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THE HARVARD PROJECT ON INTERNATIONAL CLIMATE AGREEMENTS

The goal of the Harvard Project on International Climate Agreements is to help identify key design elements of a scientifically sound, economically rational, and politically pragmatic post-2012 international policy architecture for global climate change. It draws upon leading thinkers from academia, private industry, government, and non-governmental organizations from around the world to construct a small set of promising policy frameworks and then disseminate and discuss the design elements and frameworks with decision-makers. The Project is co-directed by Robert N. Stavins, Albert Pratt Professor of Business and Government, John F. Kennedy School of Government, Harvard University, and Joseph E. Aldy, Fellow, Resources for the Future. For more information, see the Project's website: http://belfercenter.ksg.harvard.edu/climate

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When Technology and Climate Policy Meet: Energy Technology in an International Policy Context

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Introduction

International efforts to stabilize atmospheric greenhouse gas (GHG) concentrations will ultimately rest on two pillars of climate policy: (1) the architecture and stringency of international agreements to reduce emissions and (2) efforts to speed the development and diffusion of climate-friendly technology. Although emissions mitigation writ large is the central focus of international climate negotiations, technology deployment is a primary means of achieving emissions reductions. The development of cheaper and more effective technologies will be critical for reducing costs and increasing the social and political viability of deep and widespread emissions reductions. Hence, it is important to understand the international context in which new technologies might be used to achieve mitigation and the implications of technological improvements for policy-relevant issues such as regional mitigation costs, the evolution of regional energy systems, and the associated likelihood and extent of national and international mitigation actions.

One avenue for exploring these issues is to conduct experiments using long-term, global, energy-economy-climate models. This is the approach used in this paper. Although there is an extensive literature that explores international policy issues and technology issues individually using these models, efforts to explore these issues in tandem are more recent. One set of authors has focused the interaction between international policy and the rate or direction of technological change, building on a recent tradition of incorporating stylistic representations of technological change in formal energy-economy models (see, for example, Goulder and Schneider 1999; Goulder and Mathai 2000; Nordhaus 2002; Popp 2004; Manne and Richels 2002; Messner 1997). For example, Bosetti *et al.* (2007) and Bosetti *et al.* (2008), use the WITCH model, which includes endogenous representations of technological change, including international spillovers, to explore the interactions between international policy architectures and technological change.[2]

A second avenue of research explores the interactions between international policy and *technology availability*, as opposed to the rate and direction of technological change, without commenting on the sources of technological change or the costs of bringing about technological change. This approach builds on a long line of research that has explored the relative benefits and characteristics of various exogenous portfolios of technology developments (e.g., Clarke *et al.* 2008b; Clarke *et al.* 2007a; Edmonds *et al.*

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[2] In general, these representations of technological change have remained highly stylistic because the processes of technological advance are enormously complex, context specific, and highly resistant to the sorts of simplifications needed to incorporate them into formal economic models (see, for example, Grubb *et al.* 2002; Clarke and Weyant 2002; Loschel 2002; Clarke *et al.* 2006; and Clarke *et al.* 2008 for discussions about capturing endogenous technological change in formal energy–economy models).

2007; GTSP 2000; IEA 2008), often for use in research and development (R&D) planning activities, and to inform broader discussions on the role of technology in addressing climate change more generally (Pacala and Socolow 2004; Hoffert *et al.* 2002). For example, Richels *et al.* (2007) explore the value of technology in an inefficient international context by considering first-best and second-best policy structures under two sets of exogenous technology assumptions: one that limits the deployment of nuclear power and another that limits the deployment of carbon capture and storage (CCS) technology.

This paper follows the path set out in Richels *et al.* (2007). The technologically-detailed MiniCAM integrated assessment model (Kim *et al.* 2006; Clarke *et al.* 2007a; Clarke *et al.* 2008b) was used to create eight climate action scenarios based on four possible exogenous technology futures and two possibilities for international mitigation: full global participation and delayed participation by developing regions. All scenarios lead to a target atmospheric carbon dioxide (CO_2) concentration of 500 parts per million by volume (ppmv) in 2095. These scenarios provide a window into issues surrounding the national and international benefits of new technologies, the regional distribution of technology deployment, and the interactions between technology availability and regional mitigation actions.

With regard to the value of technological developments, these scenarios support the argument that the global benefits of new and improved technologies are probably larger when international participation is incomplete. Further, developed regions benefit disproportionately because more of the abatement burden falls on them, particularly in the near term, if participation by developing regions is delayed.

The scenarios in this study also reinforce the importance of technology diffusion in evaluating national R&D and other technology development programs. The mitigation cost benefits of technology development investments (e.g., R&D investments) in individual regions are strongly linked to the ability to deploy these technologies internationally. By accelerating technology diffusion, the likelihood and extent of international mitigation actions is increased, reducing the abatement burden on the countries that developed the technology. This perspective on the indirect value of investments in technology development is important; many analyses of the mitigation benefits that accrue to domestic R&D expenditures look only at reductions in the domestic cost of mitigation for a given, invariant national emissions pathway.

This analysis also supports the assertion that there are a range of near-term technology-related actions in developing regions—actions that are not formally tied to emissions mitigation—that could be seen to constitute near-term action in a global climate regime. Many climate-friendly technologies provide benefits even absent climate change concerns and might therefore be deployed for non-climate reasons. Improved energy end-use technologies; advances in nuclear power that alleviate concerns over waste, safety, or proliferation; and improvements in the cost and performance of renewable energy technologies such as wind and solar power fall into this category. Under the scenarios that assume delayed climate action by developing countries, increased deployment of these technologies leads to near-term mitigation.

Finally, the scenarios help elucidate the relationship between near-term abatement and expectations about technology availability in the long run. In particular, the scenarios highlight the interactions between mitigation technologies such as bioenergy with CCS that could be used in the long term to achieve negative emissions and global emissions pathways in which concentrations temporarily exceed long-term targets (“overshoot” pathways). Overshoot pathways are beneficial because they expand the range of very low concentration targets that are feasible, and the availability of negative emissions technologies increases the degree of overshoot that is possible. On the other hand, overshoot pathways are troubling because they lead to concentrations that exceed, at least for some period of time, the concentration target to be achieved at a later date. They are therefore associated with potentially greater environmental damage than pathways in which concentrations never exceed the long-term target. In addition, allowing emissions to follow an overshoot pathway in the near term leaves open the possibility that once the concentration target is exceeded, the necessarily steeper emissions declines required later in the century to reach the target may never materialize.

The remainder of this chapter proceeds as follows. The next section discusses the approach to the analysis and provides background on important issues that influence this approach. Subsequent sections discuss the implications of technology development and international participation in terms of emissions and concentrations, the relationship between near-term mitigation and technology deployment, and the uncertain character of future global and national energy systems. The last two sections discuss the value of technology availability in reducing mitigation costs and provide a brief summary and several closing thoughts.

Approach

The scenarios in this paper are constructed using the MiniCAM integrated assessment model. They combine four alternative sets—or “suites”—of assumptions concerning technology evolution over the course of the century with two alternative hypothetical international policy architectures, both of which aim to limit the atmospheric concentration of CO_2 to 500 ppmv in the year 2095.

MiniCAM

MiniCAM (Brenkert *et al.* 2003; Kim *et al.* 2006) combines a technologically detailed global energy-economy-agriculture-land-use model with a suite of coupled gas-cycle, climate, and ice-melt models, integrated in the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC). MiniCAM is directly descended from a model developed by Edmonds and Reilly (1985).

MiniCAM is a global, partial equilibrium model disaggregated into fourteen geopolitical regions. Energy, agriculture, forestry, and land markets are integrated with representations of unmanaged ecosystems and the terrestrial carbon cycle. MiniCAM thus produces outputs that include not only emissions of fifteen GHGs and aerosols but also agricultural prices, land use, and stocks of terrestrial carbon. The model does not attempt to address international trade in goods and services other than energy and agriculture and does not consider bilateral trade issues.

MiniCAM is solved on a fifteen-year time step and is designed to examine long-term, large-scale changes in global and regional energy systems, with a focus on the impact of energy technologies.[3] It provides substantial energy-sector detail in comparison to other integrated assessment models. Of particular relevance to this study, MiniCAM takes the availability of technology to be exogenous. This means that the scenarios considered here do not address important issues associated with the relationship between mitigation and technological change. The exogenous technology assumption can be interpreted as assigning the majority of technological change to sources that are not particularly influenced by mitigation actions and to associated changes in markets for technology (see Clarke *et al.* 2006 and Clarke *et al.* 2008 for more on this subject).

The scenarios in this paper were developed using the version of MiniCAM that was used to examine scenarios of GHG emissions and concentrations as part of the United States Climate Change Science Program (CCSP). Extensive documentation of the energy demand and technology assumptions can be found in Clarke *et al.* (2007a) and Clarke *et al.* (2007b). Of particular interest for the purposes of this paper, the scenarios assume—as do many current scenarios—a gradual shift of economic activity and emissions from the developed to the developing world over the course of the century.

Technology suites

Four technology evolution pathways, or technology suites, are explored in these scenarios (Table 1). Each of the four suites is defined by developments in eight different technology domains.

Table 1. Definitions for Four Technology Suites

Technology Suite Components*	Technology Suites			
	Reference (REF)	Advanced (ADV)	Bioenergy, CCS & Storage, Hydrogen (BIO/CCS)	Renewable, Nuclear, and Efficiency (RNE)
CCS (CCS)	Reference (not allowed)	Advanced	Advanced	Reference (not allowed)
Bioenergy	Reference (no purpose-grown bioenergy crops)	Advanced	Advanced	Reference
Hydrogen	Reference	Advanced	Advanced	Reference
End-use energy efficiency	Reference	Advanced	Reference	Advanced
Wind Power	Reference	Advanced	Reference	Advanced
Solar Power	Reference	Advanced	Reference	Advanced
Nuclear Power	Reference (no new builds)	Advanced	Reference (no new builds)	Advanced

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[3] Documentation for MiniCAM can be found at www.globalchange.umd.edu/models/MiniCAM.pdf/.

