Modeling the Economics of Greenhouse Gas Mitigation: Summary of a Workshop

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MODELING THE ECONOMICS OF GREENHOUSE GAS MITIGATION

SUMMARY OF A WORKSHOP

K. John Holmes, *Rapporteur*

Division on Engineering and Physical Sciences

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Preface

The 2010 National Research Council (NRC) workshop "Modeling the Economics of Greenhouse Gas Mitigation" was initiated by the Department of Energy (DOE) to help address the agency's need for improved economic modeling tools to use in the development, analysis, and implementation of policies to address greenhouse gas mitigation. As understanding improves of the issues addressed by and the relationships among the climate sciences, economics, and policy-making communities, techniques and modeling tools currently being used will have to be improved or modified. Critical elements in these activities include the understanding and modeling of new technologies as they move from demonstration to deployment.

This is the second NRC workshop organized with a focus on economic modeling issues. The first such workshop, "Assessing Economic Impacts of Greenhouse Gas Mitigation," was held on October 2-3, 2008, in Washington, D.C., with the goal of gaining a broader view of the variables to be accounted for and techniques used when attempting this type of modeling.[1] As a follow-up, the current workshop sought to delve more deeply into some of the key issues discussed in 2008. As with the first workshop, the second was an effort to engage leaders from the policy, economic, and analytical communities in helping to define the frontiers of and provide insight into the opportunities for enhancing the capabilities of existing models to assess the economic impacts of efforts to reduce greenhouse gas emissions.

This summary captures the major topics discussed at the second workshop. It does not include any consensus views of the participants or the planning committee, does not contain any conclusions or recommendations on the part of the National Research Council, and does not offer any advice to the government, nor does it represent a viewpoint of the National Academies or any of its constituent units. No priorities are implied by the order in which ideas are presented.

The workshop itself was divided into four major sessions (see Appendix A), each including a moderator, a number of distinguished speakers, and a panel of discussants who provided comments and additional perspectives on the speakers' presentations. The workshop was planned by a committee of experts who identified the major topics for discussion and selected speakers and participants well respected in their fields (see Appendix B for short biographical sketches). Papers submitted by the workshop speakers are reprinted essentially as received in Appendix C.

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[1] NRC (National Research Council). 2009. Assessing Economic Impacts of Greenhouse Gas Mitigation: Summary of a Workshop. The National Academies Press, Washington, D.C.

I would like to thank John Weyant, Marilyn Brown, William Nordhaus, Karen Palmer, Rich Richels, and Steven Smith for their extensive work in planning and executing this project. I also extend my gratitude to each presenter and discussant who contributed to this event. Jim Zucchetto and Peter Blair of the Division on Engineering and Physical Sciences provided valuable program direction, for which I am grateful. Jonathan Yanger also deserves special recognition for his program support on this project.

This workshop would not have been possible without the financial support of its sponsor: the U.S. Department of Energy's Office of Policy and International Affairs. Inja Paik and Bob Marlay of the Department of Energy provided the planning committee with useful input which helped it to develop a workshop that proved both timely and valuable to the various policy, economic, and analytic communities engaged in the many aspects of greenhouse gas mitigation.

This workshop summary has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for quality and objectivity. The review comments and draft manuscript remain confidential to protect the integrity of the review process.

Thanks are extended to the following individuals for their review of this workshop summary:

Paul DeCotis, Long Island Power Authority
Robert W. Fri, Resources for the Future
Charles Goodman, Southern Company (retired)
William Nordhaus, Yale University
Karen Palmer, Resources for the Future

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the content of the summary, nor did they see the final draft before its release. Responsibility for the final content of this report rests entirely with the author and the institution.

K. John Holmes
Rapporteur

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1

Introduction

Models are fundamental tools for estimating the costs and the effectiveness of different policies for reducing greenhouse gas (GHG) emissions. The wide array of models for performing such analysis differ in the level of technological detail, treatment of technological progress, spatial and sector details, and representation of the interactions between the energy sector and the overall economy and environment. These differences affect model results, including cost estimates. More fundamentally, these models differ as to how they represent basic processes that have a large impact on policy analysis—such as technological learning and cost reductions that come through increasing production volumes—or how they represent baseline conditions. Critical to the development of the federal climate change research and development (R&D) portfolio are reliable estimates of the costs and other potential impacts on the U.S. economy of various strategies for reducing and mitigating greenhouse gas emissions. Thus, at the request of the U.S. Department of Energy (DOE), the National Research Council (NRC) organized a workshop to consider some of these types of modeling issues.

A planning committee was appointed by the NRC to organize the workshop and moderate discussions. John Weyant (Stanford University), Marilyn Brown (Georgia Institute of Technology), William Nordhaus (Yale University), Karen Palmer (Resources for the Future), Rich Richels (Electric Power Research Institute), and Steve Smith (Pacific Northwest National Laboratory) worked with NRC staff to organize the 2-day event in Washington, D.C. The planning committee structured the workshop as four major sessions that addressed specific issues of interest to the modeling and policy communities: (1) Uses and Abuses of Bottom-Up Marginal Abatement Supply Curves; (2) Uses and Abuses of Learning, Experience, Knowledge Curves; (3) Offsets—What's Assumed, What Is Known/Not Known, and What Difference They Make; and (4) Story lines, Scenarios, and the Limits of Long-Term Socio-Techno-Economic Forecasting.

The workshop opened with introductory remarks and an overview from John Weyant, the chair of the NRC planning committee and director of Stanford's Energy Modeling Forum. Richard Duke, the Department of Energy's deputy assistant secretary for climate change policy, and Richard Newell, administrator of the Energy Information Administration (EIA), provided the perspective of the sponsoring agency (DOE) and the EIA, respectively, on the topics of this workshop.

John Weyant opened with a reminder that this was the second NRC workshop sponsored by the DOE's Office of Policy and International Affairs on the modeling of greenhouse gas mitigation. The previous such workshop took place on October 2-3, 2008, and a summary of that workshop was released in 2009 (NRC, 2009). The goal of the earlier workshop was to cover a broad range of issues associated with making greenhouse gas mitigation cost projections, and, specifically, to identify gaps in the underlying economic research and modeling. The current workshop, as Weyant described it, aimed to focus on a limited number of key analytic challenges that emerged from the first workshop. Weyant pointed out the extensive ties to the first workshop—the planning group chair for that event was Richard Newell, one of the introductory keynote speakers for the second workshop. Marilyn Brown, John Weyant, and William Nordhaus also served on the planning committee for or as a speaker at each workshop.

Richard Duke followed Weyant with a discussion of the motivation for the present workshop. After underscoring how much Secretary Steven Chu had hoped to be delivering the welcoming remarks himself, Duke provided some thoughts on the agenda from the perspective of someone with experience with both abatement supply curves and learning curves as well as someone involved in climate policy at DOE. He noted that, when attempting to model the long-term energy system transformations that are necessary to address climate change, it is important to try to capture speculative technology changes—and yet this is so difficult to do. He mentioned the potential for insights through marginal abatement supply curves, but also that these curves contain hidden assumptions that are fundamental to their construction. He noted the importance of the offsets and story line issues being discussed in the final session. Duke finished with a description of some recent legislative and international initiatives to address climate change, including Secretary Chu's international outreach activities.

Richard Newell followed with remarks intended to set the stage for the rest of the workshop. Newell noted that he was the chair for the planning committee that put together the first workshop in this series. He also noted that the EIA's analyses and forecasts are independent of DOE and that his views should not be construed as representing those of DOE or the Administration. He began his talk by framing two major considerations in the economic modeling of greenhouse gas mitigation. The first is establishing a baseline picture of what the future may look like without any particular greenhouse gas policy. Newell pointed out that the baseline provides a counterfactual description of the future in the absence of some policy, but that baseline itself is subject to considerable economic, technological, and policy uncertainty. The baseline is not nearly as pure as is often imagined in textbooks and includes a significant number of technology, economic, and policy assumptions. Second, in estimating the nature of a future with greenhouse gas policies, the interest of policymakers is not just the allowance prices for carbon, impacts on gross domestic product, or the total cost of the policy, but potentially much more detailed impacts as well, such as the production and consumption of specific fuels, the level of deployment of specific technologies, emission levels, and other sectoral and regional impacts. Additionally, he noted that, although modelers want to understand the effect of policy relative to the baseline, it is important to remember that many people in the world do not think in those terms. They are interested instead, for example, in what will be the trajectory of natural gas prices and use with climate policy, not in how the trajectory of both change as one moves from the baseline to the policy case. Newell cautioned that these kinds of demands emerging from the policy process need to be kept in mind when models are being developed. Modelers need to be conscious that, just because certain categories of results are desired, it does not necessarily mean that such results can always be provided.

Newell then went on to provide some thoughts on the four topics of the workshop and how they relate to baseline energy-economic modeling as well as policy analysis against the baseline. First, with bottom-up marginal abatement supply curves, Newell reminded the workshop audience of the long-running debate attempting to reconcile the large technical potential for reduction of energy use and emissions through energy efficiency with the relatively low acceptance of these technologies in the marketplace. There is an ongoing discourse about the extent to which this lack of acceptance of energy-efficient technologies is explainable by real-world costs and benefits or whether it is attributable to market imperfections owing to principal-agent problems or imperfect information. There is also the possibility of inconsistent behavior on the part of households and firms, namely that they do not minimize costs as often as is assumed in economic models. With regard to learning curves, Newell noted that there is a strong empirical observation of technical learning as indicated by the relationship between cumulative production experience and manufacturing cost reductions. This relationship is a key feature of the process of technological change that comes up in almost every conversation with industry representatives—thus appearing to Newell and most people to be a real phenomenon.

One of the modeling issues associated with learning curves is the potential for double counting—for example, including cost reductions associated with cumulative production experience and increasing R&D expenditures separately in a model. Another learning curve issue is the selective incorporation of learning, including learning-related cost reductions for some technologies but not others. On a third topic, the role of offsets in greenhouse gas modeling, the word Newell used to characterize the issue was "huge." Newell used the example of EIA's analysis of H.R. 2454 (the American Clean Energy and Security Act of 2009, or simply the Waxman-Markey bill), passed by the U.S. House of Representatives in the summer of 2009. In that analysis, offsets constitute up to 78 percent of cumulative abatement through 2030. If one limits offsets, the allowance price increases by more than 60 percent, all else constant. Offsets were one of two key sensitivities that EIA found in its analysis (the other was the cost and the availability of options for generating electricity with low or no greenhouse gas emissions).

Finally, with regard to the issue of story lines, Newell noted that model projections are not meant to be an exact prediction of the future, but rather a representation (a story line) of a plausible energy future given the current technological and demographic economic trends and what is assumed about current laws, regulations, and consumer behavior. These assumptions and projections, though, are highly uncertain, given that they are subject to many events that cannot be foreseen, such as energy supply disruption, policy changes, and technological breakthroughs. Generally, the differences between various story lines can often be useful to look at, or even more useful to look at than the results of any individual policy case. But there is often considerable debate around even the direction of an effect felt as a result of an individual factor, such as whether an individual policy initiative or behavioral trend will be a positive or a negative, a total cost or a benefit, or will lead to an increase or a decrease in emissions, or result in increased or decreased use of a particular technology.

2

Uses and Abuses of Marginal Abatement Supply Curves

The objective of the workshop's first session was to discuss the proper interpretation and use of marginal abatement supply curves, which chart the cost of reducing greenhouse gas emissions through the deployment of various technology and policy measures. For each measure under consideration, its marginal cost is plotted against the net associated emissions reduction, and the results are stack-ranked from lowest to highest cost to form the marginal abatement supply curve. Marginal cost supply curves have been in use for decades, and a 2007 report released by McKinsey & Company represents a recent application to the study of reducing greenhouse gas emissions (McKinsey & Company, 2007). Marginal abatement supply curves are often used to link the results of bottom-up engineering analyses of the cost and technical potential of technologies with top-down economic models that assess the macroeconomic and energy system impacts of reducing greenhouse gas emissions. However, embedded within such supply curves are critical assumptions, including the baseline against which the supply curve is built (which may not be internally consistent across the specific technology options included in the supply curve), cost assumptions concerning the technologies represented within the supply curve, discount rates, and even assumptions concerning how rapidly or easily technologies might be deployed. Yet these assumptions may not be apparent to analysts who incorporate such supply curves into their models, or to policy makers who use a model's results in making policy decisions. Further, a McKinsey-type supply curve that represents a broad array of technology options gives the illusion that all options have an equal probability of implementation, face no deployment constraints, and benefit from specific policies and measures identified to spur deployment, and that all lower-marginal-cost options would be exhausted before a move to the next least costly option. Such were the issues that provided motivation for this workshop session.

Issues in the use of energy conservation and greenhouse gas abatement cost curves were first discussed by Mark Jaccard of Simon Fraser University, who began his talk with a description of energy efficiency cost curves and greenhouse gas abatement cost curves. He described the possibilities offered by technology options with lower life-cycle costs (i.e., offering cost savings) that have been shown to have negative costs, meaning that the more efficient replacement technology has a life-cycle cost lower than that of the technology it replaces. Figure 2.1 shows an example of a cost curve associated with different options for reducing electricity consumption. Mapping electricity rates, one could make an argument that any of the efficiency measures, those steps on the curve in Figure 2.1 that are below electricity rates, would represent profitable actions for people to take on a private cost basis. Figure 2.1 also shows that, if society is looking at making an investment in a new supply option like a new hydropower dam, the cost of that option can be mapped on the curve and the result used to show that efficiency

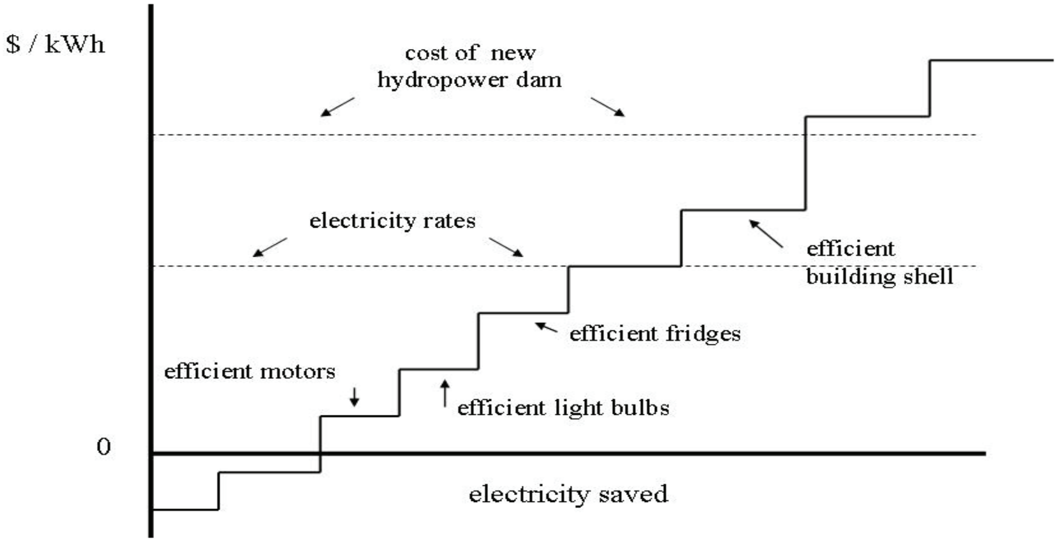

FIGURE 2.1 Sample of an electricity efficiency supply curve showing the relative costs of various efficiency options and how those costs compare to electricity rates and costs of a new supply option (a hydropower dam).

actions below the cost of a new hydropower dam would be socially profitable compared to building the dam. Jaccard described it as basically the same methodological thinking that leads to carrying the supply curve approach from a focus only on energy efficiency to a focus on greenhouse gas abatement. Efficiency cost curves were popular 30 years ago, and greenhouse gas abatement cost curves have been around for at least 20 years. But Jaccard noted that leading energy-economy modelers have moved away from the supply curve approach, arguing that the curves mislead about costs and are unhelpful with policy. Jaccard believes that is probably too strong a statement and, as someone who comes from both an economics and a technology engineering background, he expressed his belief that there is useful information in such curves and in developing hybrid approaches, while still remaining cognizant of the issues with these curves.

Jaccard focused on several issues he sees as problematic with such supply curves. The first is that the construction of cost curves implies that each action is completely independent of every other action, for example, that installing efficient light bulbs is independent of making building shells more efficient. It also assumes that market conditions are homogeneous such that the cost of deploying the first 20 percent of the technology is the same as the cost of deploying the last 20 percent. Finally, the curves assume that a new technology is a perfect substitute and that the quality of service and the risks of adopting a new technology are identical to those associated with the technology being replaced. Responses to these issues have involved modelers constructing integrated models that have energy supply and demand working simultaneously and tracking within the models different vintages of equipment stocks. Such models can also portray the heterogeneous character of market responses and estimate the behavioral parameters that explicitly or implicitly incorporate nonfinancial values such as preferences related to technology attributes. He noted that models that are technologically richer or more explicit about technologies are more often called hybrid models, and these models have algorithms that simulate how people, firms, and households choose technologies. Jaccard argued that, although these models and their parameters are highly uncertain, research on technology deployment tends to focus on them because of the general awareness of the limitations of simple supply curve approaches.

The final point in Jaccard's talk concerned the relevance of traditional supply curves for policy and what can be done to improve their use. He stated that the implicit message from traditional cost curves is that it seems very inexpensive to achieve substantial reductions in energy use or greenhouse gas emissions. Such a message can suggest to policy makers that, if the costs are so low, there is no need for the kind of compulsory policies that really change market incentives, such as emissions pricing and regulations. He recommended instead the use of integrated hybrid models to construct marginal abatement cost curves in which each point on a curve has simultaneous actions occurring in an equilibrium solution (for example, adoption of more efficient lighting occurs with improvements in building shells, and their interactions are represented), a particular action (such as use of more efficient light bulbs) occurs continuously along the curve, and that the curves incorporate intangible costs and estimated responses to policy.

The second speaker in the session was Jayant Sathaye, the head of the International Energy Studies Program at the Lawrence Berkeley National Laboratory, who discussed empirical insights possible for energy-climate modeling from efficiency (supply) cost curves. Sathaye reminded the workshop audience that efficiency cost curves were developed about 30 years ago to enable a comparison of the potential and cost of energy efficiency options with supply-side potential and costs. He discussed several issues associated with the individual energy-reducing technologies and measures represented within the cost curves: (1) the baseline against which individual savings are measured; (2) the barriers to deploying these technologies or implementing these measures; (3) the program costs needed to implement and possibly subsidize the adoption of an energy-saving measure; and (4) the time frame during which a measure is effective. Sathaye noted that capturing all the issues that impede the full deployment of the energy-reducing measures in the cost curve would produce a curve showing about 45 percent of the savings that would be estimated without including these impacts.

Sathaye went on to discuss the impacts of incorporating non-energy benefits into curves and how such benefits become very important for the industrial sector. Besides reductions in energy costs, there may be reductions in atmospheric emissions of non-greenhouse-gas pollutants, generation of liquid and solid waste materials, and operations and maintenance costs. Sathaye pointed out that reductions in energy use alone will not cause most industries to purchase efficient technologies. Including non-energy benefits can greatly alter the cost curves, in some instances significantly increasing a technology's cost-effectiveness. Figure 2.2 indicates the potential impact

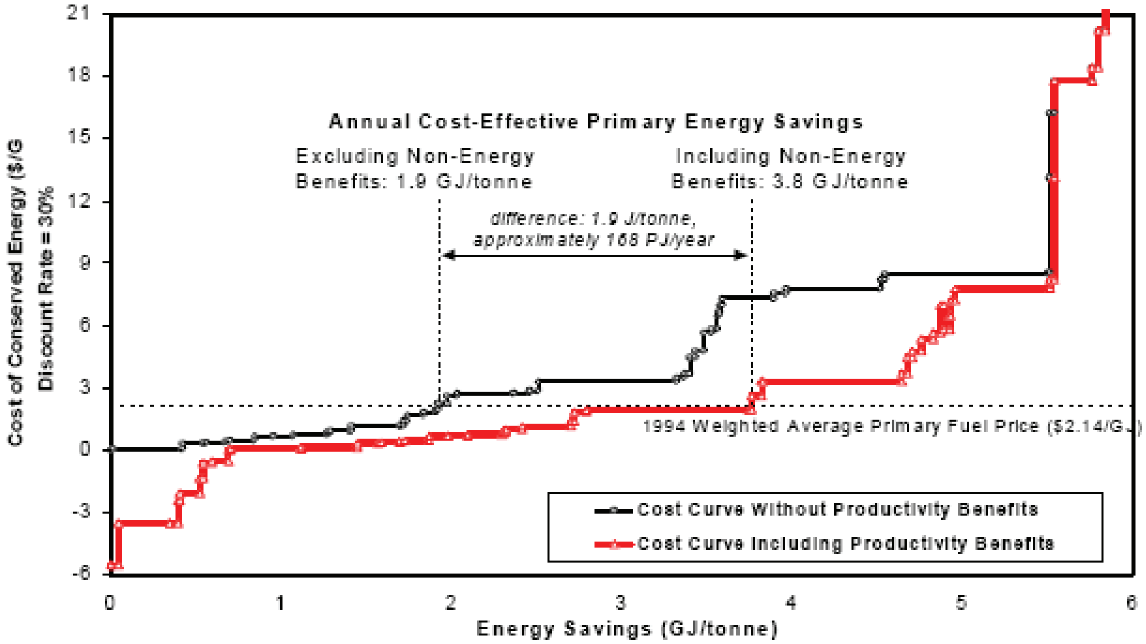

FIGURE 2.2 Conservation supply curves including and excluding the benefits of non-energy productivity, U.S. steel industry.
SOURCE: Worrell et al. (2003).

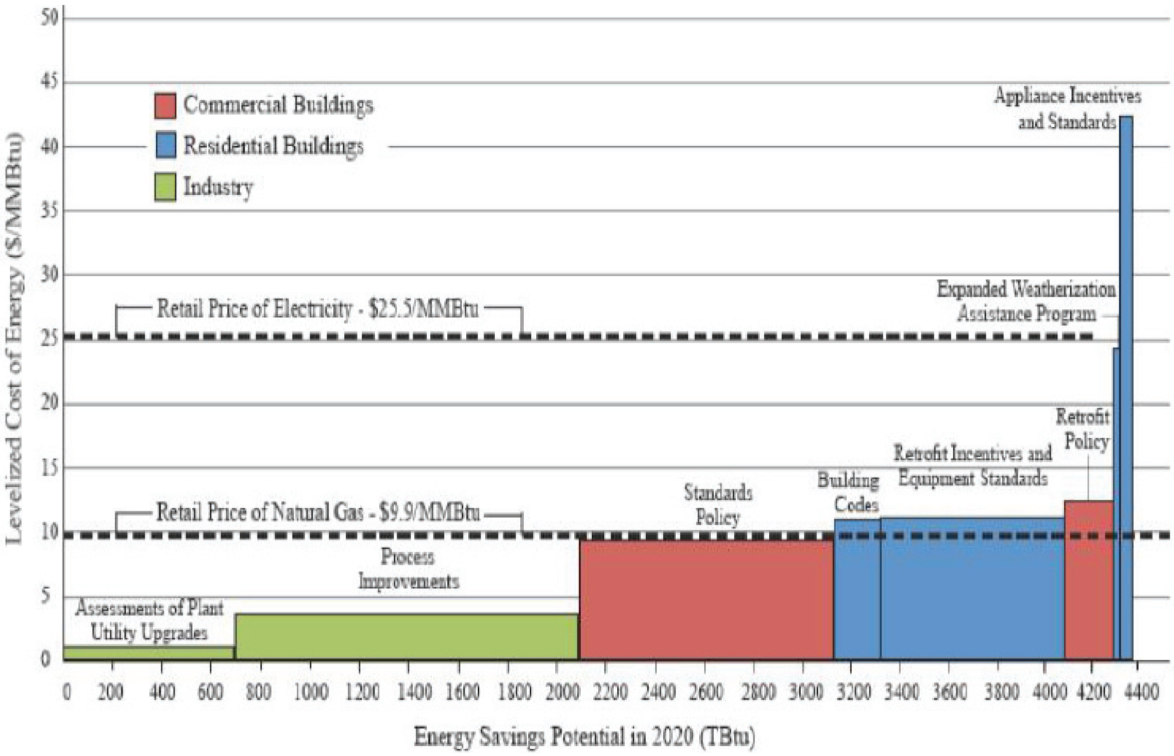

FIGURE 2.3 Example of a policy supply curve for nine energy-saving policies in the southern United States.

of including potential non-energy benefits in the supply curve for the U.S. steel industry. Including non-energy benefits also can greatly alter the ranking of the technologies in terms of their relative benefits.

The final issue brought up by Sathaye was that efficiency cost curves are constructed as though they are static in time. However, it is known that over time costs drop for various energy-saving technologies in the industrial sector, as well as in the residential and commercial sectors. Sathaye cited steel making, residential gas furnaces, and commercial air conditioning equipment as specific instances in which costs have fallen as energy efficiency has risen. Thus, cost curves should evolve over time, and this issue should be considered when applying these curves.

The remainder of the session included a panel discussion and comments from the audience. The four discussants were Marilyn Brown, a professor at the Georgia Institute of Technology and a member of the workshop planning committee; Rich Richels, head of the Climate Division at the Electric Power Research Institute and also a member of the workshop planning committee; Howard Gruenspecht, deputy administrator for the EIA; and Hillard Huntington, a professor at Stanford University and the executive director of Stanford's Energy Modeling Forum. Marilyn Brown talked about some of the ways that supply curves can be advanced to better reflect the ability of policies to make a difference in the marketplace. To address some of the concerns raised earlier in the session about the limitations of technology supply curves, Brown recommended the construction of policy supply curves that represent bundles of technologies that would be deployed in response to a policy. Figure 2.3 shows an example of such a curve from a recently released project (Brown et al., 2010). Policy supply curves allow multiple technologies to be modeled—for example, in the case of residential building codes a number of different advances and technologies that can be utilized to meet a code. Brown also noted that such curves are amenable to the inclusion of program administration costs.

Richels began by noting that the efficiency supply curves produced by the McKinsey study, echoing many studies from the early years (the late 1980s) of the climate change debate, showed many no-cost and negative-cost options that nevertheless omitted additional hidden costs. The current goals for mitigation are such, Richels felt, that the policy debate should not be about whether there is a free lunch in mitigating climate change, but rather about whether the lunch is worth paying for. He expressed the concern that the debate over "how many free $20 bills are lying on the sidewalk" is irrelevant and should not be used as an excuse for policy paralysis. Hillard Huntington recalled that most of the same issues discussed earlier in this workshop session had been brought up more than a decade ago in an Energy Modeling Forum activity on supply curves. Despite some interesting things that have to be done analytically, Huntington was convinced that it is very important to communicate with policy makers about how to use these curves and the factors that change the shape and cost-effectiveness of these curves. He noted that behavioral issues appear to be critically important to explaining the gap between the technology opportunities and other energy-saving measures shown within these curves and the adoption of these measures by individuals and companies. Howard Gruenspecht began his remarks by concluding that the presenters and commenters had made it clear that analysts need to sharpen their focus on behavior in a variety of dimensions when assessing the costs of reducing energy use and greenhouse gas emissions. He went on to note that his agency's (EIA's) models include some behavior and a lot of technology detail. The EIA models use a mixed approach whereby decisions in some sectors are benchmarked to past behavior, whereas in other sectors, such as electric power generation, decisions are assumed to be based on a pure cost-minimizing behavior. He noted that recent experience suggests too little emphasis might have been placed on behavioral considerations, even in the electric power sector.

The session ended with comments and questions from the audience. Richard Moss from the Pacific Northwest National Laboratory/University of Maryland's Pacific Joint Global Change Research Institute wondered whether the debate has moved beyond whether there are negative cost opportunities ($20 bills on the sidewalk) to the question of how we can use policy to more economically and efficiently bring about some of the transitions necessary to address climate change. Further, Moss noted that many of the claims made about different policies leading to job creation or improvements in energy security do have an economic component to them and yet are really difficult to get our hands around. He wondered how it might be possible to build on such studies of bottom-up technical potential for reducing energy use and emissions, and move onto some of these other challenging questions. Marilyn Brown responded by noting a growing appreciation that the market is not operating effectively, that intervention can improve things, and that many of the policies in place actually present barriers to efficient decision making. These barriers include the coupling of profits by the electric utility industry and the gas industry to the amount of revenue obtained, which discourages policies that reduce electricity or energy consumption. Rich Richels responded by recommending greater transparency in packaging some of the work that is being done, citing a talk he had heard recently about green jobs that mentioned only the number of jobs that would be added by adopting certain renewables, and did not discuss the potential negative impacts on other segments of the employment market. Richels' conclusion was that, unless you give the whole picture, you are setting yourself up for being discredited.

Ed Ryder from Dow Chemical brought up the point that, although supply curves provide an entry point for discussion, one of the issues from an industrial perspective is the competition for capital and whether you spend your limited resources on energy efficiency projects or on some other projects that allow you to meet other objectives such as producing products in greater volume, expanding into different regions of the country or the world, or spending in another manner that provides greater returns on investment. William Nordhaus from Yale University noted that many of the comments on supply curves have been scornful of the bottom-up engineering approaches that are used to estimate the technical potentials shown in these curves. What he finds very exciting for the next decade or two of research is to bring to bear some of the important new advances in behavioral economics or the behavioral sciences more generally on issues related to supply curves.

3

Uses and Abuses of Learning, Experience, and Knowledge Curves

Marilyn Brown of the workshop planning committee introduced the second session by noting its focus on learning curves or experience curves or knowledge curves, and pointing out that there is disagreement as to what the correct term even is (presenters at this workshop tended to use the term “learning curve”). Learning, experience, and knowledge curves are used for simulating performance improvements and cost reductions for technologies over time. In the absence of observed cost trajectories for a particular technology, modelers often use aggregate surrogates derived from other suites of technologies. The black-box nature of the learning curve results from not understanding the pathways through which technology improvements occur, how long the learning process will continue, and what specific policies might stimulate technological progress. In assessments of the economic impacts of greenhouse gas mitigation, technologies typically are assumed to compete on a cost basis. Thus, it is very important to have good cost-trajectory information. However, often it is not known how much potential a technology might have for reducing costs or how mature a technology already is.

Brown went on to state that the goal of this session wass to distill insights and obtain guidance regarding the proper interpretation and use of learning curves. She observed that it is more useful to be approximately right than definitely wrong by assuming the absence of learning. Thus, the hope for this session was to figure out how to be at least approximately right in representing learning in technological cost curves in energy and climate models.

The first speaker, Nebojsa Nakicenovic from the International Institute for Applied Systems Analysis, discussed moving beyond the black box of learning curves to focus on their use and misuse in assessments of technological change. Nakicenovic stated that the actual mechanisms represented by learning curves are unknown and that there is not a formal theoretical basis for measuring the fundamental processes characterized by such curves. He noted that it is thus not surprising that some of the uses of learning curves are very productive and some lead to more trouble than they resolve. Nakicenovic began with examples of technological progress that are ascribed to learning. Using lighting as an example, he showed how, as the source of lighting moved from kerosene to gaslights and finally to electricity, the cost of providing the service of lighting became a small fraction of what it was a century ago. A second example, shown in Figure 3.1, is the overall reduction in the cost of transporting passengers. And if one focuses on just the stagecoach, it is clear that even technologies not viewed today as having a high degree of technological sophistication can reflect enormous amounts of learning over time. However, Nakicenovic also presented a counter-example to the existence of learning as seen in the declining carbon intensity of the U.S. economy. He argued that the decline in the amount of carbon per dollar of gross domestic product did not demonstrate technological learning because this trend was the result of large structural changes to the economy. So the

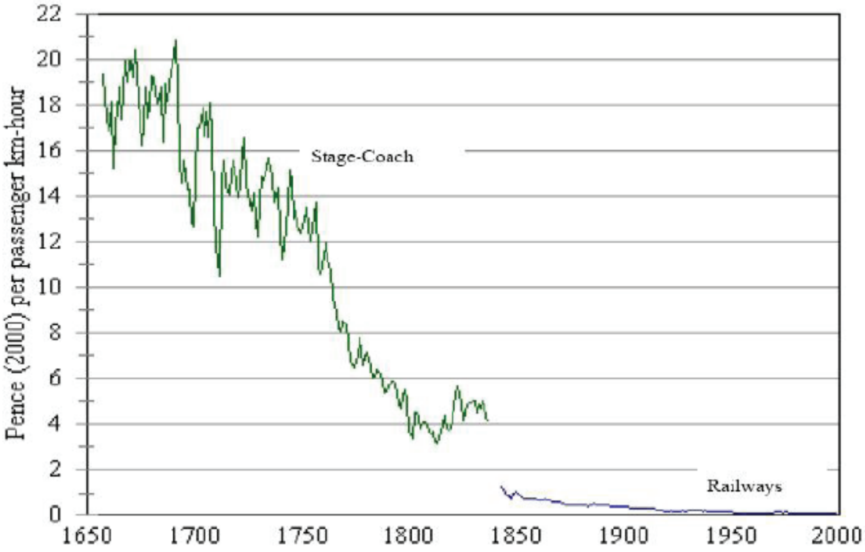

FIGURE 3.1 Price of passenger transportation in cost per passenger kilometer (km)-hour.

issues embodied in learning curves include understanding the specific processes that lurk behind the black box of technological improvement over time and, more precisely, the question of "who learns what?"

At the most general level, technological progress results from cumulative experience, but the magnitude of this progress for an individual technology or service is hugely uncertain, and there is almost nothing deterministic about the learning phenomenon. A wide range of examples shows a fairly consistent set of results indicating that cost reductions of 10 to 30 percent for a technology might be expected from a doubling of cumulative production. However, Nakicenovic reminded the workshop audience that the deterministic appearance of many of the learning curves is deceptive and that we are essentially dealing with a probabilistic phenomenon. One can find many examples of negative learning and cost escalations, including the case of the Lockheed Tristar aircraft, as well as U.S. and French nuclear reactors. In exploring learning for specific technologies, he noted that for solar photovoltaics in Japan, cost reductions were very marginal during the basic research and development phase, and costs declined rapidly only when significant funding went into applied research. Analysis of other renewables technologies shows that increasing the scale of production, the size of the manufacturing facilities, the size of devices, and the size of installations contributes to cost reductions.

In his talk William Nordhaus of Yale University focused on the perils of the learning model for representing endogenous technological change in energy-economic models. He discussed the question of the mechanisms of learning, who learns, and how learning is transmitted from one generation to the next. He stated a belief that learning is driven by cumulative production, and noted the inherent difficulties in disentangling the effects of learning from other sources of productivity growth such as research and development; economies of scale; and technologies that are imported from outside the boundaries of the firm, the industry, or even the country. Nordhaus also discussed a study of the semiconductor industry by Irwin and Klenow (1994) that showed learning was three times more powerful within firms than across firms and that also found insignificant learning effects from one generation of a technology to the next; if a technology grew rapidly in one generation or slowly in one generation, the effect on the next generation of the product was insignificant.

Nordhaus expressed his concern about using learning in models. He noted that learning has become a favorite tool for representing technological change in many models of the energy sector and global warming. He attributes this to its being one of the few "theories" of technological change that can be included easily in models because of its simple specification. Nordhaus concluded that the modeling of learning is a dangerous technique, however, because the estimated learning rates are inherently biased upward. The bias occurs if the demand function has non-zero price elasticity or if there are other (non-learning) sources of productivity growth such as improvements arising from research and development, economies of scale, or diffusion from abroad or other industries. Because estimated learning rates are biased upward, Nordhaus concluded that these approaches can seriously underestimate the marginal cost of output and can lead to overinvestment in technologies that have learning incorporated into their cost estimates.

Edward Rubin of Carnegie Mellon University focused his presentation on technologies employed solely for the purpose of reducing or eliminating emissions to the environment. These environmental technologies are different because no markets for them would exist without government regulations that require or make it economical to use these technologies to achieve compliance. His focus was on carbon capture and storage (CCS), a technology that could potentially be used to eliminate most of the atmospheric carbon dioxide (CO_2) emissions from coal-fired and gas-fired power plants or other large industrial facilities. In the modeling and policy communities, CCS is widely viewed as a critical technology for achieving the kinds of climate policy goals that are being discussed. However, CCS has not been demonstrated at full scale in fossil-fuel electricity plants, where it would be most widely used for climate change mitigation.

Rubin presented results of prior case studies of cost trajectories for post-combustion sulfur dioxide and nitrogen oxide emissions control technologies at coal-powered electricity plants. These and other case studies showed that the cost of installations often increased significantly over the course of the first few projects before eventually declining in accord with traditional learning curves. Figure 3.2 shows the results of a cost projection model for a coal-fired integrated gasification combined cycle power plant with CCS together with learning rate analogues for each major plant component based on experience with similar technologies. Models also were developed for three other types of power plants with CCS. A sensitivity analysis showed that the overall cost reductions after the equivalent of about 20 years varied by factors of 2 to 4. Rubin noted that results over such a wide range are not often expressed in many of the models that use learning curves. He concluded by discussing key factors that are

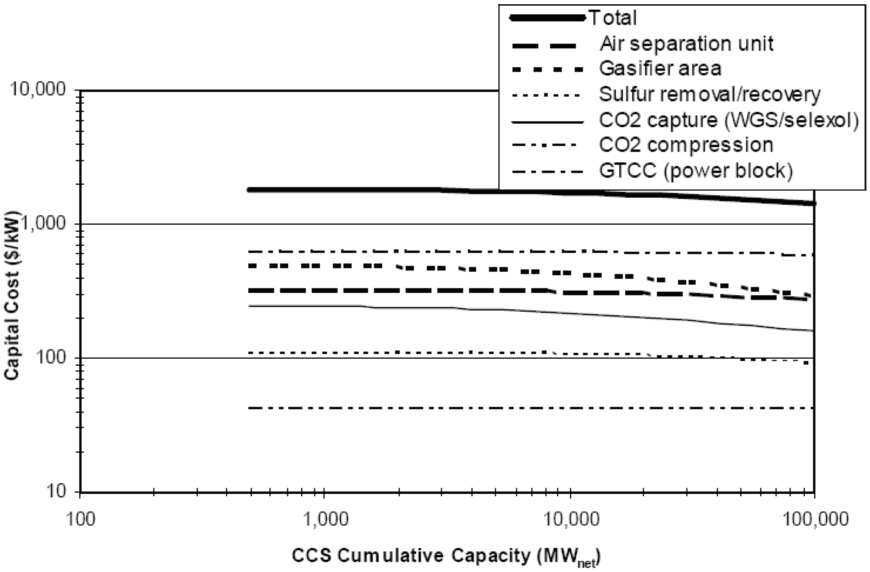

FIGURE 3.2 Estimated cost reductions for a new coal-fired integrated gasification combined cycle (IGCC) power plant with carbon capture and storage (CCS) using best-estimate learning rates for major plant components and then aggregating these to estimate a learning curve for the overall plant. Sensitivity studies yield a range of results.

typically not included in learning curve models and some improved model formulations for representing learning and uncertainty.

The remainder of the session included a panel discussion and questions from the audience. The panel of three discussants was composed of Jae Edmonds of Pacific Northwest National Laboratory (PNNL); Greg Nemet of the University of Wisconsin; and David Greene of Oak Ridge National Laboratory. Edmonds began by observing that the state of technology and assumptions made about the rate of learning are some of the largest determinants of cost in meeting any greenhouse gas emissions goal. Using differing technology assumptions alone allowed a single model, the PNNL Global Change Assessment Model (GCAM), to bracket the range of carbon prices across all 10 integrated assessment models used in a recent Energy Modeling Forum activity that looked at the costs for meeting multiple climate change stabilization goals. Edmonds also noted that the GCAM model does not include endogenous technological change, although the model does tend to show declining technology costs with increasing cumulative production due to other fundamental processes represented within the model. Nemet focused his remarks on two points that the speakers summarized. One was that if learning curves are going to continue to be central to modeling, there needs to be much more explicit characterization of the reliability of the forecasts that result from them. The second point was that there is a need to develop a more fully representative picture of the drivers of technological change. Greene concluded the discussion session by noting that learning curves encompass the "can't forecast with them, can't forecast without them" dichotomy. There is no rigorous method for predicting future learning rates, and history can serve as a guide but not a guarantee. However, he concluded by noting that we will have a much higher level of certainty for 10 to 15 years in the future, and 10 to 15 years is the planning horizon for actually executing policy. And so we can look at whether a technology (such as CCS) is developing the way we thought, and adopt policies depending upon whether it is or is not.

