non-OECD, as already noted, a gradual transition path requires emissions to increase in the near term, peak at some discrete year in the future and then decrease later to meet the 2050 target. The emissions peak occurs in the window 2020-2025 for China and 2017-2024 for India, except under POL-4 in which Indian emissions continue to rise through the end of the policy window.

Finally, it is worth calling attention to some interesting differences within the OECD and non-OECD. First, since the assumed growth in BAU emissions in the US and EU is similar (and small) in both cases, the range of relative reductions in the US implied by any of the policies considered here tends to be very similar to the range of reductions in the EU. Second, within the non-OECD, differences are far greater. As a result, the bounds on policy provided by a collection of comparability metrics do not constrain the outcome as narrowly in the non-OECD as in the OECD. In China, for example, the reductions in 2050 emissions relative 2005 levels vary between 11 and 59%, while in India the reductions vary from -112% (increase in emissions) to 32%.

Of course, our goal here is not to determine the quantitative details of an international agreement, which would require choosing among these scenarios (or devising more complex ones), but rather to explore the range of US trajectories consistent with global climate stabilization. As we have already seen, this range is reasonably well constrained, an outcome that provides useful guidance to policymakers concerned with the design of targets in a US cap-and-trade system.

[16] Text of this bill can be found at: <http://energycommerce.house.gov>.

Reconciling Climate and Energy System Constraints

The range of US emissions reductions discussed above (16-21% below 2005 levels by 2020) reflects the results of a top-down exercise in which the required global abatement burden is divided into "comparable" national commitments using a set of plausible equity metrics. It is sometimes asked whether the actual reductions implied by such a process are ultimately "consistent" with the availability of future energy technology and other abatement opportunities. However, since any targets are physically feasible if energy prices are increased sufficiently (because demand can always be reduced at arbitrarily high prices), the notion of "consistency" is not very well defined in practice. In an operational sense, one might consider targets "consistent" with technology if that technology is available at a cost and scale that caps the implied prices or costs of policy below a relevant political or economic feasibility threshold. This notion is clearly subjective, but it can at least be explicitly evaluated by defining a relevant price or cost threshold and making informed judgments about the basic characteristics of future energy technology and abatement options.

Energy models provide a useful framework in which to assemble information about emissions targets and abatement options and therefore to evaluate "consistency" or feasibility more quantitatively. Since the range of targets proposed above is largely consistent with those in recent legislative proposals (i.e. ACESA calls for a 17% reduction in energy system emissions relative to 2005 levels by 2020), we may use recent model analyses of existing legislative proposals to evaluate the compatibility of targets derived from a top-down analysis with bottom-up constraints on the energy system. For simplicity, we will focus on the set of ACESA compliance scenarios compiled by the US Energy Information Administration (EIA) using the National Energy Modeling System (NEMS).[17]

To keep the discussion tractable, we will also restrict our discussion to two scenarios in particular. The first is the so-called "basic" scenario in which, according to EIA, "key low-emissions technologies," such as nuclear, coal with carbon capture and storage (CCS) and renewables are developed and deployed on a large scale in a timeframe "consistent with the emissions reduction requirements [of the Waxman-Markey bill] without encountering any major obstacles." It also assumes that domestic and international offsets are "not severely constrained by cost, regulation, or the pace of negotiations with key countries covering key sectors." This scenario thus describes a relatively optimistic world.

[17] See EIA (2009b). Complete text is available at <http://www.eia.doe.gov/oiaf/servicerpt/hr2454/>.

The second so-called "no international" scenario is similar but includes constraints on the availability of offsets and assumes that the use of international offsets is "severely limited by cost, regulation, and/or slow progress in reaching international agreements or arrangements covering offsets in key countries and sectors." In other words, it assumes that the supply of international offsets is effectively turned off, at least for the purposes of domestic compliance. The EIA also considers scenarios in which key low-carbon baseload technologies (nuclear, coal with CCS and dedicated biomass) are limited or significantly more expensive than what is assumed in the "basic" case. Results from these scenarios will be incorporated into the discussion later on.

Table 2 shows some of the key results in 2020 for the two scenarios discussed above. The first row shows that the amount of abatement required (the difference between covered business-as-usual emissions and the number of permits issued in that year) is the same in each of the two scenarios, as one would expect (~1 Pg CO_2 per year). However, because the amount of assumed banking differs slightly between these cases, the actual amount by which emissions must be reduced also varies slightly, from 1.6 Pg CO_2 in the "no international" case to 1.8 Pg CO_2 in the "basic" case. To determine the real implications for the energy system, one must finally consider the offset supply, which differs considerably between the two scenarios because of the applied constraints in the "no international" scenario. With these differences included, the implied energy system reductions vary significantly, between 0.6 Pg CO_2 per year in the "basic" case and 1.2 Pg CO_2 per year in the "no international" case.