Geothermal Power	Reference	Advanced	Reference	Advanced

[*] Technology descriptions are similar to those documented and discussed in Clarke *et al.* (2008b). Explicit technology assumptions are documented in the input data files to MiniCAM and are available upon request.

Each technology domain is associated with a reference technology case and an advanced technology case. The approach to the advanced and reference cases varies among the technology domains. For solar power, geothermal power, wind power, and hydrogen, the reference and advanced cases are distinguished by different assumptions about technology cost and performance. The advanced cases assume greater and more rapid cost and performance improvements over the century than the reference cases.

Nuclear power and CCS are treated differently. Under reference case assumptions, neither is allowed to deploy beyond today's levels; under advanced case assumptions both technologies play a greater role based on mainstream evolutions of cost and performance over time. Several studies have concluded that both of these technologies would be deployed at significant levels under any reasonable range of cost and performance assumptions if a long-term climate goal such as the goal modeled in this paper is adopted. The issues surrounding these technologies have less to do with cost and performance, *per se*, and more to do with their fundamental availability, which in turn is based on technology and institutional structures. For example, although there are uncertainties regarding the cost of nuclear power, the main concerns regarding widespread deployment (and cost) are associated with waste, safety, and security. The uncertainties regarding CCS revolve around the long-term reliability of underground storage, but perhaps more importantly stem from the infrastructural and institutional issues that will have to be addressed to develop an entirely new infrastructure for transporting and injecting gas streams underground.

Bioenergy is treated in a similar fashion to nuclear power and CCS. The reference technology case assumes no dedicated bioenergy crops, while the advanced technology case assumes that large-scale production from dedicated cellulosic feedstocks is viable over the long term. Without technology for using cellulosic feedstocks, the negative consequences of bioenergy production—particularly taking into account the effect of deforestation to clear land for production—could put a significant long-term brake on this option. Hence, the reference case captures a world without breakthroughs in bioenergy production and therefore highly limited deployment.

Bioenergy can be considered a zero emissions fuel with respect to direct emissions. However, several authors, including Searchinger *et al*. (2008) and Crutzen *et al.* (2008) have raised questions about the indirect effect of bioenergy production on deforestation rates, crop prices, and non-CO_2 GHG emissions. Indirect emissions are addressed in MiniCAM, which accounts for agriculture, land use, land cover, and terrestrial carbon stocks and flows.[4] In this analysis, all anthropogenic carbon emissions, be they from

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[4] Note that we do not consider non-CO_2 GHG emissions in this paper, though these are tracked in MiniCAM. Similarly, MiniCAM tracks agricultural and forest product prices, which are also not reported in this paper.

fossil fuel and industrial sources or land-use change, are treated equally—that is, they receive the same carbon price. Thus, in all of the policy regimes considered in this analysis, afforestation programs are an important component of the technology response. Since energy-sector technology is the focus of this paper, discussion of the potential roles of non-energy technologies is left for future papers.

When both CCS and bioenergy are available technology options they can be applied in combination to provide electric power with negative emissions. Since biofuels derive their carbon from the atmosphere, applying CCS technology to a power plant that uses biofuels[5] has the net effect of removing CO_2 from the atmosphere. In a context where the potential exists to temporarily overshoot target concentration levels, this combination of technologies can have important implications for emissions trajectories over time.

Energy end-use technologies are treated differently. The reference and advanced technology cases assume different rates of exogenous improvement in the relationship between end-use service demands in the transport, buildings, and industry sectors—irrespective of policy or prices. Hence energy consumption is lower in the advanced technology scenarios than in the reference scenarios, irrespective of policy. A large literature argues that end-use technology choices are rife with market failures—the advanced technology scenarios assume an ability to overcome some of these barriers, as well as to improve technology.

Based on these reference and advanced technology cases across technology domains, the four technology suites can be described as follows. The reference technology suite (REF) is based on reference case assumptions in all technology domains. This is a pessimistic scenario since it assumes that GHG reductions must be achieved using currently expensive technologies such as wind and solar power along with reductions in energy services. The advanced technology suite (ADV) is based on advanced assumptions in all technology domains. It represents the most optimistic view of the future. Between the reference and advanced technology suites are two intermediate suites. One of them (RNE) assumes advances in technologies that are broadly in use today, such as energy end-use technologies, nuclear power, solar power, and wind power; it might be thought of as a “known technologies” suite. A second (BIO/CCS) uses reference case assumptions in these technology areas, but allows for the deployment of newer, largely untested technologies such as advanced bioenergy, CCS, and hydrogen.

The technology assumptions in the scenarios are exogenous. In other words, the analysis is silent on the means by which each of these technology suites emerges. It is agnostic as to whether technology advances, relative to the reference technology suite, represent the fruits of intensive and potentially expensive research campaigns, learning-by-doing, spillovers from other industries, or a serendipitous process of scientific discovery.[6] If technology advances depend on intensive R&D efforts, then all associated costs would

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[5] This option assumes that biomass can be gasified and burned in an integrated combined cycle power plant with CCS.

[6] Again, see Clarke *et al.* 2006 and Clarke *et al.* 2008 for a discussion of the implications of different modeling approaches.

have to be added to the direct mitigation costs computed in the scenarios to obtain the total cost of achieving a desired emissions mitigation result. In this exercise, however, no attempt is made to associate research investments with particular technology outcomes.

Hypothetical international policy architectures

This analysis focuses on a single potential climate goal: namely, limiting the concentration of atmospheric CO_2 to 500 ppmv in the year 2095. As none of the technology suites considered in this paper by themselves result in an atmospheric concentration that is 500 ppmv or less in the year 2095, policies that explicitly limit emissions are required to achieve this outcome.

The scenarios do not require that the concentration limit be binding before 2095: that is, concentrations can exceed 500 ppmv at any time prior to 2095. Emissions pathways that allow atmospheric CO_2 concentrations to exceed the long-term goal for some portion of the time between the adoption of the target and the target date are known as “overshoot” trajectories. By contrast, most mitigation scenarios in the literature are constructed so that the atmospheric CO_2 concentration limit that applies in the final period is never exceeded (see, for example, the scenarios developed in Clarke *et al.* 2007a). In such a “not-to-exceed” framing of the concentration limit, emissions are constrained such that the atmospheric concentration rises to the limit and is maintained at that level in perpetuity thereafter (note that any scenario in which concentrations *fall* is, by construction, an overshoot trajectory since it implies that concentrations must, for at least some period of time, have exceeded the level they will reach in the long term). The implications of overshoot for these scenarios will be discussed in more detail later in this chapter.

Two hypothetical policy architectures are used in this analysis to reach the 2095 goal. One approach reflects an idealized setting in which a price is imposed on all carbon emissions, from all sources everywhere, and raised at a rate that minimizes the total cost to the world economy of achieving that goal. While such a scenario is not likely, it provides a benchmark against which to compare other, less perfect international policy architectures. Scenarios based on this architecture are referred to as FULL participation scenarios.

A more realistic policy architecture is one in which different nations take different levels of action to mitigate carbon emissions, leading to pricing that varies across regions over time. In the DELAY scenarios, nations included in Annex I to the United Nations Framework Convention on Climate Change (UNFCCC) (United Nations 1992) as well as South Korea, begin efforts to mitigate emissions in 2012, but other regions do not follow suit until later. Table 2 shows the dates when emission limits first apply to each of the MiniCAM’s fourteen regions in the DELAY scenarios.

Stabilization of CO_2 concentrations implies a rising price of carbon. It is assumed that the Annex I plus South Korea group, and other regions as they join, share a common price of carbon and apply that price to all emissions from all sources. Since the coalition price is doubling regularly, new members of the coalition would experience an economic shock if they introduced a carbon price that was instantaneously set at the same level as the then current price in the mitigating coalition. Therefore this analysis assumes that the initial carbon price in a region that begins emissions mitigation after the year 2012 is below the price shared by the original members of the coalition. It is further assumed that the initial price assigned to a new entrant is based on gross domestic product (GDP) per capita relative to the United States in the year 2000. The price of carbon in regions that accept emissions limitations later in the century gradually rises to that of the Annex I group.

Table 2. Year in which carbon emissions limitations are first imposed in each of the 14 MiniCAM regions

MiniCAM Region	Year in which carbon emissions limitations are first imposed
United States	2012
Australia & New Zealand	2012
Canada	2012
Western Europe	2012
Eastern Europe	2012
Japan	2012
Former Soviet Union	2012
Korea	2012
China	2020
Latin America	2035
Middle East	2035
Other South and East Asia	2035
India	2050
Africa	No emissions limitations are imposed

Summary of the scenarios

Combining the two policy architectures with four technology suites leads to eight scenarios (Table 3). By comparing and contrasting scenarios, it is possible to observe the relative influences of international participation and technology in shaping the future development of the global energy system and in determining the cost of meeting the hypothetical atmospheric CO_2 limit in 2095.

Table 3. Combinations of Technology Suites and Hypothetical Policy Architectures Examined in this Paper

		Alternative Technology Suites			
		REF	RNE	BIO/CCS	ADV
Alternative Emissions Limitation Regimes	FULL	●	●	●	●
	DELAY	●	●	●	●

Emissions and concentrations: the implications of technology, participation, and overshoot

A brief overview of the implications of overshoot

Before discussing the implications of technology and participation in an international regime, it is useful to first discuss the implications of overshoot for the scenarios. These implications are important because overshoot pathways create the potential for greater variation in emissions and concentration pathways, and greater variation in climate impacts, than is possible with a not-to-exceed formulation.[7]

The potential impacts and role of overshoot pathways can be perceived in two ways. On the one hand, overshoot pathways are troubling because they lead to concentrations that exceed, at least for some period of time, the concentration target to be achieved at a later date. They are therefore associated with potentially greater environmental damage during the period in which concentrations are above the eventual goal. In addition, allowing emissions to follow an overshoot pathway leaves open the possibility that once the concentration target is exceeded, the necessarily steeper emissions declines required later in the century to reach the target may never materialize.