The session ended with comments and questions from the audience. Steve Smith of PNNL asked about the panel's perspective on selection bias when it comes to this learning curve because, when we look at examples and plot learning rates, the technologies that never got beyond zero production are not included. Nakicenovic agreed and stated that he thinks that the fact that technology losers are not included in the analysis is one of the biggest drawbacks to using historical analogies for estimating learning rates. Robert Marlay of DOE made the observation that, based on listening to the speakers, one would get the impression that learning curves have very little predictive power beyond just a very short period into the future. Marlay went on to note that policy makers need to see out further than that, or at least have some insights about the future. He questioned how we can move forward to address some of these issues. Nordhaus responded by noting that he is particularly concerned about the use of learning curves when they are used for policy purposes in situations where the models are basically driving portfolio selection among policies or technologies based heavily on assumptions concerning technology learning. Nordhaus' solution was to try different assumptions and even different models of learning to see how critical the assumptions are and whether the policy conclusions are robust to the particular assumptions. Nakicenovic was less pessimistic about the use of learning curves in modeling because he felt that quite a lot of progress has been made in their application. However, he thought that because so much of the insight comes on the basis of case studies that have been underway for years, there have to be more generic foundations for these models.

4

Offsets—What's Assumed, What Is Known/Not Known, and What Difference They Make

As Newell noted in the opening session, the existence of carbon offsets—whether from within the jurisdiction (domestic, non-covered sectors) or from outside the jurisdiction (international)—has a significant impact on estimations of the cost of reducing greenhouse gas emissions. In introducing the third session of the workshop, Karen Palmer of the planning committee noted that analysis of proposed climate legislation showed that the existence of international offsets lowers carbon allowance prices by 70 percent compared to the case where offsets are not allowed. Yet there is much confusion about how offsets are defined and, in particular, how international offsets should be treated as more countries participate in international agreements to reduce emissions. Many different models and sources of offsets have been proposed, including project-based offsets under the Clean Development Mechanism (CDM), broader-scale international programs of offsets for reducing emissions from deforestation and soil degradation (REDD), and sectoral offsets produced by reductions of emissions beyond agreed-upon target levels for a particular sector in a particular country. Each type of approach to offsets raises issues related to monitoring and verification of emissions reductions and estimation of costs. In addition, for certain types of offsets, institutional arrangements such as the existence of a centralized monopsonistic buyer of international offsets, as well as political risk in some countries, may affect the costs and the supply of offsets. There are also fundamental analytical issues as to how offsets can be represented in macroeconomic models. This session of the workshop was organized to discuss how offsets are defined, the different forms they can take, and how offsets might be used, in addition to institutional issues for both suppliers and demanders and how they affect costs, including what has been learned from the CDM experience.

Ray Kopp of Resources for the Future began the session by discussing definitions of offsets and taxonomy and some of the modeling issues associated with offsets, and by offering brief observations on the political economy of offsets. Compliance offsets allow a country that has entered a legal obligation to reduce emissions to achieve those reductions wherever doing so is least costly. For example, if the United States makes a commitment to reduce greenhouse gas emissions but finds it less costly to reduce emissions in another country, domestic or international policy might allow the United States to meet its obligation in the countries where the low-cost opportunities occur. Kopp noted that it is important to verify that such emissions reductions in the low-cost country would not have occurred in the business-as-usual case and so can be certified as *additional* reductions. Some of the critical modeling issues associated with offsets include the additionality issue mentioned above, transaction costs, and avoidance of double-counting so that an offset generated for one country is not also used by a second country to meet its obligations.

Kopp noted that there is a movement from project-based offsets (which are like those under the CDM) to sectoral offsets, whereby a baseline and an emissions cap are established for a whole sector (such as the electricity generation sector) in a given country and offsets are generated by reducing emissions to a level below that cap. There are some problems with the sectoral credits as well, such as the fact that different countries might establish their own baselines using different criteria. If those baselines are liberal, a lot of emissions credits are generated. Another problem is whether large markets for carbon will develop. The largest would be in the United States, but if there were no U.S. market would the market in Europe and other developed nations be large enough to drive the creation of the massive amounts of credits necessary for offsets to play a major role? Kopp also pointed out that bilateral deals might pose complexities in terms of their political economy. For example, in choosing certain countries with which to make bilateral arrangements, the United States will take into consideration issues beyond simply the availability of sectoral offsets in that country. Kopp noted that concerns surrounding political economy may not favor cutting sectoral deals with China, whereas Mexico may be viewed as a more suitable partner.

The second speaker, Geoff Blanford of the Electric Power Research Institute, focused on international offsets and their role in meeting U.S. targets for reduction of greenhouse gas emissions. Blanford began by noting that recent legislation (for example, H.R. 2454, the Waxman-Markey bill) proposed that several types of offsets be admissible with a high limit on international crediting. Blanford observed that emissions abatement opportunities internationally are abundant and cheap but that many institutional barriers exist in the near term. He observed that the high limit on international offsets is built in as a way to contain costs, especially for the Organisation for Economic Co-operation and Development (OECD) countries that would be the first countries with emissions caps. He also noted that if, over the long term, support for global stabilization efforts broadens and requires that the developing countries also reduce emissions, then the non-OECD countries will become less willing to export cheap abatement options. Such a situation would create a policy dilemma if offsets from non-OECD countries were desired for reducing OECD countries' compliance costs at the same time that insistence grew for non-OECD countries to accept emissions reduction targets to help meet a global stabilization target.

Blanford then outlined the potential size and cost of offsets available in a system in which emissions are capped for the United States and other OECD countries. For the United States there are domestic offsets, but only, under the Waxman-Markey bill, for forestry, agriculture, and some non-CO_2 greenhouse-gas-emitting activities. Thus offsets available domestically are quite limited. As shown in Figure 4.1, the supply of offsets available from other

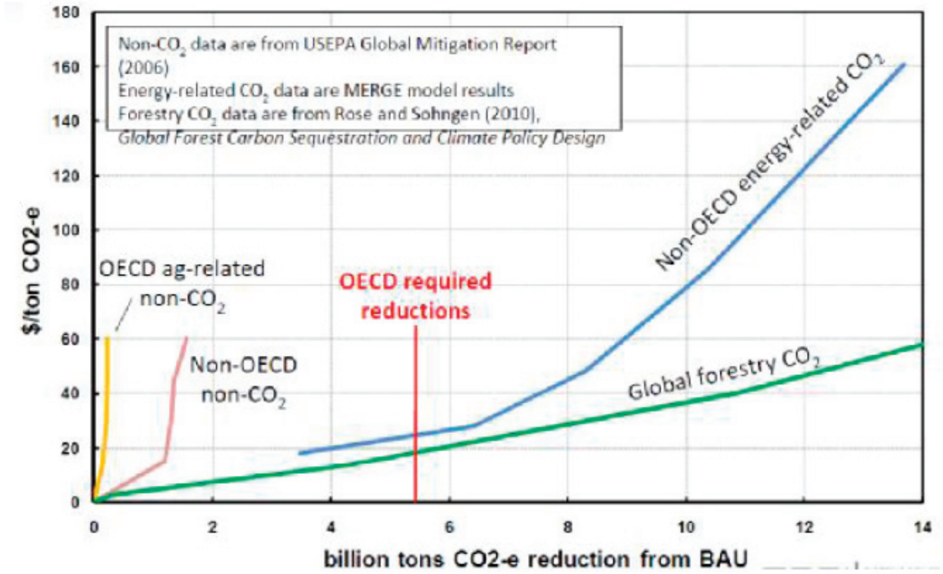

FIGURE 4.1 Supply curves for offsets in 2030 for OECD countries. SOURCE: Based on data from EPA (2006) and Rose and Sohngen (2010).

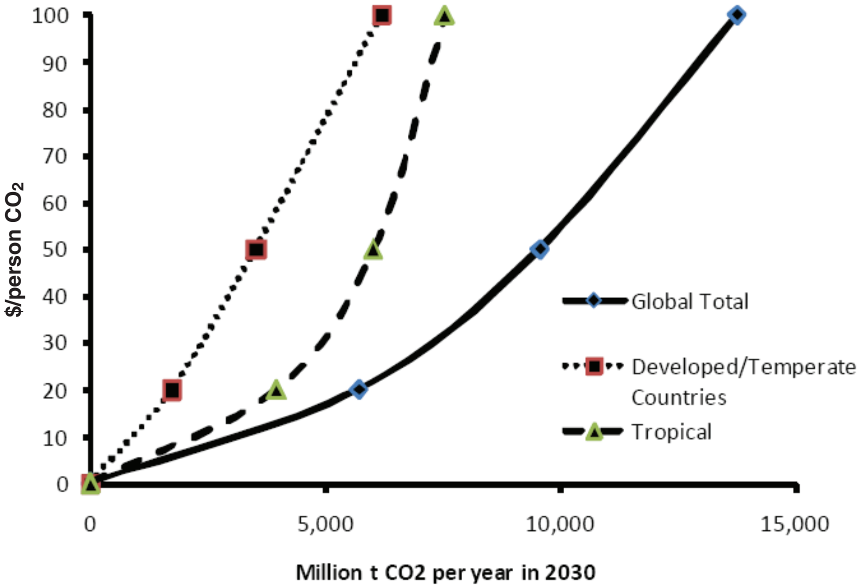

FIGURE 4.2 Supply curves for offsets in 2030 from forest carbon.

OECD countries for use by the United States in meeting its emissions cap is not forecast to be very large because these other OECD countries can be expected to have similarly stringent emissions caps subject to similar marginal abatement costs. The two largest categories of supply are global forestry, which although large, is associated with places that pose difficulties related to permanence of governance and verification of offsets, and energy-related offsets from non-OECD nations. However, Blanford reminded the audience that, despite the potentially large supply of energy-related offsets in non-OECD nations, this is precisely the category of emissions that should be capped if there is eventually to be a global effort to reduce greenhouse gas emissions. He went on to show that the largest portion of energy-related offsets generally comes from the electricity sector, particularly the electricity sector in China. Blanford indicated that negotiations with China or others must balance the host country's political position on burden sharing with the potential financial benefits of trading in offsets.

Brent Sohngen of Ohio State University followed with an assessment of forest- and other land-based offsets. He began by describing the land-based actions as forest management (afforestation, forest management, avoiding deforestation) and agricultural management (conservation tillage, methane management, control of nitrogen oxide emissions). Based on his analysis, options for offsets from forestry greatly exceed those from agriculture. Sohngen also noted that, as shown in Figure 4.2, most of the low-priced forestry offsets are in the tropical countries. His estimate for using forestry as well as energy-sector offsets to meet a global emissions target that stabilizes average global temperature change at 2 degrees Celsius indicates that these offsets could reduce carbon prices by about 40 percent. Further, Sohngen showed that including forestry offsets in a trading scheme could slow and eventually reverse deforestation. It could also result in a transfer to developing countries of about $44 billion per year with an average payment of $70 per hectare per year. However, using offsets on this scale would also cause enormous land-use changes and require projects on an enormous scale to implement such a program. For example, by 2025 100 million hectares of "new forest" would be required. Although markets can change land-use patterns in a time period that short—agricultural expansion has converted forested to cleared land on a scale of 100 million hectares worldwide over the past 15 years—there are currently no government programs that can produce this level of land-use change over such a short time period.

The policy design issues that Sohngen mentioned for carbon offsets included baselines and additionality—in essence, can it be shown that the action that generated an offset credit (e.g., planting trees) would not otherwise

TABLE 4.1 Categories for Mitigation as Sources of Greenhouse Gas Emissions

Mitigation Category	Data Source
CH_4 from landfills	EPA (2006)
CH_4 from coal mines	EPA (2006)
CH_4 from the natural gas sector	EPA (2006)
CH_4 from the oil sector	EPA (2006)
N_2O from adipic acid production	EPA (2006)
N_2O from nitric acid production	EPA (2006)
CH_4 and N_2O from livestock manure management	EPA (2006)
CH_4 from livestock enteric fermentation	EPA (2006)
CH_4, N_2O, and soil carbon from paddy rice	EPA (2006)
N_2O and soil carbon from cropland	EPA (2006)
F-Gases (11 source categories)	EPA (2006)
International forest carbon sequestration	Sohngen and Mendelsohn (2006)
International energy-related CO_2	Clarke et al. (2007)

SOURCE: Allen A. Fawcett, Appendix C, this report.

have been done? Another issue concerns permanence. Although many argue that carbon needs to be permanently sequestered to have any value in the mitigation of climate change, Sohngen argued that carbon that is only temporarily stored can and should be valued. One of the biggest policy design issues may be leakage, whereby activities designed to cut greenhouse gas emissions and implemented in one jurisdiction or project lead to the shifting of the targeted emitting activities elsewhere, thus undermining the overall effort to reduce emissions. The final design issue discussed by Sohngen was measuring, monitoring, and verification (MMV) for land-based offsets, which can require significant costs to achieve. He concluded that leakage and MMV are the two most significant issues.

The final speaker for the third workshop session, Allen Fawcett of the Environmental Protection Agency, discussed the use of offsets in policy modeling. Fawcett noted that all of the major legislative proposals allow a large amount of international offsetting (roughly 1.5 billion tons of international offsets of carbon dioxide equivalents per year) as a cost-containment feature. The costs and the availability of international offsets are among the most important factors in determining the estimated cost of legislation such as H.R. 2454. Table 4.1 shows the potential categories for mitigation that would serve as the primary sources for abatement of greenhouse gas emissions. Fawcett noted that the mitigation data for each category was adjusted to more accurately represent the amount of abatement that could actually be available to the market for offsets. These adjustments were meant to take into account the difficulties in measuring, monitoring, and verifying offset reductions in countries without a market-based greenhouse gas emissions policy, as well as the lack of a clear market signal for generating offsets. The largest sources of offsets are in the energy-related CO_2 reductions and forestry options in Group 2 countries and regions (China, the former Soviet Union, Southeast Asia, Latin America, and Africa).

Figure 4.3 shows the demand for greenhouse gas abatement under H.R. 2454, the Waxman-Markey bill, using the assumption that all Group 1 countries and regions (including the United States, Canada, Western Europe, and Japan) reduce emissions at a rate similar to those mandated for the United States under H.R. 2454 (about 80 percent from 2005 levels) and that Group 2 countries reduce emissions to about 25 percent below 2005 levels. Figure 4.1 indicates that the largest source of offsets in the early years is Group 2 forestry offsets, and in the later years, Group 2 energy-sector reductions. Fawcett then described various sensitivity cases to show how assumptions about available sources of greenhouse gas abatement, reference case greenhouse gas emissions, and climate policies in other countries can have major impacts on the estimated mitigation costs. He concluded by noting how these sensitivities highlight the importance of future research to update and improve estimates of marginal abatement cost curves for international sources of greenhouse gas abatement. This research would examine the difference

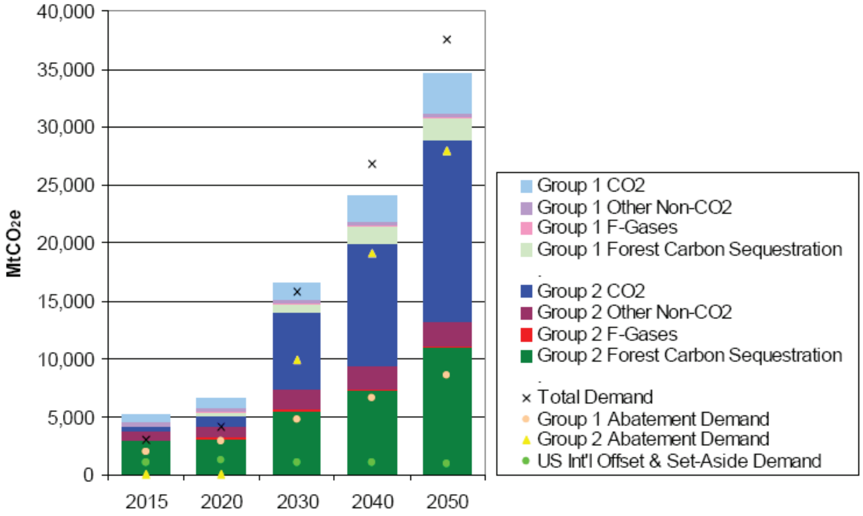

FIGURE 4.3 International supply and demand for greenhouse gas abatement by categories of abatement for analysis of recent legislative proposals (HR 2454).

in greenhouse gas abatement potential from countries with market-based climate policies versus abatement in the form of offsets or sectoral credits from countries without market-based climate policies.

The first discussant in this session was David Victor of the University of California, San Diego, who used his analysis of the CDM, which is currently the world's largest carbon offset market, to comment on political economy issues associated with offsets. He made four points. The first was that international offsets exist because of a political deal: the less-developed countries have interests different from those of the highly industrialized countries and are not going to spend their own resources in a major way on controlling emissions, and so offsets serve as a compensation mechanism to engage them in one form or another in reducing greenhouse gas emissions. His second point was that the debate about offsets is typically viewed completely through the lens of compliance costs. Many important interest groups, especially in the United States, are enthusiastic about generous offset rules because they think that offsets will contain compliance costs. However, the evidence from the CDM is that offsets are a horrendous safety valve, because the actual production of usable and bankable credits is highly erratic. The CDM is an enormously complicated administrative process that is constantly being torqued by one interest or another. Victor's third point picked up on Geoff Blanford's point about the Chinese electricity sector being a large source of offsets. Victor noted the need to be transparent about where the resources are actually going because a flow of tens of billions of dollars from U.S. firms to Chinese firms may not be politically viable. His final point concerned forestry and the politics of international offsets if forestry is added on a large scale. Although a carbon offset scheme should allow credit for any source of carbon reductions, leaving market participants to find the least costly way to meet that goal, the real political world, Victor pointed out, is different. Using the CDM as an example, he emphasized that the design of offset rules is subject to becoming highly politicized. He stated his belief that when sponsors of existing projects that attract the most CDM resources realize that forestry projects will become very low cost competitors, it is likely that they will create many procedural barriers that will make it difficult for the potential of forestry offsets to be realized in practice.

Molly Macauley of Resources for the Future then provided comments on the data needed for verification of forestry offsets. She noted that previous verification estimates have been "good enough" and, when necessary, have been improved by extensive fieldwork for a project or for an individual country. However, the currently available data are inadequate for understanding global forests. For improved understanding of the global carbon cycle as well as modeling and policy design, Macauley argued that we need better information on global forest inventories to meet verification protocols that have been proposed so far. She noted that technology is available to potentially provide the level of data needed to verify forestry offsets, but it is not deployed. She also noted that institutional and economic barriers are large because forestry resources represent both private (nationally sovereign resources) and public (carbon) goods. Macauley provided a back-of-the-envelope estimation of approximately $21 billion as the level of resources that would be necessary to make a one-time census of protocol-quality data for global forested area. There would also be the need to update the forest census periodically and perform field spot checks to ensure that leakage is not occurring. Macauley concluded by noting that countries might pay for gathering such data if their forest carbon is a valued asset and has some marketability. The marketability of forestry resources for offsets might provide the motivation for space agencies to raise the priority of monitoring land-use measures.

The third session ended with comments and questions from the audience. Adele Morris from the Brookings Institution noted that the presentations and the modeling and policy challenges discussed in these talks pointed to some of the political problems for offsets. One, based on the EPA analysis presented by Allen Fawcett, is that the United States would be spending six times as much on imported allowances under H.R. 2454 as on domestic abatements. A second issue noted by Morris is that, considering the potential for transfers of funds from U.S. firms to, for example, Chinese firms, some of that investment provides for the purchase of new technologies and the implementation of more efficient processes. This could present a competitiveness issue as U.S. firms see foreign competitors' investments in new equipment and processes being underwritten by the offset market. Clay Ogg with EPA's Office of Policy noted that there were food, fuel, and forest tradeoffs, with the food issue potentially not being sufficiently emphasized in the workshop presentations. His opinion was that initiatives that have even a very modest impact on reducing greenhouse gas emissions could have a tremendous impact on food supply and food crises. William Nordhaus from Yale University raised the concern that the economic modeling of forestry offsets does not sufficiently take into account research that shows that reforestation or anti-deforestation efforts do not have the effects on climate that are being posited. Such research shows that, even though it is possible to remove a considerable amount of carbon from the atmosphere through reforestation or by stopping deforestation, there is little impact on temperature because these efforts are also changing Earth's surface albedo and/or water cycle.

5

Story Lines, Scenarios, and the Limits of Long-Term Socio-Techno-Economic Forecasting

Steve Smith of the workshop planning committee provided context for the workshop's fourth session by noting that the socioeconomic and technological characteristics of the baseline scenario are key determinants of mitigation costs. Cost estimations of greenhouse gas reductions and other mitigation efforts do not happen in a vacuum, but rather as a change from assumed baseline conditions. The development of the baseline and alternative future scenarios has been driven largely by research needs of the integrated assessment community with interaction from other user communities. However, these scenarios increasingly are becoming end products in and of themselves. Developing them is becoming more complex and more time-consuming, and the resulting scenarios are not just research tools for one community. There also is tension between the modeling community that generates most of these scenarios and the users of these scenarios regarding how scenarios are used in the policy process. Modelers view scenarios not as predictions or forecasts, but rather as alternative images of how the future might evolve. However, outside the integrated assessment modeling community, these scenarios are often and perhaps even largely viewed as predictions. Smith went on to describe how scenarios are generated. This process starts with some fundamental assumptions about factors like population and labor productivity, which are then translated into energy service demands and the technologies that are available to serve those demands. Simply doing these calculations requires a large number of assumptions about many factors, including fertility, mortality, and the availability of new technologies that may not exist today. As a result, the uncertainties multiply as one proceeds from assumptions about population to estimates of energy use and greenhouse gas emissions. Further, these scenarios typically have been produced almost from scratch for each major application, and transparency about the methods, reasoning, and assumptions is a challenge. Thus, a fundamental issue laid out by Smith is how the modeling community moves forward in the development of new scenarios in a context where the number and the variety of scenario "users" are increasing.

Richard Moss of the Pacific Northwest National Laboratory discussed next-generation scenarios for climate modeling and analysis of adaptation and mitigation. He described as motivations for a new process for generating scenarios the need (1) to help address critiques of past scenarios, including the perceived overconfidence in scenario details; (2) to recognize evolving information needs, including the need for more information on adaptation to and mitigation of climatic change; (3) to include more scientific information, such as greater attention to feedbacks among elements of the human-climate system; and (4) to improve the coupling of integrated assessment modeling with impact, adaptation, and vulnerability (IAV) models. In the past, especially under the earlier Intergovernmental Panel on Climate Change process, the process of developing scenarios began with a set of detailed story lines laid out in a report. These story lines were then turned into various quantifications of the underlying driving socioeconomic forces. The story lines were then used to estimate emissions, atmospheric concentrations, radiative forcing, and finally, from climate models, ranges of temperature and precipitation. IAV models could then use these estimations at an aggregate level to look at impacts such as risks to species, risks from extreme climate events, distribution of impacts across societies, and aggregate economic impacts. However, this kind of activity took several years to play out so that by the time the models of impacts were producing estimates, there might have been a new generation of climate models in use. Further, Moss pointed out that there has been quite a bit of research on how people interpret these story lines and scenarios and this research indicates that there can be overconfidence in interpreting results that are simply illustrative story lines. People often begin to believe that such story lines are the most likely story lines, which is not the case. This belief can limit their thinking about alternative futures, whereas taking a broad approach is extremely important for bracketing the widest possible future conditions. Finally, Moss noted that there is not necessarily a one-to-one correspondence between the story lines generated by models and the socioeconomic quantification of those story lines.

As described by Moss, a newly developed scenario process that can help to address these issues starts with radiative forcing instead of with socioeconomic story lines. The new process begins by assuming some different levels of radiative forcing (or representative concentration pathways; RCPs) and then models in parallel both the climate scenarios that result from using the RCPs and the socioeconomic scenarios that could produce those RCPs. Some of the new socioeconomic scenarios will be consistent with the levels of emissions required to produce the RCPs, and some will be independent. Moss concluded that this new scenario process, although not perfect, presents opportunities, including greater openness and flexibility, especially for socioeconomic scenario development, that could lead to increased collaboration across the distinct research communities and improved synthesis and coordination across assessments at different scales. He noted that the challenges for mitigation and impacts analysis include the need to carefully consider what projections are needed on what time scale and how that information is going to be used. He also noted the need for approaches to performing probabilistic analysis and to communicating uncertainties.

Dale Jorgensen of Harvard University then discussed a modeling approach (the IGEM model) and scenarios for climate modeling based on the requirements specified in the Waxman-Markey bill. Jorgensen first discussed the major determinants of economic growth, including productivity changes, capital accumulation (investment), population, labor supply, and human capital. He went on to discuss the historical record of technical change for various industries in the United States and the modeling of technical change and substitution in the IGEM model. The use of econometrics in the IGEM model makes it possible to sort out what portion of the technology change occurring over the very extensive historical record is attributable to price changes like those experienced during the energy crisis periods and how much is due to changes separate from price. Jorgensen also described the modeling of household savings/investment and consumption and leisure. Finally, he described the demographic assumptions used in the IGEM model, given that projections of consumption and welfare depend on projections of population.

This model was then benchmarked to the base case in the 2009 Energy Outlook (EIA, 2009) and was used by Jorgensen to look at nine scenarios related to the Waxman-Markey bill. The modeling results demonstrate the importance of demographic and technology assumptions. Jorgensen argued that the model of technology and technological change should include substitution (“elasticities”) and technical change (“trends”) and that the IGEM econometric model provides a unified representation. Jorgensen also concluded that standard statistical techniques, based on confidence intervals generated by the econometrics, can capture uncertainties in estimated impacts, and that this econometric approach avoids the limits on dimensionality of a Monte Carlo approach.

The remainder of the session included a panel discussion and comments from the audience. Nebojsa Nakicenovic of the International Institute for Applied Systems Analysis served as the discussant, with comments that focused on story lines. His hypothesis was that the importance of story lines will increase as the RCP scenarios require additional logic and justification. He stated his belief that, because of the large numbers of parameters and complicated assumptions in coupling socioeconomic modeling to modeling of climate process, it is important to have the complementary analysis of story lines to explain the logic of how these scenarios are constructed. Finally, Nakicenovic described the story lines in the case of multiple scenarios as very helpful in explaining the logic for differentiating among the set of scenarios. During the question-and-comments period, David Montgomery from Charles River Associates noted that a conclusion to be drawn from some of his work is that it is almost always the existence of institutions that allows societies to sustain technology progress and income growth over time. However, the process described by Richard Moss, starting from an RCP, considerably narrows the possibilities of what might actually be explicitly explored with regard to institutions. Moss responded by noting that one of the advantages of starting with an RCP is to say that we have an RCP, but this does not mean that we have to have a single story line that produces a single RCP. Thus, to address an interest in a particular issue, for example institutions and governance, there is no reason to avoid developing a scenario or a story line that focuses on that interest. William Nordhaus commented that he found the RCP approach foreign in that the scenarios then seemed to be organized around variables endogenous to the socioeconomic models. Nordhaus stated that he thought the natural place to start was with baselines, using as inputs some given policies rather than intermediate variables such as RCPs. Moss responded by saying that it is important to think about the issue from the point of view of what the climate modeling community is interested in: the reason for not starting with the story lines is that a great deal of effort had to be expended upfront to get to what the climate people were interested in, and, from the climate-modeling perspective, it did not seem necessary to actually predetermine what those story lines were in order to get to a particular climate future.

6

Reflections on the Workshop

The workshop closed with reflections from planning committee members John Weyant (chair), William Nordhaus, Karen Palmer, Rich Richels, and Steve Smith. Rich Richels began by making three points. His first point was that, in the short run, modelers need to be more transparent than they have been in the past and identify the assumptions that are driving the results. The second point was that we are dealing with a situation of "act and learn and then act again," which raises the issue of the value of information. The third point was brought up by the discussion of offsets. Richels noted that offsets are characterized as an attempt by the government to contain costs. He pointed out, however, that the goal is not to drive down costs as far as possible; if that was the goal, then doing nothing would drive mitigation costs to zero. The goal is to create climate mitigation that is worth buying, and accomplishing that requires balancing costs incurred and damages avoided. It appears that the American public, in particular, is not ready to buy off on mitigation until it is clear what the value of mitigation might be. And the modeling community has not done a good job to date in explaining that.

William Nordhaus first noted that, as someone who has been in the modeling community for an extended period of time, he is impressed with the quality of the analysis. However, the scale, and not just the gravity, of the problem is growing much more complex, as is the complexity of the policy analysis. Further, Nordhaus concluded that there needs to be much improvement in modeling technology, whether it is in models that are basically projections and forecast models or in story line/scenario models. Nordhaus also noted that modeling the behavioral elements in our energy systems has taken on a new respectability, and that this is a rich area for further research. His final point was related to what he termed "hopeless" modeling territory because of the need to model a complex economy, a complex energy system, and now a complex set of policy regimes. Nordhaus concluded that the idea of having a full-blown set of models that can predict how these systems will behave, particularly in their dynamic framework, is asking too much of the human mind. Nordhaus pointed out that there will be a lot of room for looking at how these new regimes behave and for fine-tuning them over time.

Karen Palmer followed by noting that any domestic climate policy that the United States would adopt will have associated mechanisms such as standards and subsidies to encourage energy efficiency. She concluded that we need more research to identify and characterize the market or behavioral failures that contribute to the so-called efficiency gap, so that we have a better understanding of what an appropriate role for policy might be. On the flip side, we need to improve the state of the art in evaluating how energy efficiency policies work, especially approaches that account for behavior. Regarding offsets, Palmer noted that if retained, they could complement rather than substitute for a cost-containment mechanism like a price collar. This would be particularly true if the cost of offsets is likely to be highest at the times when their use would be most valuable. Thus she advocated that more research on uncertainty be done, particularly if we are going to move forward with offsets. She noted that, as pointed out in the session on offsets, there can be many political and technical uncertainties associated with offsets.

Steve Smith observed that although people might think that some of the more stringent climate targets are not realistic, to get even halfway to some of these targets will require a dramatic change from the historical trends in the energy system, which brings up a number of research questions. Smith noted that in the past energy-related technologies changed largely through market forces interacting with regulations. The scale and timing of the changes that are now contemplated are difficult to achieve in the real world, but the models represent that these changes occur very easily. Further, it was mentioned that the models tend to know prices but not costs. Smith noted that it is very difficult to pin down the costs for even some current technologies that are not mass-market technologies. A major research question for improving confidence is thus, When there are new technologies on the market that governments may be investing in, how do we make sure that we can be confident about the costs and performance of these new technologies?

John Weyant had two general reflections. The first was that he had expected a lot more discussion in the four different sessions about a “half-empty” glass and the approaches in all four areas being hopelessly misguided. Based on what he heard, he concluded that there is a lot to build on. Weyant’s second point concerned the desire to get all the “margins to line up perfectly” and to never depart from that world, which he regarded as a good discipline to impose. But Weyant noted that if we are looking for ways forward and barriers to break down and industries to reorganize and behavioral challenges to meet and regulations to reform, we have to go out for a while and develop the obvious energy efficiency programs that everyone would agree would pay off.

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Appendixes

A

Workshop Announcement and Agenda

NATIONAL ACADEMY OF SCIENCES
WORKSHOP ON MODELING THE ECONOMICS
OF GREENHOUSE GAS MITIGATION

April 15-16, 2010
Washington, DC

On behalf of the National Academies' Board on Energy and Environmental Systems and the planning committee for the Workshop on Modeling the Economics of Greenhouse Gas Mitigation, we would like to invite you to our workshop scheduled for April 15-16, 2010, at the NAS Auditorium (2100 C Street NW) in Washington, D.C. Our goal is to stimulate a dialogue about the relative strengths and weaknesses of models used to assess the economic impacts of reducing greenhouse gas emissions.

This workshop will be comprised of four major sessions taking place over the 2 days. These sessions and their times are listed below.

- **Thursday, April 15 at 9:45 am**
  Uses and Abuses of Marginal Abatement Supply Curves
- **Thursday, April 15 at 1:30 pm**
  Uses and Abuses of Learning/Experience/Knowledge Curves
- **Friday, April 16 at 8:30 am**
  Offsets—What's Assumed, What is Known/Not Known, What Difference They Make
- **Friday, April 16 at 1:30 pm**
  Storylines, Scenarios, and the Limits of Long-Term Socio-Techno-Economic Forecasting

This workshop is open to the public in its entirety, so RSVP is not necessary. For a more detailed agenda, including speakers and times, please see below.

Agenda

Thursday, April 15

8:15 AM	Registration and greeting
9:00 AM	**Welcome—Objectives and Motivation for Workshop** *John Weyant, Workshop Planning Committee Chair*
9:10 AM	**Opening Remarks** *Rick Duke, Deputy Assistant Secretary for Climate Policy, DOE*
9:20 AM	**Setting the Stage** *Administrator Richard Newell, Energy Information Administration*
9:45 AM	**Panel Session: Uses and Abuses of Bottom-Up Marginal Abatement Supply Curves** *Planning Subgroup* *John Weyant (lead)* *Rich Richels* *Karen Palmer*
9:45 AM	Issues in the Use of Energy Conservation and GHG Abatement Cost Curves *Mark Jaccard, Simon Frasier University*
10:15 AM	Efficiency Cost Curves—Empirical Insights for Energy-Climate Modeling *Jayant Sathaye, Lawrence Berkeley National Laboratory*
10:45 AM	Break
11:05 AM	Discussion Session *Marilyn Brown, Georgia Institute of Technology* *Rich Richels, Electric Power Research Institute* *Howard Gruenspecht, Energy Information Administration* *Hillard Huntington, Stanford University*
11:45 PM	Audience questions and answers
12:15 PM	Lunch
1:30 PM	**Panel Session: Uses and Abuses of Learning/Experience/Knowledge Curves** Planning Subgroup *Marilyn Brown (lead)* *Steve Smith*
1:30 PM	Beyond the "Black Box" of Learning Curves: Their Use and Misuse in Assessments of Technological Change *Nebojsa Nakicenoviic, International Institute for Applied Systems Analysis*
2:00 PM	The Perils of the Learning Model for Modeling Endogenous Technological Change *William Nordhaus, Yale University*

2:30 PM	Uncertainties in Learning Curves for Climate Policy Analysis *Edward Rubin, Carnegie Mellon University*
3:00 PM	Break
3:15 PM	Discussion Session Jae Edmonds—Pacific Northwest National Laboratory Greg Nemet—University of Wisconsin David Greene—Oak Ridge National Laboratory
4:00 PM	Audience questions and answers
4:30 PM	Adjourn

Friday, April 16

8:30 AM	**Panel Session: Offsets—What's Assumed, What is Known/Not Known, What Difference They Make** Planning subgroup *Karen Palmer (lead)* *Rich Richels*
8:30 AM	Role of Offsets in Global and Domestic Climate Policy *Ray Kopp, Resources For the Future*
9:00 AM	International Offsets: The Potential Role of the Energy Sector *Geoff Blanford, Electrical Power Research Institute*
9:30 AM	Assessment of Forests and Other Land Based Offsets: Costs and Benefits *Brent Sohngen, Ohio State University*
10:00 AM	Offsets in Policy Modeling *Allen Fawcett, Environmental Protection Agency, Climate Economics Branch*
10:30 AM	Break
11:00 AM	Discussion session Analysis of Clean Development Mechanism *David Victor, University of California, San Diego* Data Needs for Offset Verification *Molly Macauley, Resources for the Future*
11:50 AM	Audience questions and answers
12:15 PM	Lunch

1:30 PM **Panel Discussion: Storylines, Scenarios, and the Limits of Long-Term Socio-Techno-Economic Forecasting**
Planning subgroup
Steve Smith (lead)
Rich Richels
Bill Nordhaus

1:30 PM Moderator's Opening Remarks
Steven Smith, Pacific Northwest National Laboratory

1:40 PM Next Generation Scenarios for Climate Modeling and Research on Adaptation and Mitigation
Richard Moss, Pacific Northwest National Laboratory

2:10 PM Scenarios for Climate Economics Modeling
Dale Jorgenson, Harvard University

2:40 PM Audience Q&A Session

3:00 PM **Closing Roundtable—Reflections on the Workshop and Future Topics**
Workshop Planning Committee
John Weyant
Rich Richels
Bill Nordhaus
Karen Palmer
Steve Smith
Marilyn Brown

4:00 PM **End of Workshop**

B

Biographical Sketches of Planning Committee Members, Speakers, and Discussants

PLANNING COMMITTEE MEMBERS

John Weyant came to Stanford in 1977, primarily to help develop the Energy Modeling Forum. Weyant was formerly a senior research associate in the Department of Operations Research, a member of the Stanford International Energy Project, and a fellow in the U.S.-Northeast Asia Forum on International Policy. He is currently an adviser to the U.S. Department of Energy, the Pacific Gas & Electric Company, and the U.S. Environmental Protection Agency. His current research is focused on global climate change, energy security, corporate strategy analysis, and Japanese energy policy. He is on the editorial boards of *The Energy Journal* and *Petroleum Management.* His national society memberships include the American Economics Association, Association for Public Policy Analysis and Management, Econometric Society, International Association of Energy Economists, Mathematical Programming Society, ORSA, and TIMS.

Marilyn A. Brown is a professor of public policy at the Georgia Institute of Technology. Previously, she was the interim director of the Engineering Science and Technology Division at the Oak Ridge National Laboratory (ORNL). During her 22 years at ORNL, Brown researched the impacts of policies and programs aimed at advancing the market entry of sustainable energy technologies and led several energy technology and policy scenario studies. Prior to serving at ORNL, she was a tenured associate professor in the Department of Geography at the University of Illinois, Urbana-Champaign, where she conducted research on the diffusion of energy innovations. She has authored more than 150 publications and has been an expert witness in hearings before committees of both the U.S. Senate and the U.S. House of Representatives. A recent study that she co-led, *Scenarios for a Clean Energy Future*, was the subject of two Senate hearings, has been cited in proposed federal legislation, and has had a significant role in international climate change debates. She serves on the boards of directors of several energy, engineering, and environmental organizations, including the Alliance to Save Energy and the American Council for an Energy Efficient Economy, and she serves on the editorial board of the *Journal of Technology Transfer*. Brown is a member of the National Commission on Energy Policy. She has a Ph.D. degree in geography from Ohio State University and a master's degree in resource planning from the University of Massachusetts.

William D. Nordhaus is Sterling Professor of Economics at Yale University. He was born in Albuquerque, New Mexico. He completed his undergraduate work at Yale University and received his Ph.D. in economics in 1967 from the Massachusetts Institute of Technology. He has been on the faculty of Yale University since 1967 and has been a full professor of economics since 1973. Nordhaus lives in downtown New Haven with his wife Barbara, who works at the Yale Child Study Center. He is a member of the National Academy of Sciences and a fellow of the American Academy of Arts and Sciences. He is on the research staff of the Cowles Foundation and of the National Bureau of Economic Research and has been a member and senior advisor of the Brookings Panel on Economic Activity, Washington, D.C., since 1972. Nordhaus is a current or past editor of several scientific journals and has served on the executive committees of the American Economic Association and the Eastern Economic Association. He serves on the Congressional Budget Office Panel of Economic Experts and was the first chairman of the Advisory Committee for the Bureau of Economic Analysis. He was the first chairman of the newly formed American Economic Association Committee on Federal Statistics. In 2004, he was awarded the prize of Distinguished Fellow by the American Economic Association. From 1977 to 1979, he was a member of the President's Council of Economic Advisers. From 1986 to 1988, he served as the provost of Yale University. He has served on several committees of the National Academy of Sciences, including the Committee on Nuclear and Alternative Energy Systems, the Panel on Policy Implications of Greenhouse Warming, the Committee on National Statistics, the Committee on Data and Research on Illegal Drugs, and the Committee on the Implications for Science and Society of Abrupt Climate Change. He recently chaired a panel of the National Academy of Sciences; this committee produced a report, *Nature's Numbers*, which recommended approaches to integrate environmental and other non-market activity into the national economic accounts. More recently, he has directed the Yale Project on Non-Market Accounting, supported by the Glaser Foundation. He is the author of many books, among them *Invention, Growth and Welfare*, *Is Growth Obsolete?, The Efficient Use of Energy Resources*, *Reforming Federal Regulation*, *Managing the Global Commons*, *Warming the World,* and (joint with Paul Samuelson) the classic textbook *Economics*, whose eighteenth edition was published in the fall of 2005. His research has focused on economic growth and natural resources, as well as the question of the extent to which resources constrain economic growth. Since the 1970s, he has developed economic approaches to global warming, including the construction of integrated economic and scientific models (the DICE and RICE models) to determine an efficient path for coping with climate change, with DICE-2007 completed in the spring of 2007. Nordhaus has also studied wage and price behavior, augmented national accounting, the political business cycle, productivity, and the "new economy." His 1996 study of the economic history of lighting back to Babylonian times found that the measurement of long-term economic growth has been significantly underestimated. He returned to Mesopotamian economics with a study in 2002 of the costs of a war in Iraq. Recently, he has undertaken the "G-Econ project," which provides the first comprehensive measures of economic activity at a geophysical scale.