To understand the energy system implications of these reductions, we next turn our attention to the power generation sector, which is responsible for 80-90% of the emissions reductions within the energy sector in 2020. (Energy system abatement from other, non-power sectors accounts for ~ 0.1 Pg CO_2 per year in both scenarios). Under BAU, emissions from power generation account for approximately 2.5 Pg CO_2 of total emissions in 2020, with the majority of that coming from coal-fired generation and the remainder coming from natural gas. If the least expensive abatement is found in the power sector, and if most power sector abatement involves substitution away from conventional coal technology, then one may start to examine the nature of this substitution in more technological detail.

In the "basic" case, which requires ~0.5 Pg CO_2 of power sector abatement, one would expect emissions from coal to drop to approximately 2.0 Pg CO_2 (20% reduction), while in the "no international" case, which requires ~1.1 Pg CO_2 of abatement, one would expect emissions from coal to drop to about 1.4 Pg CO_2 (44% reduction). These simple calculations can be verified in **Table 2**. According to EIA, coal-based generation is projected to produce 2183 billion KWh of electricity in 2020 under BAU, whereas it is projected to produce 1778 billion KWh of electricity in the "basic case" (a drop of 19%) and 1151 billion KWh in the "no international" case (a drop of 47%), both of which are close to what is calculated above.

In order to evaluate the plausibility of these scenarios, it is important to understand what happens to the conventional coal demand that is displaced. Importantly, not all of it is fully offset by other forms of generation, because as prices rise, the demand for electricity declines slightly. This demand response accounts for perhaps another ~0.1 Pg CO_2 of abatement in 2020. The remaining abatement (0.4 Pg CO_2 in the "basic" case and 1.0 Pg CO_2 in the "no international case") must come from new capacity additions (or capacity factor increases) in renewables, coal with CCS and nuclear.

Beginning with the last of these, we find that total electricity generation from nuclear, as projected by EIA, increases by 64 billion KWh in the "basic" case and by 142 billion KWh in the "no international case" in 2020. Assuming this additional generation requires new capital deployment (i.e. that it cannot be produced by further enhancing the capacity factors at existing plants), this transformation implies installation of 8 GW or 18 GW in 2020 in the "basic" and "no international" cases, respectively.[18] On the other hand, total generation from coal with CCS increases by 82 billion KWh in the "basic" case and 143 billion KWh in the "no international case." This transformation implies an additional 12 and 20 GW of capacity in the "basic" and "no international" cases, respectively. All of these implied expansions are in addition to any assumed in the reference case (which is small for both nuclear and CCS).

In the same scenarios, total electricity generation from all renewable technologies is projected to increase by 170 billion KWh in the "basic" case and by 628 billion KWh in the "no international" case. In terms of capital deployment, this transformation implies an additional 49 GW or 179 GW of installed capacity in the "basic" and "no international" cases, respectively, relative to any new deployment under BAU. These implied additions are clearly much larger than those for nuclear or CCS. In addition, the reference case assumes a significant amount of expansion in renewables, making the total required additions even larger.

In evaluating the feasibility of such a large-scale renewables expansion, three points are worth noting. First, the "renewables" category in this analysis is intended to capture a large class of emerging technologies, so a larger expansion relative to individual technologies, such as nuclear or CCS, is not particularly surprising. Secondly, for some intermittent technologies, such as wind and solar, the capacity factors could increase well beyond what is assumed here, if energy storage were to become commercially available, thereby reducing the total capital expansion required. Finally, there is clearly a vast difference in deployment between the "basic" case, which assumes a large supply of offsets, and the "no international" case, which effectively requires twice as much abatement from the power sector.

Given the assumptions in the "basic" and "no international" scenarios, the implied allowance prices are \$32 and \$52 per ton CO_2 in 2020 and the economic costs as a share of GDP are 0.3% and 0.2% in 2020, respectively. If one believed that any of the implied capacity expansions in either scenario were physically implausible, these technologies could be constrained in the modeling exercise itself. For example, EIA considers one scenario in which CCS, nuclear and biomass cannot expand beyond their reference case capacities (and in which international offsets are also restricted). In this case, prices rise to \$93 per ton CO_2 and costs rise to 0.7% of GDP in 2020. At some point, the implied costs would be high enough to deem the targets "inconsistent" with future technology availability.