On the other hand overshoot pathways can facilitate the adoption of lower long-term concentration limits than are be achievable under a not-to-exceed approach. For some stringent concentration limits, overshoot pathways may be the only realistic option for meeting the long-term goal. The 350 ppmv emissions concentration pathway developed by Wigley, Richels, and Edmonds was an overshoot pathway that featured negative global carbon emissions in some years. Work by Van Vuuren *et al.* (2007) shows that limiting long-term radiative forcing to 2.6 watts per square meter (W/m^2) entails limiting atmospheric CO_2 concentrations in the year 2100 to below current levels. Van Vuuren *et al.* achieve this outcome by first overshooting the long-term target and then employing steep reductions in the late 21st century through the large-scale deployment of biomass-based electricity production with CCS to achieve negative global emissions.

If technologies capable of delivering negative global carbon emissions—such as the combination of bioenergy and CCS explored in these scenarios—become available, human society will have the option to move atmospheric CO_2 concentrations arbitrarily down. This potential capability raises still more questions about the long term: namely, at what concentration should humankind choose to maintain the atmosphere? Should emissions trajectories be compared in terms of the maximum GHG concentration level or temperature increase they produce rather than in terms of a long-term stabilization goal? No attempt is made to answer this question here; it is left for a deeper exploration of the implications of overshoot pathways. The key for interpreting the scenarios in this paper is

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[7] However, it must be remembered that even with a not-to-exceed formulation, variation in emissions, concentrations, and climate change exist (Wigley, Richels, and Edmonds 1996). Furthermore, there are limits to overshooting a goal, depending on the options for reducing emissions in the second half of the century. The degree of overshoot therefore depends on the suite of technologies that is anticipated to be available in the future, especially in the post-2050 future, as we discuss in more detail below.

that overshoot pathways allow for greater intertemporal flexibility in emissions reductions than not-to-exceed scenarios.

Overshoot, technology, and global emissions and concentrations

This section focuses on the emissions and concentration pathways that emerge from the FULL participation scenarios. Economic implications generally are addressed in a later section, but it is useful here to briefly touch on the carbon prices associated with different scenarios because of their relationship to emissions and concentration pathways over time. Limiting the atmospheric CO_2 concentration to 500 ppmv in 2095 is accomplished by imposing an exponentially rising price on carbon in all regions and all emitting activities in the FULL participation scenario, where all nations join in global mitigation efforts from the outset. Not surprisingly, the price path is highest for the REF technology suite and lowest for the ADV technology suite with costs for the other two technology suites falling in between (Figure 1).[8]

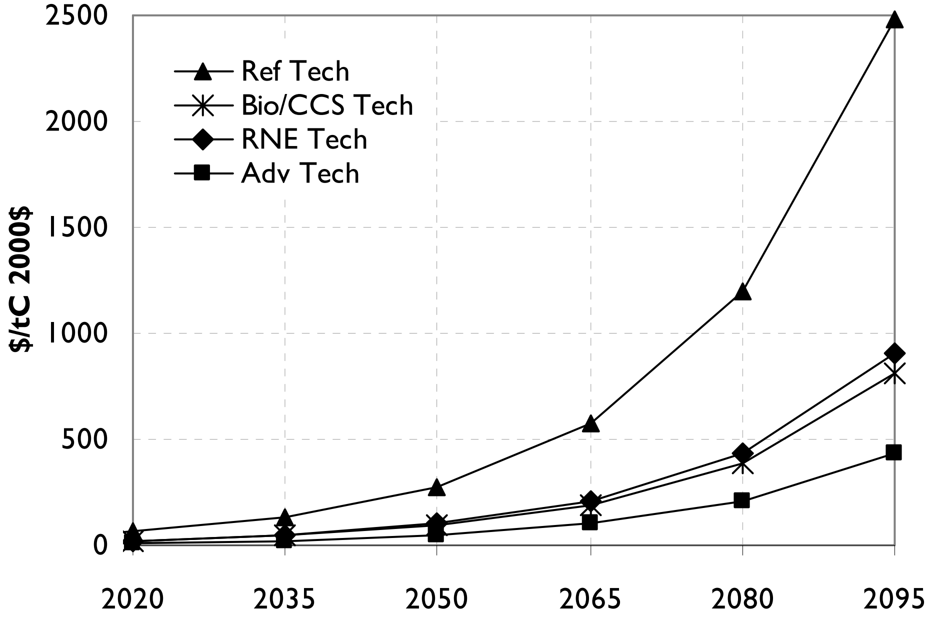

Figure 1: Carbon Price Paths that Limit Atmospheric CO_2 Concentrations to 500 ppmv for Four Alternative Technology Suites under FULL International Participation from 2012 Onward

These results illustrate the importance of expectations regarding technology availability in shaping near-term carbon prices. Because limiting atmospheric CO_2 concentrations

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[8] The carbon prices provide some insight into the contrasting arguments about whether it is possible to achieve climate goals with today's technology. Without CCS, new nuclear power plants, or dedicated bioenergy crops, the REF technology suite can roughly be interpreted as a "known technologies" suite. Hence, the scenarios support the argument that climate goals can be met with "known technologies" (Pacala and Socolow 2004). However, the economic cost is substantially higher than if more advanced technologies become available. Therefore, the scenarios also support the argument that the development of advanced energy technologies is important to the success of the enterprise (Hoffert *et al.* 2002).

involves limiting global carbon emissions over the entire century, the long-term future and present are tightly coupled. The assumption of intertemporal cost-effectiveness along with complete foresight leads to a simple intertemporal carbon price pathway with the price in each period directly linked to the price in the previous period by the rate of interest. The implication is that near-term prices depend as much on expected technology availability in the long term as they do on actual technology availability in the near term. While it is impossible to anticipate technology availability a half century or more into the future—or indeed to predict with certainty any of the other variables that define our scenarios—it is clear that near-term actions depend on *expectations* about the long term in a way that distinguishes climate change from other environmental issues, such as acid deposition or local air quality, with which society has dealt in the past. There are, of course, other interactions between near-term mitigation and carbon prices, on the one hand, and long-term technology expectations on the other. For example, near-term mitigation actions can influence technology development through induced R&D and learning-by-doing (Goulder and Mathai 2000; Grubb *et al.* 1995). Nonetheless, emissions reductions are not the only drivers of improvement in carbon-friendly technologies, and the relationship between mitigation and technology development will not alter the fundamental linkage between long-term expectations and near-term action.

Technology influences not only carbon prices, of course, but also the global emissions and concentration pathways that might be followed to meet a particular long-term target (Figures 2 and 3). To understand the influence of technology on near-term emissions, it is useful to distinguish between the influence of near-term technology availability and long-term technology availability. The influence of long-term technology in these scenarios is highlighted by the presence of CCS coupled with bioenergy production. The assumption that a radical technology option such as this one will be available in the future puts less pressure on near-term abatement efforts and allows for higher near-term emissions: The more that can be done cheaply in the future, the less it makes sense to do today. The combination of CCS and bioenergy technology allows for negative emissions in the far future, and thus diminishes pressure on near-term emissions reductions in both the ADV and BIOCCS technology suites.[9]

Near-term technology advances have the opposite effect. Lower near-term technology costs and greater availability imply larger near-term reductions. In these scenarios, the major near-term options are improved energy end-use technologies and nuclear power. The advanced end-use assumptions are based on the notion that (1) improvements to end-use technologies will be deployed irrespective of climate policy and (2) many options can provide meaningful near-term emissions reductions. The advanced nuclear assumptions are based on the notion that waste, security, and safety concerns do not limit the near- or

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[9] The presence of CCS alters the way in which bioenergy is used. A great deal of research has focused on the use of bioenergy to produce liquid fuels, primarily for transport. At lower carbon prices, this approach proves to be dominant. However, when CCS is available and carbon prices rise, bioenergy is predominantly deployed in conjunction with electric power generation. Such market forces could emerge if CCS is available and the net negative emissions of the bioenergy and CCS technology combination were appropriately rewarded.

long-term deployment of nuclear power. These assumptions result in lower near-term emissions in both the RNE and ADV scenarios.

The resulting emissions pathways reflect the interactions between near- and long-term technology availability. The BIOCCS scenario has the highest near-term emissions because emissions reductions are pushed to the future. In contrast, near-term emissions are lower in the ADV scenario because of low-cost, near-term end-use options. The REF scenario has neither of these options. Its near-term emissions are on the low side because the lack of improved mitigation options results in higher carbon prices that push emissions down through more costly means.