Karen L. Palmer is a senior fellow and associate director for electricity in the Center for Climate and Electricity Policy at Resources for the Future (RFF) in Washington, D.C., and the director of RFF's Electricity and Environment Program. Palmer specializes in the economics of environmental regulation of the electricity sector and the cost-effectiveness of energy efficiency programs. Her most recent work has focused on renewable energy and controls of multi-pollutants and carbon emissions from electrical generating plants. She has done extensive work analyzing different aspects of policy design for the Regional Greenhouse Gas Initiative. She is co-author of the book *Alternating Currents: Electricity Markets and Public Policy*, published by RFF Press in 2002. Palmer previously served as an economist in the Office of Economic Policy at the Federal Energy Regulatory Commission. She received a Ph.D. degree in economics from Boston College.

Richard Richels is senior technical executive for global climate change research at the Electric Power Research Institute (EPRI) in Palo Alto, California. He has served on a number of national and international advisory panels, including committees of the Department of Energy, the Environmental Protection Agency, and the National Research Council. Richels has served as a lead author for the Intergovernmental Panel on Climate Change (IPCC). He also served on the Scientific Steering Committee for the U.S. Carbon Cycle Program. He currently serves on the Advisory Committee for Carnegie Mellon University's Center for Integrated Study of the Human Dimensions of Global Change, the U.S. government's Climate Change Science Program Product Development Advisory Committee, and the National Academy of Sciences (NAS) Climate Research Committee, as well as on the Panel on Informing Effective Decisions and Actions Related to Climate Change for the NAS study on America's Climate

Choices. Richels received a B.S. degree in physics from the College of William and Mary in 1968. He was awarded an M.S. degree in 1973 and a Ph.D. degree in 1976 from Harvard University's Division of Applied Sciences, where he concentrated in decision sciences. While at Harvard he was a member of the Energy and Environmental Policy Center.

Steven Smith's research at the Pacific Northwest National Laboratory's Joint Global Change Research Institute focuses on long-term socioeconomic scenarios and the interface between socioeconomic systems and the climate system. His research interests include aerosols, non-CO_2 greenhouse gases, the carbon cycle, biomass energy, energy technologies, and land-use changes. His recent research concerns the role of non-CO_2 forcing agents in policy scenarios, including sulfate aerosols, black carbon, and non-CO_2 greenhouse gases. Model development efforts include implementing in the MiniCAM framework emissions of non-CO_2 greenhouse gases and aerosols (sulfur-dioxide and carbonaceous aerosols). At the Joint Global Change Research Institute, Smith is part of the team that has developed ObjECTS, a new object-oriented modeling framework. Prior to joining PNNL in 1999, Smith worked with T.M.L. Wigley as a project scientist at the National Center for Atmospheric Research, and he was a lead author for the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios. He also has served on the Panel on Public Affairs of the American Physical Society, as well as on the Executive Committee of the APS Forum on Physics and Society.

SPEAKERS AND DISCUSSANTS

Geoffrey Blanford is a program manager for EPRI's research on Global Climate Change Policy Costs and Benefits. The program conducts analysis of the economic and environmental implications of domestic and international climate policy proposals, with an emphasis on the principles of efficient policy design, the role of technology, and the value of R&D. Blanford's research activities include development and application of integrated assessment modeling to address issues such as technology policy and international climate agreements. He holds a Ph.D. in management science and engineering from Stanford University.

Rick Duke is currently deputy assistant secretary for climate policy at the Department of Energy. Previously, as the director of the National Resources Defense Council's (NRDC's) Center for Market Innovation he built a team of a dozen professionals dedicated to working with government and corporate leaders to accelerate investment in global warming solutions. Prior to joining NRDC, Duke was an engagement manager at McKinsey, where his projects included managing the firm's first global greenhouse gas abatement "cost curve" study for the European Union utility Vattenfall. He has also worked for the Federal Reserve Bank of New York, managed a small renewable energy company in Honduras, and consulted for the International Finance Corporation. He holds a Ph.D. from Princeton University, where his doctoral work focused on the economics of public investment in clean energy.

Jae Edmonds is a chief scientist and a laboratory fellow at the Pacific Northwest National Laboratory's Joint Global Change Research Institute, a collaboration with the University of Maryland at College Park. His research in the areas of long-term, global energy, technology, economy, and climate change spans three decades and has produced several books, numerous scientific papers, and countless presentations. He is one of the pioneers in the field of integrated assessment modeling of climate change. His principal research focus is the role of energy technology in addressing climate change. He is the chief scientist for the Integrated Assessment Research Program in the Office of Science at the U.S. Department of Energy. He has been an active participant in all of the major assessments of the Intergovernmental Panel on Climate Change.

Allen Fawcett is a senior economist in the Environmental Protection Agency's (EPA's) Climate Economics Branch, which is responsible for developing and applying EPA's economic models for domestic and international climate change policy analyses. Currently, Mr. Fawcett is conducting economic analyses of the leading climate change legislative proposals in the U.S. Congress using a suite of models including the Applied Dynamic Analysis of the Global Economy model (ADAGE) and the Intertemporal General Equilibrium Model (IGEM). He also helped to coordinate the Stanford Energy Modeling Forum 22–U.S. Transition Scenarios Subgroup. Allen joined the Environmental Protection Agency in 2003 after receiving his Ph.D. in economics from the University of Texas. He holds a bachelor of arts degree in economics from the College of William & Mary.

David L. Greene is a corporate fellow of Oak Ridge National Laboratory, a senior fellow of the Howard H. Baker, Jr., Center for Public Policy, and a research professor of economics at the University of Tennessee. He is an author of more than 200 publications on transportation and energy issues; an emeritus member of both the Energy and the Alternative Fuels Committees of the Transportation Research Board (TRB); and a lifetime national associate of the National Academies. He is a recipient of the TRB's Pyke Johnson Award, the Society of Automotive Engineers' Barry D. McNutt Award for Excellence in Automotive Policy Analysis, the Department of Energy's 2007 Hydrogen R&D Award, and the International Association for Energy Economics' Best Paper Award for his research on the rebound effect, and he was recognized by the Intergovernmental Panel on Climate Change for contributions to the IPCC's receipt of the 2007 Nobel Peace Prize. He holds a B.A. from Columbia University, an M.A. from the University of Oregon, and a Ph.D. in geography and environmental engineering from Johns Hopkins University.

Howard Gruenspecht is the deputy administrator for the U.S. Energy Information Administration (EIA). He has worked extensively on electricity policy issues, including restructuring and reliability, regulations affecting motor fuels and vehicles, energy-related environmental issues, and economy-wide energy modeling. Before joining EIA, he was a resident scholar at Resources for the Future. From 1993 to 2000, Gruenspecht served as director of economic, electricity and natural gas analysis in the Department of Energy's (DOE's) Office of Policy, having originally come to DOE in 1991 as deputy assistant secretary for economic and environmental policy. His accomplishments as a career senior executive at DOE have been recognized with three Presidential Rank Awards. Prior to his service at DOE, Gruenspecht was a senior staff economist at the Council of Economic Advisers (1989-1991), with primary responsibilities in the areas of environment, energy, regulation, and international trade. His other professional experience includes service as a faculty member at the Graduate School of Industrial Administration, Carnegie Mellon University (1981-1988), economic adviser to the chairman of the U.S. International Trade Commission (1988-1989), and assistant director, economics and business, on the White House Domestic Policy Staff (1978-1979). Gruenspecht received his B.A. from McGill University in 1975 and his Ph.D. in economics from Yale University in 1982.

Hillard Huntington is executive director of Stanford University's Energy Modeling Forum, where he conducts studies to improve the usefulness of models for understanding energy and environmental problems. In 2005 the forum received the prestigious Adelman-Frankel Award from the International Association for Energy Economics for its "unique and innovative contribution to the field of energy economics." His current research interests are modeling energy security, energy price shocks, energy market impacts of environmental policies, and international natural gas and LNG markets. In 2002 he won the Best Paper Award from the *Energy Journal* for a paper co-authored with Dermot Gately of New York University. He is a senior fellow and a past-president of the United States Association for Energy Economics and a member of the National Petroleum Council. He was also vice-president for publications for the International Association for Energy Economics and a member of the American Statistical Association's Committee on Energy Data. Previously, he served on a joint U.S.-Russian National Academy of Sciences panel on energy conservation research and development. Mr. Huntington has testified before the U.S. Senate Committee on Foreign Relations and the California Energy Commission. Prior to coming to Stanford in 1980, he held positions in the corporate and government sectors with Data Resources, Inc., the U.S. Federal Energy Administration, and the Public Utilities Authority in Monrovia, Liberia (as a U.S. Peace Corps volunteer).

Mark Jaccard has been a professor in the School of Resource and Environmental Management at Simon Fraser University, Vancouver, since 1986—interrupted from 1992 to 1997 while he served as chair and CEO of the British Columbia Utilities Commission. His Ph.D. is from the Energy Economics and Policy Institute at the University of Grenoble. Internationally, Jaccard has been involved in the Intergovernmental Panel on Climate Change (currently, for the special report on renewables), the China Council for International Cooperation on Environment and

Development (co-chair of task force on sustainable use of coal), and the Global Energy Assessment (convening lead author for sustainable energy policy). His research and applied focus is on the design and application of energy-economy models, especially for assessing the cost and effectiveness of climate policies.

Dale W. Jorgenson is the Samuel W. Morris University Professor at Harvard University. Jorgenson has been honored with membership in the American Philosophical Society (1998), the Royal Swedish Academy of Sciences (1989), the U.S. National Academy of Sciences (1978), and the American Academy of Arts and Sciences (1969). He was elected to fellowship in the American Association for the Advancement of Science (1982), the American Statistical Association (1965), and the Econometric Society (1964). He was awarded honorary doctorates by Uppsala University (1991), the University of Oslo (1991), Keio University (2003), the University of Mannheim (2004), the University of Rome (2006), the Stockholm School of Economics (2007), the Chinese University of Hong Kong (2007), and Kansai University (2009). Jorgenson served as president of the American Economic Association (AEA) in 2000 and was named a distinguished fellow of the AEA in 2001. He was a founding member of the Board on Science, Technology, and Economic Policy of the National Research Council in 1991 and served as chairman of that board from 1998 to 2006. He also served as chairman of Section 54, Economic Sciences, of the National Academy of Sciences from 2000 to 2003 and was president of the Econometric Society in 1987. Jorgenson has conducted groundbreaking research on information technology and economic growth, energy and the environment, tax policy and investment behavior, and applied econometrics. He is the author of 246 articles in economics and the author and editor of 32 books. His collected papers have been published in 10 volumes by the MIT Press, beginning in 1995. His most recent book, *Information Technology and the American Growth Resurgence,* co-authored with Mun Ho and Kevin Stiroh and published by the MIT Press in 2005, represents a major effort to quantify the impact of information technology on the U.S. economy. Another MIT Press volume, *Lifting the Burden: Tax Reform, the Cost of Capital, and U.S. Economic Growth,* co-authored with Kun-Young Yun in 2001, proposes a new approach to capital income taxation, dubbed "a smarter type of tax" by the *Financial Times*. Jorgenson was born in Bozeman, Montana, in 1933 and attended public schools in Helena, Montana. He received a B.A. in economics from Reed College in Portland, Oregon, in 1955 and a Ph.D. in economics from Harvard University in 1959. After teaching at the University of California, Berkeley, he joined the Harvard faculty in 1969 and was appointed the Frederic Eaton Abbe Professor of Economics in 1980. He served as chairman of the Department of Economics from 1994 to 1997.

Ray Kopp is the director of the Climate Policy Program at Resources for the Future, a leading non-partisan think-tank based in Washington, D.C., that has pioneered the application of economics as a tool to develop more effective policy about the use and conservation of natural resources. Kopp is an expert on climate change and energy issues. His current studies focus on U.S. domestic greenhouse gas mitigation and adaptation policy, U.S. foreign policy as it pertains to international negotiations on climate change, and deforestation and degradation in tropical countries. His expertise has influenced the design of state and federal policies as well as those of foreign governments. Kopp also has a long-standing research interest in cost-benefit analysis and techniques for assigning value to environmental and natural resources that do not have market prices. He has assisted numerous governments, intergovernmental organizations, and private entities conducting damage assessments for environmental claims. He was a consultant to the state of Alaska on the Exxon Valdez oil spill and to the United Nations Compensation Commission on the monetary value of environmental damage caused by the 1991 Gulf War.

Molly K. Macauley is a research director and senior fellow at Resources for the Future. Her research expertise includes the economics of new technologies, the value of information, space economics and policy, and the use of economic incentives in environmental regulation and other policy design. She has frequently testified before Congress and serves on numerous national- level committees and panels, including the National Research Council's Space Studies Board, the Climate Working Group of the National Oceanic and Atmospheric Administration, and the Earth Science Applications Analysis Group of the National Aeronautics and Space Administration (NASA). She also served as a lead author on a project under the U.S. Climate Change Science Program. She was selected as one of the National Space Society's "Rising Stars," and in 2001 she was voted into the International Academy of Astronautics. She has received awards from NASA and the Federal Aviation Administration for her research. Macauley has published widely and has also served as a visiting professor in the Department of Economics at Johns Hopkins University.

Richard H. Moss is a senior research scientist with the Joint Global Change Research Institute at the University of Maryland, a visiting senior research scientist at the Earth Systems Science Interdisciplinary Center, and a senior fellow with the World Wildlife Fund (WWF). He has served as director of the Office of the U.S. Global Change Research Program/Climate Change Science Program, vice president and managing director for climate change at WWF, and senior director of the U.N. Foundation Energy and Climate Program. He also directed the Technical Support Unit of the Intergovernmental Panel on Climate Change (IPCC) impacts, adaptation, and mitigation working group and served on the faculty of Princeton University. He was a coordinating lead author of *Confronting Climate Change* and *Realizing the Potential of Energy Efficiency*, led preparation of the U.S. government's 10-year climate change research plan, and has been a lead author and general editor of a number of IPCC assessments, special reports, and technical papers. Moss remains active in the IPCC and currently co-chairs the IPCC Task Group on Data and Scenario Support for Impact and Climate Analysis. He serves on the U.S. National Academy of Sciences' standing committee on the "human dimensions" of global environmental change and on the editorial board of *Climatic Change*. He was named a fellow of the American Association for the Advancement of Science (AAAS) in 2006, a distinguished associate of the U.S. Department of Energy in 2004, and a fellow of the Aldo Leopold Leadership Program in 2001. He received an M.P.A. and a Ph.D. from Princeton University (in public and international affairs) and his B.A. from Carleton College in Northfield, Minnesota. Moss's research interests include development and use of scenarios, characterization and communication of uncertainty, and quantitative indicators of adaptive capacity and vulnerability to climate change.

Nebojsa Nakicenovic is a professor of energy economics at the Vienna University of Technology, deputy director of the International Institute for Applied Systems Analysis (IIASA), and director of the Global Energy Assessment (GEA). Among other positions, Nakicenovic is a member of the United Nations Secretary General Advisory Group on Energy and Climate Change; a member of the Advisory Council of the German Government on Global Change (WBGU); a member of the Advisory Board of the World Bank Development Report 2010: Climate Change; a member of the International Council for Science (ICSU) Committee on Scientific Planning and Review; a member of the Global Carbon Project; a member of the Energy Sector Management Assistance Program (ESMAP) Expert Panel on Sustainable Energy Supply, Poverty Reduction and Climate Change; a member of the Panel on Socioeconomic Scenarios for Climate Change Impact and Response Assessments; a member of the Renewable Energy Policy Network for the 21st Century (REN21) Steering Committee; and chair of the Advisory Board of OMV Future Energy Fund (Austrian oil company). Nakicenovic holds bachelor's and master's degrees in economics and computer science from Princeton University and the University of Vienna, where he also completed his Ph.D. He also holds an Honoris Causa Ph.D. degree in engineering from the Russian Academy of Sciences. Among Nakicenovic's research interests are the long-term patterns of technological change, economic development and response to climate change, and, in particular, the evolution of energy, mobility, information, and communication technologies.

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Richard Newell is the administrator of the U.S. Energy Information Administration. He is on leave from his position as the Gendell Associate Professor of Energy and Environmental Economics at Duke University's Nicholas School of the Environment. Previously he served as the senior economist for energy and environment on the President's Council of Economic Advisers. He also spent many years as a senior fellow at Resources for the Future (RFF), an independent, nonpartisan environmental and resource economics research institution in Washington, D.C. He has published widely on the economics of markets and policies for energy, the environment, and related technologies, particularly alternatives for reducing greenhouse gas emissions and achieving other energy and environmental goals. Prior to his confirmation, Newell was a research associate of the National Bureau of Economic Research and a university fellow of RFF, and he served on several boards, including those for the *Journal of Environmental Economics and Management,* the journal *Energy Economics,* the Association of Environmental and Resource Economists, and the Automotive X-Prize. He has served on several National Academy of Sciences' expert committees related to energy, environment, and innovation. Newell holds a Ph.D. from Harvard University in environmental and resource economics. He also holds an M.P.A. from Princeton University's Woodrow Wilson School of Public and International Affairs, and a B.S. in materials engineering and a B.A. in philosophy from Rutgers University.

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Brent Sohngen is a professor of environmental and resource economics in the Department of Agricultural, Environmental and Development Economics at Ohio State University. He received his Ph.D. in environmental economics from Yale University in 1996. Sohngen conducts research on the economics of land use change, the design of incentive mechanisms for water and carbon trading, carbon sequestration, and nonmarket valuation of environmental resources. He developed a global timber and land use model that has been widely used to assess the implications of climate change for forested ecosystems and forest product markets and to assess the costs of carbon sequestration in forests, including reductions in deforestation. The model has recently been expanded to account for agricultural production and markets. Sohngen has written or co-written 31 peer-reviewed journal articles, 45 monographs, and book chapters. He has been published in a variety of journals, including the *American Economic Review*, *American Journal of Agricultural Economics*, *Ecological Economics*, and *Climatic Change*. He co-edited a special issue of *Climatic Change* in 2006, addressing adaptation to climate change.

David Victor is a professor at the School of International Relations and Pacific Studies at the University of California, San Diego, and director of the school's new International Law and Regulation Laboratory. Looking across a wide array of issues from environment to human rights, trade and security, the laboratory explores when (and why) international laws actually work. Most recently, Victor served as director of the Program on Energy and Sustainable Development at the Freeman Spogli Institute for International Studies at Stanford University, where he was also a professor at Stanford Law School. Previously, he directed the science and technology program at the Council on Foreign Relations (CFR) in New York, where he directed the council's task force on energy co-chaired by Jim Schlesinger and John Deutch and was a senior adviser to the task force on climate change chaired by governors George Pataki and Tom Vilsack. Victor's research at Stanford and the CFR examined ways to improve management of the nation's $50 billion strategic oil reserve, strategies for managing investment in geoengineering, and a wide array of other topics related to technological innovation and the impact of innovation on economic growth. His research also examined global forest policy, global warming, and genetic engineering of food crops. His books include *Natural Gas and Geopolitics* (2006), *The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming* (2001; second edition 2004); *Climate Change: Debating America's Policy Options*; and *Technological Innovation and Economic Performance* (2002, co-edited with Benn Steil and Richard Nelson). Victor is the author of more than 150 essays and articles in scholarly journals, magazines, and newspapers, such as *Climatic Change, Financial Times, Foreign Affairs*, *International Journal of Hydrogen Energy, Nature, New York Times, Science, Scientific American,* and *Washington Post.*

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Papers Submitted by Workshop Speakers

The 10 papers included in this appendix are reprinted essentially as supplied by their authors.

PARADIGMS OF ENERGY EFFICIENCY'S COST AND THEIR POLICY IMPLICATIONS: DÉJÀ VU ALL OVER AGAIN

Mark Jaccard[1]

May 15, 2010

Introduction

The issue of the cost of and potential for energy efficiency improvement is of great importance for the global effort to reduce greenhouse gas (GHG) emissions. The global energy system is over 80% dependent on fossil fuels, whose combustion is a major contributor to GHG accumulation in the atmosphere. Shifting, in less than half a century, from fossil fuel combustion to major contributions from renewable energy, nuclear power and carbon capture and storage when using fossil fuels will be less difficult if humanity can simultaneously improve significantly the efficiency with which it produces, transforms and uses energy (Jaccard, 2005).

During the oil price crisis of the 1970s, many energy technologists and efficiency advocates argued that great improvements in energy efficiency are economically efficient, a win-win that would increase profits while reducing energy use. Many economists, however, disputed this claim, arguing that analysis indicating the existence of profitable opportunities for energy efficiency must be overlooking some real, but perhaps intangible, costs for consumers and firms.

In the 1980s and 90s, expectations of high energy prices abated and with them the debate about the cost and potential for energy efficiency. But with rising concerns for GHG reduction, the issue of energy efficiency profitability has re-emerged. The McKinsey (2007) consulting firm has contributed to the issue by producing recent estimates of energy efficiency profitability for the United States and other countries, estimates which imply that substantial reductions of GHG emissions could be realized at little or no cost. Policy-makers who want to reduce GHG emissions are understandably attracted to this analysis as it suggests that such reductions may be cheap and easy. But for energy analysts aware of the history of this debate, it's "déjà vu all over again."

In this paper, I provide an overview of the ongoing evidence and arguments with respect to the profitability of energy efficiency and its relevance for the estimated cost of GHG emissions reduction as well as for climate policy design. I begin with a background review of the analysis suggesting the profitability of energy efficiency and the implications for the cost of GHG emissions reduction. I follow with a conceptual model to explain criticisms of this approach and to show how different perceptions of costs and market failures explain the divergent paradigms of energy efficiency profitability. I then describe recent efforts by energy analysts to design energy-economy policy models that bridge the differences between the two paradigms in order to better inform policy-makers. In conclusion, I return to the general question of how energy efficiency analysis might best aid policy makers seeking to rapidly reduce GHG emissions at the lowest possible cost to society.

The Paradigm of Profitable Energy Efficiency

For over three decades there has been an ongoing and at times aggressive debate on the potential for win-win investments that would improve both energy and economic efficiency—in other words, opportunities for profitable energy efficiency. Physicists, engineers and environmentalists, who tend to dominate one side of the debate, repeatedly find substantial opportunities for profitable energy efficiency investments in industrial facilities, buildings, equipment and transportation systems. When asked why such opportunities go unexploited in market economies, these "technologists" point to various institutional, information and financial barriers. In contrast, economists, who tend to dominate the other side of the debate, are instinctively skeptical of claims there is a large, untapped potential for profitable energy efficiency investments. They tend to assume that there must be hidden costs and risks facing firms and households such that these so-called profitable opportunities are exaggerated.

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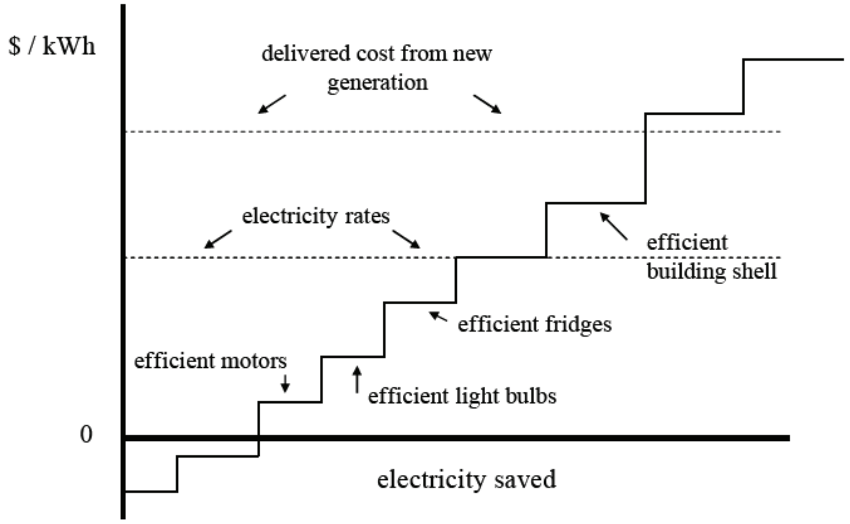

FIGURE C.1 Energy conservation cost curve.

The method to calculate the economic returns on energy efficiency investments was initially developed in the 1970s by researchers seeking to compare energy supply investments with incremental investments in greater energy efficiency that could, in effect, eliminate the need for the supply investments in the first place (Lovins, 1977). Energy efficiency in the electricity sector was especially targeted. By focusing on specific energy services (lighting, space heating, refrigeration, etc.) researchers compared the capital costs of two technologies that provided the same service. The more efficient device usually had higher capital purchase costs. Using a discount rate, the incremental capital costs of the efficient device could be set in a ratio to the discounted stream of energy savings to calculate a life-cycle cost of conserved or saved energy (for example, $/kWh saved with a more efficient fridge).[2]

Researchers then extended this analysis from a single choice between two technologies providing the same energy service to an estimate of the quantity of energy conservation that is possible throughout the economy for that service if everyone opted for the more efficient device. For each energy service, an estimate is made of the average efficiency of existing equipment stocks. Then, it is assumed that all these stocks could be converted to higher-efficiency models, which results in an estimate of the total amount of energy that could be saved for that particular end-use and the life-cycle cost per unit of conserved energy. The next step is to graph these economy-wide quantities of conserved energy in ascending order of cost, thus providing a total estimate of the energy efficiency potential at each cost level—an “energy conservation cost curve” or “life-cycle cost of conserved energy curve” (Figure C.1).

The energy conservation cost curve provides information about the value of energy efficiency from different perspectives. First, efficiency investments for which the curve is below zero indicate instances where the efficient device has a lower life-cycle cost than the device it would replace. Second, all efficiency investments whose life cycle costs are below current electricity rates are profitable from the private perspective of the firm or household. Third, if rates do not reflect the full cost of delivering electricity from new supplies (many utilities charge prices reflecting average costs rather than the costs of new supply) then those efficiency investments whose life-cycle costs are less than the cost of new supply are also profitable, albeit this time from a social rather than a private perspective.

Life-cycle cost estimates of energy efficiency became extremely influential in the 1980s in the U.S. electric

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[2] These investments were commonly known as energy conservation investments. At the risk of irritating physicists, who note that all energy is conserved since it can be neither created nor destroyed, I follow the common practice of using interchangeably the terms energy efficiency and energy conservation.

utility industry, with utility regulators in most states requiring utilities to use this analysis to determine how to apportion their spending between new supply and "acquiring" energy efficiency—the latter referred to as demand-side management (DSM). Since utilities lack the mandate to apply regulations or pricing adders to motivate efficiency investments, the only DSM policies available to them were programs to educate and inform firms and households of profitable efficiency opportunities (labels, audits, advertisements, public engagement campaigns) and some application of subsidies for the acquisition of high efficiency devices. In the policy discussion below, I explain what recent hindsight analyses now suggest about the efficacy of these policies.

The interest in energy efficiency declined in the 1990s with the advent of electricity market reforms that emphasized competition in supply and threatened the ability of monopoly utilities to collect the revenues needed to run DSM programs. Over the last decade, however, interest in energy efficiency has re-emerged as this is one of the few options to reduce energy-related GHG emissions and as the stalled electricity reform movement has left distribution utilities and, in some cases, vertically integrated utilities in a position to continue their DSM efforts.

Moreover, some analysts have applied basically the same life-cycle costing methodology to estimate the costs of GHG emissions reductions investments. In this method, technologies that provide the same service (energy demand or energy supply or some other service in the economy that produces GHG emissions) are compared on the basis of their capital and operating costs using a discount rate to produce life-cycle costs for each technological option. One of the competing options will be a low- or zero-emission technology. An estimate is made of the average emissions of existing equipment stocks for that service, which then provides the basis for estimating the GHG emissions that could be abated by converting all stocks to the low- or zero-emission alternative. These are again graphed in ascending order of cost—cost being defined as the incrementally higher life-cycle cost of switching to the lower-emission alternative—to produce a GHG abatement cost curve. The lowest steps on the curve might even have negative costs if the life-cycle-cost of the low-emission alternative is lower than that of its high-emission competitor.

Whether the curve is for energy efficiency or GHG emissions, this approach of looking at individual energy services and then explicitly assessing the technologies that could meet that service is referred to as "bottom-up analysis" or "bottom-up modeling." This is in contrast with the analysis and models of most economists, which conventionally do not include explicit representation of technologies.

Figure C.2 shows a recent bottom-up GHG abatement cost curve for the United States produced by the McKinsey (2007) consulting firm. I have overlaid a circle to show that energy efficiency completely dominates the low-cost options for GHG reduction. The energy efficiency analysis in Figure C.1 is closely linked to the GHG abatement cost estimates in Figure C.2, meaning that the analytical approach that produced profitable and low-cost estimates for energy efficiency is equally responsible for the low cost estimates of GHG abatement. In the case of the United States, the graph suggests that about 40% of U.S. GHG emissions could be eliminated by 2030 at a cost of less than $50/t$CO_2$ and that the net cost to the economy is likely to be zero, given the substantial profits from so many of the energy efficiency actions. This is shown in the figure by the shaded area below the line being equal to the shaded area above the line for 3 gigatonnes of reductions—about 40% of total U.S. current emissions.

Debates on the Profitability of Energy Efficiency

While technologists have mostly focused on estimating the magnitude of the profitable energy efficiency potential, they have also been asked to explain why it exists. Their response usually points out the lack of awareness of efficiency opportunities by firms and households ("information barriers"), the difficulty of borrowing money for the up-front costs of an efficiency investment ("financial barriers"), the inadequate level of technical know-how for installing and maintaining high-efficiency devices and structures ("capacity barriers"), and a disconnect between those responsible for investment costs and those responsible for operating costs ("split-incentive barriers"), such as the landlord who pays for appliances and the tenant who pays the electricity bills (Geller, 2003).

In contrast, economists tend to argue that all technology choices face these types of barriers and that even new technologies that are more energy-intensive may face lack of information, financing constraints, inadequate know-how and split-incentives. While economists might agree that some real market failures, like average cost pricing by utilities, or unpriced environmental harms, can be used to justify greater energy efficiency, they would

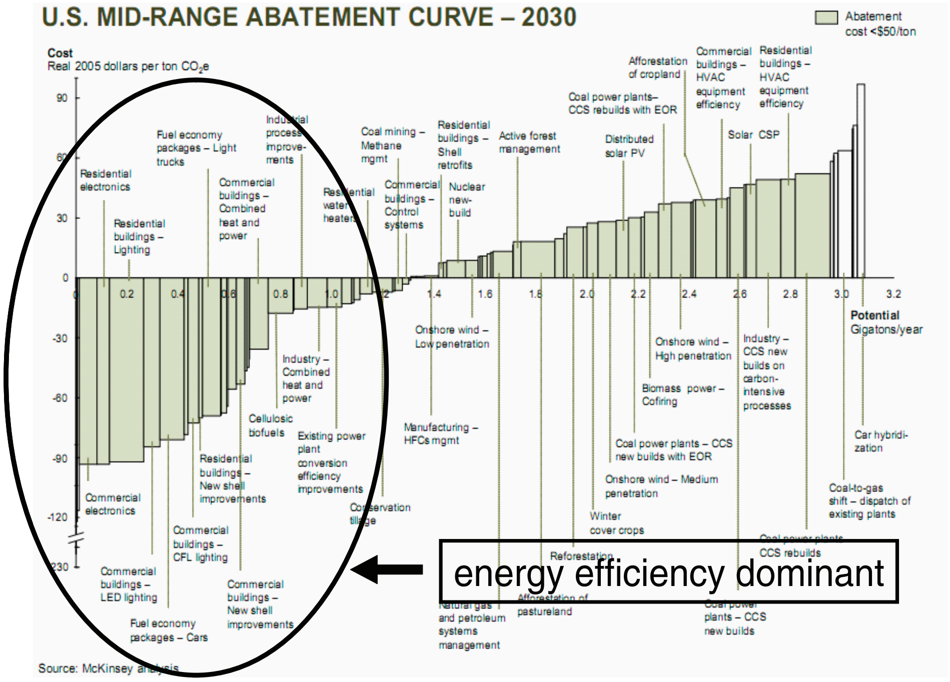

FIGURE C.2 GHG abatement cost curve.
SOURCE: Adapted from McKinsey, 2007.

be interested in research that probed the intangible costs and risks that may be associated with acquiring more efficient technologies (Jaffe and Stavins, 1994; Jaffe et al., 1999; Jaccard et al., 2003).

Figure C.3 depicts these two competing perspectives, or paradigms, of the amount of the profitable energy efficiency. The base of the figure is the current level of efficiency, with upward movement indicating an increase in efficiency.

The energy efficiency of individual devices and structures is usually increasing over time. As capital stocks are renewed, the general (but not universal) tendency throughout most of the past several decades has been for firms and households to acquire more efficient devices than the average efficiency of existing stocks. This means that at any given time, a technology survey can find opportunities for energy efficiency, even though these very opportunities will naturally be exploited as devices and structures are renewed over the coming years. In the figure, this natural rate of energy efficiency is depicted as the "baseline efficiency trend," efficiency that will occur simply through capital stock replacement.

It is possible that society could accelerate this natural rate of stock turnover, but then the cost would be not just the incremental capital cost of a more efficient device, but also some part of the full cost of the existing equipment, since that device was otherwise slated to operate for several more years. When technologists estimate the potential for profitable energy efficiency, they are not usually referring to costly expenditures that prematurely retire existing equipment and structures. Only with a model that provides a detailed representation of the age structure of the capital stock, and its natural rate of turnover, is it possible to estimate how the profitability of energy efficiency is affected by the rate of stock turnover.

Moving up the vector, many economists acknowledge there are market failures that prevent the adoption of energy efficient technologies that would be profitable from a societal or private perspective. From a societal perspective, it could be that the energy prices facing businesses and households do not reflect the emerging cost of providing that energy. This is often found where monopoly electric utilities are regulated to set customer tariffs that

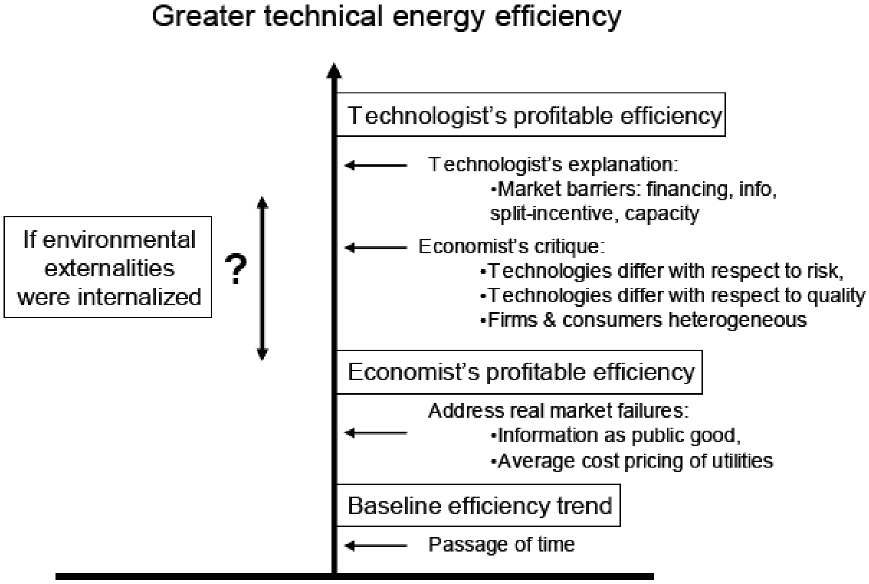

FIGURE C.3 Competing depictions of energy efficiency profitability.
SOURCE: Author, inspired by Jaffe et al. (1999).

reflect only the average costs of production and delivery, in order to prevent excessive profits by these monopolies. If the cost of new supply is higher than the average cost, then there could be energy efficiency investments that are not profitable when compared to average costs but are profitable when compared to the incremental costs of producing and delivering new energy supply. Although such an investment is not profitable for a private company or household (given the regulated, average-cost tariffs they face), it is profitable from a societal point of view. Economists recognize that there will be energy efficiency investments that become profitable if average rates are adjusted to reflect the marginal cost of new energy supply.

From a private perspective, there are profitable energy efficiency investments that do not occur because the decision maker is unaware of them. This is what technologists call the information barrier. To the economist, in some circumstances information can be a "public good," meaning that its social value exceeds the value to any one individual who might provide it for themselves. Because the individual cannot capture all the value from information provision, it tends to be underprovided by the market, hence a "market failure." Economists are generally willing to recognize the public good market failure associated with information and would thus acknowledge the potential value of efficiency investments that would occur were this information provided. This leads to the "economist's profitable efficiency" level in the figure.

But there is one caveat. The economist would argue that one should include the "cost of providing information" when estimating the amount of efficiency that is profitable. If, for example, government or a utility must outlay considerable funds, with teams of energy auditors visiting plants, offices and homes, in order to provide information about efficiency potential before it is acted upon, it could be that some of the efficiency potential is not actually profitable when these additional costs are included. The cost of correcting a market failure may be so high that society is better off not to correct it. This is a question for which the answer may change over time as society improves its capacity to disseminate at low cost information about efficiency opportunities.

Finally, economists also recognize environmental externalities as a market failure. If these externalities were priced, this could increase the amount of energy efficiency that is profitable. The size of the efficiency potential depends on the magnitude of the price changes implied by internalizing externalities into prices, which is highly uncertain. This uncertainty is depicted on the left side of the vector by a question mark. It is kept separate from issues on the right side of the vector. This is because the technologist's argument for profitable energy efficiency is that its potential is large even when environmental externalities are zero or are completely ignored. If externalities were priced, and did lead to rising energy prices and some investments to improve energy efficiency, the higher prices would also enable technologists to find additional efficiency investments that were now profitable but not being realized.

The top level in Figure C.3 depicts the amount of efficiency that technologists claim is profitable. As noted, the technologist explains the gap between the economist's position and this upper technologist's position as the result of market barriers that prevent firms and households from making energy efficiency investments that are otherwise profitable. These barriers include lack of information (without the economist's qualification that the cost of information provision must be counted), inability to get financing for profitable efficiency investments, lack of capacity in terms of technical know-how for selecting, installing and maintaining efficient technologies, and a disconnect between the efficiency incentive for the user (tenant) but not the acquirer (landlord) of some buildings and equipment.

Many economists suggest, however, that these so-called barriers may simply be a reflection of true differences between technologies in terms of the risks they present and the quality of service they provide. The common light bulb provides an example. To a technologist, an incandescent light bulb and a compact fluorescent light bulb might be considered perfect substitutes if they both produce 700 lumens of light. This allows one to focus on their different capital costs, electricity use and life expectancies when estimating the profitability of acquiring the more efficient bulb. But life expectancy estimates, for example, are usually based on laboratory testing. The risk of a user accidently breaking a light bulb is not considered. In reality, however, the capital cost risks of the two technologies (risk being probability of occurrence multiplied by outcome) is not the same. For while the probability might be the same that a user will accidentally break a light bulb during a given year, the negative outcome (financial loss) in the case of the more expensive, more efficient bulb is likely to be higher than for the cheaper, less efficient bulb. The "expected" (adjusted for risk) capital cost of the compact fluorescent light bulb might be 1.3 times its off-the-shelf cost while the expected cost of the incandescent light bulb might be 1.1 times its off-the-shelf cost. Yet technologists' energy efficiency studies do not adjust capital costs of efficient technologies to reflect this asymmetric risk.