The problem, of course, is that the assumptions about future technology are inherently uncertain. One response to this uncertainty would be to adjust the targets *ex ante* to account for the possibility of deployment bottlenecks. However, scaling back the level of program ambition effectively guarantees that the most transformative outcomes associated with aggressive targets will not be realized, even if technology turns out to be more plentiful than anticipated. In other words, it eliminates downside risk by simultaneously eliminating the chances for upside gains. To mitigate downside risk while maintaining upside potential, one could alternatively maintain ambitious

[18] In making these conversions, we assume a capacity factor 0.9 for nuclear, 0.8 for coal and 0.4 for renewables.

targets while hedging the risk associated with technological uncertainty by adding additional compliance provisions to adjust targets *ex post* if the availability of abatement opportunities turned out to be more limited than anticipated.

The take-home message from this analysis is that the very notion of "consistency" is ambiguous at best. Even with a more rigorous operational definition (in terms of economic costs) in hand, consistency can be difficult to determine because the technology assumptions themselves are extremely uncertain and subjective. Given policies like the ones considered here, available evidence suggests that the implied targets are plausibly consistent with the demands on future technology. However, since it is possible that deployment bottlenecks could raise costs beyond the limits of political or economic enforceability, policymakers could hedge such downside risk through compliance flexibility mechanisms. These sorts of approaches to cost containment are discussed at greater length in a related brief (Mignone, 2009).

CONCLUSIONS

The primary purpose of this paper is to provide useful guidance to policymakers concerned with the design of emissions reduction targets in a US cap-and-trade system. We began by showing that the 2-degree C temperature target is largely consistent with common sense notions of "dangerous interference." We also suggested that a global CO_2 emissions reduction of approximately 50% below 2005 levels by 2050 would be compatible with such a target, albeit on the low end of what might ultimately be required if emissions of non-CO_2 gases cannot be reduced significantly or if the climate sensitivity turns out to be greater than 3 degrees C.

In order to examine the means by which such a global target might be satisfied, we considered the implications of four different equity metrics, three of which reasonably incorporate the notion of "common but differentiated" responsibilities envisioned by the UNFCCC. While the implied reductions in the non-OECD are rather sensitive to the choice of equity metric, the reductions in the OECD and in the US in particular, are relatively robust to this choice. Given the 50% global target, the implied emissions reductions in the US vary between 16 and 21% below 2005 levels by 2020. These targets are comparable to those being discussed in current legislative proposals.

Finally, we find that the implied demands on the energy system fall within a plausible range, given what is currently known about future technological availability. Model-based analyses of targets similar to the ones described above suggest that most of the abatement in 2020 will rely on substitution away from coal-fired generation in the power sector, with a large share of that coming from new rewnewable capacity additions. While it is possible that deployment bottlenecks will constrain the amount of abatement that can be supplied by such technology, the level of current uncertainty does not warrant *ex ante* revision of the emissions targets. If policymakers are concerned about future technology deployment, they could hedge this risk by coupling the emissions targets to carefully designed cost containment provisions.

Ultimately, a successful policy will require broad international cooperation. However, a key conclusion from this analysis is that near-term US commitments are relatively insensitive to the details of a future international agreement, because they are constrained more fundamentally by the global climate target and the assumed rate at which all countries can feasibly move away from BAU. As a result, policymakers is the US may design targets without being concerned that such targets will later turn out to be incompatible with international action.[19] In light of concerns about technology deployment, they may hedge such risk by designing provisions more finely tailored to these purposes, but when it comes to choosing emissions reduction targets, the path forward is clear.

19 That is, policymakers need not be concerned that the targets will be inconsistent with global environmental goals. Of course, they may be worried about the economic and domestic competitiveness implications of unilateral US action. The design of provisions to address these concerns is discussed in a related paper (Fischer and Morgenstern, 2009).

References

Aldy, J. E. and R. N. Stavins (Eds). 2007. *Architectures for Agreement: Addressing Global Climate Change in the Post-Kyoto World*. Cambridge: Cambridge University Press.

Barrett, S. 2003. *Environment and Statecraft: The Strategy of Environmental Treaty-Making*. Oxford: Oxford University Press.

Benedick, R. E. 1998. *Ozone Diplomacy: New Directions in Safeguarding the Planet*. Cambridge: Harvard University Press.