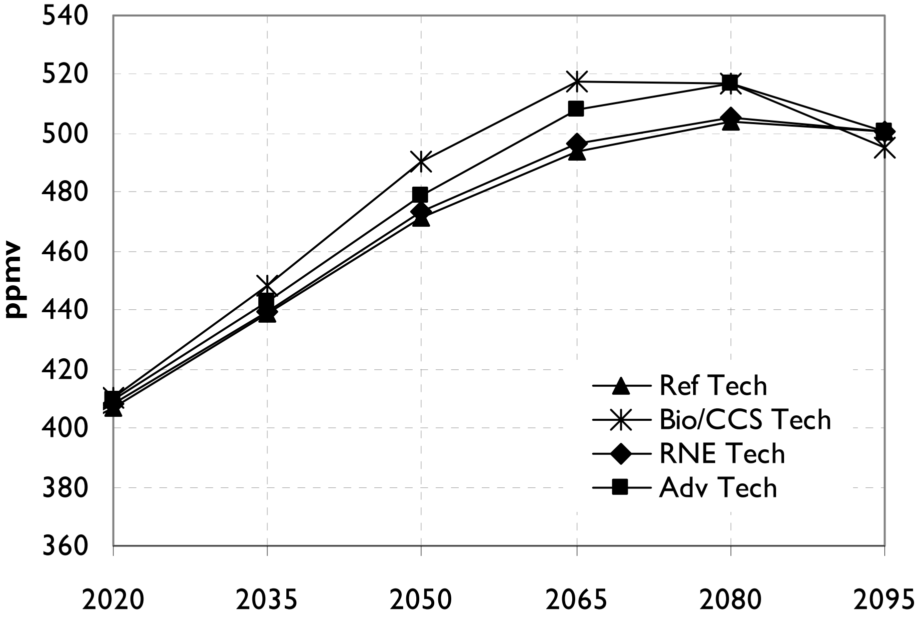

Figure 2: CO_2 Concentration Paths for Four Alternative Technology Suites under FULL International Participation from 2012 Onward

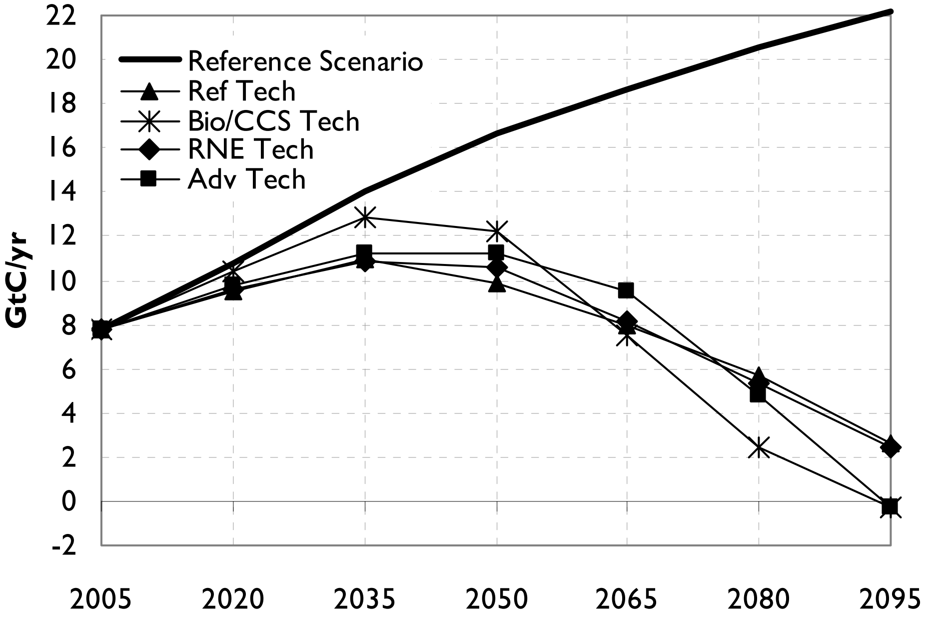

Figure 3: Carbon Emissions Paths that Limit Atmospheric CO_2 Concentrations to 500 ppmv for Four Alternative Technology Suites Under FULL International Participation from 2012 Onward

Delayed participation, technology, and regional emissions mitigation

Previous sections discuss the role of technology assuming full international participation in a global GHG control regime. This section compares the results from these idealized scenarios with outcomes under a hypothetical international control regime with delayed participation. We focus here on three observations. First, the variation in global carbon emissions across technology regimes is significantly larger than the variation across different international regimes for achieving a given concentration goal (Figure 4). This is a consequence of the discipline that the carbon cycle imposes on possible pathways to a given concentration target. While some flexibility exists in shifting emissions forward and backward in time—with a given technology regime, that ability is limited. Emission shifts across time depend on available technology. That is, the ability to sharply reduce emission in the BIOCCS technology suite implies higher near-term emissions as compared with other technology suites. It is worth noting that the ability to overshoot and return to the long-term concentration target brings the time-shift of emissions into relief, but the effect is present even with a not-to-exceed formulation of the concentration limit.

Second, although the global emissions pathway for achieving a given concentration target is less sensitive to the international policy environment than to technology availability, the same is not true at the regional scale. With REF technology, the DELAY international policy architecture results in India having higher emissions relative to the "no climate policy" reference scenario (Figure 5). This is the result of emissions leakage from participating regions: Their mitigation efforts result in lower demand, and hence lower international prices, for fossil fuels. This in turn leads to increased fuel use and higher emissions in non-participating regions. Only after India joins the set of emissions mitigating regions do its emissions begin to decline. In contrast, emissions in the United States decline almost linearly to zero by 2065 under the DELAY international policy architecture (Figure 6). This outcome is dramatically different than the outcome modeled under the FULL participation international policy architecture. In that scenario, which assumes India and all other regions of the world begin emissions mitigation in 2012, United States emissions are approximately two-thirds of 2005 levels in 2065. These results follow from the earlier observation that for a given technology suite there is relatively little ability to shift global emissions mitigation over time. Thus, participating regions are forced to compensate for the emissions mitigation that is not forthcoming from non-participating regions. The availability of improved abatement options over time in the ADV technology suite does substantially mute the shift in burden.

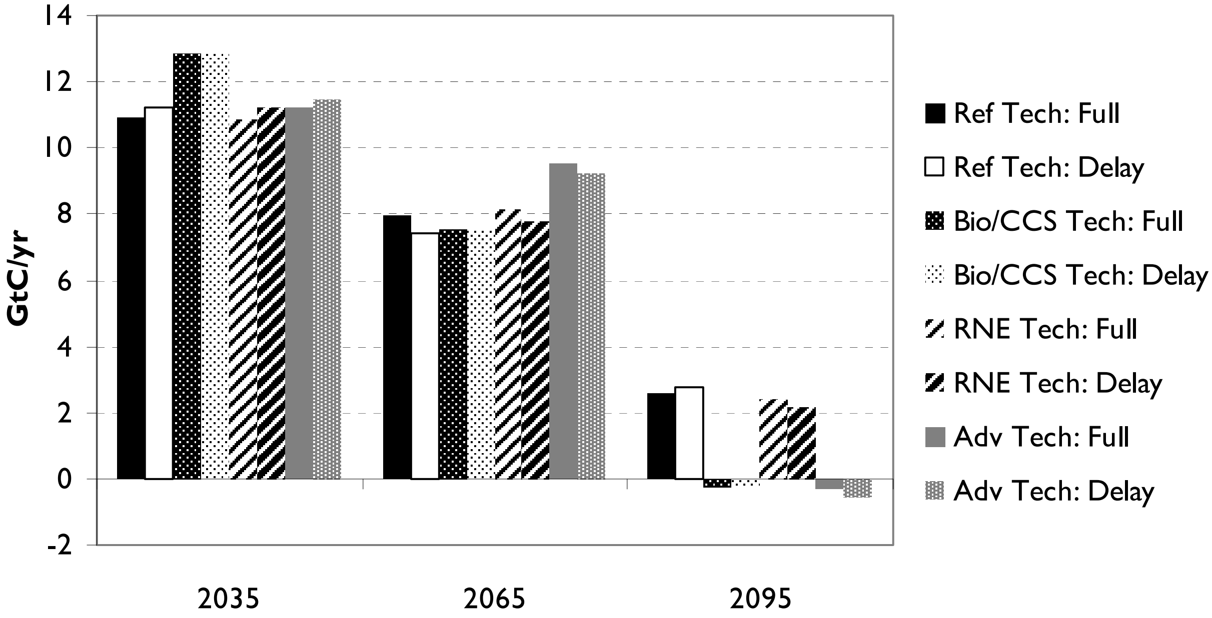

Figure 4: Global Emissions in 2035, 2065 and 2095 across the Eight Atmospheric CO_2 Concentration Limitation Scenarios