This risk differential between technology substitutes is not only a function of long payback investments—it is also a function of newness. More efficient technologies are usually newer technologies and because these tend to fail more frequently their capital cost should again be multiplied by a factor different than that applied to a conventional technology. Again, however, technologist studies of the profitable potential for energy efficiency do not adjust technology capital costs upward to reflect this risk.

Technologies may differ not just with respect to financial cost risk. They may also not be the perfect substitutes suggested by a simple analysis of their services, such as of the amount of lumens produced by efficient and inefficient light bulbs. For much of the first two decades of their commercial availability, compact fluorescent light bulbs provided a markedly different quality of service than incandescent bulbs in terms of hue of the light, size and appearance of the bulb, timing to reach full intensity, compatibility with light dimmers, resistance to cold, and other attributes. These are what economists refer to as intangible or non-financial costs, which are very real to the firms and households contemplating technology acquisition. Again, however, technologist studies of the profitable potential for energy efficiency do not adjust the costs of more efficient technologies to reflect these non-financial considerations that have an immediate bearing on the value of an energy efficiency investment.

Finally, it is important to understand that market conditions are not the same everywhere, with different firms and consumers facing different costs of learning about, finding, acquiring, installing, operating and maintaining more efficient devices. Thus, single point estimates based on the most favorable financial costs of efficient devices will exaggerate the total benefits of the economy-wide adoption of such devices.

Implications for Energy-Economy Modeling

Figures C.1 and C.2 show how bottom-up energy efficiency cost curve analysis has been used to provide estimates of the profitable amount of energy efficiency and GHG abatement. While economists argue that these curves are likely to underestimate the full costs of energy efficiency, an additional concern is expressed by energy system modelers who point out that any step on the curve (an efficiency or GHG abatement action) must be assessed simultaneously with all other steps, rather than in the piecemeal fashion of bottom-up cost curve analysis. In the following text and figures I explain these problems and show how their correction results in alternative cost curves whose meaning must be interpreted differently.

First, energy system modelers point out that bottom-up cost curve analysis represents a form of extreme "partial equilibrium analysis" in that each step on the cost curve (energy efficiency or GHG emissions reduction) is calculated while assuming the other steps are kept frozen. In reality, there is likely interdependence of many steps. At the level of distinct energy services, changing the efficiency of lighting affects the costs of actions to improve building shell efficiency and the efficiency of equipment for heating, ventilation and air conditioning. At the level of energy supply and demand interaction, greater electricity efficiency will lower the price of electricity generation, which in turn will reduce the profitability of energy efficiency investments from a private and social perspective. Likewise, changing the GHG emissions produced by the electricity sector will change the emissions that are saved by more efficient fridges, and thus the costs of GHG abatement by this action. The response of most energy researchers to this problem has been to abandon conventional cost curves in favor of an integrated energy-economy model that treats all actions (efficiency, GHG abatement) as happening simultaneously. This is why such models have been developed and are frequently relied upon by decision-makers. The NEMS model of the Energy Information Administration (2009) in the United States is an example of such an energy system model.

Second, bottom-up cost curve analysis assumes that market conditions are homogeneous for each energy service. In reality, the life-cycle cost of more efficient, or lower GHG, equipment will be different for different market segments—such as increasing efficient fridges from 10% to 20% market share versus increasing them from 80% to 90% market share. This is because of differences throughout the market in terms of the age of existing equipment and the costs of learning about, finding, acquiring, installing, operating and maintaining more efficient or lower emission devices. This is why models have been developed that keep track of capital stocks and reflect market heterogeneity. Again, the NEMS model is an example.

Third, bottom-up cost curve analysis assumes that, with the exception of their differences in capital and operating costs, two technologies are perfect substitutes for a given energy service. As described above, competing technologies often differ in terms of the quality of service they provide and the risk profiles they present, and there are transaction costs to acquiring more efficient devices as these tend to be less well known and relatively untested. These factors mean that the steps of the cost curves are likely to under-represent the full costs of energy efficiency or GHG abatement such that the real-world cost curves should be higher. This is why modelers have developed technology simulation models with parameters that reflect how firms and households value different technologies. Again, the NEMS model is an example.

Figure C.4 depicts graphically how an energy-economy systems model can be used to produce a cost curve that is comparable to yet different from that produced by the bottom-up cost curve approach, in this case in terms of GHG abatement. The curve in this figure represents the amount of GHG emissions reduction that occurs as ever higher prices are applied to emissions in model simulations to the year 2030. Modelers refer to this as a marginal abatement cost curve. It is distinct from the previous bottom-up cost curve because a given action, like the acquisition of efficient fridges, occurs all the way along the curve, instead of at a single step, to reflect market heterogeneity. Also, at each point on the curve, simultaneous actions are occurring within energy demand and between energy supply and demand, as in the real world. Finally, the curve includes transaction costs and intangible differences in quality and risk, so it is likely to be higher than the initial bottom-up abatement cost curve.

In the debates about the cost of energy efficiency and GHG abatement, technologists have repeatedly countered that the type of curve depicted in Figure C.4 is equally not reflective of reality in that, as normally depicted by economists, it starts at or above the origin. This implies the absence of any profitable energy efficiency opportunities anywhere in the economy, or at least none once the model accounts for efficiency gains that occur normally as capital stocks are renewed (these are absent because the curve only shows incremental GHG abatement associated with a rising price for GHG emissions). Technologists argue that the energy-economy models of most economists exclude a priori the potential for profitable energy efficiency because they present only an abstract ("top-down") representation of technologies and assume that the existing set is optimal from the cost-minimizing perspective of firms and households.

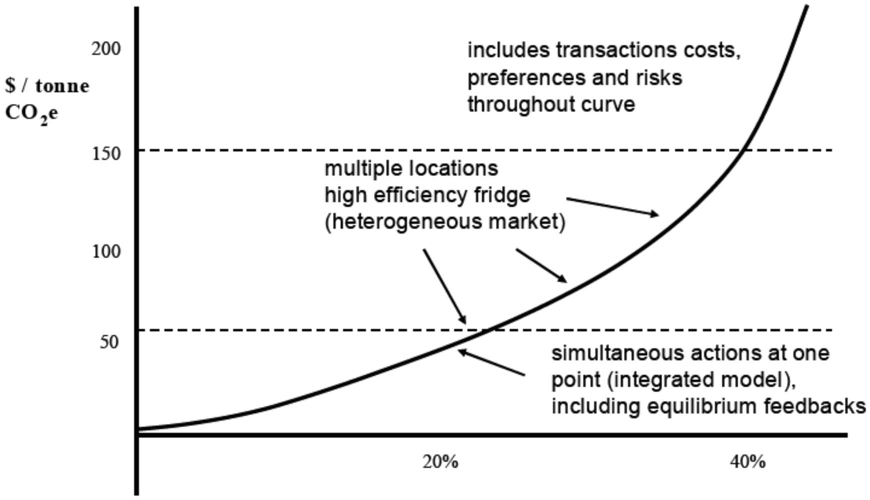

FIGURE C.4 Energy-economy model: marginal abatement cost.

In the past, this criticism has had validity in that economists have indeed favored such models. But over the past two decades, many energy-economy modelers have developed technology-explicit models that keep track of equipment stocks and can estimate the potential for profitable energy efficiency once all intangible costs, preferences and risks have been taken into account. These are sometimes referred to as "hybrid" models and, once again, the NEMS model of the U.S. EIA is an example. Another example is the CIMS model, which I have been involved in developing over the past two decades, with applications to Canada, the United States and other countries (Jaccard, 2009). This model is technologically explicit, keeping track of vintages of capital stocks of different efficiency and other qualities, but its behavioral parameters are estimated from a combination of market research into past technology choices (revealed preferences) and discrete choice surveys of possible future technology choices (stated preferences).

Figure C.5 overlays the results of a CIMS hybrid model simulation of a rising price for GHG emissions in the United States, producing a marginal abatement cost curve, with the McKinsey bottom-up cost curve that was depicted in Figure C.2—both of these for what could be achieved by the year 2030. As expected, the hybrid abatement cost curve is higher than the bottom-up cost curve. Unlike a typical top-down curve, however, it does suggest that some reductions of GHG emissions in the United States would be profitable, presumably from energy efficiency actions (the line starts below the origin). But it suggests that a reduction of 3 gigatonnes from projected levels would require much greater costs and an emissions price of $\$200/tCO_2$ instead of the $50 suggested by the McKinsey bottom-up cost curve.

Implications for Policy Assessment

These competing paradigms of the profitability of energy efficiency are relevant not just for estimating the cost of GHG abatement. They are also important in terms of GHG policy design. If a considerable amount of energy efficiency is profitable, it might be easy to achieve with a package of non-compulsory policies like information programs and strategically placed subsidies, essentially the DSM policies that electric utilities have applied for much of the past three decades. If, however, energy efficiency is more expensive, it may be that stringent regulations on fuels and technologies and/or pricing policies (like a carbon tax or an emissions cap and trade system) must dominate the policy package.

Fortunately, electric utility DSM programs of the past three decades provide a rich data set for assessing the effectiveness of information and subsidy programs. Government departments have also implemented for several

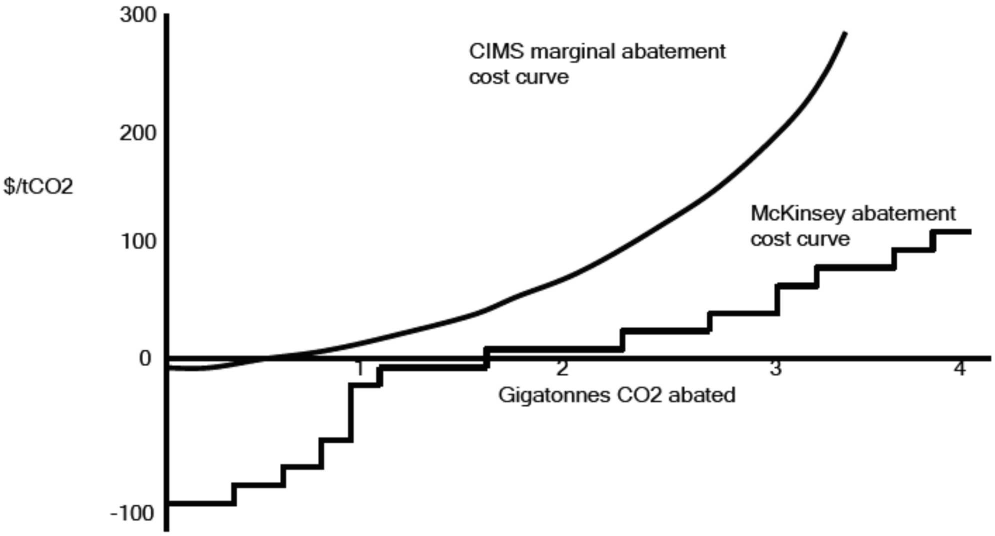

FIGURE C.5 U.S. abatement cost: bottom-up versus hybrid.
SOURCE: Author (CIMS curve) and inspired by McKinsey (2007).

decades energy efficiency policies that emphasized this lighter approach to accelerating the economy's normal trend toward more efficient devices, although governments sometimes also tightened efficiency regulations on equipment, vehicles, appliances and buildings. Data on these utility and government programs is available either as evidence in utility regulatory processes or in the budgetary records of government departments and agencies. Arimura et al. (2009) summarize empirical studies of the effectiveness of these past programs and assemble a comprehensive data set of utility and government efficiency programs from which they provide their own estimates. Their results suggest that energy efficiency subsidy and information programs have not achieved all the predicted energy efficiency gains and that, as a consequence, the cost of achieving energy efficiency in this way is higher than assumed. It should be noted, moreover, that these utility cost estimates would already have been higher than the pure bottom-up cost estimates from studies such as that of McKinsey because utility predictions of DSM effects try to incorporate the intangible costs that may cause firms and households to forego energy efficient options.

Thus, the research suggests that utilities would generate higher cost estimates for energy efficiency than would a conventional bottom-up study of the type shown in Figure C.2. In addition, once the effectiveness of information and subsidy policies is taken into consideration, the actual achievement of energy efficiency through these policies is likely to be much less than if one assumed that all of the so-called profitable efficiency gains identified by McKinsey- type studies could be somehow realized.

Research into the effectiveness of subsidy programs in particular highlights the problem of "adverse selection," meaning that such subsidies are often captured by firms and households to help pay for efficiency improvements they were going to make anyway, improvements that were part of the natural rate of efficiency gain. Such beneficiaries of subsidy programs are sometimes referred to as "free riders" in that they benefit from the subsidies for doing nothing different than they would have done anyway—such as upgrading the insulation when retrofitting their home. From a policy design perspective, it is impossible to prevent this from occurring, which is a substantial challenge for subsidy programs.

Because subsidies represent a transfer payment from one group of taxpayers and/or ratepayers to another, the subsidies do not affect the profitability of the efficiency actions themselves. The only issue is the extent to which subsidies can be effective as a policy tool for accelerating the efficiency trend. If, because of ineffectiveness, really large transfers are required for only small gains in efficiency, there will also be equity concerns with respect to the costs incurred by those who are unable to participate in the subsidy programs for some reason: having already made efficiency investments, ignorance of the subsidy program, slowness in applying for limited subsidy funds, or having a low income or poor credit rating that hinders the ability to get financing to cover the non-subsidized portion of the efficiency investment.

Conclusion

For over three decades, some technologists have argued that there are extensive opportunities for profitable energy efficiency investments. For much of these three decades, however, some economists have countered that these estimates of profitable energy efficiency overlook important intangible costs facing firms and consumers. These include transaction costs, investment risks facing new technologies and long payback investments, heterogeneity in the market, and differences in quality of service. While these costs are usually ignored by technologists, economists have done little research to estimate their actual magnitude—so fault lies on both sides.

These competing paradigms are confusing to policy makers trying to assess the cost-effectiveness and likely contribution of energy efficiency to efforts to reduce GHG emissions. Bottom-up cost curve analysis by technologists suggests an extremely large and profitable potential, which implicitly suggests that information and subsidies alone may reduce emissions substantially. Top-down marginal abatement cost curve analysis by economists suggests the opposite, implying the need for strong emissions pricing and/or regulations. More recent research with hybrid models that are technologically explicit but behaviorally realistic suggests that while there is some profitable potential for energy efficiency, strong pricing and regulatory policies will indeed be required for a modern economy to achieve substantial GHG emissions abatement over the coming decades.

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ENERGY EFFICIENCY COST CURVES: EMPIRICAL INSIGHTS FOR ENERGY-CLIMATE MODELING

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Abstract

In this paper, we report on implications of key energy efficiency issues such as barriers that include market failures; policies and programs; co-benefits; and historical changes in costs. We show examples for their representation in selected energy climate (EC) models and other analytical approaches. We report on two approaches for the quantification of barriers. Our analysis of California utilities' efficiency policies and programs exemplifies a cost effective approach to overcoming these barriers. The analysis of energy efficient clothes washers shows the importance of including water savings as an invaluable co-benefit, and the examples of iron and steel and cement show significant reduction in costs of energy efficiency options from inclusion of multiple co-benefits. Lastly, we illustrate the changes in costs of efficient products in U.S. industrial and residential end uses over time, which call for the use of dynamic as opposed to static cost curves in EC models.

Keywords

Energy efficiency, cost of conserved energy, empirical insights, energy-climate modeling, co-benefits, dynamic cost curves.

Introduction

Adoption of efficient end-use technologies is one of the key measures for reducing GHG emissions. In many cases, these are cost effective investments that an energy consumer could make for improving energy productivity while reducing GHG emissions. With the rising interest in policies and programs to reduce GHG emissions, estimating the costs of energy efficiency options and managing them has become increasingly important for policy makers and consumers around the world.

Energy-climate (EC) models are classically used for analyzing the costs of reducing carbon and other GHG emissions for various types of technical and policy measures. An increasing number of models[3] are now representing energy efficiency measures because an accurate estimation of these costs is critical for identifying and choosing the measures, and for developing related policy options to accelerate their market adoption and implementation. However, the accuracy of assessing GHG-emission reduction costs by taking into account the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in the models. For example, if the models do not include end-use technologies with an appropriate level of detail in their modeling framework, it will be difficult to estimate the costs and benefits of reducing GHG emissions with certainty.

In this paper, we review three topics related to the representation of energy efficiency improvement opportunities in energy-climate models. These include the treatment of (1) barriers to energy efficiency as a no- regrets option,[4] (2) co-benefits and costs, e.g., due to water and labor savings, and (3) changes in energy efficiency costs over time.

In the second section, we review the literature on energy efficiency cost curves as a way of representing cost and benefits associated with energy efficiency options and also broadly describe the representation of energy efficiency in EC models.

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[3] For example, those participating in the EMF24 exercise.

[4] No-regrets options are those whose benefits such as reduced energy costs and reduced emissions of local and regional pollution equal or exceed their cost to the society, excluding the benefits of avoided climate change (IPCC 2001, p. 21).

Representation of energy efficiency as a no-regrets option requires an estimate of the costs indirectly imposed by the barriers to their adoption or conversely of the costs of policies and programs that are established to address these barriers. In the third section, we review these issues and summarize the results of the empirical analysis we have conducted on this topic on the quantification of the principal agent barrier in the U.S. residential sector. We also undertake an empirical assessment of the costs and benefits for overcoming these barriers by policies and programs by analyzing the energy efficiency programs implemented by utilities in California, which are one of the world's largest energy efficiency programs. The section also includes a brief description of the use of such costs and benefits in EC models.

In the fourth section, we focus on the importance of considering the co-benefits of adopting energy efficiency measures. Based on the empirical analysis of the U.S. iron and steel industry, and residential clothes washers, we show how the estimates of the potential of no-regrets options changes when co-benefits are included in the analysis.

In the fifth section, we report on the historical changes in the cost curves in industrial and residential sectors, and how these dynamic changes are likely to influence the costs of carbon emissions reduction. The last section summarizes our findings and provides recommendations for future work.

Representation of Energy Efficiency: Cost Curves and Energy-Climate Models

In this section, we first review the use of cost curves, one of the commonly used approaches to represent and compare various GHG mitigation options including energy efficiency improvements. We then broadly review how energy efficiency improvement options are represented in energy climate models.

Energy Efficiency Cost Curves

The energy sector comprises the major energy demand sectors (industry, residential and commercial, transport, and agriculture), and the energy supply sector, which consists of resource extraction, conversion, and delivery of energy products. Greenhouse gas emissions occur at various points in the sector, from resource extraction to end use, and accordingly, options for mitigation exist at any of these points.

The bottom-up approach involves the development of scenarios based on energy end uses and evaluation of specific technologies that can satisfy demands for energy services. One can compare technologies based on their relative cost to achieve a unit of GHG reduction and other features of interest. This approach gives equal weight to both energy supply and energy demand options. A variety of screening criteria, including indicators of cost-effectiveness as well as non-economic concerns, can be used to identify and assess promising options, which can then be combined to create one or more mitigation scenarios. Mitigation scenarios are evaluated against the backdrop of a baseline scenario, which simulates the events assumed to take place in the absence of mitigation efforts. Mitigation scenarios can be designed to meet specific emission reduction targets or to simulate the effect of specific policy interventions. The results of a bottom-up assessment can then be compared to a top-down analysis of the impacts of energy sector scenarios on the macro-economy.

In this paper, we will focus on energy efficiency options and the representation of their marginal cost curves, typically referred to as cost of conserved energy (CCE) curves. CCE curves were developed about three decades ago to place energy-efficiency cost estimates at a level comparable to that for supply-side options (Meier, 1982). A CCE curve is made up of a combination of several options and can be sector-specific or economy-wide. The CCE is estimated for each mitigation option and plotted against its resulting energy or emissions savings.[5] A combination of such calculations yields a curve of CCE for a suite of mitigation options. The CCE calculation is based on investment theory[6] and it is expressed as:

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[5] One criticism that has been directed at the calculation of CCEs is that they may err by aggregating across the entire stock, without differentiating costs, and discount rates for various classes of consumers. One way to avoid this mistake is illustrated by Sathaye and Murtishaw (2004) in the clothes washer analysis by disaggregating potential adopters by income class.

[6] Stoft (1995) offers an alternative expression that avoids the problem of double counting due to dependence among measures on a curve.

$$CCE = \frac{1 \cdot q}{ES} \qquad (1)$$

$$q = \frac{d}{(1-(1+d)^{-n})} \qquad (2)$$

Where:

CCE = Cost of conserved energy for an energy-efficiency measure (or mitigation option), in \$/GJ
I = Incremental Capital cost (\$)
q = Capital recovery factor (yr^{-1})
ES= Annual energy savings (GJ/yr)
d = Discount rate
n = Lifetime of the mitigation option (years)

These savings are estimated by comparing the electricity use of an efficient and an inefficient end-use technology, a compact fluorescent lamp (CFL) vs. an incandescent bulb for example. The comparable device has to be such that it offers the same service in terms of the lumen output, color rendering, and robustness to quality of electricity supply. The above expression can easily be converted to a cost of avoided GHGs by applying emission factors to the affected energy source. Appropriate terms can be added to the equation (1) to take into account various other costs such as operating and transaction costs (such as search costs), and benefits such as material and labor savings and environmental benefits.

Representation of Energy Efficiency in Existing Energy-Climate Models

Integrated assessment models originally emerged primarily from economic and energy modeling approaches that were for the most part developed for, and applied to, industrialized economies (Sanstad and Greening, 1998). Increasingly, however, these models have been enhanced and extended over time, and in many cases created, to encompass the global economy at various levels of regional and sectoral disaggregation.

Integrated assessment modeling of climate policy uses various top-down models that describe the general economy and its interactions, and the effects of price changes. Many of these models include a sectoral representation of the economy (see Ross, 2005) for the description of the ADAGE model, as an example of a top-down model). The existing empirical basis for modeling of technologies that represent these sectors is often weak, and largely arises from limited literature at the sectoral level rather than technology-level. There is a need to constantly investigate and improve the representation of end-use technologies in energy-climate models, in coordination with EC modelers who will stand to benefit from this research.

Bottom-up models, on the other hand, have detailed representation of GHG mitigation technologies including those of the demand side. However, often the representation of supply side options is more rigorous and detailed than that on the demand side. Further, the representation of various barriers to adoption of efficiency measures that appear to be cost effective from a societal perspective is often indirect. For example, most bottom-up models calibrate the adoption of energy efficiency measures predicted by the model to that observed in reality by artificially increasing the discount rate (also known as the hurdle rate) used by consumers to evaluate these investments or by introducing artificial limits to cost effective technology updates. The effect of policies and programs is indirectly modeled by changing the discount rate (see for example Latiner and Hanson, 2006, for such analysis using the AMIGA model). These methods are indirectly trying to represent various barriers faced by consumers in adoption of energy efficiency options. Only a limited number of analyses attempt to model the impact of energy efficiency policies and programs which address some of the barriers to adoption of energy efficiency and have limited empirical basis of how the effect of policies and programs is modeled (see for example, Roland-Host, 2006 which considers the effect of efficiency policies and programs while undertaking energy climate modeling of California's economy using the BEAR model).

Although most energy-climate models consider technological change in energy supply and use, modeling of technological change in demand-side energy efficiency technologies endogenously is a new topic. Given the growing importance of technological improvement (e.g., energy efficiency) as an avenue to mitigate long-term climate change, it is critical that technology characteristics, their evolution and response to energy and carbon price be understood better than has been the case to date. This is also particularly true of developing countries where obsolete technologies are likely to see a more rapid transformation, as their markets integrate into the global economy, while newer technologies are likely to be adopted faster due to evolving global markets and more availing policy support. In the following sections, we discuss how the analysis of energy efficiency as a mitigation option can be improved in analyses performed using energy climate models or other methods, by addressing some of the issues raised above.

Energy Efficiency as a No-Regrets Option

The Intergovernmental Panel on Climate Change defines no-regrets options in its Third Assessment as "…those options whose benefits such as reduced energy costs and reduced emissions of local and regional pollution equals or exceeds their cost to the society, excluding the benefits of avoided climate change" (IPCC 2001, p. 21). This definition suggests that no-regrets options should be pursued even without considering their benefits of avoided climate change. Alternatively, the benefits of avoiding climate change do not result into net costs to the society but in fact result in net benefits to the society. Hence no-regrets options are also known as negative-cost (equivalently net-benefit) options for avoiding climate change.

There is a lot of debate on the availability of no-regrets options (Ostertag, 2006). Those who posit that significant no-regrets options do not exist (see for example, Sutherland, 1991) argue that if no-regret options were available, they would have been pursued by the market. They typically argue that engineering-economic studies which show a large potential for no-regrets options such as cost effective energy efficiency measures often do not take into account many indirect costs of these measures such as search costs and transaction costs. Further, these studies do not take into account the effect of various market failures and consumer preferences, which hinder the adoption of no-regret options that appear to be cost effective in an engineering-economic type of analysis. Researchers who posit that significant no-regrets options do not exist argue that cost effective ways of reducing these indirect costs and correcting various market failures which hinder the adoption of energy efficient technologies are rarely available. On the other hand, those who posit that significant no-regret options exist generally argue that there are various cost effective policy measures which could reduce the indirect costs associated with no-regret options and correct some of the market failures which hinder their adoption. We review some of the literature on barriers (including transaction costs) and approaches to characterize the potential for energy efficiency as a GHG mitigation option and the associated policies and programs that address these barriers

Barriers, Potentials, and Policies: Overview

Earlier reports have enumerated lists of several factors (barriers) affecting the penetration of energy-efficient devices by customer class or tariff category, region and/or sector (Reddy, 1991; Golove and Eto, 1996; Eto, Prahl, and Schlegel, 1997; Sathaye and Bouille et al., 2001). These factors include lack of information, lack of access to capital, misplaced incentives, flaws in market structure, performance uncertainties, decisions influenced by custom and habits, inseparability of features, heterogeneity of consumers, hidden costs, transaction costs, bounded rationality, product unavailability, externalities, imperfect competition, etc. The extent of their inclusion affects both costs and the mitigation potential of a technology or a mix of technologies. Sathaye and Bouille (2001), following on the work of Jaffe and Stavins (1994), classify factors into two categories. The first category refers to factors that economists may typically classify as "market failures," the second, to factors that are manifestations of consumer preferences, custom, cultural traits, habits, lifestyles, etc.

Associated with each category is the concept of potentials for GHG mitigation (Figure C.6). Each concept of the potential represents a hypothetical projection that might be made today regarding the extent of GHG mitigation. The leftmost line, labeled *market potential* indicates the amount of GHG mitigation that might be expected to

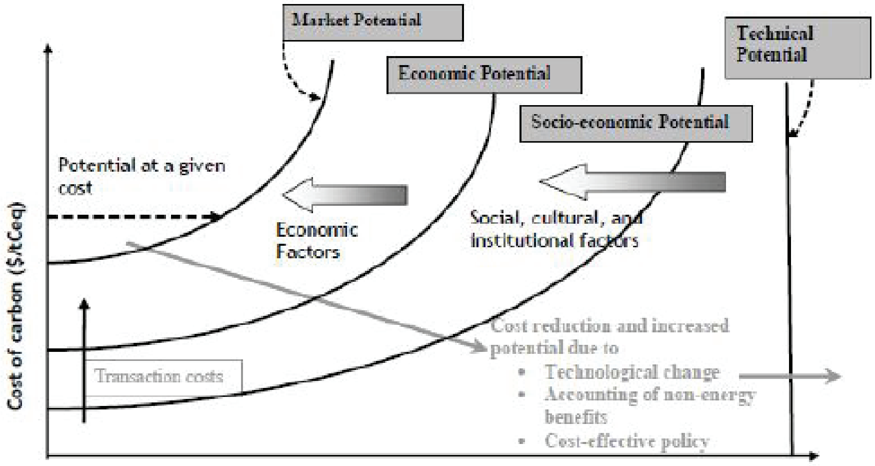

FIGURE C.6 Penetration of mitigation technologies: A conceptual framework.

occur under forecast market conditions, with no changes in policy or implementation of measures whose primary purpose is the mitigation of GHGs. At the other extreme, the *technical or physical potential* describes the maximum amount of GHG mitigation achievable through technology diffusion. This is a hypothetical projection of the extent of GHG mitigation that could be achieved over time if all technically feasible technologies were used in all relevant applications, without regard to their cost or user acceptability.

Definitionally, we can say that whatever physical, cultural, institutional, social, or human factors are preventing us from reaching the technical potential are barriers to the mitigation of GHG via technology diffusion. Since our ultimate goal, however, is to understand policy options for mitigation, it is useful to group these factors in a way that facilitates understanding of the kinds of policies that would be necessary to overcome them. As we create these different categories of factors, we correspondingly create intermediate conceptions of the potential for GHG mitigation. Starting at the left in Figure C.6, we can imagine addressing factors (often referred to as market failures) that relate to markets, public policies, and other institutions that inhibit the diffusion of technologies that are (or are projected to be) cost-effective for users without reference to any GHG benefits they may generate. Amelioration of this class of *market imperfections* would increase GHG mitigation towards the level that is labeled as the *economic potential*. The economic potential represents the level of GHG mitigation that could be achieved if all technologies that are cost-effective from consumers' point of view were implemented. Because economic potential is evaluated from the consumer's point of view, we would evaluate cost-effectiveness using market prices and the private rate of time discounting, and also take into account consumers' preferences regarding the acceptability of the technologies' performance characteristics.

Some of the market failures listed above can be broadly grouped together as cognitive factors affecting product diffusion. By this, we mean that there are limitations to consumers' ability to gather and process information. Before any consumer can make the decision to adopt a technology, he or she must at a minimum be aware of its existence. Once aware, a consumer needs to make some effort to gather the information needed to make an informed decision about whether a given technology provides more benefits than it costs. In order to do this, an individual needs the analytic capacity to fairly accurately quantify the benefits and costs. Even an aware, informed, capable consumer must ultimately make the effort to assess benefits and costs before making the decision to adopt.

A consumer who has made the decision to adopt needs to find a vendor for the product in question. Relatively new technologies are likely to be less widely available than their more standard counterparts. Thus, limitations on cognitive resources are described by factors such as performance uncertainty, information costs, and bounded rationality.

Elimination of all of these market imperfections would not produce technology diffusion at the level of the *technical potential*. That is, even if these factors are removed, some GHG-mitigating technologies may not be widely used simply because consumer preferences operate against their acceptance. These factors, which define the gap between economic potential and technical potential, are usefully placed in two groups separated by a socio-economic potential. The socio-economic potential represents the level of GHG mitigation that would be achieved if all technologies that are cost effective on the basis of using a social, rather than a private, rate of discount (including externalities, with the use of appropriate prices devoid of taxes and subsidies) were implemented. The socio-economic potential may or may not require a change in consumer preferences. Finally, even if all market, institutional, social, and cultural factors whose removal is cost-effective from a societal perspective were removed, some technologies might not be widely used simply because they are still too expensive. Elimination of this requirement would therefore take us to the level of the *technical potential*, the maximum technologically feasible extent of GHG mitigation through technology diffusion. Moving from right to left, the figure shows that factors increase costs and reduce the savings potential of a mitigation technology.

Another commonly considered factor in the development of cost curves is the increased use of energy that might be prompted by the reduction in total cost of energy use due to the adoption of efficient devices. Indeed, several papers show that a rebound effect can range from 10 to 40% (Sorrell 2009; Geller and Attali 2005) A rebound effect, however, would also be accompanied by increased consumer welfare or increased production of goods due to the increased energy use. Moreover, Ehrhardt-Martinez and Laitner (2010) suggest that the magnitude of rebound can be mitigated by the adoption of smart "people-centered" or behavioral initiatives that enable households and businesses to more effectively manage their overall levels of energy consumption.

Figure C.6 also presents a snapshot in time of the factors and potentials for the penetration of technologies. Over time, technological progress, discoveries of new resources and/or technologies, and cost-effective government policies and programs could eliminate some of the factors and hence move the potential lines (including the technical potential) to the right, thereby increasing the savings from a mitigation option. The figure also shows that transaction costs add to the cost of the mitigation option. As a market matures, the decline in transaction costs caused by learning by doing and standardization will push the cost curve lower, which will increase the market penetration of a technology.

The focus of this paper is on the factors affecting the realization of GHG reductions from energy efficiency. The price of energy plays a role in determining the energy savings potential—the higher the price, the larger the potential, and vice versa. The price or tariff line is seen to intersect the marginal cost curve of energy efficiency savings. Should the tariff be higher, then more of these savings would be cost effective than would be the case otherwise.

Barriers, Policies, and Programs: Insights from Empirical Analysis

As discussed above, various barriers cause the market potential for energy efficiency improvements to be smaller than its economic potential. Quantifying the impact of diverse barriers on energy efficiency cost and potential is a challenging task but it provides a better understanding of the reasons for the difference between the market and economic potentials and the benefits of addressing various barriers through policies and programs. An earlier report by Sathaye and Murtishaw (2004) predicted several likely barriers (split incentives, access to capital and efficient products, lifetime and consumption uncertainty, limited product and vendor information, and consumer preferences) that prevent the purchase of efficient residential lamps and clothes washers. For each barrier, they estimated its effect on the capital cost, annual costs, equipment lifetime, or discount rate in the CCE Equation 1, and on the number of consumers that are likely to adopt this measure, which influences the total potential energy savings.

Barriers such as split incentives for example do not directly increase the costs of adopting energy efficient products; however, they limit the consumer base that is likely to adopt this measure. Barriers such as limited product and vendor information and uncertainty in performance directly add to the cost of adoption. The analysis showed the relative share of these costs in shifting from the socio-economic potential to the market potential shown in Figure C.6 above. The cost of *accessing information* and the *uncertainty about equipment lifetime* turned out to be the largest contributors to the costs imposed by various barriers in their analysis.

A second approach quantified the impact of the principal agent problem on the sales of efficient U.S. residential appliances (Murtishaw and Sathaye, 2007 and De La Rue du Can and Sathaye, 2008). This analysis and its results are described in the section "Quantifying the Impact of Barriers" below.

It has been demonstrated that policies and programs which address various barriers lead to increased adoption of energy efficiency (see section entitled "Costs and Benefits of Policies and Programs That Address Barriers"). These policies and programs also incur some costs such as administrative, marketing, installation, and financial incentives (which are more of a transfer than actual cost). From a societal perspective, the desirability of these programs depends on whether the benefits of these policies and programs outweigh their costs and empirical evaluation of the same is warranted. Further, it is important to analyze the impact of policies and programs to estimate how the impact of energy efficiency gets adopted. We report the results of our empirical analysis of utility energy efficiency programs in California, which are one of the largest and most comprehensive energy efficiency programs in the world.

Quantifying the Impact of Barriers

Multiple barriers have been listed in the previous section, but until recently few studies to our knowledge had attempted to quantify the "excess" energy consumed due to any particular barrier or the savings potential from mitigating it. Murtishaw and Sathaye (2007) and De La Rue du Can and Sathaye (2008) focused on the principal agent (PA)[7] or split incentives problem because quantifying its extent and the excess energy consumption it causes was perceived to be more tractable than for other market failures.[8]

In residential energy use, this commonly occurs in two critical transactions, one between home builders and prospective buyers, and the second between renters and landlords (Jaffe and Stavins, 1994). Home builders may have difficulty conveying the benefits of energy efficiency technologies to prospective buyers because these technologies and their future energy use consequences are not observable. Likewise, landlords may not be able to recover all of the value of such investments in the form of higher rents, where renters pay fuel bills, and tenants who make these investments in cases where the landlord pays the energy bill may not be able to get reduced rents.

From a policy perspective, split incentives can block or delay utility price signals from reaching the end-user. Murtishaw and Sathaye (2007) thus provide a quantitative basis for supporting other forms of government interventions that complement price policy for increasing the penetration of cost-effective energy efficient products. Such interventions may include the provision of additional and targeted information, energy performance standards and labels, and building codes.

In order to determine whether any particular end use is affected by the PA problem, three questions must be answered. First, who uses the device? Second, who selects the device? Third, who pays the energy cost? Theoretically, if the answer to these questions is not the same person or entity, a PA problem exists, albeit of two different types. If the person paying the utility bill is not the person using the device, the user may consume more energy services than if he were not shielded from the price of energy. Similarly, if the person paying for energy is not the person choosing the device, the buyer will generally choose among the cheapest, and often least efficient, options. Thus, the PA problem can arise from two kinds of split incentives, one concerning usage (demand for energy services) and the other concerning the technical efficiency of the end-use device. For any given device, determining the cases involving a PA problem may be conceptualized as a two-by-two table that classifies the device according to a user's ability to choose the device and the user's responsibility for paying associated energy costs (Table C.1).

The analysis confirms that price signals alone may have a limited effect on inducing energy conservation in the U.S. residential sector because a significant share of energy is consumed by end users who either have little or no control over the efficiency of energy-using equipment (Case E) or who are shielded to some extent from

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[7] The PA problem arises in many spheres of economic activity, when one person, the principal, hires an agent to perform tasks on his behalf but cannot ensure that the agent performs them in exactly the way the principal would like (Bannock et al. 1992). The efforts of the agent are impossible or expensive to monitor and the incentives of the agent differ from those of the principal. Thus, the PA problem is a function of incentives, information asymmetry, and enforcement capacity.

[8] Results of this study are also reported in an International Energy Agency (IEA) publication, Mind the Gap (IEA 2007). The IEA publication reports on case studies that used the same methodology in Japan, the Netherlands, and Norway primarily in the commercial and residential sectors.

TABLE C.1 Shares of Site Energy by End Use Affected by Principal-Agent Problems

	Can Choose Device	Cannot Choose Device
Direct Energy Payment	**Case N:** **No PA Problem** Refs: 72% WH: 31% SH: 64% AC: 63%	**Case E:** **Efficiency Problem** Refs: 25% WH: 59% SH: 31% AC: 31%
Indirect Energy Payment	**Case B:** **Usage and Efficiency Problem** Refs: <1% WH: negligible SH: negligible AC: <1%	**Case U:** **Usage Problem** Refs: 3%[a] WH: 10% SH: 5% AC: 6%

[a] Refrigerators are an exception since no usage problem exists in Case U, assuming same agent (e.g. landlord) chooses the device and pays for energy.

the costs of their energy consumption (Cases B and U). Table C.1 highlights the fact that a conspicuous share of energy use falls into Cases E and U. The bulk of the energy affected is characterized by Case E.

In order to assess the potential energy savings by overcoming PA problems, we applied to PA affected households the same Energy Star appliances penetration rate that was applied to non-affected households for each end use. Table C.2 provides a summary of the results by end use.

Space and water heating were estimated to have the largest potential. This is in part due to the fact that these end uses represent the largest share of energy use in the residential sector (47% for space heating and 17% for water heating in 2001) and also because the penetrations of Energy Star boilers and furnaces are much higher than for the other appliances considered, thus increasing the potential savings for PA-affected households.

A recent statistical evaluation of the U.S. residential energy consumption survey (RECS) data by Davis (2010) reconfirms the above analysis. Its results show that, controlling for household income and other household characteristics, renters are significantly less likely to have energy efficient refrigerators, clothes washers and dishwashers.

Can this type of information be included in the types of EC models that were discussed above? A model such as NEMS for example generates projections of total residential energy demand and appliance stocks. It is a complex model, with a detailed accounting system for tracking appliance stocks over time in each of nine different census regions. However, new appliance purchase decisions in the model are based on a fairly simple methodology, including three housing types and three market share “logit” equations. Appliance energy use for any given household type varies as a function of the efficiency of appliances (as determined above), the rebound effect and the price elasticity of energy demand.

Models such as NEMS that are designed to include or already include a representation of end uses can be modified to provide an explicit consideration of the PA problem. The household groupings shown in Table C.1

TABLE C.2 Estimated Energy Savings per End Use

	Energy Savings (Tbtu)	
End Use	Site Energy	Primary Energy
Space heating	8.65	9.86
Water heating	4.60	5.90
Refrigerators	0.16	0.49
Air conditioning	0.20	0.60

have different price elasticities of demand to purchase appliances and to use them. Group N households readily change both purchase and use behavior in response to a shift in energy price (high price elasticity to buy and use). Group E households change use when the price shifts, but are slow to change purchase behavior (low price elasticity to buy; high price elasticity to use). Group U households are slow to change use and purchase behavior in response to price shifts (low price elasticity to buy and use). Data permitting, a more detailed representation of the four categories of households and associated different elasticity values would give explicit representation of the PA problem in these models.