Chakravarty, S. et al. 2009. Sharing global CO_2 emission reductions among one billion high emitters. Proceedings of the National Academy of Sciences 106: 11884-11888.

Clarke, L. E. et al. 2007. *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations*. Sub-report 2.1A of Synthesis and Assessment Product 2.1 by the US Climate Change Science Program and the Subcommittee on Global Change Research. Washington, D.C.: US Department of Energy, Office of Biological and Environmental Research.

EIA 2009. International Energy Outlook 2009. Report DOE/EIA-0484. Washington, D.C.: US Energy Information Administration.

EIA 2009b. Energy Market and Economic Impacts of H.R. 2454, the American Clean Energy and Security Act of 2009. Report SR/OIAF/2009-05. Washington, D.C.: US Energy Information Administration.

Fischer C. and R. Morgenstern. 2009. "US Industry and Cap-and-Trade: Designing Provisions to Maintain Domestic Competitiveness and Mitigate Emissions Leakage." Energy Security Initiative Policy Brief 09-06. Washington, D.C.: The Brookings Institution.

Hansen, J. 2005. A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? *Climatic Change* 68: 269-279.

Hardin, G. 1968. The tragedy of the commons. *Science* 162: 1243–1248.

IPCC 2007. Summary for Policymakers in *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson, Eds.). Cambridge: Cambridge University Press.

IPCC 2007b. Technical Summary in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S. et al., Eds.). Cambridge: Cambridge University Press.

Mignone, B. K., R. H. Socolow, J. L. Sarmiento and M. Oppenheimer. 2008. Atmospheric stabilization and the timing of carbon mitigation. Climatic Change 88: 251-265.

Mignone, B. K. 2009. "Cost Containment for Cap-and-Trade: Designing Effective Compliance Flexibility Mechanisms." Energy Security Initiative Policy Brief 09-03. Washington, D.C.: The Brookings Institution.

Mintzer, I. M. and J. A. Leonard. 1994. *Negotiating Climate Change: The Inside Story of the Rio Convention.* Cambridge: Cambridge University Press.

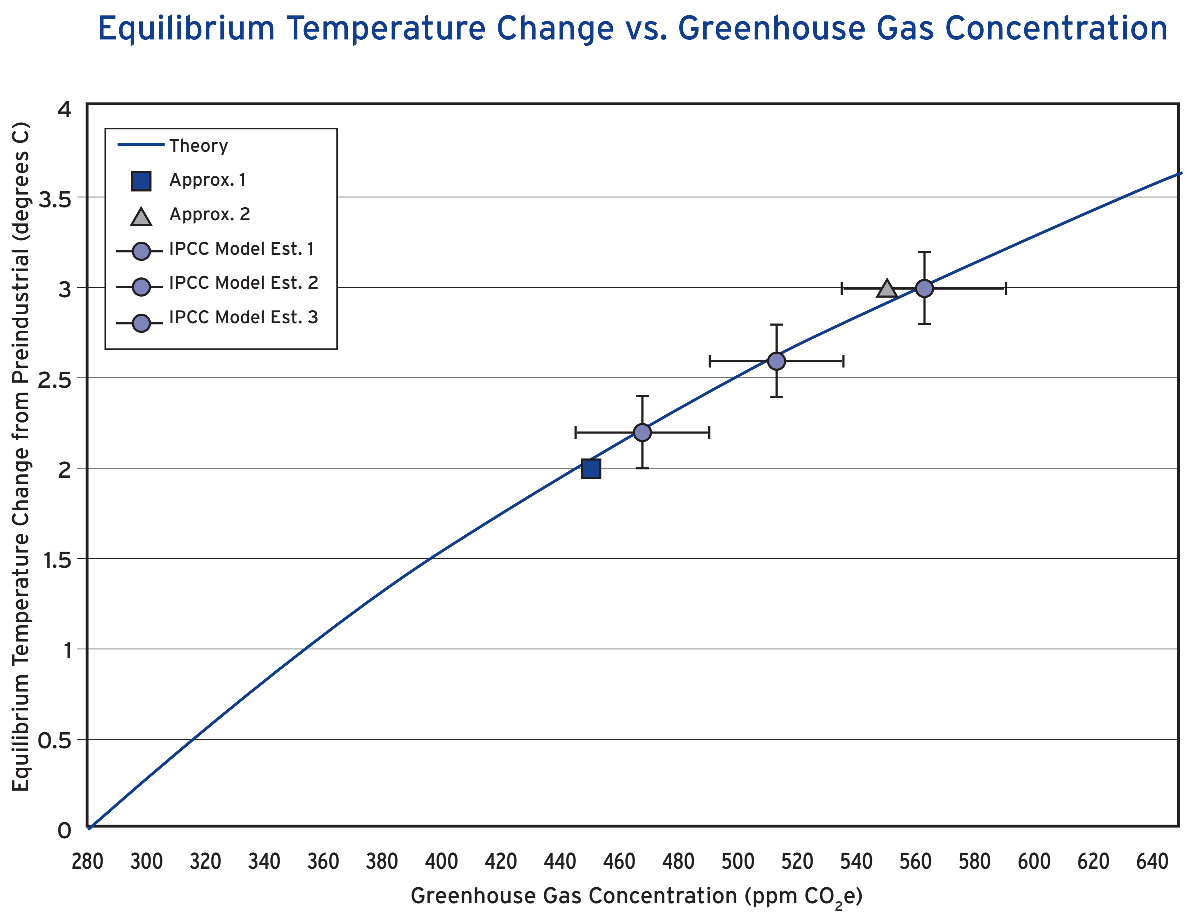
O'Neill, B. C. and M. Oppenheimer. 2002. Dangerous climate impacts and the Kyoto Protocol. *Science* 296: 1971-1972.