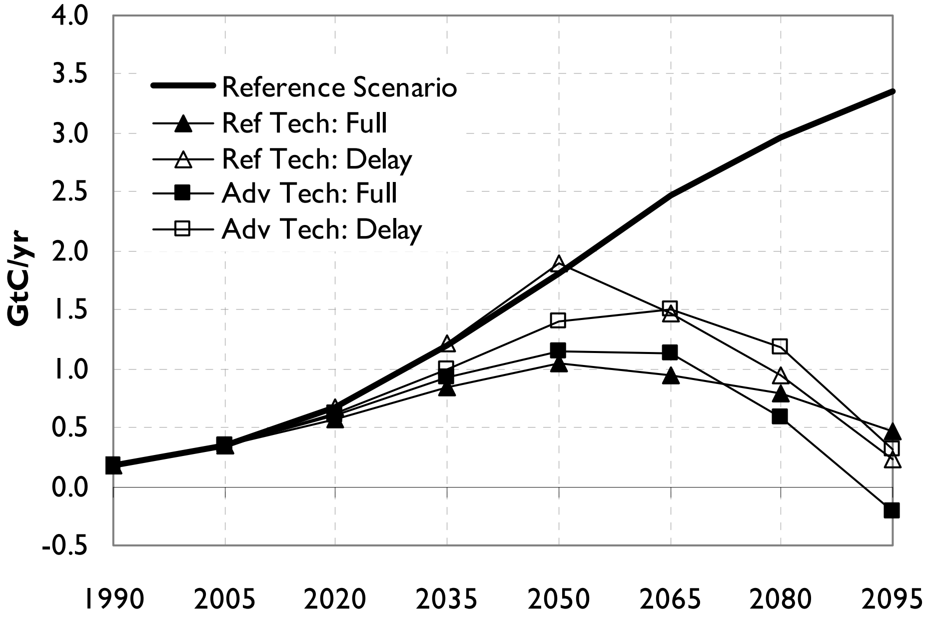

Figure 5: Emissions Pathways in India for Selected Scenarios

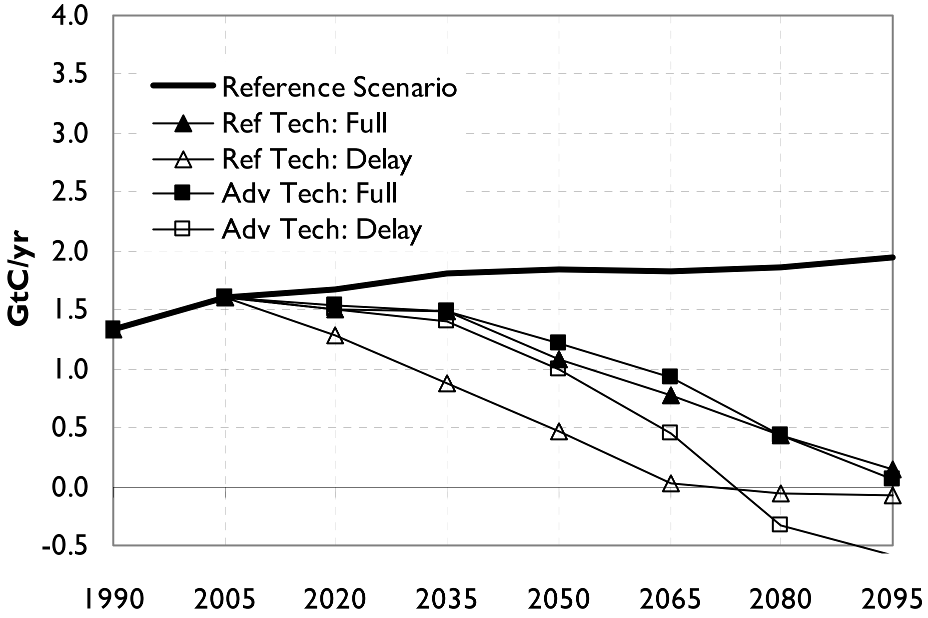

Figure 6: Emissions Pathways in the United States for Selected Scenarios

Third, the availability of near-term abatement options such as nuclear power and end-use technology options allows for some mitigation even in non-participating countries. When the ADV technology suite is modeled, Indian emissions are lower relative to the no-climate-policy reference scenario, even though India is not participating in a climate regime. Under these technologies assumptions, the United States benefits from lower costs to meet a given domestic emissions target, plus some relief in terms of the stringency of that target due to Indian reductions. This result highlights the point that not all mitigation needs to be a function of climate policy—as researchers have noted repeatedly in calling attention to the technological improvements already embodied in reference or “no-policy” scenarios. Although technology cannot solve the challenge of climate mitigation without the impetus of climate policy, accelerated diffusion of currently available technologies could provide a means for achieving near-term emissions reductions in developing countries that are not inclined toward accepting explicit emission-reduction commitments. The mitigation effect in these scenarios is somewhat artificial, due the construction of the reference and advanced technology assumptions for nuclear power and end-use technologies. Nonetheless, the results highlight the potential benefits that could be achieved if developing countries were able to overcome barriers and failures in markets for energy efficiency; develop the technological or institutional structures needed to allow for greater penetration of nuclear power; and take advantage of near-term advances in wind and solar power along with associated technologies for facilitating system integration, such as batteries.

The composition of technology deployment in the near term and long term

Long-term technology evolution

To meet the sorts of long-term goals explored in this paper, fossil fuel technologies that freely emit carbon must be virtually removed from the energy system by the end of the century. A view of the Chinese and United States energy systems in 2095 under all eight of the mitigation scenarios along with the reference scenario (Figure 7 and Figure 8) illustrates this requirement. However, though all the scenarios share this common feature, they lead to otherwise dramatically different energy systems, for reasons that have to do with the evolution of both technology and international policy over the course of the century. This variation illustrates the inherent uncertainty in attempting to forecast how technology might evolve and be deployed to meet a climate goal. Although it is well understood that dramatic change is necessary, the nature of that change is highly uncertain, especially in the far future.

Technology deployment varies in the long run due to both of the dimensions explored in this study: the evolution of technology availability and the evolution of international participation in global mitigation efforts. That deployment varies depending on technology availability is not surprising. In general, the absence of any single technology requires greater contributions from other technologies and additional reductions in energy use. Scenarios with improved end-use technologies rely to a greater extent on energy-use reductions (RNE and ADV), as do higher cost scenarios (REF). On the other hand, scenarios with greater options for low-carbon supply allow for less emphasis on energy-demand reductions (RNE, BIOCCS, and ADV).

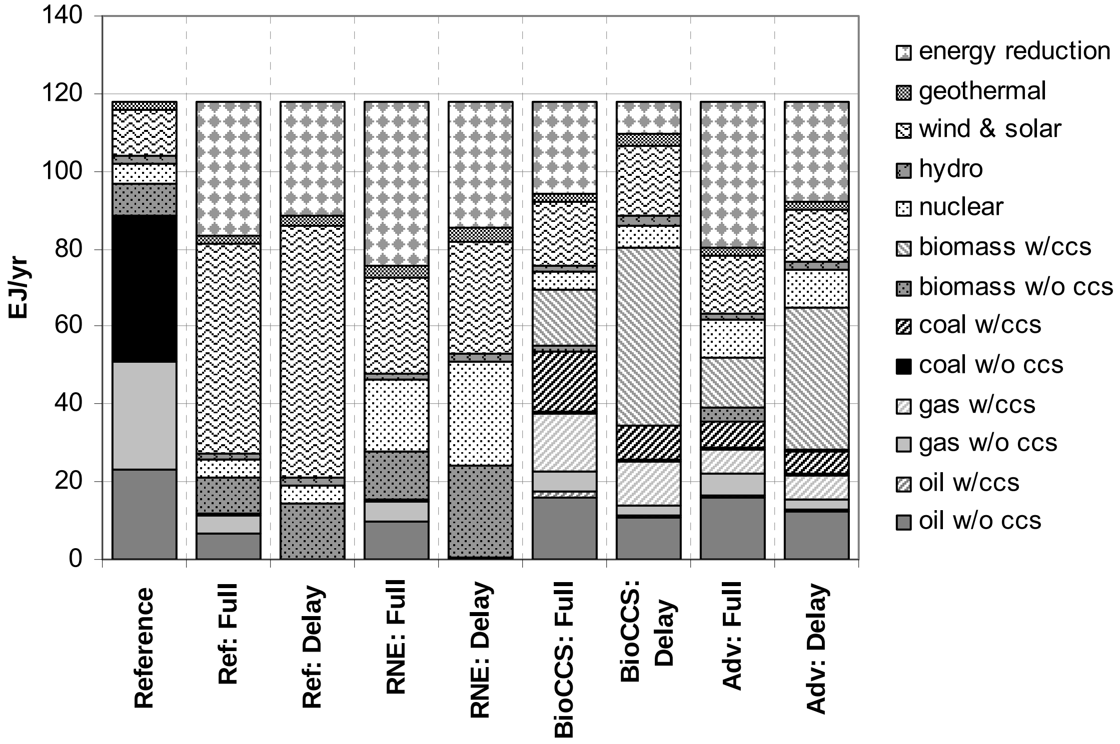

Figure 7: Primary Energy, United States, 2095 for Four Alternative Technology Suites under FULL and DELAY International Policy Architectures

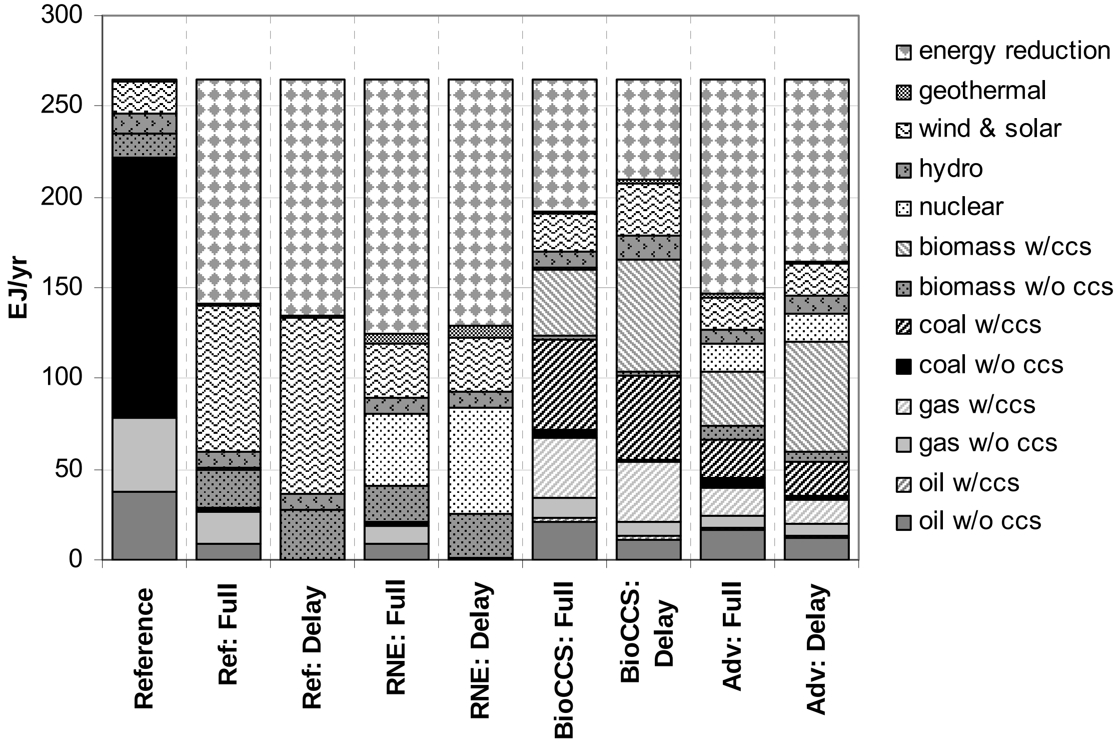

Figure 8: Primary Energy, China, 2095 for Four Alternative Technology Suites under FULL and DELAY International Policy Architectures

International participation influences the long-term composition of energy systems through several avenues. For one, delay increases long-term carbon prices, leading to greater long-term deployment of low or negative emissions technologies across all of the technology suites. Delay also affects long-term technology deployment through any continued differences in participation that may persist through the end of the century. Those countries participating in mitigation will see still higher carbon prices than those that do not participate (Africa in 2095) or those that participate at lower relative carbon prices (India and Latin America in 2095). Finally, the path of investments in technology over the course of the century is influenced by international participation, and some of these effects will linger. Note, for example, the earlier and continued deployment of bioenergy in the REF DELAY scenario relative to the REF FULL scenario (Figures 7 and 9).