Costs and Benefits of Policies and Programs That Address Barriers

As shown in Figure C.6, cost effective policies and programs can address some of the barriers and increase the energy efficiency potential that can be achieved. Hence understanding the cost, benefit, and potential for these cost effective policies and programs is critical for accurately estimating/representing the role EE can play as a mitigation option. In the United States, utility programs address these barriers to capture some of the "negative-cost" potential, and expenditures on these programs provide an estimate of the cost of overcoming some of these barriers. Hence by adding these program costs to the cost of efficiency measures typically estimated by engineering economic studies, one can potentially estimate the societal cost of energy efficiency as a mitigation option. Many energy climate models, which focus on analyzing the role of various mitigation options in climate stabilization scenarios, can consider these program costs and model accelerated adoption of cost effective measures due to these programs. Most energy-climate models do not undertake this exercise given the lack of empirical information on program costs especially at the measure level.

We present the results of the analysis of efficiency programs implemented by California utilities during 2006-2008. California has long been a national leader in promoting energy efficiency: the state's policies, programs, and standards have served as a model for federal policies as well as initiatives in other states. California utilities undertake one of the largest ratepayer funded energy efficiency initiatives in the world. The state's utility energy efficiency programs are numerous, costing about one billion dollars per year. These programs are funded by resources collected from ratepayers and are overseen by the California Public Utilities Commission (CPUC), which regulates the investor owned utilities (IOUs) in the state. IOUs are required to file monthly, quarterly, and annual reports, which provide various details on the outcomes of their energy efficiency programs to the California Public Utilities Commission.

Table C.3 shows the average net consumer cost per kWh, rebate and non-rebate utility expenditures per kWh, and the societal cost of conserved energy. The incremental marginal cost borne by consumers (IMC) ranges from 1.73 to 2.85 cents/kWh. The rebate offered by each utility company is shown in the second column (0.9-1.22 cent/kWh). The third column shows the net cost to consumers (Net Cost = IMC cost – rebate cost) (0.83-1.63 cents/kWh). Non-rebate utility expenditures vary widely from 0.5 cent/kWh for SCE up to 1.1 cent/kWh for SDG&E.

TABLE C.3 Cost of Conserved Energy (cents/kWh), 2006-2008

Utility	Consumer Incremental Marginal Cost / kWh	Rebate / kWh	Net Consumer Cost / kWh	Non-rebate Utility Exp/ kWh	Societal Cost / kWh
PGE	1.73	0.90	0.83	0.99	2.72
SCE	2.85	1.22	1.63	0.50	3.35
SDGE	2.34	0.98	1.36	1.10	3.44

PGE—Pacific Gas and Electric,
SCE—Southern California Edison,
SDGE—San Diego Gas and Electric.

The societal cost of conserved energy, which is the sum of the rebate, net consumer cost, and non-rebate utility expenditures, ranges from 2.72 cents/kWh for PG&E to 3.44 cents/kWh for SDG&E, within the expected range for an energy efficiency portfolio. The societal cost is much lower than the cost of supply from various generation technologies in California. A CEC report calculated that the levelized cost of IOU-owned plants brought online in 2007 is 9.6 cents/kWh for integrated gasification combined cycle, 6.7 cents/kWh for Class 5 wind, and 19 cents/kWh for concentrated solar PV (CEC 2007). The societal CCE is also much lower than electricity tariffs; PG&E's average rate was 17.6 and 17.9 cents/kWh for residential and commercial consumers respectively. The non-rebate utility expenditure on incentives and other program implementation items such as providing information and installation services, which address some of the barriers to adoption of energy efficiency measures, are substantially lower than their benefits indicating that such programs are a cost effective way of addressing barriers to adoption of energy efficiency measures.

These numbers are consistent with findings of other studies of the cost effectiveness of energy efficiency programs. A ACEEE report lists the cost of conserved energy in California as 3 cents/kWh (Kushler et al., 2004).[9] The CCE for New Jersey and Vermont is also similar at 3 cents/kWh, while Connecticut is at the low end with 2.3 cents/kWh and New York at the high end with 4.4 cents/kWh.The rebate (subsidy) provided to consumers ranged between 42-52% of the total IMC. The substantial rebate decreases the payback period, or the amount of time needed for consumers to recover their initial outlay. For example, the simple payback period (without discounting) for PG&E's energy efficiency measures is 1.7 years for electricity savings, and roughly 80% have a simple payback period of 1 year or less. In contrast, if no financial incentives were provided, the simple payback period would be 3.1 years.[10] The utilities are thus attempting to overcome consumer myopia by providing rebates and reducing their payback period.

If we believe that the utilities are using incentives optimally—that is, providing the minimum amount of incentive to achieve a certain target of savings over a given period—then the implication is that the payback period must be brought down substantially (to 1 year or less in this particular instance) for large-scale promotion of energy efficiency measures. Indeed, given the many barriers to adoption of energy efficiency measures, such as limited availability of information, uncertainty about performance, split incentives, and limited product availability, this reduction in the payback period may be essential.

Utility expenditures, which are categorized into administrative, marketing/ advertising/outreach, and direct implementation costs, averaged 1.72 cents/kWh to 2.08 cents/kWh over the 3-year program cycle (see below). As mentioned above, direct implementation costs include labor for installation and service, hardware and materials, rebate processing, and rebates for customers. The average rebate per kWh of energy savings is represented by the dotted line in Figure C.7.[11] For PG&E and SDG&E, the average rebate is about 47% of total expenditures, while SCE's average rebate is 71% of total expenditures, at 1.2 cents/kWh.

Energy-climate models can use the empirical information on policy and program cost and impacts to evaluate the role that energy efficiency policies and programs can play in GHG reduction. For example, the analysis of GHG mitigation options by Roland-Holst (2006) using the BEAR model illustrates one approach to incorporating these costs in an EC model. The cost of implementing these programs and policies is assumed to be borne entirely by the government and is added to the government expenditure. The estimated gains in energy efficiency due to these policies and programs are used to modify the assumptions about the energy intensity of economic output in the model. Roland-Holst (2006) estimates that implementing no-regret options in California could lead to a reduction of 83 Mt $CO_{2eq.}$ by 2020 (which is 50% of the emission reduction target set by California Assembly Bill 32) and would result in a net economic benefit of $58.8 billion.

Bottom-up models can take advantage of some of the additional empirical information available at each energy efficiency measure level while modeling the adoption of energy efficiency technologies. Bottom-up models like NEMS estimate the effect of programs such as providing rebates to consumers to accelerate the adoption of

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[9] Kushler et al. (2004) Five Years In: An Examination of the First Half-Decade of Public Benefits Energy Efficiency Policies. ACEEE.

[10] Payback periods were calculated using PG&E's average residential, commercial, industrial, and large agricultural rates in the second and third quarter of 2007.

[11] These rebate numbers are calculated from the rebate amount offered for each energy efficiency measure and do not include expenditures for rebate processing and applications.

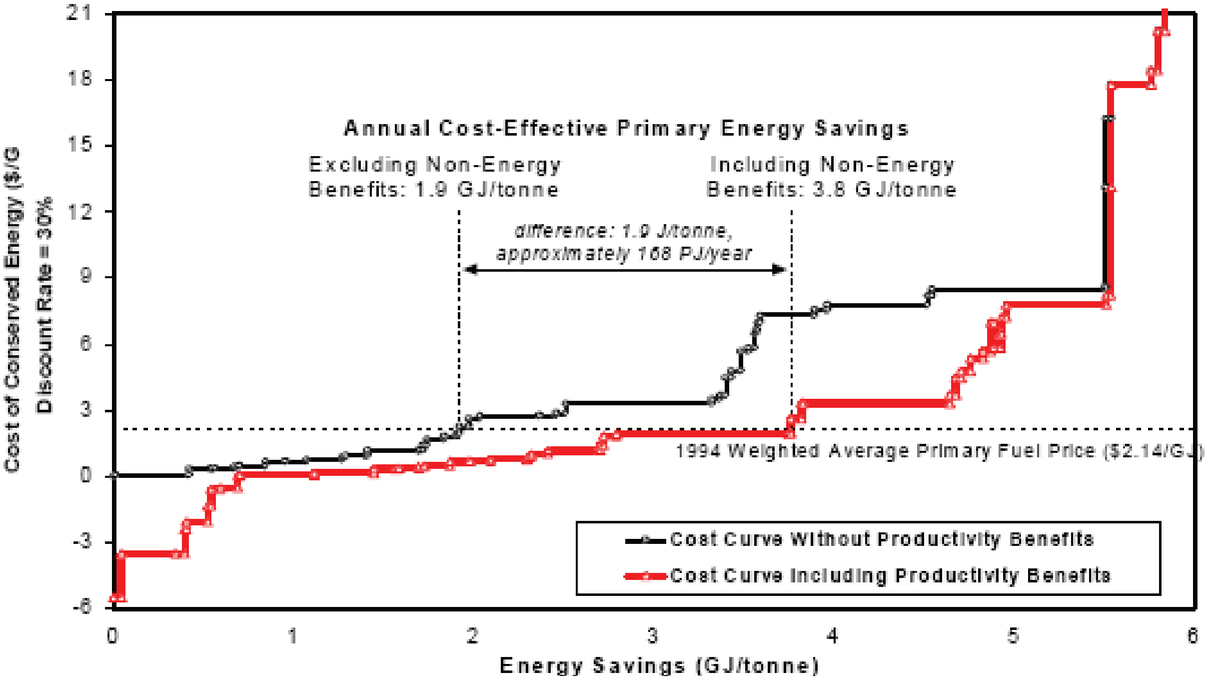

FIGURE C.7 Conservation supply curves with and without including non-energy productivity benefits, U.S. steel industry (Worrell et al., 2003).

energy efficiency technologies. Such models can utilize the information available on the rebates provided in energy efficiency programs and their impact of increasing penetration levels. Further, bottom-up models can incorporate empirical information on other program costs to accurately model the cost, benefit, and impact of energy efficiency programs.

Consideration of Non-Energy Benefits and Costs

Accounting for "hidden benefits" requires that bottom-up models look beyond the energy markets and examine the cost considerations in light of their impact on other resource markets. Below we illustrate an example of the inclusion of such costs in the residential clothes washer, and iron and steel industry sectors.

Residential Clothes Washers

Residential clothes washers use a large amount of water whose costs in a California study were higher than the cost of energy used in the washer (Sathaye and Murtishaw, 2006). Most of the energy saving in efficient washers is due to avoided energy use from reduction of hot water consumption.

The analysis offered a quantitative explanation of reasons that might prevent certain consumers from purchasing efficient washers and other products. Due to the differences in the cost of water, as well as electricity, the analysis segmented the market into low-, middle-, and high-income households.

The inclusion of non-energy (water savings) benefits has a crucial impact on the cost-effectiveness of efficient washers. The initial weighted average CCE for all households when water savings were not counted was $0.136/kWh, compared to $0.049/kWh when they were included.

Efficient washers that use electricity are significantly more cost-effective that those using natural gas-heated water due to the higher cost per unit of energy for electricity. For example, although the initial CCEs for wash-

TABLE C.4 Non-energy Benefits from Efficiency Improvements (Worrell et al., 2003)

Waste	Emissions	Operation and Maintenance
Use of waste fuels, heat, gas	Reduced dust emissions	Reduced need for engineering controls
Reduced product waste	Reduced CO, CO_2, NO_x, SO_x emissions	Lower cooling requirements
Reduced waste water		Increased facility reliability
Reduced hazardous waste		Reduced wear and tear on equipment/machinery
Materials reduction		Reductions in labor requirements
Production	**Working Environment**	**Other**
Increased product output/yields	Reduced need for personal protective equipment	Decreased liability
Improved equipment performance	Improved lighting	Improved public image
Shorter process cycle times	Reduced noise levels	Delaying or reducing capital expenditures
Improved product quality/purity	Improved temperature control	Additional space
Increased reliability in production	Improved air quality	Improved worker morale

ers using gas and electric-heated water in high-income households are virtually the same ($0.016 and $0.017 respectively), the benefit-cost ratios differ significantly, due to the reduced benefit of saving a cheaper fuel (1.4 versus 2.5).

The CCE varies by income groups due to differences in the costs of water and power among these groups, the differing shares of residency in units with washer/dryer hook-ups, and the fact that some lower income households may not be able to secure credit for the resource-efficient washer.

Iron and Steel Sector Cost Curves

Worrell et al. (2003) reported cost effective annual primary energy savings of 1.9 GJ/tonne for the U.S. iron and steel industry in 1994 which may be compared to the primary energy price of $2.14/GJ in 1994. Corresponding to the implementation of an array of 47 measures, the cost of supplied energy conservation are generally reduced when productivity benefits associated with labor and material cost savings are included in the calculation during the operation of an efficient iron and steel plant. Table C.4 shows the non-energy benefits that were included in their analysis. These included waste streams, emissions, O&M costs, production costs, working environment and other items. Inclusion of such productivity benefits increased the potential from cost-effective measures to 3.8 GJ/tonne at the same unit price of primary energy ($2.14/GJ in 1994). When including productivity benefits, the CCE ranking of technologies also changed dramatically. Inclusion of all resource benefits thus is crucial to understanding the full cost impacts of a technology. This may be particularly relevant to end-use energy efficiency technologies whose main goal often is not only saving energy but also providing some other form of service for the production of an industrial product.

How different are the emissions reductions using the two different types of cost curves in a EC model? We tested this using the COBRA model[12] (Wagner and Sathaye, 2006). The model tested results from U.S. cost curves for the iron and steel and cement sectors (Sathaye et al., 2010; Xu et al., 2010). Since the cost curves included negative cost options (no regrets options (NRO)), which are often not captured in efficiency scenarios of a top-down model, we tested the results with and without inclusion of NRO. The difference between the results with

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[12] COBRA is a bottom-up global energy model that uses linear optimization to design cost-minimal long-term scenarios on the basis of exogenous demand projections. COBRA can be operated at various levels of geographical, technological and temporal resolution. For the present study we use a version with ten-year time steps until 2100 and ten world regions (USA, EU, Rest of OECD90, REF, India, China, Rest of ASIA, Brazil, South Africa, Rest of ALM—where OECD90, REF, ASIA and ALM are the four world regions of the SRES study (Nakicenovic et al., 2000)). COBRA distinguishes the electricity producing sector from the rest of the sectors and further divides the latter into residential, transport, industry, and other. In order to address specific questions for individual industries, for the present study we have further divided the industry sector into iron and steel, fertilizer production, paper and pulp, cement production, aluminum production, and other industries.

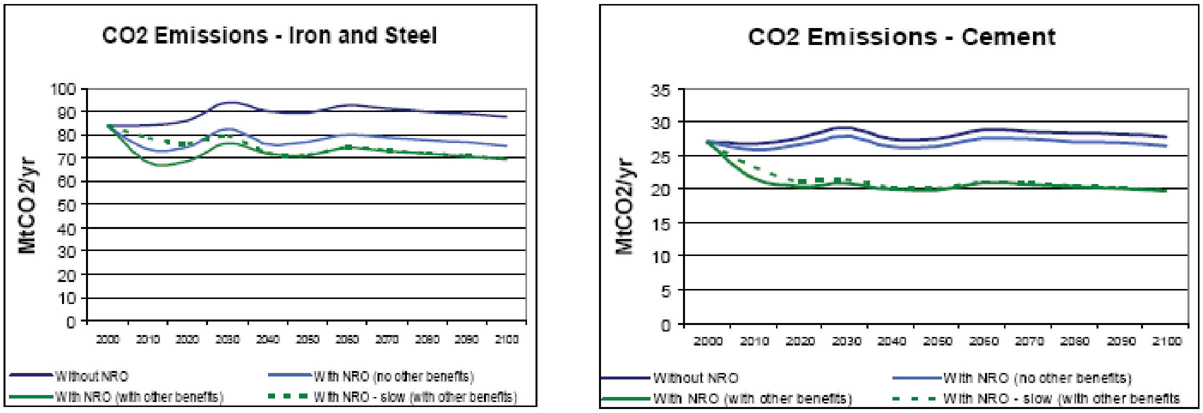

FIGURE C.8 Effect of demand-side efficiency improvements on U.S. industry emissions.

and without inclusion of the NRO options is not very large for the cement sector, but it is quite significant (13%) for the iron and steel sector. The inclusion of other non-energy savings benefits yields further reduction in energy use at the same CCE (Figure C.8), which translates into larger CO_2 emissions reductions for the cement sector than for the iron and steel sector. The dotted line in Figure C.8 illustrates savings in cases where implementation is slower than what a techno-economic potential might imply.

Historical Change in Energy Efficiency Cost Curves

In this section, we provide examples of changes in cost curves for the industrial and residential sectors over time. While no analysis exists of extrapolating these changes over future time periods, it is evident that their inclusion will significantly impact the estimated cost of future emissions reductions if static cost curves are used in EC models.

One of the popular approaches to take into account the future changes in the cost of technologies (including energy efficiency technologies) is using learning or experience curves which specify a relationship between cumulative installed capacity and the cost of a technology. This relationship is typically specified as a learning rate or a progress ratio which is the reduction in costs per doubling of cumulative installed capacity. Many studies have estimated learning rates for demand side technologies. A review of these studies by Weiss et al. (2010a) finds a widespread trend towards declining prices at an average learning rate of 18 ± 9%.

Experience curve analysis has many limitations in explaining and predicting the decline in prices of clean energy technologies. Many factors such as learning, economies of scale, innovation, competition, and decline in prices of factors of production (due to reasons such as shifting of production to regions with lower labor costs) can potentially contribute to decline in prices of clean energy technologies. Learning curve approach is a black box approach at it lumps the effect of all these factors in only one explanatory variable, the cumulative installed capacity. Further, learning curve estimates have significant uncertainty depending on the time period considered for the analysis. The question of whether the learning curve analysis is a useful input for policy formulation thus needs to be examined given the uncertainty in learning curve estimates (Nemet, 2010). Only a few studies attempt to address these limitations of learning curve analysis by qualitatively examining or empirically estimating the effect of various factors contributing to the decline of prices of specific energy consumption in case of demand side technologies (see for example, Nemet, 2006; Ramírez, and Weiss et al., 2009; Worrell, 2006). Nemet (2006) is the only study that estimates the effect of factors such as learning, economies of scale, and R&D using empirical analysis and finds that they contributed 8%, 43%, and 35% respectively to the decline of PV costs in the United States during 1979-2000. More such studies need to be conducted in order to gain policy relevant insights into factors that contribute to decline in prices of clean energy technologies.

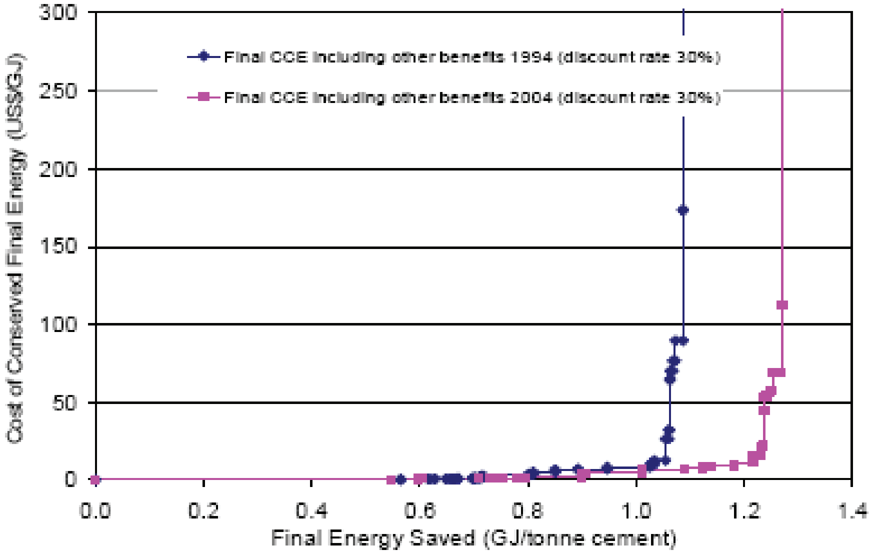

FIGURE C.9 U.S. cement sector example with other benefits included: changes in energy savings potential between 1994 and 2004 at 30% discount rate.

One potential approach to better understand the factors contributing to improvement of energy efficiency (decline in specific energy consumption) is to evaluate the trends in the incremental cost of various component technologies that contribute to efficiency improvement options. This approach is more appropriate for examining technological change in end uses and sectors where multiple component technologies can contribute to efficiency improvement options. For example, improvements in the efficiency of compressors, motors, and drives contribute to the decline in the specific energy consumption of refrigerators. Economies of scale and learning in these technologies may be driven not just by cumulative sales of refrigerators but by various other products such as air conditioners, which use similar component technologies. Standard experience curve approach, which only examines the trend at a single appliance level cannot capture this effect. Analyzing trends in the incremental cost of various efficiency improvement options becomes even more important for end-uses that are more complex such as industries that have several component systems, with each of them having potential for efficiency improvement. The first step in such approach is to review trends in the incremental cost of various efficiency improvement options (which are due to improvements in different component technologies or systems) and examine potential factors contributing to their improved performance and declining costs. We present our analysis of the trends in incremental cost of various efficiency improvement options in select appliances and industries.

Figure C.9 shows two cost curves, one that was developed for 1994 and another for 2004 for the U.S. cement sector (Sathaye et al., 2010). Each of the two curves shows the costs of conserved energy versus energy-savings potential for one time period. It shows that the energy-savings potential in 2004 was larger than that in 1994 when given the same cost of conserved energy (i.e., exhibited by a same Y-value in the chart). The energy-savings potential for instance at the cost of $40/GJ increased from 1.06 GJ/tonne to 1.24 GJ/tonne (by approximately 15%) over this decade. Such historical changes in the magnitude of savings potential may become useful for predicting future trends in energy climate modeling. Sathaye et al. (2010) also provide details of the cost of efficiency improvements in various component technologies or systems. Analysis of time trends in each of these enables the assessment of the degree to which various component technologies or systems have contributed to efficiency improvements in the U.S. cement sector.

Changes in cost curves over time have been estimated for residential and commercial sectors as well. Figure C.10 shows such a set of curves for the U.S. commercial air conditioning equipment and heat pumps. In both

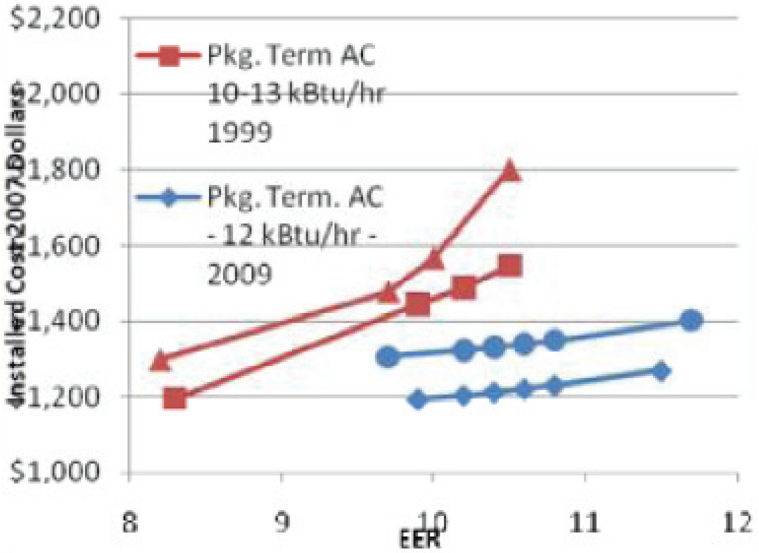

FIGURE C.10 Efficiency Improvements in U.S. Commercial Air Conditioning Equipment between 1999 and 2009. SOURCE: Sathaye, EMF 25 Presentation, 2009.

cases, the curves demonstrate that the cost of installation (including the product cost) for achieving the same level of energy efficiency ratio (EER) was lower in 2009 compared to 1999 and ranged from 8% to 15%. Similar data exist for several other types of products that are used in both these sectors. The primary sources for these data are the Technical Support Documents (TSDs) published by the U.S. Department of Energy that develop estimates of incremental cost of efficiency improvements in appliances and equipment by assessing the cost and potential of efficiency improvements in their components and systems.[13] These estimates are based on engineering and empirical analysis and form the basis of minimum energy performance standards (MEPS) set in the United States.

By assessing the trends in the incremental cost and saving opportunities in various component technologies and systems, one can estimate the degree to which each of these have contributed to the changes in the cost and potential of efficiency improvement opportunities in appliances and equipment. This is the focus of our ongoing research focused on understanding various factors contributing to changes in the cost and potential of efficiency improvement options in key energy consuming appliances and equipment.

Summary and Conclusions

It is important to evaluate what role improvements in energy efficiency can play in GHG mitigation especially when it has been demonstrated that significant efficiency improvements that lead to GHG mitigation can be realized at a net societal benefit unlike many other GHG mitigation options. In this paper, we analyzed some key issues in evaluating energy efficiency as a GHG mitigation option and how its representation can be improved in energy-climate models.

We report on an empirical analysis of the cost imposed by various barriers to the adoption of energy efficient end-uses in California as an example of how these barriers impose large enough costs that might prevent consumers from adopting technologies that appear highly cost effective from a societal perspective. We also demonstrate an approach to quantifying the cost imposed by the PA problem on a national scale, and show how the quantification

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[13] See for example TSD for residential air conditioners and heat pumps at http://www1.eere.energy.gov/buildings/appliance_standards/residential/central_ac_hp.html.

could be included in NEMS and MARKAL type models. Further, improved understanding of the costs imposed by these barriers would lead to a better understanding of the benefits of policies and programs that address these barriers.

It has been demonstrated that policies and programs that deal with various barriers lead to increased adoption of energy efficiency. These policies and programs also incur some costs such as administrative, marketing, installation, and rebates. From a societal perspective, the desirability of these programs depends on whether the benefits of these policies and programs outweigh their costs and empirical evaluation of the outcomes of these policies and programs is warranted. Further, it is important to analyze the impact of policies and programs in terms of their performance in accelerating the adoption of energy efficiency measures.

We report the results of our empirical analysis of utility energy efficiency programs in California, which are among the largest and most comprehensive energy efficiency programs in the world with budgets of close to one billion dollars per year. We find that program implementation and financial incentive costs are relatively minor compared to their benefits. We also find that a majority of the costs of the utility programs are financial incentive costs, which reduce the payback period of consumers on their efficiency improvement investments to less than a year in most of the instances. Financial incentives are a transfer and not an actual cost from a societal perspective. We evaluate various ways using the results of such type of analysis to improve the representation of energy efficiency as a GHG mitigation option in energy climate models and find that both bottom-up and top down energy-climate models can incorporate information on policy and program costs to model their impact.

Many times energy efficiency improvements result in reduction not only of energy costs but also other costs such as maintenance and materials. Estimation of these co-benefits is required for accurately estimating the cost and potential of EE improvements. We present the results of our empirical analysis for the residential clothes washers and iron and steel sector to show the consideration of co-benefits influences the cost and potential of EE improvements. For $40/GJ, we find that the cost effective potential for iron and steel sector increases by 15% when some of the co-benefits are considered.

Technological change influences the cost and potential of various GHG mitigation options. Learning or experience curve approach, one of the popular approaches to model technological change, is a black box approach as it lumps the effect of various factors such as learning, economies of scale, innovation, competition, and decline in prices of factors of production into one explanatory variable, the cumulative installed capacity. One potential approach to better understand the factors contributing to improvement of energy efficiency (decline in specific energy consumption) is to evaluate the trends in the incremental cost and efficiency improvement opportunities in component technologies and systems. This approach is more appropriate for examining technological change in end uses and sectors where multiple component technologies can contribute to efficiency improvement options. We present our analysis of the trends in incremental cost of various efficiency improvement opportunities in component technologies and systems for some key energy consuming industries and appliances in the form of cost curves and find that efficiency improvement opportunities have increased and costs of the same have decreased over time.

We conclude that analysis of energy efficiency as a mitigation option, undertaken using energy climate models or any other methods or tools, needs to consider the issues identified in this paper to improve its assessment. Empirical analyses which forms the basis of improved understanding of these issues needs to be expanded significantly, potentially drawing on some of the analyses presented in this paper.

Acknowledgments

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THE PERILS OF THE LEARNING MODEL FOR MODELING ENDOGENOUS TECHNOLOGICAL CHANGE

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Abstract

Modeling of technological change has been a major empirical and analytical problem for many years. One approach to modeling technology is learning or experience curves, which originated in techniques used to estimate cost functions in manufacturing modeling. They have recently been introduced in policy models of energy and global warming economics to make the process of technological change endogenous. It is not widely appreciated that this is a dangerous modeling strategy. The present study has three points. First, it shows that there is a fundamental statistical identification problem in trying to separate learning from exogenous technological change and that the estimated learning coefficient will generally be biased upwards. Second, we present two empirical tests that illustrate the potential bias in practice and show that learning parameters are not robust to alternative specifications. Finally, we show that an overestimate of the learning coefficient will provide incorrect estimates of the total marginal cost of output and will therefore bias optimization models to tilt toward technologies that are incorrectly specified as having high learning coefficients.

The Challenge of Endogenous Technological Change

Most studies and models of environmental and climate-change policy—indeed of virtually all aspects of economic policy—have sidestepped the thorny issue of endogenous technological change or induced innovation. These terms refer to the impact of economic activity and policy upon research, development, invention, innovation, productivity change, and the diffusion of new technologies. Most models assume that technological change is exogenous, that is, it proceeds with a rate and direction that is determined by fundamental scientific and technological forces but is unaffected by prices or tax and regulatory incentives.

This shortcoming has been recognized for many years. It arises both because of the lack of a firm empirical understanding of the determinants of technological change as well as because of the inherent difficulties in the modeling of economic processes with externalities and increasing returns to scale. While we suspect that we know the direction of the omission of induced innovation—to overestimate the cost of emissions reductions and the trend increase in climate change—we have little sense of the magnitude of the effect or the importance of this omission. Would including induced innovation have a large or small impact on climate change and on climate-change policies? This is a major open question.

There have been two major approaches to including induced innovation—the Romer model and the learning model. The Romer model of induced innovation arose in the 1960s in an attempt to understand why technological change appears to have been largely labor saving.[15] More recently, theories of induced technological change have

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[14] This is a summary version of the full study available as William Nordhaus, “The Perils of the Learning Model For Modeling Endogenous Technological Change,” NBER Working Paper 14638, January 2009, available at http://www.econ.yale.edu/~nordhaus/homepage/recent_stuff.htm. I am grateful for comments from Christopher Magee, Nebosja Nakicenovic, Ed Rubin, and John Weyant, as well as participants at the Energy Modeling Forum, the Santa Fe Institute, and two workshops at the U.S. National Academy of Sciences.

[15] See R.R., Nelson, “The Simple Economics of Basic Scientific Research,” *Journal of Political Economy,* 67:297-306, 1959; Kenneth J. Arrow, *“Economic Welfare and the Allocation of Resources* for Invention,” in Richard Nelson, *The Rate and Direction of Inventive Activity,* Princeton University Press for National Bureau of Economic Research, 1962; C. C. von Weitzsaecker, “Tentative Notes on a Two-Sector Model with Induced Technical Progress,” *Review of Economic Studies,* 33, 95, July 1966, 245-51.

been resuscitated as the "new growth theory," pioneered by Paul Romer and others.[16] The thrust of this research is to allow for investment in knowledge-improving activities. Such investments improve society's technologies, and a higher level of investment in knowledge will change society's production possibilities and may improve the long-run growth rate of the economy. Virtually all studies of induced innovation have been theoretical.[17] With few exceptions, they do not lay out a set of testable hypotheses or ones that can be used to model the innovation process at an industrial level.[18]

The alternative approach to modeling induced innovation is the learning model. This approach has become particularly popular in recent years as models increase the granularity of the technological description down to individual technologies. It has also been attractive in policy studies because it can rationalize early investments in technologies that are presently uneconomical but have the promise, if they can "move down the learning curve," of being competitive in the future.

The present study examines the analytical and statistical basis of learning models. This is a technical study because the issue that is raised is primarily a statistical issue of identification of learning functions. The basic message, however, is simple. First, the paper shows that there is a fundamental statistical identification problem in trying to separate learning from exogenous technological change. As a result of the identification problem, estimated learning coefficients will generally be biased upwards. Second, we present two empirical tests that illustrate the potential bias in practice and show that learning parameters are not robust to alternative specifications. Finally, we show that an overestimate of the learning coefficient will generally lead to an underestimate of the total marginal cost of output; because of this underestimate, optimization models tend to tilt toward technologies that are incorrectly specified as having high learning coefficients. This implies that policy proposals that rely upon learning models are likely to overestimate the returns to research investments to the extent that they use estimated learning coefficients.

The present note provides the basic results of the study. The full study with tables and figures is available as the background paper cited in the first footnote.

The Fundamental Identification Problem

Models of learning and experience have a long history in studies of manufacturing productivity.[19] Because of their perceived successes in technological forecasting, they have recently been introduced in policy models of energy and global warming economics to make the process of technological change endogenous.

This approach has serious dangers. We proceed to examine this issue in three steps. In the present section, we show that there is a fundamental statistical identification problem in trying to separate learning from exogenous

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[16] See Paul Romer, "Endogenous Technological Change," *Journal of Political Economy*, vol. 98, October 1990, part 2, pp. S71-S102. Also see the extensive survey in Dale W. Jorgenson, "Technology in Growth Theory," in Jeffrey C. Fuhrer and Jane Sneddon Little, eds, *Technology and Growth*, Conference Proceedings, Federal Reserve Bank of Boston, 1996. pp. 45-77.

[17] For a recent overview, see Vernon Ruttan, *Technology, Growth, and Development,* Oxford University Press, New York, 2001.

[18] One example of incorporating technological change in policy analysis is the work of Dale Jorgenson and his colleague; see for example Dale W. Jorgenson and Peter J. Wilcoxen, "Reducing U. S. Carbon Dioxide Emissions: The Cost of Different Goals," in John R. Moroney, ed., Energy, Growth, and the Environment, 1991, JAI Press Greenwich, Conn., pp. 125-128.Also see Lawrence H. Goulder and Stephen H. Schneider, "Induced technological change and the attractiveness of CO2 emissions abatement policies," *Resource and Energy Economics*, 1999, 21: 211-253. An explicit calibrated model is contained in William Nordhaus, "Modeling induced innovation in climate-change policy," in *Technological Change and the Environment*, edited by A. Grübler, N. Nakicenovic and W. D. Nordhaus. Washington, DC: Resources for the Future, 2002, pp. 182-209 and in David Popp, "ENTICE: endogenous technological change in the DICE model of global warming," *Journal of Environmental Economics and Management,* 2004, 48: 742-768.

[19] The literature on learning curves is vast, going back more than a century, and no single reference can adequately capture the major issues. The original concept of an experience curve was documented with telegraph operators in W.L. Bryan and N. Harter, "Studies on the Telegraphic Language: The Acquisition of a Hierarchy of Habits," *Psychology Review*, 6:345-75, 1899. Two particularly influential articles were T.P. Wright, "Factors Affecting the Cost of Airplanes," *Journal of Aeronautical Sciences*, Vol. 3, No. 4, 122-128, 1936; and K. J. Arrow, "The Economic Implications of Learning-By-Doing," *Review of Economic Studies,* Vol. 29, 155-173, 1961. A recent comparison of alternative approaches is in Boyan Jovanovic and Yaw Nyarko, "A Bayesian Learning Model Fitted to a Variety of Empirical Learning Curves," *Brookings Papers on Economic Activity. Microeconomics,* (1995), pp. 247-305. A comprehensive survey of learning curves is contained in Louis E. Yelle, "The Learning Curve: Historical Review and Comprehensive Survey," *Decision Sciences,* 10, 302-328, 1979).

technological change and that the estimated learning coefficient will generally be biased upwards. In the next section, we present two empirical tests to examine the potential bias in practice. In the final section, we show that an overestimate of the learning coefficient will generally lead to an underestimate of the total marginal cost of output and tile policies toward technologies that are incorrectly specified as having high learning coefficients.

The basic idea is that productivity improves or costs decline as workers or firms gain experience with a production process. While there can be little doubt that productivity benefits from experience, the exact mechanism is poorly understood. In particular, it is unclear whether the learning is embodied in individual workers and firms, whether there are interindustry or international spillovers, and whether the improvements lead to durable technological changes, and even whether the learning effects can be distinguished from other technological changes.

In this section, we focus on the problem of identifying differences in productivity due to learning from exogenous changes. We begin by showing why it is impossible without further identifying assumptions to distinguish learning from exogenous technological change, and why the learning coefficient is generally biased upwards. To simplify for this exposition, we assume that all processes are exponential. Output (Q_t) is assumed to grow at constant growth rate g, so $Q_t = Q_0 e^{gt}$. Cumulative output at time t (Y_t) is therefore:

$$(1) \qquad Y_t = \int_{v=-\infty}^{t} Q_0 e^{gv} dv = Q_0 e^{gt} / g$$

Taking the logarithmic derivative of (1) shows that the growth rate of Y_t is g.

The experience curve is assumed to have a true experience coefficient, b. In addition, there is an assumed constant rate of exogenous technological change at rate h. The cost function is therefore:

$$(2) \qquad C_t = C_0 e^{-ht} Y_t^{-b}$$

“Exogenous technological change” in this context denotes all sources of cost declines other than the learning-curve-determined technological change. It would include inter alia spillovers from outside the industry, the returns to research and development, economies of scale and scope, as well as exogenous fundamental inventions.

Assume that prices are proportional to current instantaneous marginal cost, so the rate of decline in cost (c_t) equals the decline in price (p_t), which is given by:

$$(3) \qquad P_t = c_t = h + bg_t$$

Because marginal cost is constant, price is under these assumptions exogenous to current demand. Demand is determined by a demand function with constant price elasticity (ε), elasticity of per capita demand with respect to aggregate output (λ), where the growth in aggregate per capita output is (W_t), and constant population growth is n. These yield the growth in output (demand) as:

$$(4) \qquad g_t = \varepsilon p_t + \lambda w_t + n$$

We can substitute $z_t = \lambda w_t + n =$ the autonomous (non-price-induced) growth rate of demand. Solving (3) and (4), we get the following reduced-form equations for the rate of cost (price) decline and the rate of output growth. Since the growth rates are constant, we suppress the time subscripts. Price decline is:

$$p = h + bg = h + b(\varepsilon p + z)$$

or

$$(5) \qquad p = \frac{h + bz}{1 - b\varepsilon}$$

which is the equation for cost (price). The equation for output growth is:

$$g = \varepsilon(h + bg) + z$$

or

$$g = \frac{\varepsilon h + z}{1 - b\varepsilon} \tag{6}$$

From equations (5) and (6), we can calculate the slope of the *behavioral learning curve, β.* This is equal to *p/g,* or:

$$\beta = p / g = \frac{h + bz}{\varepsilon h + z} = b(1 + \phi) \tag{7}$$

where

$$\phi = \frac{h(1 - \varepsilon b)}{b(\varepsilon h + z)} \tag{8}$$

Note how difficult it would be to separate the true learning parameter *(b)* from the tangle of coefficients in (7).[20] To obtain the true learning parameter, we would need to have reliable estimates of the rate of exogenous technological change, the demand elasticity, and the rate of autonomous growth of demand.

Furthermore, the empirical experience parameter will be unbiased $(\beta = b)$ only when exogenous technological change is zero $(h = 0)$. It will be biased if $h \neq 0$. The size of the bias is determined by the sign of $(1 - \varepsilon b)$. For demand elasticities that are relatively low (less than 4), we would expect that $\varepsilon b > 1$, in which case the bias is upwards.

A numerical example will illustrate the result. A typical industry might have a price elasticity of $\varepsilon = 1$, an exogenous demand growth of $z = 0.04$ per year, and a rate of exogenous technological change of 0.01 per year. With a zero learning effect (true $b = 0$), we have from (7) that:

$$\beta = \frac{0.01 + 0 \times 0.04}{1 \times 0.01 + 0.04} = \frac{0.01}{0.05} = 0.2$$

In this case, therefore, the empirical learning coefficient is 0.2 even though the actual learning coefficient is zero.