Oppenheimer, M. 2005. Defining dangerous anthropogenic interference: The role of science, the limits of science. Risk Analysis 25: 1399-1407.

Oppenheimer, M. and A. Petsonk. 2005. Article 2 of the UNFCCC: Historical origins, recent interpretations. Climatic Change 73: 195-226.

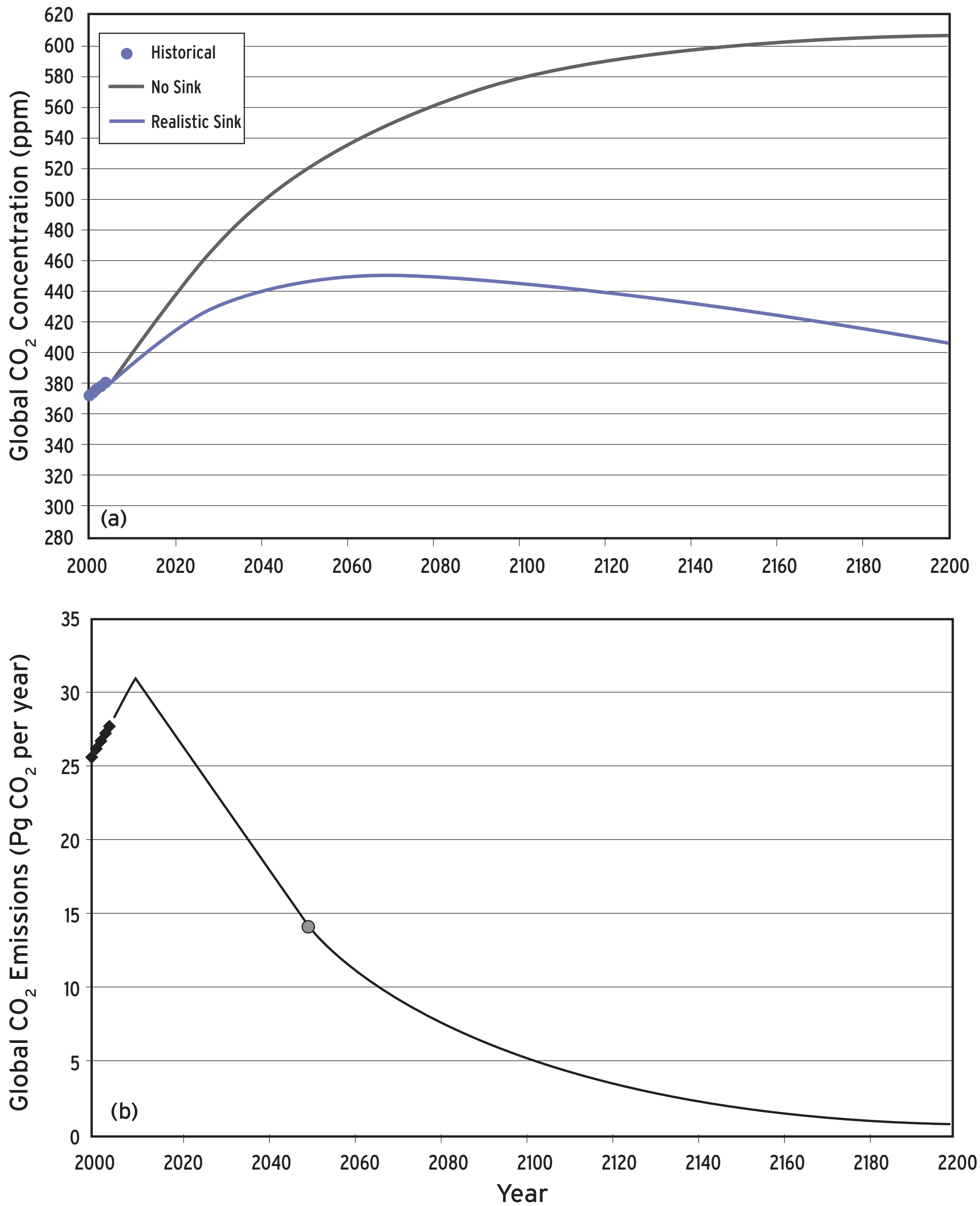
Figures and Tables

Figure 1



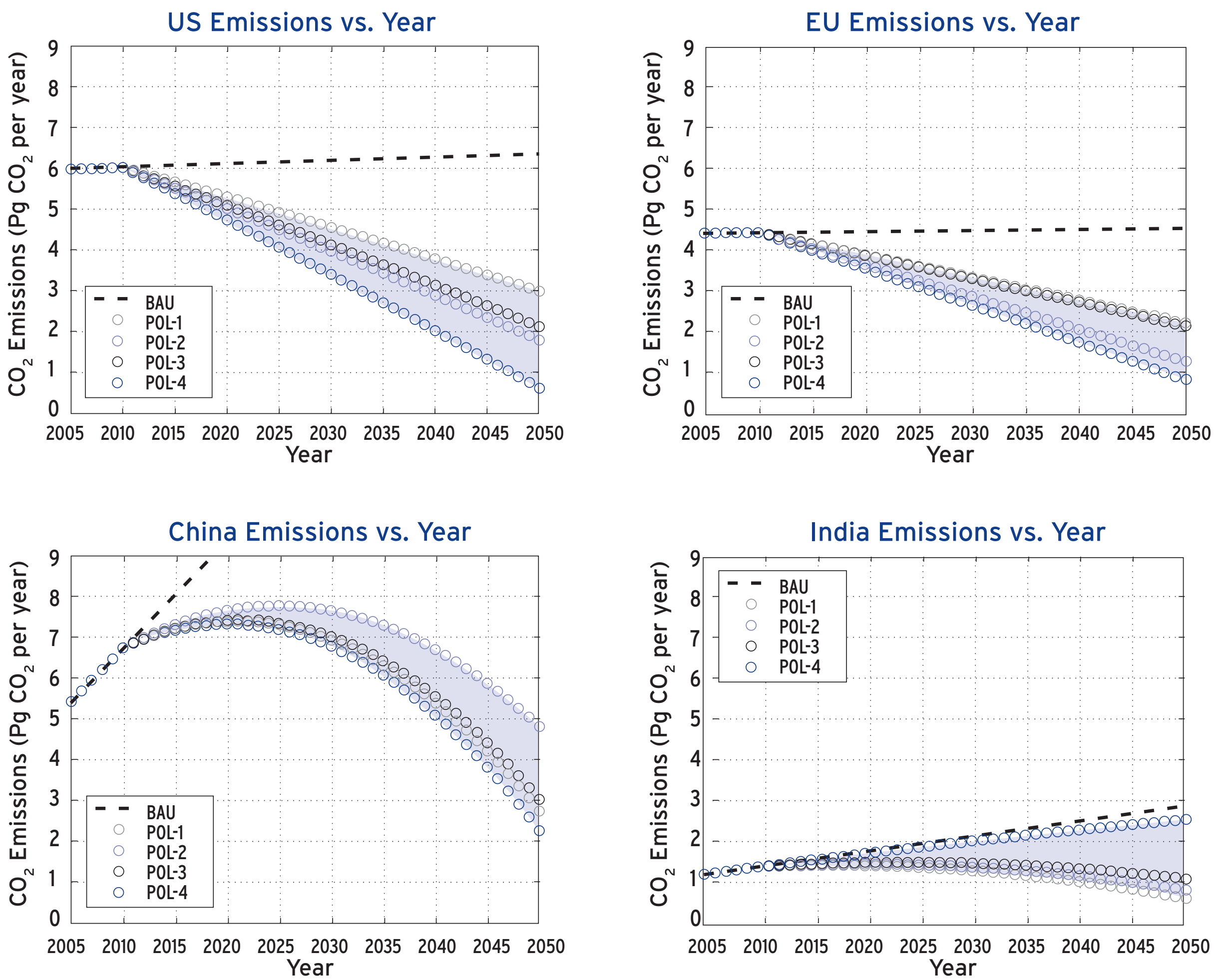
Equilibrium temperature change (in degrees C) as a function of the total atmospheric greenhouse gas concentration (in ppm CO_2e). The solid blue curve assumes that the climate sensitivity is 3 degrees C per doubling of the greenhouse gas concentration above its preindustrial value. The blue square and grey triangle are two commonly used approximations, namely that stabilization at 450 ppm CO_2e would lead to an equilibrium warming of 2 degrees C and that stabilization at 550 ppm CO_2e would lead to warming of 3 degrees C. The three other points (with error bars) are compiled model projections discussed in the IPCC. See footnote 11 for the complete citation.