Near-term technology deployment in a long-term context

Figure 9 and Figure 10 show the United States and Chinese energy systems in 2035 under the reference scenario and the eight mitigation scenarios. Recall that China has a lower carbon price in 2035 than the United States due to its delayed entrance into the global coalition. In contrast to the results for 2095, which show dramatic variation in the energy supply mix for different scenarios and include widespread deployment of low-carbon energy sources, the results for 2035 reflect the continued influence of the capital stocks, infrastructure, and institutions that existed in 2005. The 2035 composition varies primarily in terms of total production from fossil fuels, which continue to dominate in all scenarios regardless of the technology suite that ultimately becomes available. The contribution from low-carbon energy sources remains small relative to the total size of the energy system.

The primary effects of technology are similar to those observed in the FULL participation scenarios and discussed in a previous section. Expectations regarding future abatement options influence the carbon price, and higher carbon prices lead to greater near-term emission reductions. Given turnover rates in the energy system, much of this near-term mitigation is achieved through energy demand reductions and fuel switching. More effective near-term options also lead to near-term adjustments, particularly energy demand reductions achieved through the increased availability and use of more efficient end-use technologies.

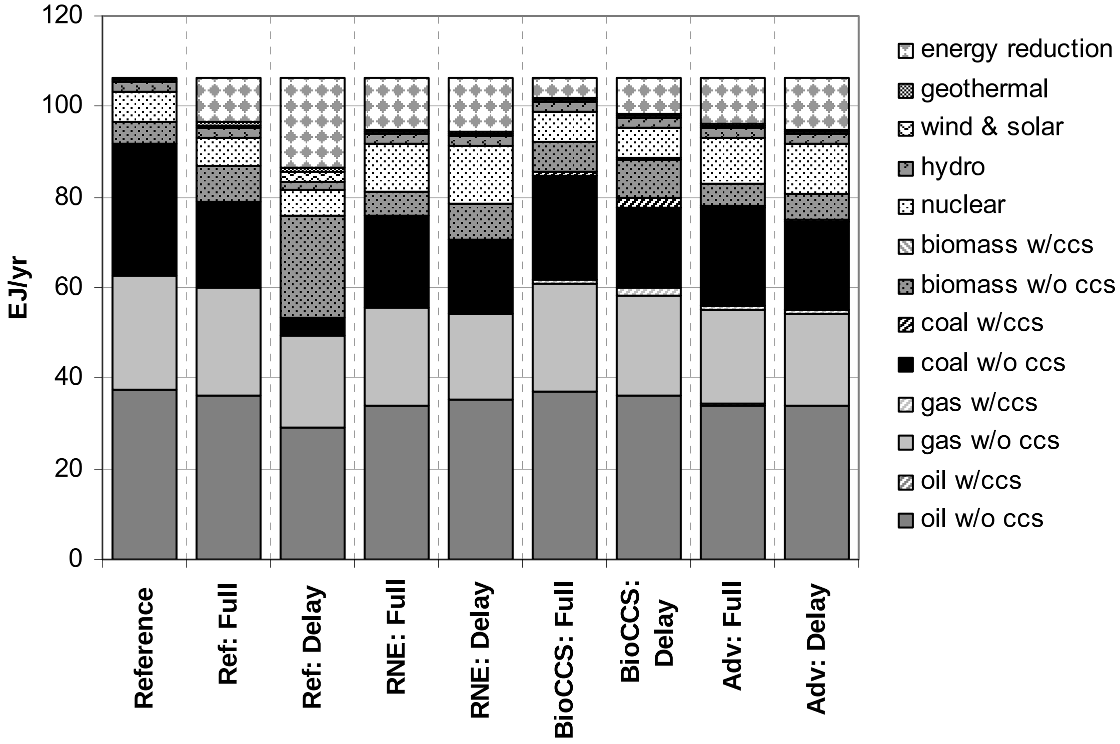

Figure 9: Primary Energy, United States, 2035 for Four Alternative Technology Suites under FULL and DELAY International Policy Architectures

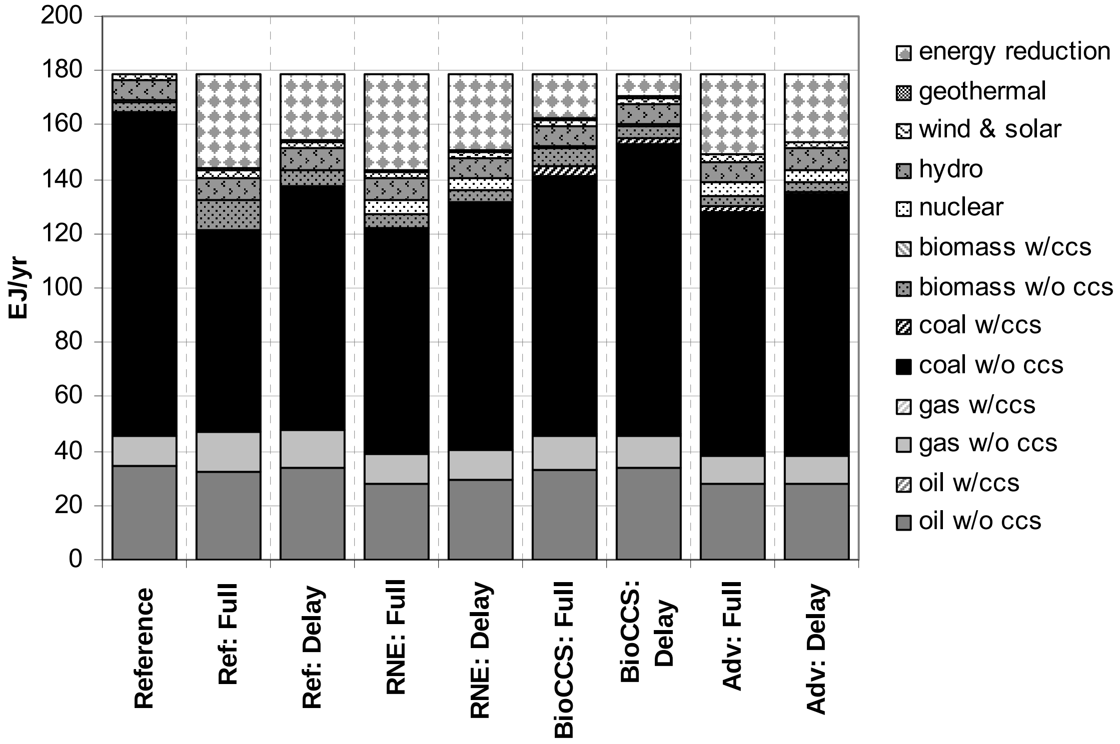

Figure 10: Primary Energy, China, 2035 for Four Alternative Technology Suites under FULL and DELAY International Policy Architectures

Several interactive effects related to delayed participation bear discussion here. First, mitigation efforts are simply more aggressive in the participating countries, and this leads to obvious differences in energy demand reduction and low-carbon technology deployment. Second, asymmetric emissions mitigation will lead to a drop in global fossil fuel prices, pushing consumption toward those countries that are taking no action or little action. This leakage effect is manifest in higher emissions for non-participating countries compared to the reference case (see, for example, Figure 5). Third, the results point to increased use of bioenergy in participating nations relative to a full participation scenario. Bioenergy is produced around the world, but it is the participating nations that will demand bioenergy for climate purposes. To the extent that bioenergy production is associated with emissions from land-use changes, this means that delayed participation involves substantial emissions leakage—not simply through asymmetric fuel prices, but also through the exporting of land-use change emissions for bioenergy production to non-participating countries.

The contrasting composition of energy systems in 2095 and 2035 informs questions regarding the nature and aggressiveness of required near-term technology deployments for meeting the sorts of long-term goals similar to the long-term goal explored in this paper. It is not surprising that the long-term composition of the energy system is highly uncertain and dependent on the availability, cost, and performance of future technology and on the architecture of emissions mitigation policies. How should decision makers *today* respond to this uncertainty and what near-term actions should they take with regard to technology policy, from basic science through deployment policies? What does it mean to begin to lay down the foundation for the future energy system today?

All pathways to stabilization include a gradual movement toward a new and differently composed energy system. Given uncertainty about the long-term character of that system, it should be remembered that the goal of near-term technology-related actions is not simply to reduce emissions through technology deployment. Additional goals of near-term action are (1) to promote investments that will maximize the number of long-term options for mitigation, including R&D and technology deployment to spur innovation and learning; (2) to ascertain which will be the most effective long-term options; and (3) to build the social, institutional, and physical infrastructure needed to support the dramatic changes of the future. Put another way, in addition to mitigating emissions, the near-term focus must be on preparing for a dramatic long-term transformation of the energy system about which we are not fully informed today. The question from the perspective of technology deployment is how long this period of uncertainty might last: How long do we have until the deployment of energy technology must truly reflect the character of the long-term energy system?