Next, change the assumption to add a true experience curve coefficient of $b = 0.25$. Then the empirical learning coefficient becomes:

$$\beta = \frac{0.01 + 0.25 \times 0.04}{1 \times 0.01 + 0.04} = \frac{0.02}{0.05} = 0.4$$

In this case, the empirical experience coefficient is biased upwards from 0.25 to 0.4.

The general conclusion is that because of the interaction of demand, output growth, exogenous technological change, and learning, behavioral learning curves will generally have an upward bias in estimated learning coefficients. The only general case in which the coefficient is unbiased is when exogenous (non-learning) technological change is zero.

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[20] E.R. Berndt, *The Practice of Econometrics: Classic and Contemporary*, Addison-Wesley, New York, 1991, is a useful survey of the literature and econometric issues. Zvi Griliches, “R&D and Productivity: Econometric Results and Measurement Issues,” in P. Stoneman (Ed.), *Handbook of Economics on Innovation and Technological Change*, Blackwell, Oxford, 1995 reviews the more general questions of the econometrics of technological change.

Some Empirical Tests

We can take actual data on output and productivity to show the difficulty in measuring learning from historical data. For a first example, we take U.S. data on multifactor productivity in the non-farm business sector for the period 1948-2007. While this is a highly aggregated data set, it has very high quality input and output data that are constructed by U.S. statistical agencies. The data are available at www.bls.gov.

We construct cumulative output for the period 1800 to 2007. These are based on government data for 1929 to 2007 and extrapolate backwards from 1929 using an assumed constant growth rate of 3.9 percent per year. I then estimate bivariate learning functions and exogenous technological change rates. The estimated rate of exogenous technological change for the 1948-2007 period is 0.0105 (±0.00038). A learning equation without exogenous technological change has a learning coefficient of 0.278 (±0.0093). If we combine the two variables, learning and time, the learning coefficient rises to the implausibly high level of 2.1491 (±0.27). The results also show very high autocorrelation of the residuals. For example, the simplest learning model has an estimated first-order serial correlation of the residuals of 0.89 (±0.047). This simple example shows that learning models generally have coefficients that are not robust to specification changes.

As a second example, we estimate learning parameters for 34 major industry groups (see the Bureau of Economic Analysis (BEA) web site for the industry definitions).[21] For this purpose, we use data on industry output from the U.S. national income and product accounts. We select only those industries where the output and prices are "well measured."[22]

The basic approach is to assume that output is produced by a constant returns to scale production function either with or without learning, as above. Average hourly earnings (AHE) are assumed to represent a reasonable proxy for the cost of production with unchanging technology.[23] Prices are proportional to average instantaneous costs, and learning is assumed to be excluded from pricing, or if included to be a multiplicative factor. [24] Under these assumptions, the rate of change in the ratio of the AHE to the product price (call this the real price decline) will equal the rate of cost decline given by equation (2). We can then examine the relationship between the real price decline and factors such as learning as represented by cumulative output or time.

The data on output and inputs have been prepared by the BEA and provide both gross output and price indexes for the period 1947-2007 for major industry groups and for 1959-2007 for all other industry groups. For each group, we estimate cumulative output for the initial year as the first-year output index divided by the growth rate for the first 7 years.[25]

For these data, two results are clear. First, the learning coefficients are wildly variable. Figure 1 [in the paper named in footnote 14] shows a histogram of the empirical learning coefficients estimated from the linearized version of equation (2) with zero exogenous technological change. Clearly, the estimates of the learning parameter are highly variable. For the 34 industries, assuming zero exogenous technological change, only 4 have estimated empirical learning coefficients in the plausible range between 0 and 0.5. The mean and median are well above the plausible range, which suggests a positive bias in the estimation. Additionally, the results are highly sensitive to an AR1 correction, which produce yet different learning coefficients. (See the background paper cited in the first footnote for the detailed results.)

In addition, we estimated the learning coefficients with exogenous technological change [i.e., with h estimated in the linearized version of equation (2)]. The estimates with exogenous technological change are very different from those without exogenous technological change. The correlation between the two estimates is 0.009. Clearly,

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[21] See http://www.bea.gov.

[22] The notion of well-measured industries is discussed in William Nordhaus, "Baumol's Diseases: A Macroeconomic Perspective," *Berkeley Journal of Macroeconomics,* Volume 8, Issue 1, 2008, Article 9, pp. 1-37.

[23] The reference on the use of wages as a proxy for technological change is analyzed in William Nordhaus, "Baumol's Diseases: A Macroeconomic Perspective," *Berkeley Journal of Macroeconomics,* Volume 8, Issue 1, 2008, Article 9, pp. 1-37.

[24] Prices might reflect life-cycle costs if the firm believes that there are learning effects (see for example C. Lanier Benkard, "Learning and Forgetting: The Dynamics of Aircraft Production," *American Economic Review*, 2000, vol. 90, pp. 1034-1054). However, as long as the processes are exponential and the learning coefficient is constant, the effect of learning on the ratio of marginal cost to price would be invariant over time.

[25] The BEA data are available at http://www.bea.gov/industry/index.htm#annual.

the estimates are highly sensitive to the specification. These tests show that the estimates of the learning coefficients are not robust to specifications. Moreover, the estimates are often well outside the theoretically acceptable range.

Readers might wonder about whether it is appropriate to use such aggregated data to estimate learning equations. One advantage of the industry data is that we have very carefully prepared indexes of output and price, so the measures are close to the ideal. The appendix in the background study shows the conditions under which elemental processes can be aggregated to determine an aggregate learning function. The results indicate that there are three sources of potential bias. The first bias would arise if the growth rate in individual industries deviated from exponential growth; the second bias relates to the correlation between the learning coefficient and output growth; and the third bias comes from potential biases in productivity measurement.

The Perils of Learning in Optimization Models

Learning has become a favorite tool for modeling technological change in many models of the energy sector and of global warming. It is convenient because learning-by-doing is one of the few "theories" of technological change that is easily included in models because of its simple specification.[26] It is a dangerous modeling technique, however, because the estimated learning rates are biased upwards and because these approaches therefore seriously underestimate the marginal cost of output. We showed the first point above and address the second in this section.

The danger in using learning to model exogenous technological change arises when the models select technologies on the basis of their cost characteristics. Learning models have total marginal costs that are lower than current marginal costs because an additional unit of output lowers all future costs as producers move down the learning curve. We can see this point by starting with a total cost function, which is defined as the present value of all current and future production (V_0), given by the following:[27]

$$V_0 = \int_{t=0}^{\infty} Q_t C_t e^{-rt} dv = \int_{t=0}^{\infty} Q_t [k_0 e^{-ht} Y_t^{-b}] e^{-rt} dv \tag{9}$$

We consider an increment θ of output at time 0, which yields a changed present-value cost as follows:

$$V_0(\theta) = (Q_0 + \theta) C_0 + \int_{t=0}^{\infty} Q_t [k_0 e^{-ht} (Y_t^{-b} + \theta)] e^{-rt} dv \tag{10}$$

Taking the derivative of (10) with respect to current output yields total marginal cost. From equations (5) and (6), we have the growth of output (g) and the decline in cost (p), yielding the total marginal cost as:

$$V'(\theta) = C_0 - b \int_{t=0}^{\infty} Q_t C_0 e^{-pt} \left(\frac{Q_t}{g} \right)^{-1} e^{-rt} dv = C_0 \left[1 - \frac{bg}{r+p} \right] \tag{11}$$

Equation (11) shows that total marginal cost is equal to current marginal cost times 1 minus a "learning discount." The learning discount is linear in the learning coefficient and the growth rate of output, and is inverse to the dis-

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[26] Examples of studies that use learning in energy and global warming models are T. Barker, H. Pan, J. Köhler, R. Warren, and S. Winne, "Decarbonizing the Global Economy with Induced Technological Change: Scenarios to 2100 using E3MG," *The Energy Journal Special Issue, Endogenous Technological Change and the Economics of Atmospheric Stabilization*, 241-258, 2006; and M. Grubb, J. Köhler, and D. Anderson, "Induced Technical Change in Energy and Environmental Modeling: Analytic Approaches and Policy Implications," *Annual Review of Energy and Environment*, Vol. 27, 271-308, 2002.

[27] The formula for marginal cost was developed in the context of industrial organization in Pankaj Ghemawat and A. Michael Spence, "Learning Curve Spillovers and Market Performance," *The Quarterly Journal of Economics,* Vol. 100, Supplement (1985), pp. 839-852 and Saman Majd and Robert S. Pindyck, "The Learning Curve and Optimal Production under Uncertainty, "*The RAND Journal of Economics*, Vol. 20, No. 3 (Autumn, 1989), pp. 331-343. The marginal cost is empirically estimated and used in the context of a dynamic programming formulation in C. Lanier Benkard, "Learning and Forgetting: The Dynamics of Aircraft Production," *American Economic Review*, 2000, vol. 90, pp. 1034-1054.

count rate minus the growth of costs. Since all the terms in the discount are positive, this implies that the discount is positive if there is learning.

As an example, suppose that the growth of output is 10 percent per year for a dynamic new product, that the discount rate is 5 percent per year, and that the learning rate is 0.3. Total marginal cost is 63 percent of the current marginal cost. In other words, because an extra unit is produced today, future units get a productivity bonus of 0.37 additional units.

Note that this additional 0.37 units is spread over a huge number of units, so there is little incentive for any individual unit to enter into a Coasean bargain with current producers. However, in a frictionless competitive world without rent-seeking and with perfect information, a Pigovian "learning curve" subsidy of 37 percent would be an efficient policy to induce higher output and move the economy down the learning curve. Another approach, which is often advocated, is for the government to purchase or subsidize early plants so as to stimulate learning.

We can also see the dangers of using learning curves to subsidize early production or choose a portfolio of projects if the learning parameters are incorrectly calculated. Suppose, for example, that the true learning parameter is 0.1 and because of the biased discussed above the estimated parameter is 0.3. With a 3 percent discount rate and a 10 percent growth rate, the learning discount is overestimated by a factor of two. (For a full set of calculations, see the background paper.)

This bias becomes particularly important in energy and global warming models that are designed to choose among different emerging technologies and where the technology is assumed to have an important learning component. For example, suppose that a policy calculation solves for future paths of solar and wind technologies based on current cost and different learning coefficients. Based on high learning rates, the model might suggest that technology A is a good bet for research and development. But this recommendation would be incorrect if the learning coefficient is based on a biased estimate of learning.

The point to emphasize here is that, in analyses that pick technologies on the basis of total discounted cost of production (as is entirely appropriate), then an upward bias in the learning rate can have a major impact on the apparent benefit of technologies with learning. The estimated costs can easily be underestimated by a factor of two. This danger is reinforced because, as shown in the first section, of the tendency to estimate learning rates in bivariate relationships, which will generally lead to strong upward biases in the learning coefficient.

UNCERTAINTIES IN TECHNOLOGY EXPERIENCE CURVES FOR ENERGY-ECONOMIC MODELS

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Abstract

The use of log-linear experience curves (or learning curves) relating reductions in the unit cost of energy and environmental technologies to their cumulative production or installed capacity has become a common method of representing endogenous technical change in energy-economic models used for policy analysis. Yet, there are significant uncertainties in such formulations whose impact on key model results have been insufficiently examined or considered. This paper characterizes and discusses the major types of uncertainties and their implications. We first review the literature on theoretical and empirical foundations for the log-linear experience curve formulation and its implied causality. We then review the recent literature presenting other models of causality and evidence for other (non-linear) shapes of an experience curve. The latter includes data on historical cost trends in the early deployment of environmental technologies for power plants, which depart substantially from the log-linear model. Ignoring these and other types of uncertainties that are discussed can result in erroneous or misleading model conclusions with policy implications. Suggestions are offered on ways to improve the characterization and reporting of uncertainties and their impact on the results of energy-economic models.

Keywords: Experience curve, learning curve, learning-by-doing, uncertainties, endogenous technological change, energy-economic models.

Introduction

Assumptions concerning the nature and rates of technological change are arguably among the most critical assumptions for assessments of long-term energy and environmental issues such as global climate change. In the past, large-scale modeling efforts commonly treated technological change as an autonomous process in which factors like the efficiency of energy production and utilization improved with the passage of time at a specified rate, independent of other factors [1-4]. More recently, however, many (but not all) long-term integrated assessment models for energy and climate policy analysis have incorporated some mechanism of endogenous technological learning in which the rate of technological improvement and/or cost reduction depends on other parameters in the model. The influences of experience from learning-by-doing, knowledge spillovers from other industries and the level of research and development (R&D) expenditures are among the factors that have been most often modeled [5-8].

Models of learning-by-doing are most often presented in the form of a learning curve or experience curve. Technology experience curves relate changes in specific investment cost (or other cost measure) to the cumulative installed capacity of the technology. While this is regarded as an important step toward more realistically representing the dependency of cost reductions on other variables, experience curves remain an imperfect representation of technical change. It is argued, for example, that the statistical correlation between a reduction in unit cost and the cumulative installed capacity of an energy technology offers little explanation for the underlying process of technological change and the causality between these two variables [6, 8-10].

Aside from the issue of causality, the use of experience curves for forecasting or modeling future cost trends in energy-related technologies is beset by a number of other uncertainties. For example, for the models currently in use, what is the “correct” learning rate for a new energy or environmental technology, or for a currently mature technology at some time in the future? More generally, what is the appropriate functional form of an experience curve for a

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selected technology? Does the learning rate remain constant over time, or does it change over the modeling period? Do costs always decline, or might they also increase and if so, why or how? Because there are still no definitive answers to such questions, it is important to recognize that these are sources of uncertainty that can significantly influence the results of energy-economic models. In this paper we explore the nature of these uncertainties.

In the second section, we briefly review the origins of technology experience curves used most widely for modeling and forecasting. In the third section we survey alternative functional forms of an experience curve and the theoretical and empirical basis for these formulations and the choice of explanatory variables. In the fourth section, we focus on uncertainties in the shape of experience curves, especially as they apply to environmental technologies in the early stages of commercialization. Finally, in the fifth section we summarize and discuss the implications of these uncertainties for large-scale integrated assessments and energy-economic modeling.

Origins of the Technology Experience Curve

In 1936, the aeronautical engineer Thomas P. Wright published a landmark paper in which he observed that the average direct man-hours required to manufacture a given model of Boeing aircraft dropped systematically with each unit produced [11]. Wright captured this phenomenon with an equation representing what he termed a "progress curve":

$$Y = ax^b \qquad \text{(Equation 1)}$$

where Y is the estimated average direct man-hours per unit for x units; a is the direct man-hours needed to manufacture the first unit; and b $(b<0)$ is a parametric constant. Wright demonstrated that the labor input, Y, dropped by 20 percent for every doubling of cumulative output, x—an 80 percent "progress ratio," where the exponent b was -0.32.

Wright's work remained relatively obscure until it was revisited a decade later by a group of economists at the then recently founded RAND Corporation (a "think tank" created by the U.S. Air Force in 1946 to develop a complete "science of warfare" during the Cold War era). The RAND economists became vitally interested in the application of Wright's work to the production of war materials—a phenomenon they would eventually call "learning-by-doing." When later applied to an industry or class of product (rather than to a specific manufacturing process), Wright's "learning curve" equation became referred to as an "experience curve."

Subsequent work by the Boston Consulting Group [12] applied Wright's equation to the relationship between the average unit price and cumulative output of 24 selected industrial products. Since then, this formulation (Equation 1) has been adopted in empirical studies to characterize learning phenomena in a wide range of sectors [13-15], including manufacturing [16], ship production [17, 18], consumer products [19], energy supply technologies [20-28], fuel technology [29-34], energy demand technologies [35], and environmental control technologies [36-38].

Equation 1 can be re-written as:

$$\log(Y) = b \log(x) + \log(a) \qquad \text{(Equation 2)}$$

Today, this log-linear form of the experience curve remains the most popular equation used to represent the expected cost improvements of a technology. Studies of conventional and renewable energy systems also have employed this equation to calculate technology progress ratios based on cumulative installed capacity [20, 39-41]. Any nonlinearities in the underlying empirical data are most often ignored, however, and only the "best fit" progress ratio (the value of 2^{-b} in Equation 1) or learning rate (the value of one minus the progress ratio) is typically reported. On this basis, Dutton and Thomas [42] surveyed 100 empirical and theoretical studies of progress functions in industrial engineering, economics and management. Reported progress ratios generally fell in the range of 60% to 94% (i.e., learning rates of 6% to 40%). However, studies showing price *increases* were not included in their analysis. For energy-related technologies, McDonald and Schrattenholzer [43] found a range of learning rates varying from 14% to 34% with a median value of 16%. In all energy-related studies, the cumulative installed capacity of a technology is most commonly used as the independent variable and the reported progress ratio typically applies to a period *after* the technology is commercialized.

Alternative Models of Causality

When applied to a class of technology like a particular energy or environmental control system, experience curves based on Equation 1 say that cost reductions depend solely on increased deployment of the technology. Clearly, that is an oversimplification. While Wright's initial formulation of a one-parameter model may have accurately explained observed decreases in the time needed to manufacture a particular airplane, extension of that learning curve model to experience curves for a class of technology is certainly not as simple. At best, the parameter of cumulative installed capacity of a technology serves only as a surrogate for a combination of factors that contribute to cost reductions—including not only learning-by-doing and learning-by-using, but also continued investments in R&D, spillovers from other activities, and a host of other possible factors.

Despite several decades of research, our understanding of the factors that contribute to technological learning and cost reductions is still rather limited. Various theories have been proposed to explain observed reductions in unit cost as cumulative output increases. Generally, they fall into three categories: (1) costs fall due to changes in production that include process innovations, worker familiarity in the use of tooling, improved management and economies of scale; (2) costs fall due to changes in the product itself including product innovations, re-design and standardization; and (3) costs fall due to changes in input prices. While intuitively satisfying, most of these explanations are only qualitatively descriptive and provide little quantification of the direct relationships or contributions of each factor to overall learning or cost reductions.

Some researchers also suggest that the overall learning rates derived from empirical experience curves many overestimate the actual contribution of true learning-by-doing. Others present theoretical arguments that the feedback mechanisms between cost reduction and cumulative production can be explained by other factors including R&D (or learning-by-researching) [6, 44-46], knowledge spillovers [6], increased capital investments [47, 48], and economies-of-scale [25, 49, 50]. Studies suggest that ignoring such variables provides a false sense of precision and overestimates the true contribution of learning [6, 10, 46]. A particular concern voiced by Nordhaus [6] is that models that "miss critical pathways or ascribe influence inappropriately could potentially arrive at erroneous, incomplete, or misleading policy conclusions."

To take into account additional factors that contribute to learning, alternative models have been developed. Here we review several of these formulations, focusing on their applications to energy and environmental technologies and policies.

Two-Factor Learning Curve Models

Two-factor learning curve models describe a relationship in which cumulative R&D expenditures as well as cumulative production or capacity are assumed to be the main drivers of technology cost reductions [46]. R&D contributes to an expanded knowledge base, which in turn can stimulate further technological innovation, cost reductions and technology diffusion. The relative importance of these two factors may vary, depending on the stage of product development: R&D may play a larger role at early stages of development, while learning-by-doing may dominate as the product or technology matures. The model of Equation 2 is now expanded to include an additional factor:

$$\log(Y) = \mathrm{b}_{LBD} \log(x) + \mathrm{b}_{LBR} \log(RD) + \log(\alpha) \qquad \text{(Equation 3)}$$

where:

b_{LBD} = learning-by-doing parameter
b_{LBR} = learning-by-researching (R&D) parameter
RD = cumulative R&D investment or knowledge stock
α = specific cost at unit cumulative capacity and unit knowledge stock.

There has been some work to validate this formulation with empirical data [46, 51-53]. Jamasb [46] examined the impact of R&D spending on technology cost reductions using estimates of the combined government and private

R&D expenditures in the United Kingdom. This was coupled with cumulative installed capacity data (representing learning-by-doing) for twelve power generation technologies for the period 1980 to 2001. These included mature technologies (e.g., pulverized coal plants, natural gas combined cycle gas plants, large hydropower), reviving technologies (e.g., new combined cycle plants, combined heat and power, small hydropower), evolving technologies (e.g., nuclear power and wind power) and emerging technologies (e.g., solar thermal power and offshore wind turbines). R&D expenditures were estimated from a broad survey of sources including government R&D databases, R&D expenditure estimates for specialized companies, plus several indirect methods of estimating private R&D investments [54]. The results show that the importance of R&D versus learning-by-doing varied across the different categories of technology, but in general, R&D contributed more to cost reductions than learning-by-doing in all stages of technological development. In addition, the study found very little elasticity of substitution between the two factors; i.e., R&D expenditure and capacity expansion were distinctly different and non-interchangable. Other studies also found significant correlations between time-lagged cost reductions and cumulative R&D expenses and/or R&D-based knowledge stock [46, 51-53].

Two-factor experience curves have been used in models including MERGE [55], ERIS [56], and other simulation-based tools [57]. In general, studies found that incorporating these two factors tended to lower the cost of environmental policies and achieve higher emission abatement levels than with no learning model or with only one of the factors alone [45, 57-60]. It was also found that the incorporation of R&D may lead to less aggressive near-term actions due to the increased level of near-term societal costs [56].

While the concept of a two-factor learning curve is theoretically appealing, others have noted two significant problems with this approach. The first is data availability. Reliable data on public and (especially) private-sector R&D spending is hard to collect and the quality of available data is often an issue [54]. The use of such data to estimate a "knowledge stock" (time lagged and depreciated R&D investment) is approximate at best and sensitive to the assumed rate of knowledge depreciation [56].

The second major shortcoming is the high degree of co-linearity between the two variables. That is, both R&D investments and cumulative production or capacity may respond to the same drivers and/or directly influence one another [53, 56]. An increase in product sales, for example, may stimulate R&D spending to further improve the product. In addition, from a policy point of view there is a distinct difference between government-funded and private-sector R&D. Since these funding sources can have very different impacts on the cost and performance of a specific technology [61], R&D policy conclusions based on a single (combined public/private) R&D indicator can be quite misleading.

Three-Factor or Multi-Factor Learning Curve Models

Several studies have used regression analysis or decomposition techniques to estimate unit cost reductions for a technology. Explanatory variables in addition to cumulative production or capacity have included economies-of-scale [25, 51, 62], input prices for materials [25, 51, 62], labor costs [62], efficiency improvement [25, 62], and other factors. Not surprisingly, these studies typically find smaller learning rate impacts for cumulative installed capacity compared with studies using the one-factor learning curve. Multi-factor models of this type offer improved explanations of the processes that contribute to cost reductions for the technology under study. Thus, they provide greater precision in projecting the effect of a given factor change on the future cost of that technology. A key drawback, however, is that the formulation and results from these models cannot be easily extrapolated or used to make cost projections for other technologies with different characteristics.

Component-Based Learning Curves

Component-based learning curves are essentially an extension of the one-factor model, in which the overall cost of a technology at any given point is the sum of the costs of individual components or sub-systems of the technology. Thus:

$$y = \sum_{i=1}^{n} a_n x^{b_n} \qquad \text{(Equation 4)}$$

where:

n = a given technology component
a_n = specific cost at unit cumulative capacity for cost component n
b_n = learning parameter characterizing cost component n.

In this case, the capacity or experience base, x, is usually a projected future value rather than an observed historical value. This method of estimating the future cost of a technology has been applied to cost projections for several types of power plants with carbon capture systems [63], as well as to micro-cogeneration of heat and power [35]. In each case, the overall plant is disaggregated into a number of sub-sections (such as boilers, gasifiers and air pollution control systems for power plants). The cost of each sub-section is then projected based on the historical learning rate for the same or similar technology components. The future cost of each component (after some specified increment of cumulative capacity) is then summed to obtain the future cost of the overall plant. The rationale for this approach is that for complex technologies like a coal-fired power plant, different components are currently at different levels of maturity. Thus, the cost of newer components like a carbon capture system may fall more rapidly than the cost of mature component like boilers or steam turbines. Disaggregation is thus believed to give the best estimate of a learning rate for the overall system.

Uncertainties at the component level give rise to uncertainties in the overall result. Such uncertainties derive from the same set of questions that apply to any application of a one-factor experience curve: When does learning begin (and end)? What is the appropriate learning rate or progress ratio? What is the appropriate measure of capacity or experience? The latter question, in turn, raises the additional issue of "spillover" effects, i.e., the extent to which learning is shared across a range of technologies or applications. For example, experience with carbon capture systems in the oil and gas industries may directly benefit similar applications in the electric utility industry. This concept of "clustered learning" has been used in integrated assessment models such as found in Seebregts et al. [64].

Another type of component-level learning model [65] projects the cost of gas turbine technology based on learning vs. non-learning for different types of costs. Here, some cost components such as raw materials and labor may experience no learning or even become more expensive over time. As in all cases where projections are based on past rates of technological change, there is inherent uncertainty as to whether past experience is indeed the best indicator of future rates of change in complex systems.

Other Models of Technological Learning

Other recent approaches to modeling technological change incorporate time in the experience curve formulation so as explicitly separate the effect of true learning from that of progress that occurs exogenously over time [10, 46, 65, 66]. Such an approach argues that there is a constant rate of exogenous technological change that is independent of learning-by-doing, such as inter alia spillovers from outside the industry, returns to research and development, economies of scale or scope and exogenous fundamental inventions. The incorporation of these factors implies a much smaller rate of true learning for a technology [10]. To date, this model has been tested only at a high level of technological aggregation (economic sectors). As with other multi-variate formulations, empirical data to develop and test such models for specific technologies (or classes of technology) is currently limited or unavailable.

Another more recent development is the integration of technical growth (diffusion) into the experience curve—the so-called endogenous learning-diffusion model [9, 46, 53, 56]. This model accounts for the fact that reductions in unit cost can increase the diffusion and adoption of a technology in the marketplace [46]. In turn, faster adoption of the technology may stimulate higher learning rates and vice versa. This approach provides a greater ability to explain changes in the learning rate over time (or with cumulative production), controlled by the rates of growth and cost reduction. We discuss this further and offer empirical examples of variable learning rates in the following section of this paper.

Uncertainty in the Shape of an Experience Curve

Historically, a number of authors have suggested alternative models for the shape of an experience curve, especially deviations from log-linearity (Equation 2) at the beginning and tail end of the curve. Here we review some of the earlier literature on that topic as well as evidence of deviations from a log-linear model in a number of cases.

The S-Shaped Learning Curve

Long ago, Carr [67] argued that based on empirical observations the cumulative average learning curve for airplane production was best represented by an "S-shaped" curve in which slow initial improvements were followed by a more rapid rate of improvement, followed by an eventual leveling off. Concavity in the initial phase of a learning curve also was recognized independently by the Boeing Airplane Company [68] and the Stanford Research Institute (SRI) [69, 70]. The SRI researchers proposed adding a term, called the "*B*" factor, to the conventional formula (Equation 1) to represent the equivalent units of experience available at the start of a manufacturing program. The SRI studies claimed that the revised formula, $Y = a\,(x+B)^b$, described the empirical production data better than the conventional log-linear function. Other recent studies also show significant deviation from linearity at the beginning of a learning curve, where much lower learning rates were observed [29, 30].

Prior studies of environmental technologies at coal-fired power plants [36], also found that experience curves with initial concavity best fit the data for two widely used technologies—flue gas desulfurization (FGD) systems for sulfur dioxide (SO_2) control and selective catalytic reduction (SCR) systems for nitrogen oxides (NO_x) control (see Figure C.11) [32]. We hypothesize that these low initial learning rates resulted in large part from the rapid deployment of "first generation" technology in response to new environmental regulatory requirements, with little

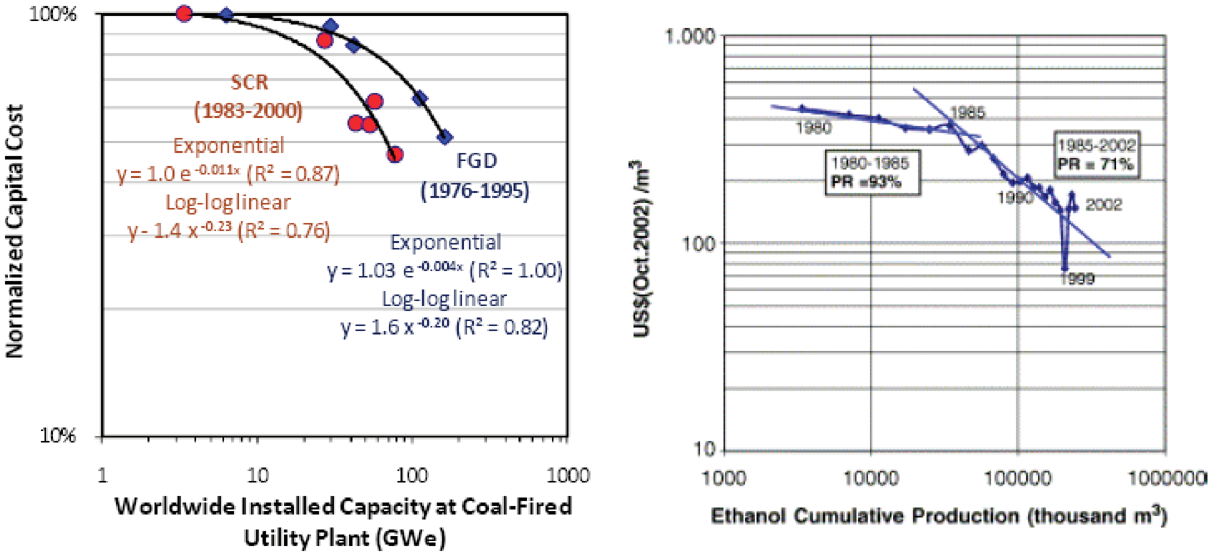

FIGURE C.11 Best-fit experience curves for capital costs of flue gas desulfurization (FGD) and selective catalytic reduction (SCR) systems at standardized U.S. coal-fired power plants (as defined in Figures 2 and 3) (E.S. Rubin, et al., Estimating the Future Trends in the Cost of CO_2 Capture Technologies. Report No. 2006/6. 2006, IEA Greenhouse Gas R&D Programme (IEA GHG): Cheltenham, UK). Also shown on the right is the experience curve for Brazilian ethanol production (J. Goldemberg, et al., Ethanol learning curve-the Brazilian experience. Biomass and Bioenergy, 26 (2004) 301-304), which exhibits similar characteristics.

time for learning. This was followed by improvements in succeeding generations of the technology based on factors including continued R&D and experience with existing installations, as documented by Taylor, et al. for FGD systems [71, 72] and by Yeh et al. for SCR systems [32, 38].

Others have challenged the log-linearity assumption for the latter part of an experience curve. Guibert [73] viewed the progress curve as having a horizontal asymptote that was approached after a large number of aircraft units had been produced. A study by Boeing of cost reductions on the L-15 airplane concluded that the unit cost curve became flat (exhibiting "level-off") at large cumulative output. They believed this was due to limitations imposed by a given set of tooling. They also found that the level-off point seemed to occur sooner for processes exhibiting steeper learning rates prior to level-off and for the manufacture of small aircraft compared to large planes. Similarly, Asher [74] analyzed data for nine models of fighter aircraft and found that the learning curve began to level off after about 125 units; extrapolating from 100 units out to 1000 units would result in an error of about 25%.

An extensive survey by Conway and Schultz [75] studied the existence of learning in four firms manufacturing products with complex as well as simple designs and cumulative production quantities from fifty to two hundred million units. Their survey also found leveling-off, or a decrease in the learning curve slope, when large cumulative production quantities were reached. More recently, Klepper and Graddy [76] assembled data on the number of firms, outputs and prices for 46 new products from their initial introduction through the year 1972. They developed both quantitative and qualitative measures characterizing the evolution of new industries. They found that all products appeared to follow a similar pattern over time, though with considerable quantitative variations. The study found that during both the growth and shakeout stages, the number of firms and total output grew while prices fell. However, once the number of firms stabilized, the rates of price reduction and increase in output leveled off and remained constant over time, typically after 30 to 40 years.

In the case of energy technologies, some have proposed that resource, market and theoretical technical constraints eventually put a floor on technology-specific costs [21, 65]. Many large-scale energy-economic models, which project costs many decades into the future, have imposed long-run price floors for specific energy technologies, below which learning curve projections cannot fall [7, 77]. This, in essence, changes the assumed shape of the long-run experience curve.

Cost Increases During Early Commercialization

For many large-scale technologies such as power plants and their environmental control systems, initial cost estimates for new technologies based on experience from smaller-scale projects or pilot plants are typically lower than the costs subsequently realized for the initial set of full-scale commercial plants. Thus, costs often increase rather than decrease in the early phase of commercial deployment. The reasons for such increases are typically linked to shortfalls in performance and/or reliability resulting from insufficient data for scale-up and detailed design, or from new problems that arise during full-scale construction and operation.

Although this phenomenon has been long recognized and often described qualitatively [78], there are relatively few empirical studies that document such trends for energy and environmental technologies. One recent study, however, reported an experience curve progress ratio above 100 percent for natural gas combined cycle (NGCC) systems for the period 1981-1991 [79]. This was followed by subsequent cost declines. Studies of British and German wind power [41] and photovoltaic technologies [80] also found progress ratios above 100 percent (i.e., cost increases) during early deployment. Though no explanations were provided in the original studies, these cost increases are consistent with the observation that the total cost of new technology often cannot be reduced as quickly as costs are added through design changes and product performance improvements in the early stages of commercialization [22].

Analysis of past experience for power plant FGD and SCR systems also revealed cost increases during early commercialization. We present this data below, along with reported cost estimates for CO_2 capture at coal-fired power plants—a technology that has been widely studied but is not yet commercially deployed at power plants.

Cost Trends for FGD Systems

Under provisions of the Clean Air Act, the U.S. federal government funded research and development on SO_2 removal processes from power plant flue gases starting in the 1960s, including several conceptual design and cost studies [71]. Early cost evaluations for those technologies involved many assumptions since technical data were limited. Most vendors had yet to fabricate and erect the large gas scrubbing devices required for full-scale systems and very little data were available to properly select materials of construction for the service involved. In many cases, the "technological optimism" of process developers tended to maximize process potential and minimize problem areas such as corrosion, scaling, solids disposal, sulfite oxidation, mist elimination, gas reheat, operational turndown and pH control. Cost estimates in the early 1970s were subject to further uncertainties in scale-up factors based on experimental and prototype installations. Despite some commercial applications on oil-fired power plants in Japan, there was no established basis to accurately assess the full-scale performance and cost of FGD installations on U.S. coal-fired plants. Thus, early FGD costs were considerably lower than later costs due to the optimistic view that system unknowns would be readily controlled and that inexpensive materials of construction could be utilized [81, 82]. As early FGD installations subsequently proved to be unreliable and unable to perform as required, the cost of re-designed systems increased considerably [83, 84]. Thus, in the 1970s, the two issues of greatest concern to the utility industry regarding FGD systems were their reliability and cost [85, 86].

Figure C.12 shows the historical trend of FGD costs for a typical coal-fired plant. The cost of early installations increased by as much as a factor of five as designs were modified to achieve the system reliability and performance needed to comply with regulatory requirements. After a decade of experience and learning, costs finally began to decline in the 1980s.

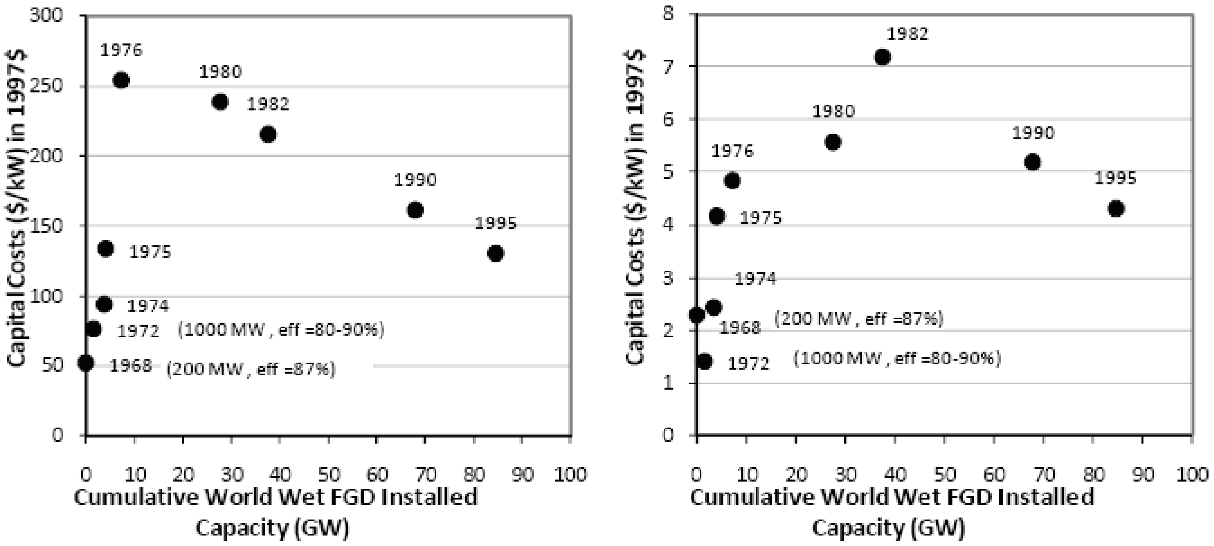

FIGURE C.12 Capital and annualized operating and maintenance (O&M) costs of a wet limestone FGD system for a standardized new coal-fired power plant (500 MW, 3.5% sulfur coal, 90% SO_2 removal) as of 1980. Many earlier plants did not achieve the high levels of availability and reliability required for utility operations, leading to more costly designs in later years (E.S. Rubin, et al., Estimating the Future Trends in the Cost of CO_2 Capture Technologies. Report No. 2006/6. 2006, IEA Greenhouse Gas R&D Programme (IEA GHG): Cheltenham, UK; M. Taylor, The Influence of Government Actions on Innovative Activities in the Development of Environmental Technologies to Control Sulfur Dioxide Emissions from Stationary Sources, in Department of Engineering and Public Policy. 2001, Carnegie Mellon University: Pittsburgh, PA; E.S. Rubin, et al., The Effect of Government Actions on Environmental Technology Innovation: Applications to the Integrated Assessment of Carbon Sequestration Technologies, Final Report of Award No. DE-FG02-00ER63037 from Carnegie Mellon University, Pittsburgh, PA to Office of Biological and Environmental Research, U.S. Department of Energy, Germantown, MD, 2004).

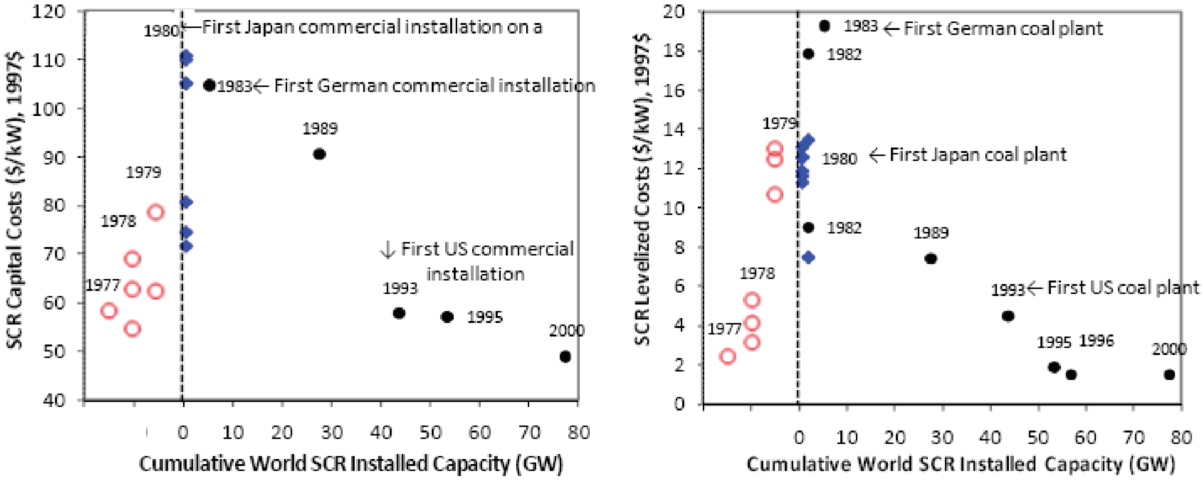

FIGURE C.13 Capital cost and total levelized costs of SCR for a standardized new coal-fired power plant (500 MW, medium sulfur coal, 80% NOx removal), as of 1983. Solid diamond symbols are earlier studies based on low-sulfur coal plants, which have lower SCR capital cost. Empty circles are studies evaluated prior to any commercial SCR installation on a coal-fired utility plant (E.S. Rubin, et al., Estimating the Future Trends in the Cost of CO_2 Capture Technologies. Report No. 2006/6. 2006, IEA Greenhouse Gas R&D Programme (IEA GHG): Cheltenham, UK; S. Yeh, et al., Technology innovations and experience curves for NOx control technologies. Journal of the Air and Waste Management Association, 55 (2007) 1827-1838).