Figure 2



Panel (a) shows the projected atmospheric concentration response to the CO_2 emissions path in panel (b), in which emissions drop by 50% relative to 2005 levels by 2050 (grey circle) and fall at 2% per year thereafter. The black trajectory in panel (a) assumes that all of the CO_2 emitted from 2005 onward remains in the atmosphere indefinitely (no sink). The blue trajectory assumes a realistic ocean and land sink that evolves in response to changing atmospheric CO_2 concentrations.

Figure 3



Implied emissions trajectories between 2005-2050 for the four regions and four scenarios discussed in the main text. The dashed black lines show the BAU trajectories for each region, and the range of values obtained across scenarios is indicated by the blue shading.

Table 1

	BUSINESS AS USUAL (BAU)										
	EMISSIONS			GDP		POP		E/GDP		E/POP	
	2005	2020	2050	2005	2050	2005	2050	2005	2050	2005	2050
TOTAL	28.3	35.5	50.0	57.0	194.8	6511	9868	496.0	256.5	4.3	5.1
OECD	13.6	14.0	14.8	34.2	76.8	1169	1431	399.1	193.5	11.7	10.4
NON	14.7	21.5	35.1	22.9	118.1	5342	8437	640.5	297.5	2.7	4.2
US	6.0	6.1	6.4	12.4	29.4	297	436	481.5	217.1	20.1	14.7
EU	4.4	4.5	4.5	13.8	29.8	536	601	321.2	152.0	8.2	7.5
CHINA	5.4	9.4	17.2	5.4	41.8	1313	1603	1007.4	411.9	4.1	10.7
INDIA	1.2	1.8	2.9	2.4	15.1	1134	1833	487.7	190.2	1.0	1.6

	POL 1: EQL EMIS RED REL TO 2005 in 2050						POL 2: EQL EMIS RED REL TO BAU IN 2050					
	E(2005) (%)		E(BAU) (%)		E/GDP	E/POP	E(2005) (%)		E(BAU) (%)		E/GDP	E/POP
	2020	2050	2020	2050	2050	2050	2020	2050	2020	2050	2050	2050
TOTAL	3.9	-49.5	-17.2	-71.4	73.3	1.4	2.9	-50.5	-18.0	-72.0	71.8	1.4
OECD	-10.9	-49.9	-13.5	-54.0	89.0	4.8	-15.6	-69.5	-18.0	-72.0	54.2	2.9
NON	17.7	-49.2	-19.7	-78.8	63.1	0.9	20.1	-32.9	-18.0	-72.0	83.3	1.2
US	**-11.3**	**-50.0**	-13.3	-53.2	101.6	6.9	**-16.1**	**-70.1**	-18.0	-72.0	60.8	4.1
EU	**-12.1**	**-50.0**	-12.8	-51.2	74.2	3.7	**-17.3**	**-71.3**	-18.0	-72.0	42.6	2.1
CHINA	**36.1**	**-49.3**	-21.0	-84.0	65.9	1.7	**41.2**	**-11.3**	-18.0	-72.0	115.3	3.0
INDIA	**18.1**	**-49.7**	-19.8	-79.2	39.6	0.3	**20.8**	**-32.3**	-18.0	-72.0	53.3	0.4