The length of this near-term period will depend on a range of factors, including the stringency of the long-term climate goal—clearly it would be shorter for more aggressive long-term goals than those considered in this paper. Though the level of action by 2035 in all the mitigation scenarios here is substantial, and though changes at investment margins increasingly reflect the nature and evolving character of new technology options, much of the near-term action is focused on energy-demand reductions. The deployment of new low-carbon energy sources over the next quarter century remains far below the levels that will eventually be required for long-term stabilization.

On the surface, comparing the level of technology deployment in 2035 to the level in 2095 indicates a large degree of flexibility to alter course moving forward from 2035. In some sense, the die has not been cast with respect to the character of the long-term energy system by 2035. However, this does not mean that the sorts of near-term actions needed to prepare for a long-term transformation have not been undertaken. For any of the long-term futures modeled in this study to emerge beyond 2035, near-term actions must have laid the necessary technological and scientific foundations, resolved some uncertainty regarding optimal choices for future energy systems, and established the social and institutional structures that would allow for dramatic transformations to emerge. An analysis such as this can only hint at the magnitude of these efforts. What it does show, however, is that it is these foundation-laying efforts, along with the deployment of effective near-term technologies such as those associated with energy-use reductions, that constitute near-term action.

Technology, policy, and the cost of emissions mitigation

A range of studies have demonstrated that technology is critical for lowering the costs of addressing climate change. Indeed, technology was identified as perhaps the most important driver of differences in mitigation costs in the mitigation scenarios generated by the United States CCSP (Clarke *et al.* 2007a). Mitigation costs are important not just because they drive welfare impacts for achieving any given long-term climate goal, but also because of their influence on the long-term goals that might be considered socially and politically feasible. The degree of action that countries take to mitigate GHG emissions is in large part a function of the perceived costs associated with different levels of action, regardless of whether that calculation is made qualitatively or using rigorous cost-benefit analysis. This section explores the cost implications of different assumptions about technology availability based on results from the scenarios at both the global and regional levels.

The global benefits of technology

The scenarios in this paper indicate that the global economic benefits of improved technology, in terms of reduced mitigation costs, are greater when policy regimes are less than ideal. Figure 11 shows discounted global mitigation costs over the course of the century across four alternative technology suites under FULL and DELAY international policy architectures. The value of technology can be measured as the difference between mitigation costs with reference technology and mitigation costs with more advanced technology suites. The global cost reduction from advanced technology under a regime of delayed participation approaches twice the magnitude of the global cost reduction when international participation is complete and immediate. In other words, technology development and deployment is an even more important component of the climate policy portfolio if markets for climate mitigation are not fully formed.

Two factors influence this differential impact on mitigation cost. First, in less efficient regimes, costs will be higher irrespective of technology because participating regions will have to exercise abatement options with higher marginal cost earlier than under a more efficient regime. This means costs to achieve any given abatement target will be higher. A second, and more ambiguous, factor is that higher marginal costs in participating regions interact with the suite of technologies that is available for deployment. It is possible that some technologies provide larger benefits for lower or intermediate reductions while others provide larger benefits for deep reductions. This paper has not focused on this dynamic (see Baker *et al.* 2006 for a lengthier discussion of this issue). Here we simply note that the global economic benefits of improved technology are higher when the international policy architecture deviates from full participation.

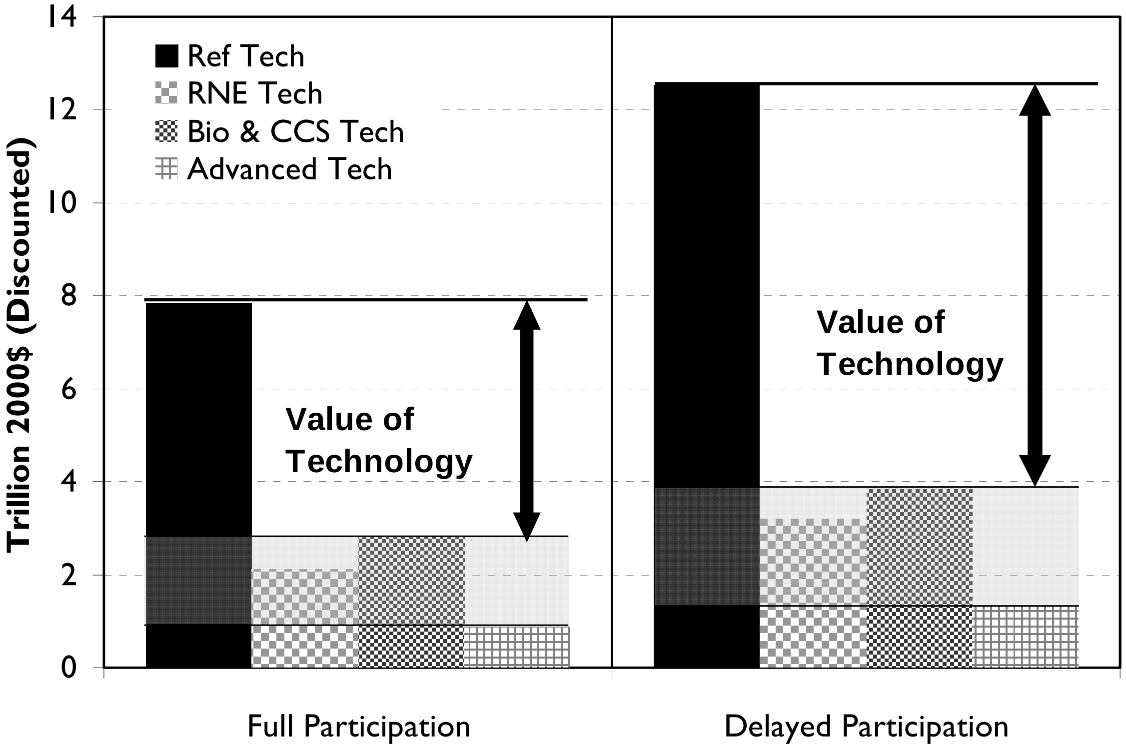

Figure 11: Total Global Present Discounted Mitigation Costs, 2005 through 2095, for Four Alternative Technology Suites under FULL and DELAY International Policy Architectures

The regional benefits of technology

Although global costs are important, most technology R&D activities are conducted at the *national* or *regional* level, and the national benefits to technology advances are usually the basis for justifying these expenditures. Furthermore, though global costs are an important indicator of the social value of technology, the distribution of mitigation costs across regions has an important influence on the degree and distribution of action. Hence, the regional benefits of technology are a relevant unit for analysis.

Unfortunately, it is impossible to determine the ultimate financial effects for any country participating in an international mitigation regime, even within the rarefied environment of an integrated assessment model, without considering the allocation of burdens across regions. The precise mechanisms that are used internationally, from offset crediting programs such as the Clean Development Mechanism (CDM) to technology deployment incentives to full carbon trading, will determine the final burdens carried by individual countries and regions. This analysis is silent on these distributional issues, noting only the global costs.

At the same time, though, it is clear that the value of technology will be higher in the developed regions under delayed participation, assuming a given long-term goal as is assumed in this study. Early participants in a global mitigation regime, generally assumed to be the developed regions, must undertake more abatement to meet a given climate goal under delayed participation than they would under idealized conditions with full participation. As a result, they incur higher costs, because of the larger emissions reductions they must achieve and because achieving these larger reductions requires implementing mitigation options with higher marginal costs. As early participants are expected to be developed countries, they are unlikely to be on the receiving end of financial transfers (such as permit trades or CDM), so they will bear the bulk of near-term global costs. By contrast, developed regions may bear something less than the total global cost in a full participation scenario. In that case, developing regions would bear some costs, although perhaps not their full in-country mitigation costs, depending on the particulars of the burden-sharing regime. Even if the developed countries were to fully compensate developing regions for their mitigation costs under a full participation regime, their near-term costs would still be lower than under a delayed participation regime in which developed countries have to exercise less efficient domestic mitigation measures while the developing regions are delaying participation.

A second element of regional technology value derives from the public goods nature of technology development and diffusion and the public goods nature of reductions in global stock pollutants such as GHGs. There are two mechanisms—a direct effect and an indirect effect—by which domestic R&D activities can alter mitigation costs for the nation conducting them. The direct effect is to reduce the costs of meeting any national mitigation goal, irrespective of international efforts. The indirect effect—the emissions burden effect—is to reduce the mitigation effort required at the national level to meet any given long-term global concentration target by inducing greater emissions reductions internationally; if technology makes mitigation cheaper internationally, it will lessen the national mitigation requirement to meet any long-term climate goal.

The relationship between direct and indirect effects is important because many national-level investments in climate-related R&D are supported by analyses of direct effects. This approach tends to downplay the benefits of international technology deployment and diffusion in justifying domestic R&D activities.

To illustrate the importance of this indirect effect, we conducted an experiment in which we applied the advanced technology assumptions, first only inside the United States and then only outside the United States. The experiment was conducted under the assumption of full global participation, and only the reference technology and advanced technology suites were considered. Comparing global mitigation costs in these two cases (and leaving aside the distribution of burdens) illustrates the relative impacts of US versus international technology deployment.