Cost Trends for SCR Systems

Early economic evaluations of SCR costs for U.S. coal-fired power plant showed a trend similar to FGD systems, although in this case SCR technology was not actually deployed at U.S. coal plants until nearly two decades later. The earliest cost estimates were based on extrapolations of Japanese experience with SCR on oil and gas-fired plants [88]. Differences in plant operating conditions and fuel characteristics (such as sulfur and heavy metals content) were recognized, but not factored into these early estimates. Subsequent studies projected higher costs, which included contingencies for lack of experience with SCR systems and high-sulfur U.S. coals [89, 90].

Figure C.13 shows the historical trend in SCR cost estimates for a typical U.S. coal-fired plant. Note the initially optimistic assessments prior to the first commercial SCR installations. Cost estimates for U.S. facilities eventually declined after a decade of Japanese and German experience, together with U.S. pilot programs. These facilities demonstrated increasingly lower capital and operating costs, longer catalyst lifetimes and lower catalyst prices than assumed in earlier studies (the results of learning and competition in both non-U.S. and U.S. markets) [38].

Cost Trends for CO_2 Capture Systems

Environmental technologies that capture and sequester CO_2 from power plant flue gases are of growing worldwide interest as a potential climate change mitigation measure [91]. Experience curves for CO_2 capture technologies already have been incorporated into some large-scale energy-economic models [92, 93]. Current commercial technology for separating CO_2 from flue gas streams utilize an amine-based absorption system of the type used worldwide for other gas purification applications, mainly in the petroleum and chemical industries. Flue gas scrubbing systems employing monoethanolamine (MEA) are thus among the leading technologies proposed to control greenhouse gas emissions at fossil fuel power plants [94]. The earliest studies of CO_2 capture costs at coal-fired plants [95, 96] were motivated by the demand for CO_2 for enhanced oil recovery (EOR) at a time when world oil prices were at their peak (around 1976-1985). It was not until the 1990s that capturing CO_2 at electric power plants (in conjunction with geological storage) gained serious attention as a greenhouse gas abatement option.

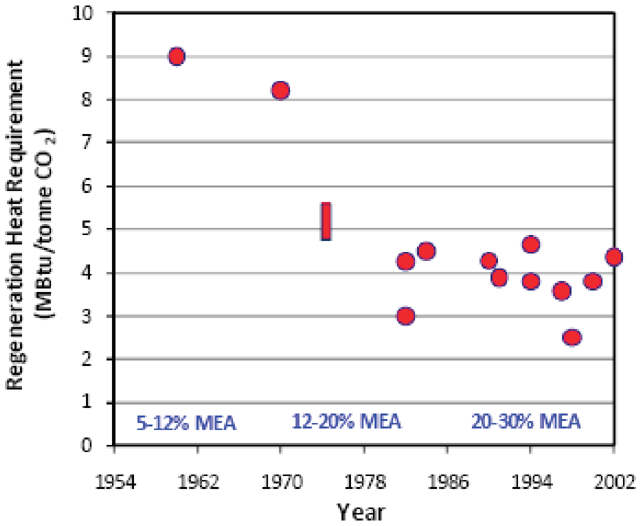

FIGURE C.14 Decreasing trend of regeneration heat requirement with increasing concentration of MEA solvent in CO_2 capture systems (E.S. Rubin, et al., The Effect of Government Actions on Environmental Technology Innovation: Applications to the Integrated Assessment of Carbon Sequestration Technologies, Final Report of Award No. DE-FG02-00ER63037 from Carnegie Mellon University, Pittsburgh, PA to Office of Biological and Environmental Research, U.S. Department of Energy, Germantown, MD, 2004). Because of its corrosive nature, MEA is typically mixed with water, which also must be heated to regenerate the solvent, thus adding to the energy penalty. New developments such as "inhibited" amines have permitted higher solvent concentrations in commercial systems.

The main challenge facing post-combustion CO_2 capture technology is to reduce both capital and operating costs, especially the energy requirement for regenerating the amine solvent [94]. Toward this end, new amine formulations commercialized over the past several decades allowed the use of increasingly higher solvent concentrations (Figure C.14). This, in turn, significantly reduced the energy penalty associated with this technology. At the same time, requirements for corrosion-resistant materials contributed to higher capital costs during this period (Figure C.15). By the early 2000s, however, improvements in overall system design led to a decline in the estimated capital cost of an MEA capture unit [94, 97-99]. It is anticipated that continued technology advances will lead to further long-term reductions in capital and operating costs [100, 101], although other factors, such as the recent worldwide escalation in raw materials cost, could offset gains from technology innovation.

Interestingly, the capital cost trend in Figure C.15 shows an initial increase followed by a gradual decline, much like the earlier trends for FGD and SCR systems. However, unlike FGD and SCR systems, no CO_2 capture systems have yet been built at coal-fired plants at the 500 MW scale (the basis for Figure C.15). While a number of demonstration projects are currently planned, to date only a few commercial projects have captured CO_2 from a small portion of the flue gas at coal-fired units, selling it as a commodity used in food processing [94]. Thus, all cost estimates shown in Figure C.15 have yet to be validated by actual CO_2 capture projects. The potential for cost *increases* with scale-up and early commercialization cannot be ruled out based on the experience with other power plant environmental technologies.

Discontinuities and Forgetting

Another uncertainty in the use of experience curves is the potential for organizational "forgetting" in which the knowledge acquired through learning-by-doing may decay or depreciate over time [16, 102, 103]. For example, Argote found that the unit production cost of the Lockheed L-1011 TriStar aircraft fell as production increased from 1972-1975, but increased after a production cut in late 1975, after which costs rose to exceed price. This "forget-

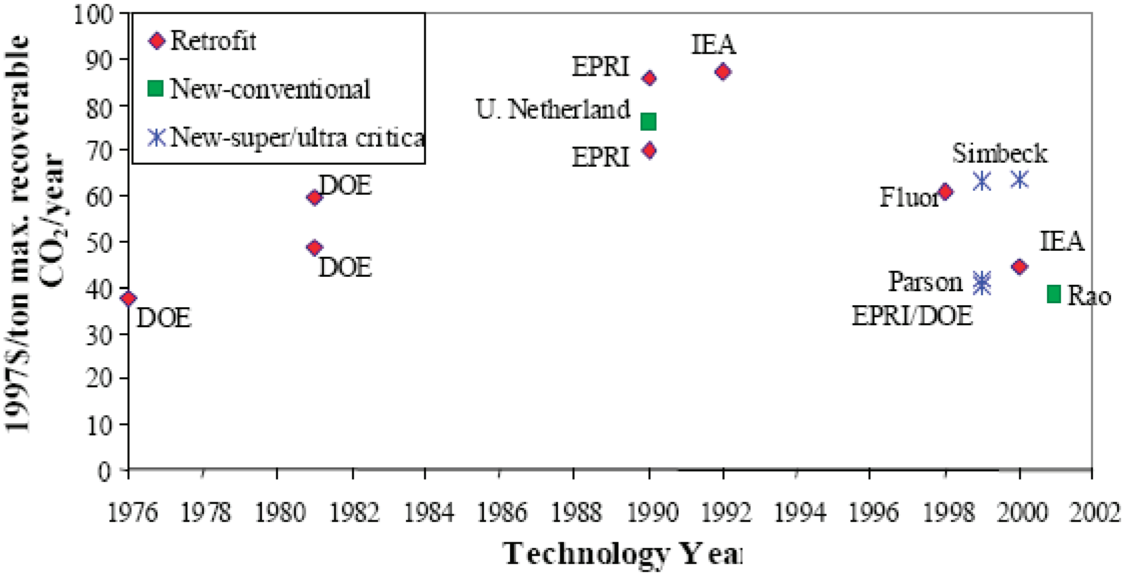

FIGURE C.15 Estimated capital cost of an amine (MEA) carbon capture system at a standardized coal-fired power plant (500 MW, 90% CO_2 removal). These costs include the cost of CO_2 compression (to about 2000 psia) and drying but do not include the cost of power plant capacity needed to supply the energy required for capture plant operation (E.S. Rubin, et al., The Effect of Government Actions on Environmental Technology Innovation: Applications to the Integrated Assessment of Carbon Sequestration Technologies, Final Report of Award No. DE-FG02-00ER63037 from Carnegie Mellon University, Pittsburgh, PA to Office of Biological and Environmental Research, U.S. Department of Energy, Germantown, MD, 2004).

ting-by-not-doing" was attributed to the loss of knowledge associated with laying off many experienced workers, leading to shortages of personnel and parts and a lack of experienced workers when production later resumed.

Similarly, Sturm [104] analyzed the operating experience of nuclear power plants in Eastern and Western Europe, the former Soviet Union and the United States from 1981 to 1991. He found that while all western countries reduced their unplanned outages, the former Soviet Union and all countries in Eastern Europe experienced increases in unplanned outages and a decrease in plant availability. He suggested this might have resulted from political and economic reorganizations that caused labor turnover, difficulties in maintaining plants or obtaining spare parts and a lack of incentives for adequate training programs—additional illustrations of organizational forgetting.

Social, Economic and Political Factors

The shape of an experience curve also can be affected by societal factors that influence the cost of a technology. For example, changes in work rules, or new environmental, health and safety standards can increase the cost of a technology even though the unit cost of wages, materials and equipment may be static or declining. Thus, Cantor and Hewlett [105] found that despite significant learning-by-doing benefits at the firm or constructor level, new regulations imposed by the Nuclear Regulatory Commission (NRC) contributed to unprecedented increases in construction costs for U.S. nuclear power plant from 1979-1988.

Similarly, Hewlett [106] found that real O&M costs for U.S. nuclear plants escalated at an annual rate of about 11 percent from 1975-1987, primarily because of new safety regulations imposed by the NRC. In a study of U.S. coal-burning power plants, Joskow and Rose [62] found that the real construction cost per unit of plant capacity declined during the early and mid-1960s, stabilized in the late 1960s, then climbed substantially during the 1970s and 1980s. The latter increases appeared to reflect the added costs of responding to new environmental, health and safety regulations during that period, coupled with increased construction times and a decline in construction productivity.

Finally, societal factors such as public opposition to a technology also can strongly influence rates of technology diffusion and learning, hence, the shape of an experience curve. Perhaps the most well-known example is nuclear power, where public opposition has effectively halted the diffusion of this technology in many countries (e.g., no new plants constructed in the United States since 1978) [107]. Even renewable technologies are not immune to this phenomenon: in a number of countries (including Norway and the United States), the siting of new wind energy systems has been opposed on aesthetic and other grounds. Because the importance and nature of societal influences on technology experience curves can vary considerably across (as well as within) different countries, it is arguably one of the most uncertain sources of uncertainty.

Discussion and Conclusion

It is widely recognized that long-term cost projections for energy and environmental technologies are uncertain and highly sensitive to assumed rates of technological change—whether specified exogenously as a function of time, or endogenously in the form of a learning curve or experience curve. For the commonly used log-linear form of an experience curve (Equation 2), uncertainties in future technology costs are reflected by uncertainties in the learning coefficient, b, and the appropriate value of cumulative production or capacity of a technology (or cluster of technologies), x. Strictly speaking, the latter parameter represents only the influence of learning-by-doing. When used to derive an experience curve, however, it is a surrogate for all factors that influence technology costs.

Efforts to better understand and explain the causes of observed cost reductions have led to a number of more complex formulations of experience curves, as reviewed in the third section of this paper. Notwithstanding these important efforts, future costs based on new model formulations remain highly uncertain [35, 63, 65].

In this paper we also examined (in the fourth section) empirical evidence that calls into question the common assumption of a log-linear shape of an experience curve, particularly during the early commercialization stage of a new technology. This was especially evident in case studies of environmental technologies for power plants, where the market for such technology was driven by the need to comply with new environmental regulations. The literature reviewed also showed that technology learning rates tended to decline at the later stages of technology development and diffusion, in essence putting a floor on the cost of a particular technology. This too contributes to non-linearities in the experience curve. The overall result in many cases is an "S-shaped" experience curve rather than a log-linear form. Further studies applying new models developed in recent years, such as component-based experience curves and endogenous learning-diffusion models, may help explain some of the non-linear features of experience curves discussed in this paper.

The cost *increase*s often observed for newly commercialized technologies and also seen in cases of institutional forgetting, are additional sources of uncertainty that can affect the outcomes of energy-economic models. To date, no large-scale models have yet incorporated such cost increases, though some have incorporated slowdowns or limits in technology diffusion rates to control the growth of emerging technologies. In contrast, a slow initial learning rate for a new technology (characteristic of an S-shaped experience curve) can discourage the early adoptions and investments needed for long-term growth and innovation relative to competing technologies with more "optimistic" cost reduction profiles (such as the prevailing log-linear shape). As a result, some technologies may be "locked-out" of the longer-term picture, affecting the overall cost, technology mix and other outcomes of policy interest, including the role of R&D expenditures [108]. The latter factor is explicitly incorporated in some experience curve formulations (two-factor models) to distinguish the effects of R&D from those of learning-by-doing. In principle, these models can be used to address such questions as the amount and "persistence" of public and private-sector R&D spending needed to achieve a proposed climate goal at minimum cost. These models too, however, are beset with significant uncertainties, as discussed in the third section of this paper.

So what are energy modelers to do in the face of all these uncertainties? In the near term, a broader set of sensitivity studies could be helpful to assess the impacts of different types of uncertainties on key model results. Although computationally more demanding, the use of input *distributions* of learning rates and other experience curve parameters would better represent our limited understanding of the processes underlying technological progress. For example, Grubler and Gritsevskii [109] used a simple optimization model with endogenous technological change represented by a traditional log-linear experience curve, but added uncertainty in the learning rate, represented by a lognormal distribution function around the mean value. They showed that when the rate of learning was certain (i.e., perfect foresight), the optimal solution was to invest heavily and early in the "winning" technology. Barreto and Klaassen [59] found similar results. However, when learning rates were uncertain (as in the real world), the optimal solution also became less certain. As a result, there were broader investments in a portfolio of technologies, with slower diffusion and market entry of any particular technology. Messner et al. [110] also incorporated uncertainties in future technology performance and found that it tended to spread risk over a larger number of options to cope with uncertainties in technology development paths.

Over the longer term, continued research into the underlying factors that govern or influence technological innovations may yield improved models that can reliably forecast the implications of proposed energy and environmental policy measures. In the meantime, more concerted efforts are needed to explore, understand and display the consequences of uncertainties in current formulations of technology experience curves (or other models) used to project the future cost of technology in energy-economic modeling and policy analysis.

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ROLE OF OFFSETS IN GLOBAL AND DOMESTIC CLIMATE POLICY[30]

Raymond J. Kopp[31]

Introduction

Greenhouse gas (GHG) offsets are a mechanism by which mitigation policy can achieve emissions reductions where they are least expensive—a characteristic Manne and Richels (1997) term "'where' flexibility" [32]—in much the same manner as emissions trading. Offsets incentivize cost-effective reductions from sources that generally have no obligations to reduce emissions and thereby can increase the economic efficiency of GHG mitigation policy at the national, regional, and global scale. Whether they will indeed play this important role has a great deal to do with the nature of the mitigation policy design.

This paper has two objectives. First, it provides definitions and a taxonomy that will be helpful in sorting through the complex offset landscape. With this taxonomy in mind, the paper then considers the role offsets could play given likely states of the world with respect to mitigation policy.

Definitions and Taxonomy

Perhaps the first time the term "offsets" was used in a context relevant to GHG mitigation policy was in the U.S. Clean Air Act.[33] Under the act, an expansion of a polluting activity in a nonattainment area[34] could be accommodated if the added pollution at the new or expanded source was offset by reductions in emissions at another source within the nonattainment area.

Since the early introduction of the term in the Clean Air Act more than 40 years ago, a loose and confusing terminology has developed in which "offsets" has been used to label very different concepts. One can argue this lack of precision has not only caused a great deal of confusion around the concept, but also has led to a negative perception of offsets as tools of GHG regulatory policy among policymakers, at least in the United States.[35]

Generally speaking, a GHG offset refers to a ton of greenhouse gas[36] that that has not been emitted due to

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[31] Senior Fellow and Director, Center for Climate and Electricity Policy, Resources for the Future.

[32] "When we assume that reductions take place wherever it is cheapest to do so (regardless of geographic location) we refer to this as 'inter-regional' or 'where' flexibility" (Manne and Richels 1997, 255).

[33] "In order to reduce the cost of compliance with air pollution reduction requirements, several Flexible mechanisms were introduced in the United States in the late 1970's. Referred to generally as emissions trading, they included emissions offsets, plant-specific 'bubbles,' and emission reduction credits. The offset mechanism was introduced to permit economic growth in areas that were not meeting air quality goals. For example, a new source could locate (or an existing source could expand) in a nonattainment area by reducing emissions at another source (usually by more than the increment of new emissions). In this way, the economy could grow and the environment could improve" (McLean 1999).

[34] A nonattainment area is a location that is in violation of National Ambient Air Quality Standards under the Clean Air Act.

[35] In the fall of 2008 and over the course of two months, Resources for the Future staff interviewed more than 30 congressional staffers—Republicans and Democrats, from committee and personal offices, and in both the House and the Senate—to determine their views on the role of international offsets in general and forest carbon in particular. With respect to offsets generally, "most respondents said that international forest carbon was frequently perceived only or primarily as a form of offset. A significant coalition of members opposes offsets of any kind as reducing the impetus for domestic emissions reductions." The perception of international offsets is based on "negative perceptions about the Clean Development Mechanism (CDM) in particular, as well as more general perceptions that international offsets are not managed well, do not produce real reductions, and are inappropriate because developing countries need to 'do their own part on climate change'." See Leonard et al. forthcoming 2010.

[36] Usually denominated as a ton of carbon dioxide equivalent (CO_2e).

resources applied and some purposeful action taken. An important feature of the resources and the action is that that they are "additional" to normal business-as-usual (BAU) behavior.[37]

Perhaps the most important distinction to draw with respect to offsets concerns the motivation that gives rise to the offset—that is, the motivation that causes resources to be devoted to an action to reduce GHGs. The motivations arise from an economic return that can be earned by selling the offset (reflecting a ton of reduced emissions) to a buyer. There generally are two classes of buyers: those who do not have any legal obligation to reduce emissions and choose to buy offsets for other reasons, and those who do have legal obligations and can meet those obligations by purchasing offsets.

The greatest popular press attention has focused on the first class of offsets that reside in what might be termed the "voluntary market." Examples of these voluntary offsets are sold by companies like Terrapass.[38] An individual who is concerned about his or her GHG emissions due to personal behavior—for example, air and auto travel—can purchase offsets equal to the emissions the individual seeks to offset. The same is true for private business. Firms that have no legal commitments to reduce GHGs may still undertake projects to reduce their own emissions or purchase offsets from entities like Terrapass or on commercial exchanges like the Chicago Climate Exchange.[39]

The volume of voluntary offsets has been growing over time, and a small industry of offset developers and third-party verifiers has been established to support this growth. However, it is unlikely that motivations for voluntary investments in such offsets, either by private individuals or corporations, will ever be so large as to require the modeling community to incorporate them in analysis of mitigation efforts. Therefore, the paper does not consider them further.

Compliance entities are those with a legal obligation to reduce their GHG emissions. Should a cap-and-trade system for GHGs be deployed in countries like the United States,[40] the market for compliance offsets can be quite large if obligations can be met with these purchased offsets. Countries are compliance entities with respect to the Kyoto Protocol, private businesses are compliance entities in the European Union Emission Trading Scheme (EU-ETS)[41] and within the United States under provisions of H.R. 2454,[42] and proposals exist for individual carbon trading, where the compliance obligations rest with individuals (Roberts and Thumim 2006).

The obligations of entities can vary. Countries under the Kyoto Protocol must keep their emissions under their Kyoto limits or purchase either Certified Emission Reductions Units (CERUs,[43] in the form of Clean Development Mechanism (CDM) credits) or Emission Reduction Units (ERUs,[44] quantified emissions-limitation and -reduction commitments from other Annex 1 Kyoto parties). Private firms under domestic cap-and-trade programs like the EU-ETS and H.R. 2454 must hold allowances in amounts equal to their emissions. Or, they may buy domestic and international offset credits[45] or purchase international emissions allowances.[46] Volumes of CERUs, ERUs, U.S. GHG market allowances, EU-ETS allowances, other international emissions allowances, and domestic and international offsets credits can be expected to be large and therefore important to modeling efforts.

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[37] Additionality plays an important role in the generation of an offset. For example, suppose a new office building is being constructed, and the plans call for water heating via natural gas as the least-cost option. Combustion of the natural gas will cause GHG emissions. Suppose someone comes to the building owner and agrees to pay the added cost of rooftop solar panels to heat the water in lieu of natural gas. Use of the solar panels will eliminate the GHG emissions, but importantly, if this individual did not compensate the building owner for the added cost of the solar panels, the owner would use natural gas, and emissions would take place. Thus, the purposeful action—providing the additional resources to the building owner to install rooftop solar—was additional. Because the solar installation would not have occurred under business as usual, the GHGs that were not emitted due to the solar panels are "additional" and could be valid offset credits.

[38] See http://www.terrapass.com/ (accessed April 2010).

[39] See http://www.chicagoclimatex.com/ (accessed April 2010).

[40] EIA (2009) suggests that 1.2 billion tons of domestic and international offsets would be traded in the U.S. market in 2020.

[41] See http://ec.europa.eu/environment/climat/emission/index_en.htm (accessed April 2010).

[42] American Clean Energy and Security Act of 2009, passed by the U.S. House of Representatives in the 111th Congress, http://www.govtrack.us/congress/bill.xpd?bill=h111-2454 (accessed April 2010).

[43] Article 12 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, http://unfccc.int/kyoto_protocol/mechanisms/clean_development_mechanism/items/2718.php (accessed April 2010).

[44] Article 3 of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, http://unfccc.int/resource/docs/convkp/kpeng.pdf (accessed April 2010).

[45] H.R. 2454, Part D.

[46] H.R. 2454, Part C, Section 728.

From the perspective of the compliance entity, any legally recognized instrument that satisfies its compliance obligation can be viewed as an offset—that is, as a ton of reductions that can be purchased rather than physically reduced by the entity. However, as a general matter, analysts sort these legal instruments into two groups—uncapped tons and capped tons—and generally refer to the first group as offsets and the second group as allowances.

Uncapped Tons

Uncapped tons are "additional" emissions reductions from sources that do not have a compliance obligation. If an uncapped ton is purchased by a compliance entity, the emissions within the source category to which the entity belongs will rise above the cap. Examples drawn from H.R. 2454 include domestic offsets,[47] international sector-based credits,[48] Kyoto CERUs and other credits issued by an international body,[49] and international credits for reducing deforestation and forest degradation in developing countries (REDD).[50] Examples drawn from the current Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC) and negotiations under the UNFCCC for beyond 2010 include CDM credits[51] and sectoral crediting.[52]

Capped Tons

Capped tons originate from sources that have compliance obligations. Examples include H.R. 2454 allowances, Regional Greenhouse Gas Initiative (RGGI) allowances,[53] EU-ETS allowances, Kyoto ERUs, and any allowances from a sovereign cap-and-trade program (sectoral or economy-wide) that has binding domestic limits. For capped tons purchased by a compliance entity where the ton reduced originated from within the entity's source category, emissions within that source category will not rise. For capped tons purchased by a compliance entity where the ton reduced originated from outside the entity's source category, emissions within the entity's source category will rise, but emissions aggregated across the two categories will not rise. An example would be an EU-ETS allowance purchased by an entity with a H.R. 2454 obligation.

Offsets Generally

We tend to think of offsets as mechanisms within the context of a cap-and-trade regulatory approach, but as the reference in the introduction to the Clean Air Act points out, regulatory programs amenable to offsets can be very broad. Setting aside voluntary actions, offsets have value if an emitting entity has a legally binding obligation with respect to its emissions. These obligations could be in the form of standard cap-and-trade regulation, emissions taxes, fixed emissions limits, and performance standards. An offset is a mechanism by which a regulatory obligation can be discharged. Equivalence formulas can be established that would define the relationship between an offset ton and any of the above four forms of obligation.

Offsets and Some Difficult Modeling Issues

Numerous issues concerning offsets can be important for modelers, and while these issues are beyond the scope of this paper, they are worth identifying. As mentioned previously, the issue of additionality is important. What GHG mitigation actions would not have been taken by sources in a BAU world (absent any compliance obligation) and therefore would qualify as a valid offset? Unless regulators have detailed the projects or actions that they deem additional, the modeler can do little to make this determination.

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[47] H.R. 2454, Section 732.

[48] H.R. 2454, Section 743(c).

[49] H.R. 2454, Section 743(d).

[50] H.R. 2454, Section 743(e).

[51] Article 12 of the Kyoto Protocol.

[52] UNFCCC 2009a, section 73(e).

[53] See http://www.rggi.org/home (accessed April 2010).

Project-level offsets like those of the CDM and those proposed in H.R. 2454 can have non-trivial transactions costs that must be added to the marginal cost of emissions control. These transactions costs are often a function of each unique regulatory environment and are not directly observable. When data on transactions costs are available to the modeler, those data are likely specific to a regulatory environment and not easily generalizable broadly throughout the model.

International offsets pose particular problems when modelers have information about the marginal cost of control for particular classes of offsets but little or no reliable information about country-level investment environments that have a direct bearing on the country's ability to generate offsets. This is particularly true in the case of REDD offsets, where the biology and economics of specific countries suggest the availability of large quantities of offsets at very low cost but where the governance and readiness of the country suggest the opposite. Generally speaking, modelers rarely have access to governance and readiness data, and when they do, they lack parameters that map such country data to investment performance.

Sectoral offsets are a new class of offsets under consideration by UNFCCC negotiations and already are embedded in U.S. legislative proposals.[54] Sectoral offsets hold out the promise of offsets on a large scale and at lower transactions costs than project-level offsets like the CDM. However, from a modeler's perspective, issues arise. To properly model the supply of sectoral offsets from any particular country, a modeler needs a BAU emissions path for the sector, a marginal-cost-of-control function for the sector, and a baseline emissions path (lying somewhere below the BAU path) against which actual emissions will be measured and thereby the generation of offsets calculated. Data necessary to develop the first two are hard but possible to obtain. However, the baseline will often be the result of a political negotiation, and the results of that negotiation could be quite country specific.[55]

Sectoral offsets can also pose some difficult double-counting problems. Countries could put forth low carbon–growth paths complete with registries of nationally appropriate mitigation actions (NAMAs) and at the same time negotiate bilateral offset programs with specific countries like the United States.[56] Since the NAMAs are official government statements regarding the future mitigation actions of developing countries, modelers could use the NAMA registries to develop emissions paths for these countries. However, they must then track down any bilateral or multilateral offset deals and net them out.

Offsets in a Post-Copenhagen World and the Value of Flexible Mechanisms

Flexible mechanisms, particularly offsets, based on project-level crediting can be greatly improved with a movement to sectoral-based approaches that lowers transactions costs and considers additionality. Perhaps more important, a move to offset credits that are generated for reductions below negotiated baselines, rather than BAU emissions paths as embodied in most CDM-like project-level crediting, requires more aggressive developing-country participation and therefore greater global GHG reductions. However, the ultimate usefulness of enhanced offsets depends on the state of the world. That is, the usefulness of offsets (and therefore the size of the offset market and dollars flowing from developed to developing countries) depends on the nature of domestic and international climate policy. In some scenarios, offsets will be useful, in others, useless.

Consider two states of the world:

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[54] See UNFCCC 2009a, H.R. 2454.

[55] For example, in H.R. 2454 the baseline-setting process is part of a bilateral negotiation between an offset-supplying country and the Unites States.

[56] The concept of nationally appropriate mitigation actions (NAMAs) originated in the final action of COP13, the "Bali Roadmap." Section 1(b)(ii) of the text refers to mitigation actions by developed and developing countries calling for "Enhanced national/international action on mitigation of climate change, including, inter alia, consideration of: … (ii) Nationally appropriate mitigation actions by developing country Parties in the context of sustainable development, supported and enabled by technology, financing and capacity-building, in a measurable, reportable and verifiable manner" (UNFCCC 2007). Section 5 of the "Copenhagen Accord," the product of COP15, contains the agreement that "Non-Annex I Parties to the Convention will implement mitigation actions, including those to be submitted to the secretariat by non-Annex I Parties in the format given in Appendix II by 31 January 2010, for compilation in an INF document, consistent with Article 4.1 and Article 4.7 and in the context of sustainable development" (UNFCCC 2009b) These mitigation actions referenced in the accord are the NAMAs of the Bali Roadmap. The posting of the NAMAs in Appendix II of the accord and the further compilation is considered the registry of NAMAs.

- *World 1*—Kyoto II, emanating from the UNFCCC Kyoto track (Ad Hoc Working Group on Further Commitments for Annex I Parties under the Kyoto Protocol), is a top-down Kyoto regime of legally binding international emissions-limitation commitments, common but differentiated responsibilities with respect to non-Annex 1 parties, and developed-country commitments that are consistent with aggressive climate goals—for example, halting global warming at 2°C.
- *World 2*—Bottom-Up Carbon Markets, possibly emanating from the UNFCCC non-Kyoto track (Ad Hoc Working Group on Long-Term Cooperative Action), or the Major Economies Forum, is characterized by broad and deep GHG cap-and-trade programs in the major emitting Annex 1 economies[57] that encourage large-scale use of international offsets. With this group of countries, the largest potential market for international offsets would be the United States.

In both worlds, offsets play a very important and useful role in their capacity to add "where" flexibility, but as we deviate from these two scenarios, the usefulness of offsets declines. As a result, it is important to examine the likelihood that either of these states emerges.

The Likelihood of World 1—Kyoto II

I believe it is reasonable to argue that the post-Copenhagen world is decidedly not Kyoto II. The shape of a future international accord will not be a remake of the top-down Kyoto–Berlin Mandate world (UNFCCC 1995).

Legally binding international emissions-limitation commitments have been replaced with NAMAs, and no forces are pushing the process back to embrace the Berlin Mandate. Abandonment of the Berlin Mandate means the heart of a post-Copenhagen international accord no longer involves binding international emissions-limitation commitments, the burden sharing that implies, and therefore the need for considerable "where" flexibility. As a consequence, pressure to reform and use enhanced and scaled-up flexible mechanisms like sectoral offsets has diminished.

In the post-Copenhagen world, there is at best a weak interpretation of Article 4 of the Kyoto Protocol (common but differentiated responsibilities), and non-Annex 1 rapidly industrializing nations are expected to take domestic actions to reduce their emissions (Annex 1 nations will presumably do more). A reinterpretation of Article 4 places more burden on the rapidly developing emitter nations (the ones with the greatest potential to offer up sectoral offsets) to establish and finance their own domestic mitigation actions. Thus, flexible mechanisms taking the form of offsets are no longer seen as the primary policy by which non-Annex 1 countries will act to reduce their domestic emissions.

Current Annex 1 commitments offered up post-Copenhagen are likely inconsistent with a goal of halting global warming at 2°C (certainly when combined with the non-Annex 1 offerings) and likely are more in line with 4°C, meaning less aggressive domestic action than anticipated in a Kyoto-II world. The implicit rejection of the 2°C goal (implicit in the actions pledged in the wake of Copenhagen) further diminishes the developed world's political need to seek low-cost international tons through offset mechanisms as a means of cost control.

The Likelihood of World 2—Bottom-Up Carbon Markets

Absent the Berlin Mandate and the Kyoto structure of binding international emissions-limitation commitments, there is no longer a need at the sovereign level to meet international commitments with domestic reductions or to utilize the flexible mechanisms. However, to the extent that domestic regulatory policy has been developed in such as manner as to devolve legal responsibility for emissions reductions to the private sector (for example, through a cap-and-trade system) and regulatory approaches admit the private-sector use of flexible mechanisms, especially offsets, the usefulness of such mechanisms remains.

With the passage of H.R. 2454 this past June and the prospect of a very large U.S. cap-and-trade program that

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[57] Australia, the European Union, Japan, New Zealand, Russia, and the United States.

admits international offsets, the political and economic value of enhanced and scaled-up flexible mechanisms was quite high. Indeed, these mechanisms were to provide the offsets necessary to contain compliance cost within politically acceptable limits, while at the same time providing a source of U.S. funds to aid developing countries.

Unfortunately, within the U.S. Senate, the prospects for comprehensive GHG policy generally, and an economy-wide cap-and-trade approach in particular, are not good at the present time. If the United States chooses another regulatory approach—for example, regulation under the Clean Air Act or a strict standards approach appended to an energy bill like S. 1462[58]—the demand for offsets and flexible mechanisms by the United States could likely be zero. Moreover, without a U.S. GHG market, it is unlikely that the EU-ETS combined with other country programs would be of sufficient size to drive a large-scale sectoral offset program.

Offsets in a World Without Kyoto Commitments or Large-Scale Carbon Markets

Offsets do provide "where" flexibility and therefore enhance the economic efficiency of global mitigation policies. However, as noted above, the future of the two major institutional features that make offsets viable—a Kyoto-like global regime and large-scale GHG markets—are in doubt. If the regime for global cooperation on climate change follows a bottom-up pledge-and-review model and large-scale GHG markets fail to develop, are there alternative domestic policy structures that would support offsets?

Government Funding

Governments can of course continue to purchase offsets to support their domestic GHG policies. However, given the stressed budgets of many Annex 1 countries, how long will that practice continue after the forcing function of the Kyoto Protocol expires?

The developed countries, including the United States, pledged in Copenhagen to amass $100 billion annually by 2020 to support mitigation and adaption activities in developing countries, and these funds could be used to finance offsets. However, in the case of the United States, the bulk of these funds were to originate from private-entity purchases of international offsets, not from the U.S. Treasury. If a cap-and-trade program does not develop in the United States, it is highly unlikely Congress will authorize the use of tax money to fund large-scale purchases of offsets.

Smaller-Scale Carbon Markets

There is good reason to believe the EU-ETS will continue as a cornerstone of EU mitigation policy. Whether the member states will open the market to wider acceptance of offsets remains to be seen. The European Union has shown little enthusiasm for admitting REDD credits, in part for fear these offsets would substantially drive down the allowance price thereby diminishing the economic incentives to control domestic EU emissions. It seems unlikely that this policy will be reversed (especially if there is no U.S. market) and even more unlikely that the European Union would accept sectoral credits from countries like China and India.

Absent a U.S. federal GHG market, states seem prepared to move ahead. The RGGI market already exists, and planning continues for the much larger California market as well as the market that might develop from the Western Climate Initiative, an organization of western U.S. states and Canadian provinces. Similarly, GHG markets in Australia, New Zealand, and even Japan are being developed or discussed. Offsets could become integral components of these markets, but given the size of the markets and some limits on the use of offsets, they are not likely to accommodate large volumes.

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[58] *American Clean Energy Leadership Act of 2009*, sponsored by Senator Jeff Bingaman (D-NM) in the 111th Congress, http://www.govtrack.us/congress/bill.xpd?bill=s111-1462 (accessed April 2010).

Tax Offsets

While seemingly not as popular as cap-and-trade systems, GHG taxes (usually carbon dioxide taxes) are still discussed as viable GHG policies. President Obama has created by executive order the National Commission on Fiscal Responsibility and Reform to examine the huge federal deficit and make recommendations for tax reform to address the deficit. A slim chance remains that GHG control policy could be recast as deficit-reduction policy in which revenues from carbon tax are used to reduce the deficit. Legislation enacting such a tax could contain provisions whereby tax liability could be reduced through international offsets.

Tradable Renewable Energy Credits

Developed and developing countries have shown a great deal of interest in renewable energy and policies to enhance their commercialization and deployment abound. Thirty-eight U.S. states have some form of mandatory or voluntary renewable energy standard,[59] and the chances are quite high that a federal standard will soon be adopted. Renewable energy standards are finding their way into the developing world as well. India recently announced a proposed renewable energy standard of 15 percent by 2020 (Wheeler and Shome 2010). Trading renewable credits is already popular in the United States, and such trading could be expanded internationally to support more aggressive developing-country mitigation goals.

The Future Economic Value of Project and Sectoral Offsets

CDM is a flexible mechanism under the Kyoto protocol. CDM credits have economic value since they can be used to meet compliance obligations for countries that are signatories to the Kyoto Protocol. Moreover, countries that have adopted or are considering cap-and-trade programs to regulate domestic emissions may admit CERs into the domestic systems as uncapped offset credits (for example, in the EU-ETS and provisions of H.R. 2454).

With the expiration of the Kyoto Protocol in 2012 and prospects for a successor slim, the value of existing CERs going forward will depend to a great extent on the EU-ETS and other domestic markets that may come into being. It is important to recognize that individual domestic markets may impose particular restrictions on the character of CDM credits they admit into their markets. Such restrictions are already in place in the EU-ETS and emerging policies in New Zealand, Australia, and Canada (Aasrud et al. 2009). Thus, to maintain the value of CERs, reformers of the CDM who are operating within the structure of the UNFCCC must be cognizant of the various domestic carbon market demands and not focus exclusively on the CDM as a component of a successor to Kyoto.

In addition, the project-level character of the CDM and the BAU baseline may cause developed countries to further restrict their acceptance of CERs to the poorest of developing countries and require the more advanced countries like China and India to move toward sector-wide crediting with aggressive below-BAU baselines. This evolution in the global regime for climate cooperation and trends in the development of domestic mitigation policies does not suggest a bull market for CDM credits going forward.

In the absence of a Kyoto successor, the value of sectoral offset credits and the magnitude of the supply will depend in large part on the multiplicity and vagaries of domestic policies within individual offset–demanding countries. For example, one crucial feature of a sectoral crediting system is the baseline. While a BAU baseline may enjoy the support of many developing countries within the UNFCCC that are potential credit suppliers, it may not be acceptable to countries that are credit demanders. In the case of the Unites States, H.R. 2454 already has expressed a preference for bilateral negotiations over decidedly non-BAU baselines between the United States and supplying countries. Aggressive, non-BAU baselines limit the supply and raise the price of offsets.

Moreover, the bilateral negotiation model contained in H.R. 2454 means that each offset-supplying country could be treated differently by the large offset demanding countries. Some suppliers may be granted lenient baselines, others aggressive baselines, and perhaps some countries excluded entirely.

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[59] See http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm (accessed April 2010).

If large-scale domestic GHG markets are established and are hospitable to offsets (particularly international offsets), mechanisms to "share" the economic rent associated with offsets will likely be deployed. These mechanisms could include government aggregators serving as monopsonistic buyers of international offsets who would in turn sell the offsets in the domestic market, with the intent of using monopsonistic power to shift some of the economic rent from the offset supplier to the demander (Purvis et al. 2009). The economic results of this government intervention in the international offset market are to lower the offset sales price and reduce the profit to be earned by offset suppliers.

Conclusions

The future is highly uncertain for all offsets, including those from domestic and international sources, as well as existing CDM credits and proposed REDD and sectoral credits. The uncertainty emanates from unsettled domestic policy—primarily in the United States—and as-yet poorly shaped international policies that are developing for coordinated action on GHG mitigation.

If future international policy takes the form of bottom-up pledge and review, rather than an extension of the Kyoto architecture, then the usefulness and economic value of offsets generally depends on the breadth and depth of regional GHG markets (logically tied to cap-and-trade programs). While it is true that offsets could exist and have value absent formal markets, they would likely play a very small role in domestic and international climate policy.