	POL 3: EQUAL EMIS/GDP IN 2050						POL 4: EQUAL EMIS/POP IN 2050					
	E(2005) (%)		E(BAU) (%)		E/GDP	E/POP	E(2005) (%)		E(BAU) (%)		E/GDP	E/POP
	2020	2050	2020	2050	2050	2050	2020	2050	2020	2050	2050	2050
TOTAL	3.3	-50.7	-17.7	-72.1	71.6	1.4	2.3	-50.7	-18.5	-72.1	71.7	1.4
OECD	-13.2	-59.5	-15.7	-62.8	72.0	3.9	-19.3	-85.2	-21.6	-86.4	26.3	1.4
NON	18.7	-42.5	-19.0	-76.0	71.4	1.0	22.3	-18.6	-16.5	-66.0	101.1	1.4
US	**-14.8**	**-64.5**	-16.7	-66.8	72.1	4.9	**-20.8**	**-89.7**	-22.6	-90.4	20.8	1.4
EU	**-12.5**	**-51.6**	-13.2	-52.8	71.8	3.6	**-19.9**	**-81.6**	-20.5	-82.0	27.4	1.4
CHINA	**36.8**	**-44.3**	-20.6	-82.4	72.5	1.9	**34.9**	**-58.2**	-21.7	-86.8	54.4	1.4
INDIA	**24.3**	**-9.1**	-15.6	-62.4	71.5	0.6	**42.9**	**112.8**	-3.0	-12.0	167.4	1.4

Summary of the four burden sharing scenarios discussed in the main text. In the top row of boxes, emissions are reported in Pg CO_2 per year, GDP is in trillion USD, and population is in millions. BAU projections are from the EIA (see footnote 14). In all panels, emissions per GDP and emissions per capita are reported in Pg CO_2 per million USD and Pg CO_2 per person, respectively. The boxes shaded in blue are the global emissions reductions in 2050 relative to 2005 levels (same in all scenarios). The boxes shaded in grey indicate which equity metric is aligned in each scenario and the value of that metric in 2050. Bold blue type highlights US emissions and bold black type highlights emissions in other key regions.

Table 2

2020		BAU	BASIC	NO INTL
CARBON BALANCE (Pg CO2/yr)	MITIGATION GOAL	-	1.0	1.0
	BANK	-	0.8	0.6
	EFF MITIGATION	-	1.8	1.6
	ENERGY SYSTEM	-	-0.6	-1.2
	(POWER)	-	(-0.5)	(-1.1)
	OFFSETS	-	-1.2	-0.4
GENERATION BY TECHNOLOGY (TWh)	COAL	2183	11778	1151
	NATURAL GAS	714	694	700
	CCS	15	97	158
	NUCLEAR	876	940	1018
	RENEWABLES	708	878	1336
	TOTAL	4496	4387	4363
GENERATION DIFFERENCE FROM BAU (TWh)	COAL	-	-405	-1032
	NATURAL GAS	-	-20	-14
	CCS	-	82	143
	NUCLEAR	-	64	142
	RENEWABLES	-	170	628
	TOTAL	-	-109	-133
IMPLIED CAPACITY CHANGE FROM BAU (GW)	COAL	-	-57.8	-147.3
	NATURAL GAS	-	-3.8	-2.7
	CCS	-	11.7	20.4
	NUCLEAR	-	8.1	18.0
	RENEWABLES	-	48.5	179.2
	TOTAL	-	-	-
C PRICE	($/t$CO_2$)	-	31.7	52.1
GDP CHANGE	(%)	-	-0.3	-0.2

Summary of required abatement and energy system transformation in 2020 under the Waxman-Markey bill as projected by two different simulations conducted by the US Energy Information Administration (see footnotes 16-17). The top row of boxes shows that the required abatement (difference from BAU emissions) varies between 1.6-1.8 Pg CO_2 per year when banking is included. The burden on the energy system varies between 0.6 and 1.2 Pg CO_2 per year (0.5 and 1.1 Pg CO_2 per year in the power sector) depending on the underlying assumptions about offsets (see text for discussion). The rows of boxes below this top row show the transformation in generation technology projected by this analysis, the implied changes in installed capacity relative to BAU, and the projected allowance prices and GDP impacts of the bill. All numbers appear as reported by EIA, except the implied capacity changes that are calculated from the generation numbers directly, using fixed capacity factor assumptions (see footnote 18).

BROOKINGS
The Brookings Institution
1775 Massachusetts Ave., NW
Washington, D.C. 20036
brookings.edu