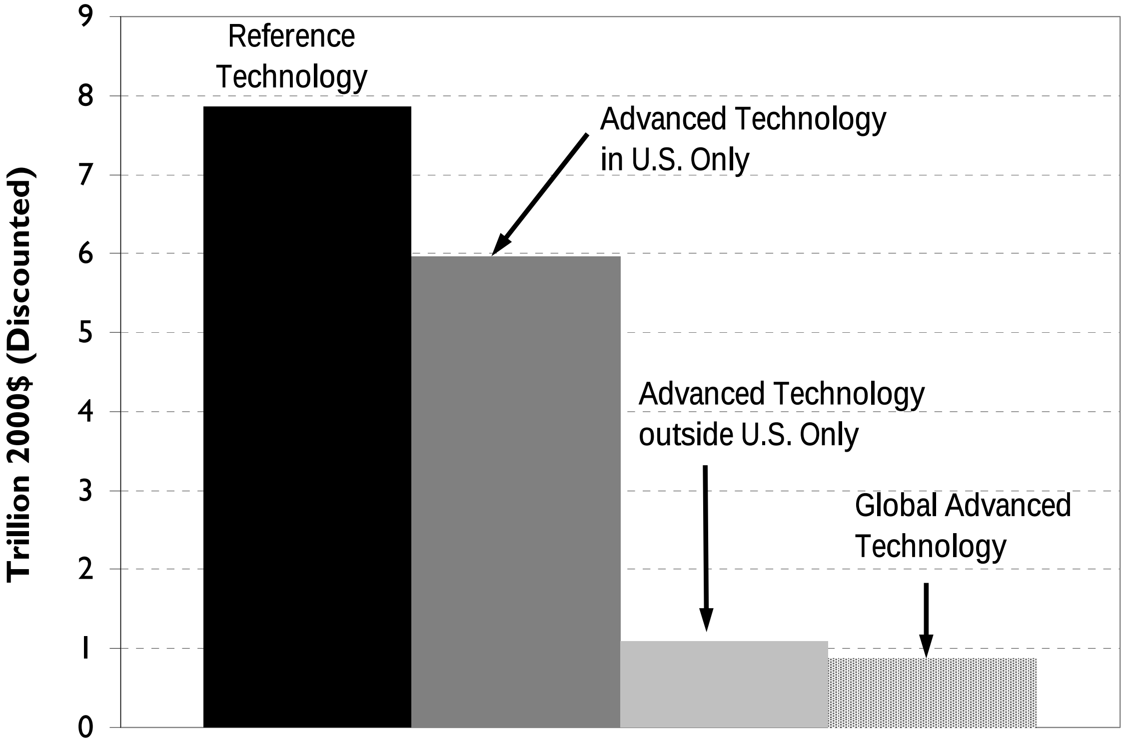

Figure 12: Global Discounted Mitigation Cost, 2005 through 2095, under Varying Deployment Assumptions

Not surprisingly, if advanced technology is available everywhere but the United States, the total global costs of abatement are smaller than if advanced technology is only available in the United States (Figure 12). Although the United States has historically been among the largest GHG emitters, it does not account for the majority of global emissions; moreover, the United States share of global emissions will decline over time as emissions from the developing countries continue to grow more rapidly than those in developed countries. Hence, deploying advanced technologies outside the United States allows these technologies to be applied to a larger quantity of global emissions, reducing global costs.

The United States results provide more direct insight into the domestic impacts of domestic and international technology deployment (Figure 13). When deployment is limited to the United States, mitigation costs to the United States, under full participation, are higher. With increased technological capacity to mitigate, the United States is called on to do more than other countries. In this case, the indirect effect—a higher domestic mitigation burden—is larger than the direct cost savings from access to improved technology. In contrast, when technology is deployed only outside the United States, domestic costs are dramatically lower even though there has been no change in United States technology. To meet a particular long-term environmental goal—in this case limiting atmospheric CO_2 concentrations to 500 ppmv by the end of the century—greater options for mitigation outside the United States lead to a lower United States emissions reduction requirement.

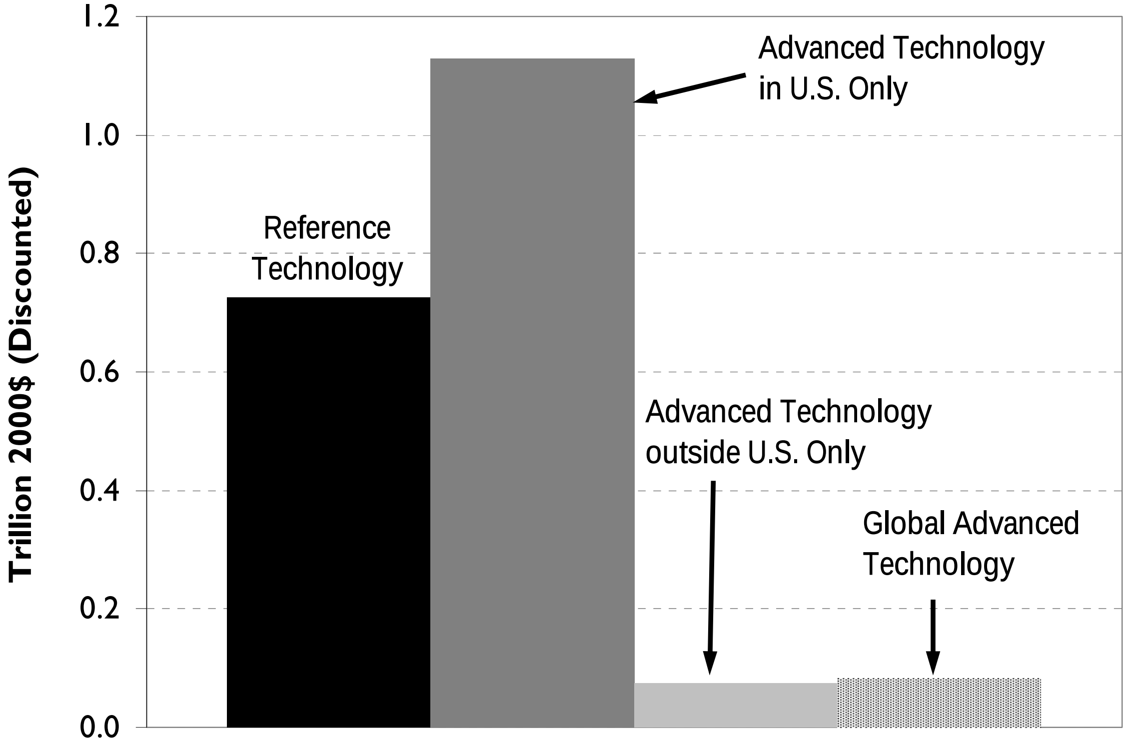

Figure 13: Discounted Mitigation Cost in the United States, 2005 through 2095, under Varying Deployment Assumptions

The caveat to these results is that it is impossible to determine the ultimate financial effects for any country participating in an international mitigation regime, as discussed above, without considering the allocation of burdens across regions. The results shown in Figure 12 and Figure 13 were developed assuming a global carbon tax or, equivalently, a global cap-and-trade regime in which emissions quantities are perfectly allocated to achieve the least costly overall distribution of mitigation efforts so that there will be no trading. In reality, the net burden on any region will not be the same as its mitigation costs. Permit allocations, wealth transfers, and other financial flows associated with mechanisms such as emissions trading or CDM can shift the economic burden across regions.

This caveat notwithstanding, the experiment makes a strong case for the public goods nature of technology investments in addressing climate change. If countries were to choose targets independently, without considering the international context, then international diffusion and the associated indirect effect of technology development—the emissions burden effect—are not relevant to domestic R&D decisions. On the other hand, to the degree that countries such as the United States are looking toward a long-term environmental goal and are interacting with other countries to meet that goal, there is strong evidence that the international diffusion of technology is a larger driver of *domestic costs* than domestic deployment. This argues strongly for domestic incentives to promote the international deployment of climate technologies, and it also argues strongly for considering the effects of international deployment when analyzing the benefits of domestic investments, such as R&D investments, to develop technology. Simply put, the international benefits of climate change R&D can be as or more important than the domestic benefits.

Concluding thoughts

This paper has explored how international policy architectures and technology availability interact and how they influence the degree and character of emissions mitigation actions that individual countries and the global community must take in both the near term and the long term. The analysis uses the MiniCAM integrated assessment model to explore these issues in the context of a long-term concentration goal of limiting atmospheric CO_2 concentrations to 500 ppmv in the year 2095. It adds to recent research that applies formal energy-economy-climate models to explore these issues (see, for example, Richels *et al.* 2007; Bosetti *et al.* 2007; Bosetti *et al.* 2008). The results touch on, and reinforce, a range of themes relating to the availability of new and improved technology and international participation in climate mitigation. We conclude here by summarizing three main insights that emerge from this work.

First, there is nothing in this analysis that contradicts the ever-growing body of research indicating that technology is fundamental to the costs, and therefore the political viability, of achieving climate mitigation. Indeed, this research suggests that technology is even more valuable—from a global perspective and from the perspective of individual nations—if international participation is less than perfectly efficient, which will undoubtedly be the case.

Second, national-level activities to promote technology development should be viewed not only from a national perspective, but also from an international perspective. It is widely understood that if mitigation is to occur, nations may benefit by establishing leadership in related technology areas, while a failure in this regard could adversely affect their competitiveness. This study has highlighted another, equally important, international dimension to the rationale for domestic technology investments. Any country that places priority on achieving a long-term climate goal understands that international mitigation efforts are fundamental for meeting this goal: The more other countries contribute to abatement, the less must be done domestically. Technology diffusion is therefore not simply a competitiveness issue, it is fundamental for fostering international mitigation efforts. Hence, assessments of the benefits from domestic technology development activities should be based not simply on improved national mitigation options, but also the potential for increased mitigation internationally, which in turn means a lower national burden on participating countries to meet any given long-term climate goal. Indeed, even without explicit climate policies in many nations, there are improvements to technology, or policies to better take advantage of existing technologies, that could lead to emissions reductions.

Finally, investments in technology development must be viewed from a long-term as well as a near-term perspective. R&D activities, and technology policies for climate change more generally, should certainly focus on the near term to facilitate action at the national and international levels, but they must also continue to lay a foundation for the deeper and wider reductions in emissions that will be required decades into the future. Regardless of international participation in the near term, global emissions must ultimately move toward zero to achieve any long-term stabilization goal. This will require the participation of all nations, and it will require energy systems that are far different than those of today. Tomorrow will ultimately turn into today, and without the scientific and technological foundations for achieving and sustaining a long-term transformation of the world's energy systems, the deep reductions necessary for stabilization may not be socially and politically viable.

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