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CARBON OFFSETS IN FOREST AND LAND USE

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Introduction

Since the 1980s, forests and agricultural soils have been widely considered as an important, and low cost, option to reduce net atmospheric greenhouse gas emissions (Richards and Stokes, 2004). Recently, as the United States and international community have inched closer to making stronger legally binding commitments to reduce greenhouse gas emissions, policy makers have further recognized the potential benefits that forestry and other land based offsets can provide. If, as their promoters suggest, forest carbon offsets cost less than options in the energy sector, they may be able to reduce the overall costs of climate mitigation to society. Some studies have suggested that forestry carbon offsets can reduce the costs of stringent carbon mitigation policies by up to 40% (Tavoni et al., 2007; Sohngen, 2009).

Given the important role land use plays in mitigating climate change, this paper examines and reviews the current literature on carbon sequestration in forests and agriculture. The paper reviews in particular data, methods and results from a wide range of studies to provide estimates of the potential for land use options based on current knowledge. Given that a large share of the total body of work has been conducted in the forestry area, the report focuses more effort on forestry, but some review of the agricultural options is provided. The report then addresses several issues that have arisen in the implementation of land-based carbon offsets, namely issues like additionality, permanence, leakage, measuring, monitoring and verifying. These issues are important to consider regardless of whether the projects are forestry or agriculture based.

Methods Used to Estimate Costs

The paper begins with an examination of the methods that have been used to estimate the costs of carbon sequestration in forests or agriculture. To date, three general methods have been used to estimate the costs of carbon sequestration in forests and agriculture: bottom up/engineering approaches, econometric approaches, and dynamic optimization approaches. Bottom up/engineering approaches build up estimates by modeling the process and attaching costs and estimates of the carbon gains to various components of the process. They do not account for adjustments in market prices that might arise if the carbon sequestration programs are scaled up. Examples of bottom up models include Moulton and Richards (1990), Parks and Hardie (1995), and Sohngen and Brown (2008).

Econometric approaches rely on large cross sectional datasets, or possibly time-series data sets, and estimate specific economic relationships. Modelers often postulate particular models, and then estimate reduced form components of the broader model. For instance, the 2 model developed by Plantinga et al. (1999) estimates the share of land devoted to different land uses as a function of the returns to different uses, and other factors that influence land quality. Such a model can then be used to calculate a marginal cost curve by altering parameters in the modeling and assessing the resulting predictions of land use change. More recent models have used point data on specific locations and more spatially explicit methods to estimate the probability of land conversion across different uses (e.g. Lubowski et al., 2006). Econometric estimates have also been used to calculate the costs of carbon sequestration in agricultural soils (Pautsch et al., 2001 and Antle et al., 2007).

Optimization approaches focus on modeling the economic system typically by maximizing consumers and producers surplus. In the case of forestry, the optimization models adjust the stock of forests (and consequently the carbon in forests) by altering the age of timber harvest, management inputs, and timberland area. Adams et al. (1999) is an example of a forestry model applied to the United States, and Sohngen and Mendelsohn (2003) is an example of a global forestry model. Optimization approaches have been widely applied to assess the costs of changes in forest management, e.g., increases in rotation ages or increases in management intensity. Similarly, they have been used to assess the costs of changes in management of agricultural land, e.g., adoption of conservation tillage, or changes in nitrogen fertilizer rates, for example, Murray et al. (2005), and Choi and Sohngen (2009).

There is debate in the literature over which methods are "best" (e.g., Stavins and Richards, 2005; Lubowski et al., 2006), but it is not likely possible to determine which methods are best, or even better, for estimating the costs of carbon sequestration. Each method handles different problems and can be used effectively under a given set of circumstances. For example, bottom-up studies can be very effective tools to get an initial sense for potential costs of different alternatives, particularly when data is limited. Econometric approaches, of course, have the benefit of producing estimates that allow calculation of statistical properties such as confidence intervals. Both econometric and bottom-up estimates, however, typically assume that input and output prices are exogenous, an assumption that may not be tenable under the fairly large land use change programs they seek to evaluate. Recent econometric approaches have developed process-based optimization approaches that utilize the econometric estimates within the context of an optimization model (e.g., Lubowski et al., 2006).

Top down, optimization models, on the other hand, model forest and land management directly, with feedbacks between output, output prices, and the intensity of management. To accomplish this, they are typically constructed to be much more aggregate than the econometric and bottom-up approaches. That is, the typical unit of observation may be a forest type in a specific region of the country (or multiple counties). As computer speeds have increased, modelers have been able to increase their level of disaggregation. The benefit of this approach is that as carbon sequestration policies are modeled, they have impacts on overall land use, which impacts output prices and resource costs. These are modeled explicitly in optimization approaches, allowing direct calculation of the opportunity costs of shifting land from one use to another.

There are relatively few direct comparisons of the approaches. Van Kooten and Sohngen (2007) conducted a meta-analysis of many different studies of carbon sequestration costs and found that methodological differences explained very little of the differences in marginal cost estimates. There is some limited evidence that optimization and econometric estimates are higher cost than bottom up studies, but these results are very dependent on functional form and thus not all that robust. Thus, across a range of 68 currently available studies, their results provide little evidence to support using one method over another to obtain more realistic costs.

Current Cost Estimates

Marginal cost functions for carbon sequestration in forests for three general regions of the world, as derived from IPCC (2007), are shown in Figure C.16. The largest potential exists in tropical countries, due to the carbon benefits (and low costs) of reducing deforestation. The potential in developed countries is fairly large as well, although it is driven by increased forest management. Table C.5 breaks out annual estimates for a number of studies by region and activity, including reduced deforestation, afforestation, and forest management, at a fixed carbon price of \$15 per t CO_2. These results indicate that around 4.1 billion t CO_2 could be sequestered in global forests through various activities over the period 2020-2050 for \$15 per t CO_2.

At similar carbon prices, \$15 per t CO_2, national level estimates in the United States of the potential for conservation tillage on cropland to sequester carbon range from 8 t CO_2 per year to 168 t CO_2 per year (Lewandrowski et al., 2004; Murray et al., 2005). Both of these estimates utilize optimization approaches. The Lewandrowski et al. (2004) study is a single period optimization approach, while the Murray et al., (2005) approach is a multi-period, or dynamic, optimization approach.

A number of regional studies in the United States have examined carbon sequestration through conservation tillage on cropland as well, and they seem to suggest relatively high costs for this activity. Choi and Sohngen (2009) find that in Ohio, Indiana, and Illinois, around 4.1 million t CO_2 per year could be sequestered on cropland for \$15 per t CO_2. These three states account for 26% of the total corn and soybean crop in the United States, so extrapolating these results nationally[60] suggests a total potential of only 15.5 million t CO_2 per year for \$15 per t

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[60] The extrapolation is made for expository purposes only, making the very strong assumption that cropland is of similar productivity in other parts of the country and that opportunity costs are similar.

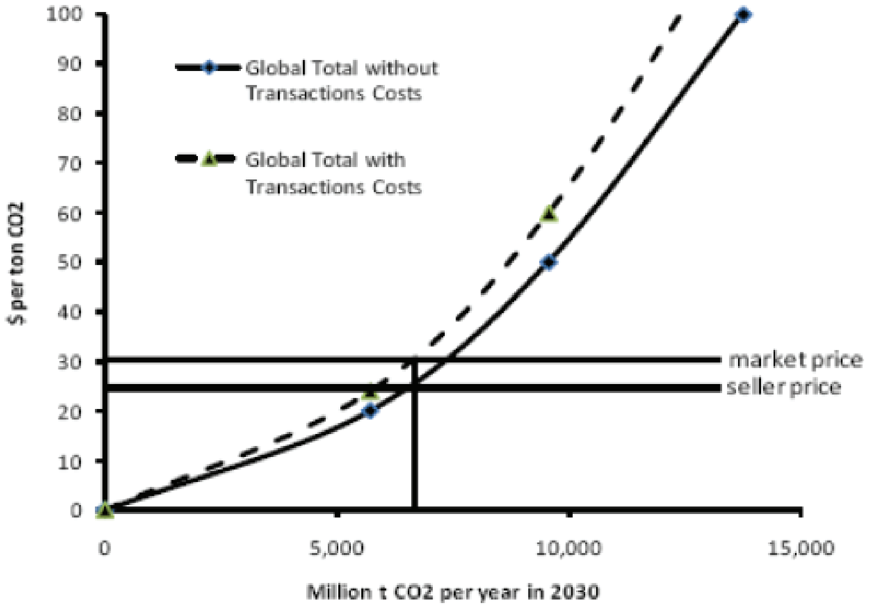


FIGURE C.16 Global marginal cost curve for 2030 with and without transactions costs. Transactions costs in this case are assumed to be 20% of the total costs.
SOURCE: Based on Figure 4 in Sohngen, 2009.

TABLE C.5 Average Annual Potential Net Emissions Reductions Through Forestry for the Period 2020-2050

	Afforestation	REDD1	Management	Total
Million tons CO_2 per year for the period 2020-2050				
Temperate				
United States	2,652 (190-800)	0	1,603 (101-219)	425
Canada	18	0	61	79
Europe	5	0	34	39
Russia	15	0	346	362
China	73	0	304	377
Japan	14	0	3	17
Oceania	12	0	10	22
Total temperate	403	0	918	1,321
Tropics				
South and Central America	98	6,064 (199-1039)	0	704
SE Asia	92	3,184 (41-846)	314	725
Africa	198	10,464 (588-1455)	0	1,244
India	143	0	1	144
Total tropics	531	1,970	315	2,816
Total all	933	1,970	1,234	4,137

NOTE: Carbon price assumed to be constant at $15 per t CO_2. Average estimates drawn from Global Timber Model of Sohngen and Mendelsohn (2007), unless otherwise noted. Cost estimates include opportunity costs, and implementation and management costs, but not measuring, monitoring, and verification costs, and other transactions costs.

CO_2 for the entire United States. Antle et al. (2007) come to a similar conclusion. Looking at 22 Midwestern U.S. states (encompassing the entire corn belt plus additional states further south and west), they find that for $14 per t CO_2, 12.8 million t CO_2 per year could be sequestered in corn and soybeans. The results from these and other regional studies (Antle et al., 2003; Pautsch et al., 2001) seem to imply that conservation tillage is a fairly high cost option.

Other types of offsets are possible in agriculture, for example by reducing nitrogen oxide and methane emissions. Estimates are most widely available for the United States. Within the United States, Murray et al. (2005) calculate that at $15/t CO_2, 32 million t CO_2 equivalent emissions could be reduced each year by optimizing N_2O and CH_4 uses and emissions on farms. A bottom up study by DeAngelo et al. (2006) estimates that the United States can reduce emissions through N_2O and CH_4 reductions in agriculture by a maximum of 42 million t CO_2 per year (at costs as high as $54 per t CO_2). A general equilibrium analysis by Golub et al. (2009) indicates that for marginal cost of $27 per t CO_2, N_2O emissions would be reduced by 59 million t CO_2 per year in the United States, and CH_4 emissions could be reduced by 22 million t CO_2 per year.

Globally, the study by DeAngelo et al. (2006) suggests that an additional 580 million t CO_2e per year of offsets can be generated from N_2O and CH_4 reductions for less than $54 per t CO_2. Golub et al. (2009) suggest substantially higher global potential, with up to 1,000 million t CO_2 per year of offsets from N_2O and CH_4 emission reductions for less than $27 per t CO_2e. The scale of these offsets globally appears to be around 20% of the total available from offsets generated by forestry.

Data for Estimating Carbon Sequestration Costs

One of the key issues associated with estimating the costs of carbon sequestration in forestry lies with the data. Clearly developing good models and good estimates relies on having access to good data. In general, modelers and researchers have access to some of the best data available in the United States. The USDA Forest Service Forest Inventory and Analysis database (http://www.fia.fs.fed.us/) provides fairly accurate information on the stock of forests in the United States at a given time, and it is available freely to everyone via the Internet. Other developed countries have equally good inventory methods and statistics, but they typically do not provide the data to the public as easily for use in modeling and analysis (see Sohngen et al., 2009 for a description of some of those sources).

Data for estimating carbon sequestration costs in developing countries have been derived from FAO in many circumstances (UN FAO, 2006). Waggoner (2009) illustrates the many problems associated with using the FAO (and many other sources) as a source of data. His data indicates relatively massive potential errors in nearly all estimates of existing forest areas and carbon stocks globally, particularly those currently derived by FAO in tropical countries. For developed, temperate countries, his results indicate that methods have been developed to reduce errors to some extent, but that these errors still could have important consequences. Further, he calculates that the cost of the U.S. forest inventory is about $0.24 per hectare of forestland. Based on this estimate, extrapolating these methods globally to the roughly 3.5 billion hectares of forests out there could cost $800 million per year.

There are other datasets available in developed countries. For instance, in the United States, the National Resources Inventory conducted by the U.S. Department of Agriculture has been widely used by researchers over the years (http://www.nrcs.usda.gov/technical/NRI/). This dataset is collected on farm plots in 5-year intervals. The USDA changed their methodologies in the late 1990s, so the newer datasets are not consistent with older datasets and this presents some problems for long-term analysis, but nonetheless, good data on land uses at present continues to be widely available to researchers.

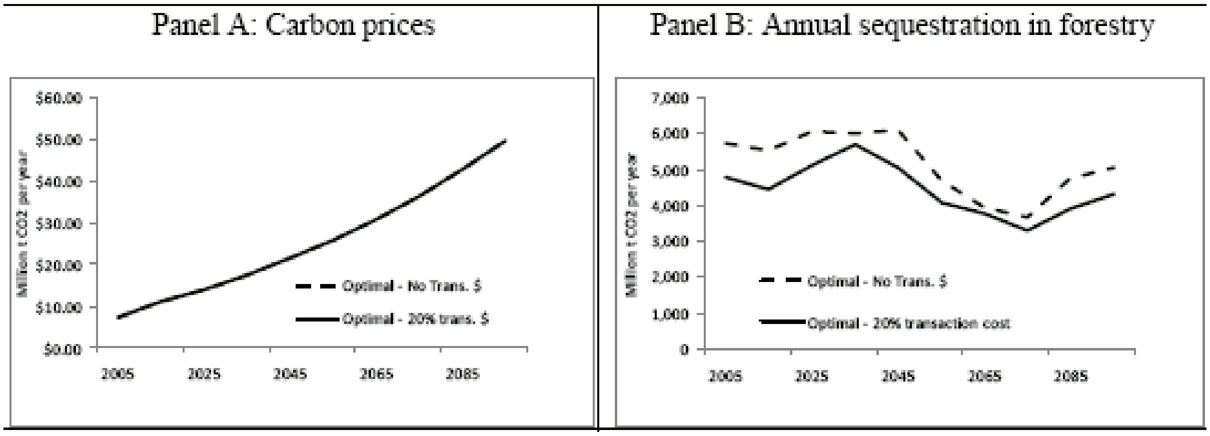
When considering land use (and not the stock of carbon on forests or the exact type of crop) it is possible to use satellite imagery. The study by Waggoner (2009) suggests that these methods are not yet perfected, although they do provide hope that it will be possible to use them widely in the future to at least pin down the forest area in a given area. It may take longer to develop estimates of the forest stock based on satellite imagery, but of course this technology is coming along.

Carbon Project Implementation Issues

Although the estimates of models suggest that forest and agricultural carbon are relatively low cost compared to other sources, a number of important implementation issues are likely to hinder their widespread adoption. In fact, these issues already seem to have had an effect. For example, the Kyoto Protocol in 1997 included a fairly significant role for forests in the text, but during the course of implementing the agreement, the role for forests has been minimal. Key questions emerged about whether forest carbon credits could be shown to be "real," "additional," and "permanent." Countries were able to include credits from afforestation and forest management (to some extent) in their national allocations, but despite estimates of reasonably low costs, these credits have been a small part of the total. Credits also were supposed to be tradable across country boundaries through the Clean Development Mechanism (CDM), but this mechanism has not worked well for forestry actions. Avoided deforestation thus has not been pursued, despite the large economic potential estimated by various models.

Failing to implement the full range of activities that are possible can have economic implications. A recent paper by Rose and Sohngen (2010), for instance, examined the effects of not allowing credits for avoided deforestation, either in the short-term or in the long-term. Their results show, not surprisingly, that incomplete forestry policies are inefficient. That is, policies that never allow avoided deforestation as an option may cause exceedingly large leakage (Figure C.17). Society can limit the extent of the inefficiency, however, by agreeing in the future to develop more comprehensive programs. Thus, if society just delays the implementation of alternative options like forest management and avoided deforestation, then there will still be some leakage, but leakage will be greatly reduced, particularly in the long run (see Figure C.17).

The surprising scale of potential forestry sequestration raises questions about whether or not these estimates are even realistic. The cost estimates in Figure C.16 imply that society could sequester up to 151 billion tons CO_2 in forests by 2030 by shifting management, and by converting into forests an additional 376 million hectares (globally) of land that would otherwise be used for crops. Changes of this scale imply changing land use on 18-19 million hectares per year, or stopping 11 million hectares per year of tropical deforestation, and afforesting in the temperate zone by 7-8 million hectares per year. Society does not have much experience with government programs this large, let alone with programs like this that have been successful. Developing carbon sequestration programs certainly could introduce large transaction costs in the form of broker fees, measuring and monitoring fees, handling fees, insurance fees (including possibly self-insurance), etc. It is important to consider just how society could design a program to actually obtain carbon and to keep these transaction costs at the lowest possible level.


Panel A: Carbon prices

Panel B: Annual sequestration in forestry

FIGURE C.17 Carbon prices and annual forest carbon sequestration in the optimal scenario of Sohngen (2009) with and without transaction costs.

Measuring, Monitoring, and Verification

A forestry carbon sequestration or emission reduction program can only work if a valid system of measuring, monitoring and verifying (MMV) carbon credits on the landscape can be developed and implemented cost-effectively. The article by Waggoner (2009) described above suggests that there is fairly little hope for the emergence of a global measuring and monitoring system that may be effective, but the reality may be more hopeful than his study implies. Waggoner indicates that the United States spends $72 million per year on its USDA Forest Service Forest Inventory and Analysis Program. This program measures, to a reasonable degree of statistical "certainty," both the extent of forests and the quantity biomass and carbon in the forests. For the 256 million hectares of forestland in the United States (USDA Forest Service, 2008), this suggests measuring and monitoring costs of around $0.28 per hectare per year.

The United States has around 156,540 million t CO_2 stored in forests, including above and below ground stocks as well as soil stocks. This means that the costs to measure each ton of CO_2 are well less than $0.01 per t CO_2. Of course, we are interested in the change in carbon (e.g., the annual sequestration or emission), not the stock, per se. Current estimates of stock changes in forests in the United States are around 650 million t CO_2 sequestered each year. This would imply that the costs of measuring carbon changes currently are around $0.11 per t CO_2. The $ per hectare number is probably most useful since the measurement program will be essentially the same regardless of the total tons and regardless of the change in tons.

The measurement cost estimates made with the USDA Forest Inventory and Analysis data are far less than those of made by Antle et al. (2003) and Antinori and Sathaye (2007), who suggest that measuring carbon in biological systems could cost around $1-2 per t CO_2. Antle et al. (2003) considered soil carbon sequestration, so this may explain to some extent their higher costs. Their results do not consider a program of measurement quite at the same scale as the USDA Forest Service FIA results, but they do show that costs will decrease if larger areas are included in the measurement scheme and economies of scale can be found. The estimates made by Antinori and Sathaye (2007) come from actual carbon sequestration projects, so they likely reflect the relatively large costs of putting infrastructure in place to do measurements where it was not in place before.

In reality, society will ultimately need both sorts of measurements, i.e., national scale systems that are relatively cheap on a per hectare basis, but which provide overall information on the direction and scale of carbon stocks, as well as specific surveys of forests that have been included in a "carbon project." Obviously, individuals who buy carbon offset credits from specific locations have great interest in knowing whether the carbon actually resides in those locations (not to mention the interest society has in knowing this). They may be willing to pay to install the infrastructure to conduct the local carbon surveys every 1-5 years to detect either changes in carbon storage or maintenance of the sink.

Other Transactions Costs

Other types of transactions costs may have important impacts in the market as well. Given the sheer number of actors in the land using sectors, aggregators who work with individual landowners to create carbon assets are likely to emerge. These aggregators will bundle the carbon assets of individuals with carbon assets of other individuals and then sell those bundles to people who value them. There may be several layers of "bureaucrats" in the middle, between the landowners and those who value the credits, and each of these steps will cost some money.

It is not yet clear how large or important the costs of this bundling activity will be. In a developing country context with many small landholders, Cacho and Lipper (2007) suggest that transactions costs for the buyers alone could be $5-$7 per ton CO_2, including MMV costs. Sohngen (2008) looks at the Conservation Reserve Program (CRP) in the United States, which has changed land use on over 12 million hectares in the United States since the early 1980's, and finds that transactions costs of that program, ignoring MMV costs, would amount to less than $2 per t CO_2. In the case of the CRP program, the transactions costs include the costs of the government office-workers and engineers who do the work that aggregators do. These two studies give a reasonably useful assessment of the range of potential transactions costs of $2-$7 per t CO_2.

Implications of MMV and Other Transactions Costs

MMV and transactions costs will raise the overall costs of carbon in forestry and land use type projects, but the implications will depend on carbon prices themselves. Obviously, if the market price is only $5 per t CO_2, then a $7 per t CO_2 transaction cost will prevent forestry or land use activities from participating. In reality though, carbon prices will probably be far higher. A recent analysis by Sohngen (2009) examines the potential role of transaction costs on sequestration. That study linked a large scale global land use model with the most recent version of the DICE model of Nordhaus (2008). In one scenario, benefits and costs were balanced to determine the optimal set of carbon prices over time. The author assumed no transaction costs and a 20% transaction cost, whereby 20% of the value of each permit would be "eaten up" by brokers. The 20% transaction cost basically shifts the marginal cost curve for each activity upwards by 20% at each location, as shown in Figure C.16.

The results of the analysis indicate that for this "optimal" scenario, the 20% transaction cost would have little effect on carbon prices, but it would reduce the annual sequestration in the forestry sector. The reduction averages about 14% over the century. Transaction costs do have important implications for carbon sequestration in carbon policy in that total sequestration is projected to be lower, but these transactions costs do not suggest that the level of carbon sequestration should be zero.

Additionality and Leakage

Much is made of additionality. Additionality is a problem because it is virtually impossible to determine, or know, what actions landowners will undertake with their land before a carbon project is implemented. We can perfectly well observe what they did with their land after the fact, but not before. The carbon we are actually interested in saving on the landscape, though, is the carbon that someone actually will release into the atmosphere. Paying individuals who would not otherwise have released carbon to hold it raises the total costs of a carbon sequestration program.

The marginal cost estimates above assume that society is able to determine which carbon is additional. Society may choose to pay for all carbon that is stored, not only the incremental storage, but it still must know how much carbon is additional, and therefore an offset that can be credited. Determining which carbon is additional for each carbon contract will require substantial effort. Examples of methods have been undertaken for a number of carbon projects to date (Antinori and Sathaye, 2007; Sohngen and Brown, 2004), and for entire countries (e.g., Murray et al., 2005), so it is plausible to determine baselines and additionality, but this task may be costly.

Leakage is likely to be a far more important problem for carbon sequestration for a number of reasons. First, it is unlikely that all countries will be able to move quickly to national level carbon accounting, and it is even more unlikely that the carbon accounting most countries do will be suitable immediately for measuring leakage within a country. Thus, many countries or regions will experience leakage within their boundaries. Second, it is unlikely that all countries will enter into a global climate treaty at the same time. Because some countries remain outside the scope of the regulatory regime, and because some countries will develop programs that are geographically limited in scope, leakage will occur. Empirical estimates of leakage illustrate the seriousness of the problem. Estimates from the project level indicate that leakage could range from 10-90% (Murray et al., 2007). Sohngen and Brown (2004) found a slightly smaller range of leakage for a carbon sequestration project in Bolivia, but leakage of 20-50% was still prevalent. A recent paper by Sun and Sohngen (2009) suggests that leakage could be nearly 100% in the near-term under a global policy that seeks to set aside forests with high carbon potential.

From an efficiency standpoint, leakage is the most important problem for carbon sequestration policies. Within-country leakage is probably the easiest to deal with because international negotiators can link cross-border payments to the establishment of measurement and monitoring programs that will ensure that leakage is counted. Thus, while it may not be possible to control leakage in all countries, countries that do engage in carbon sequestration could be required to develop adequate MMV systems that allow for leakage detection before they are allowed to sell carbon permits internationally.

Cross-border leakage will be more difficult to handle because it is unlikely that all forested countries will engage in climate policy and in carbon sequestration programs. Thus, some countries could remain out of the system and leakage could occur in those countries as timber and agricultural commodity prices respond to carbon trading. The question here is whether international negotiators can design an international system that engages a large share of forested countries in it. Given that all estimates currently point to leakage potentially being very large, it is important to examine ways in which we can increase the number of countries who will become part of any international carbon sequestration program.

Conclusions

This paper examines the potential for carbon sequestration as a low cost option to mitigate global climate change. A number of different types of models have been developed to estimate carbon sequestration costs. The literature in forestry is fairly well developed with numerous estimates made internationally in the last 20-30 years. The literature in agriculture is less well developed, although more and more studies are being conducted over time. Estimates presented in this paper suggest that around 4.1 billion t CO_2 per year could be sequestered in forests through a range of activities for $15 per ton CO_2. Around 23% of the carbon would be derived from afforestation, followed by 30% from forest management, and the remainder (47%) from avoided deforestation. Avoided deforestation occurs primarily in tropical countries, so a large share of the total mitigation potential in the forestry sector is derived from activities that occur in developing, tropical countries. Results from one international study on N_2O and CH_4 mitigation in agricultural found that for $27 per t CO_2, an additional 1.0 billion t CO_2 emissions could be reduced in the agricultural sector.

The results of the studies that have been conducted so far depend on a variety of data sources that are of varying quality. Data for developed countries, in particular the United States, appears to be fairly widely available for researchers to use. Internationally, there are some question marks around the data sets that need to addressed over time. These improvements in datasets could equally benefit economic estimates of costs of carbon sequestration and they could also improve the actual carrying out of carbon sequestration contracts (e.g., the MMV requirements).

While forestry and land use carbon mitigation have been discussed widely in the literature, they have only been used in actual policy settings sparingly. For instance, carbon credits through forest sequestration are part of the Kyoto Protocol, but have so far seen limited use. Furthermore, the Kyoto Protocol severely limits the type of land based credits that can be included. Some studies have shown that such limitations may have serious efficiency consequences, potentially eliminating a large share of the benefits. For instance, one study showed that if afforestation is the only policy option considered, leakage could be 100% in the short- term, and up to 50% in the long-term. The extent of leakage can be minimized by moving towards more comprehensive programs over time.

Other types of implementation issues are equally pressing and important. The paper discusses many of them, including additionality and baselines, leakage, and MMV. The paper presents some results indicating that transactions costs, which would include the costs of developing and implementing MMV systems and calculating baselines and additionality, do reduce the total amount of carbon that could be sequestered, but they do not appear to be large enough to suggest that we should not pursue land based options.

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MEASUREMENT AND MONITORING OF FORESTS IN CLIMATE POLICY DESIGN

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Improved data are required for quantitative assessment of the role of forests in climate policy. The attraction of including forests in the shaping of climate policy is twofold. Managing trees to store carbon by reducing deforestation and maintaining forest health can physically counterbalance, or offset, greenhouse gas emissions (GHG).[62] Carbon dioxide is taken in by trees and other plants during respiration and sequestered in plant tissue and the surrounding soil.[63] Estimates of emissions released in deforestation vary widely, ranging from 7 to possibly 30 percent of all sources of GHG emissions (Denman et al 2007, Houghton and Goetz, 2008). The lack of good data severely limits the capacity to refine these estimates. The data gap also limits the design of cost-effective greenhouse gas abatement regimes, including, for example, the use and monitoring of forest sequestration offsets.

For an individual project or for an individual country, some estimates of forested area and carbon sequestration have been available and when necessary, improved by extensive fieldwork. However, the currently available data are poor for understanding *global* forests. The only data about global forests are in the form of nationally self-reported information compiled roughly at 5-year intervals by the United Nations' Food and Agricultural Organization (FAO). The limited quality of these data is widely recognized by the FAO (for example, see discussion in Matthews and Grainger 2002) and by many other experts (for instance, Irland 2009, Grainger 2008). The data limitations confound estimates of net primary productivity, in turn the basis for deriving marginal costs of forest carbon (see Naidoo et al, 2007; Kindermann et al, 2006). Changes in forest are also poorly documented. For instance, measures of deforestation in tropical countries and rates of reforestation or afforestation in boreal and temperate countries are often unreliable (Waggoner 2009).

Remote sensing technology from the vantage point of instruments on satellites and aircraft is available to potentially provide the quality of data needed to improve estimates of forest carbon sequestration and to monitor forestry offsets, but the technology is not yet fully deployed. The institutional and economic barriers are large because forestry resources represent both private (nationally sovereign resources) and public (carbon sequestration) goods. Nations might pay for gathering and reporting such data if, for example, their forest carbon is a valued asset and has some marketability. Voluntary carbon initiatives include some requirements for a census of protocol-quality data for global forested area.[64]

Because forested area is only part of the allometric equation by which to estimate forest carbon storage, fusing or integrating data from different types of remote sensing instruments will overcome some limits. For example, Asner (2009) has led a recent effort to use medium resolution satellite imagery to map the areal extent of tropical forests and then use airborne LIDAR to map a sample of the region. LIDAR (Light Detection And Ranging) uses scattered light to find the distance to an object. LIDAR can penetrate the tree canopy and provide data on the topography of the underlying terrain with estimates at about 80 percent accuracy (Fagan and DeFries). Combining estimates of area and timber volume enable a closer approximation of forest carbon than area measures alone.

Remote sensing can serve additionally to help monitor how forests are being used and provide information

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[62] More technically, these processes represent stocks and fluxes (changes in stocks requiring measures of carbon gas uptake and release, including influences such as vegetation productivity, pest infestations and the extent and frequency of fires). Above ground carbon in trees represents, on average, less than half of the total carbon in forests (although this varies greatly among forests; see Fagan and DeFries 2009). Significant carbon pools exist in belowground biomass (roots), soil organic matter, dead wood (fallen trees), and litter (such as leaves and branches).

[63] Note that wood products produced from forest timber store carbon.

[64] Japan's Advanced Land Observing Satellite uses a related but different type of instrument, PALSAR, which is radar operating in the "p-band" of the electromagnetic spectrum. Research using PALSAR data suggest that it may be very promising for improved estimates of biomass. At present, however, Japan has limited the number of researchers who may access these data (Fagan and DeFries). The first map of global forest heights using one uniform method was completed in July 2010 by scientists using data from three satellites operated by the U.S. National Aeronautics and Space Administration. The scientists based the map on data collected during seven years.

for both monitoring the global carbon cycle and enforcing possible policy mechanisms (for example, if forestry offsets are included GHG management). Managing forests to store carbon, given the opportunity cost of forested land including agricultural production and timber supply, could lead to changes in land use elsewhere and in turn complicate modeling and design of effective climate policy. The effort to decrease deforestation or increase afforestation in one geographic area and the shifting of deforestation to another area is a concern that has come to be called leakage. Murray et al. (2004) estimate leakage at 10 to 90 percent for various activities within the U.S. and Sohngen and Brown (2004) examine leakage in an international context (see also discussion in Sohngen 2010). Some forest carbon management proposals allow discounting or rental of forest assets and transferability of the assets to account for the possibility of their impermanence (Pfaff et al. 2000, Kim et al 2008). For these reasons, there would also be the need to update periodically the observations of global changes in forests.

One of the largest challenges to deployment of technology to serve these measurement and observational purposes is the financing of investments in instruments, spacecraft, and aircraft. Discussion of climate policy design has tended to overlook investment requirements. The existing fleet of instruments and craft has largely been underwritten by the space programs of national governments, and national space programs serve a wide range of objectives (Macauley et al. 2009). Moving forward, the financing of measurement and monitoring optimized for forest carbon remains a question.

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INTERNATIONAL OFFSETS USAGE IN PROPOSED U.S. CLIMATE CHANGE LEGISLATION

Allen A. Fawcett[65]

Abstract

International offsets play a central role in the cost containment strategies of both the Clean Energy and Security Act of 2009 (H.R. 2454), proposed by Congressmen Waxman and Markey and passed by the U.S. House of Representatives in 2009, and the Clean Energy Jobs and American Power Act of 2009 (S. 1733) proposed by Senators Kerry and Boxer and reported out to the Senate Environmental and Public Works Committee in 2009. Both bills allow over one billion tons of international offsets to be purchased each year to demonstrate compliance in lieu of purchasing domestic emissions allowances. The effectiveness of international offsets at controlling the cost of a domestic cap-and-trade policy is dependent on the cost and availability of international offsets. This paper explores how EPA has modeled the international offset market in its analyses of H.R. 2454, and how various uncertainties about the international offset market impact costs estimates for H.R. 2454.

JEL Classification Numbers: C68, Q43, Q54, Q58
Keywords: Climate Change, Environmental Policy, CGE, Offsets

Introduction

The U.S. Environmental Protection Agency has produced several analyses of the American Clean Energy and Security Act of 2009, H.R. 2454 sponsored by Congressmen Waxman and Markey in the 111th Congress, and an assessment of the economic impacts of the Clean Energy Jobs and American Power Act of 2009, S. 1733 sponsored by Senators Kerry and Boxer in the 111th Congress. The analyses use two computable general equilibrium models (the Applied Dynamic Analysis of the Global Economy model, and the Intertemporal General Equilibrium Model), and focus on the impacts of H.R. 2454 on greenhouse gas emissions, national and regional macroeconomic indicators, specific sector characterizations, electricity generation technologies, trade implications, and markets for domestic offsets and international credits. The analyses have shown that the cost and availability of offsets, particularly international offsets, are one of the most important factors in determining the cost of a cap-and-trade policy. This paper describes how EPA has modeled the market for international offsets, and explores how sensitive allowance price estimates for H.R. 2454 are to various assumptions about international offsets.

The first section of this paper focuses on the legislative basis for offsets exploring the specific provisions that allow offsets in H.R. 2454 and S. 1733. This section focuses on how the offsets provisions differ between the two bills and the consequences of those differences.

The second section describes the data and models used by EPA to analyze the supply and demand of international GHG abatement in the context of EPA analyses of proposed climate legislation. The demand for international GHG abatement is characterized by the assumed international reference case GHG emissions, and the climate policies that are assumed to be adopted by other countries. This section also describes the international marginal abatement cost curves, including the data sources and adjustment processes used in their construction. Finally this section describes how the reduced-form Intertemporal General Equilibrium Model (IGEM) is used to integrate estimates of GHG abatement supply and demand to model the offsets market.

The third section of the paper presents EPA projections of international offsets usage under H.R. 2454. This section focuses on results from EPA's January 29, 2010 analysis of H.R. 2454 using the IGEM model. This section describes how non-binding limits on international offsets change how estimates of domestic allowance prices are interpreted under various sensitivities. The section then turns to sensitivities on the availability of international

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TABLE C.6 Summary of Key Offset Provisions

	H.R. 2454	S. 1733
Overall offset limits	2 billion tons[a]	2 billion tons
Source level offset limits	Does not aggregate to the overall limit	Aggregates to the overall limit
Domestic and international offset limits	International: 1 billion tons Domestic: 1 billion tons	International: 0.5 billion tons Domestic: 1.5 billion tons
Criteria for adjusting international offset limit	Domestic offset usage below 0.9 billion tons	Domestic offset usage below 0.9 billion tons
Revised international offset limit	1.5 billion tons	1.25 billion tons
Performance standards	Landfill and coal mine CH_4 covered by performance standards, reducing their ability to supply offsets.	Landfill and coal mine CH_4 are not covered by performance standards.

[a] Note that all references to tons in this paper refer to metric tons.

offsets under H.R. 2454. Finally, this section describes how post-2050 caps can be modeled by assuming a terminal bank of emission allowances must be held at the end of a model run in 2050.

The final section of this paper describes EPA modeling of the market for international GHG abatement that supplies international offsets to the United States. This section quantifies the sources of international GHG abatement supply by region and type, and describes demand for abatement by region. This section then examines the effects of alternative reference emissions projections and alternative cap levels for other countries. Finally this section explores how the availability of reduced emissions from deforestation and degradation (REDD) affect the international GHG abatement market.

International Offsets in Proposed U.S. Climate Legislation

H.R. 2454 and S. 1733 both establish offsets credits as an additional method for entities to comply with the requirement to hold an emissions allowance for each ton of greenhouse gas emissions (see Table C.6).[66] Instead of purchasing an emissions allowance for each ton of emissions, entities may also demonstrate compliance by purchasing an offset credit that represents reductions in greenhouse gas emissions (or increased sequestration of greenhouse gases) from a non-covered source (e.g., reduced emissions from landfill CH_4, increased CO_2 sequestration from changed agricultural tillage practices, or increased CO_2 sequestration from afforestation). The non-covered sources providing offset credits can either be domestic or international.

Both H.R. 2454 and S. 1733 limit annual offset usage to 2 billion tons, [67] and then specify how the overall offset limit should be calculated on a per covered source basis to generate source level limits on the use of offsets.[68] The formula for establishing the source level offset limit in H.R. 2454 does not add up to the overall 2 billion ton limit.[69] S. 1733 corrects this problem so the source level limit is now consistent with the overall 2 billion ton limit

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[66] This section is largely drawn from the author's work on the EPA's assessment of the economic impacts of S. 1733 (U.S. EPA, 2009c).

[67] H.R. 2454 sec. 722 (d)(1)(A) and S. 1733 sec. 722 (d)(1)(A).

[68] H.R. 2454 sec. 722 (d)(1)(B) and S. 1733 sec. 722 (d)(1)(B).

[69] H.R. 2454 Sec 722 (d) (1) (A) allows covered entities to satisfy a specified percentage of the number of allowances required to be held for compliance with offsets credits. H.R. 2454 Sec 722 (d) (1) (B) states that for each year, the specified percentage is calculated by dividing two billion by the sum of two billion and the annual tonnage limit for that year. For example, in 2012, when the cap level is 4.627 GtCO2e, the percentage would be 30.20%; and in 2050, when the cap level is 1.035 GtCO2e the percentage would be 65.90%. The number of allowances required to be held for compliance is equal to the amount of covered emissions, so for any given firm the amount of offsets they are allowed to use is equal to the product of their covered emissions and the percentage specified above. The total amount of offsets allowed is equal to the product of the total amount of covered emissions and the specified percentage. In order for this to be equal to the 2 billion ton limit on offsets specified above, total covered GHG emissions would have to be equal to the cap level plus 2 billion tons. There are several reasons

on offset usage.[70] For the purposes of economic analysis or modeling, this change is not likely to have any impact on allowance prices, as the limits on offset usage were not binding in EPA's analysis of H.R. 2454, and the revised limits in S. 1733 would also not be constraining.

In addition to the overall limits placed on the amount of offsets a covered entity can use, both H.R. 2454 and S. 1733 place limits on the amount of offsets that can come from either international or domestic sources. H.R. 2454 states that not more than one-half of offsets can come from domestic offset credits and not more than one-half can come from international offset credits. S. 1733 differs from H.R. 2454 in that not more than three-quarters of offsets can come from domestic offset credits and not more than one-quarter can come from international offset credits.[71]

After placing limits on domestic and international offset usage, both H.R. 2454 and S. 1733 state conditions under which those limits are modified. In both bills, if the estimated usage of domestic offsets is expected to be below 0.9 billion tons in any year, the limits on international offsets usage are modified. When this condition is met, H.R. 2454 allows additional international offset credits equal to the difference between 1 billion tons and the amount 1 billion tons exceeds the estimated domestic offset usage, up to an additional 0.5 billion tons of international offset credits. This has the potential to increase the limit on international offset credits in H.R. 2454 to 1.5 billion tons per year. In contrast, when this condition is met, S. 1733 allows additional international offset credits equal to the difference between 1.5 billion tons and the amount 1.5 billion tons exceeds the estimated domestic offset usage, up to an additional 0.75 billion tons of international offset credits. This can potentially increase the limit on international offset credits in S. 1733 to 1.25 billion tons per year, 0.25 billion tons less than in H.R. 2454.[72]

The 0.9 billion ton domestic offset trigger for allowing additional international offsets has the potential to create an unintended threshold effect, particularly in S. 1733. Consider the following hypothetical example, domestic offset usage in a particular year is 899 million tons, since this is below the 0.9 billion ton trigger, the limit on international offset usage under S. 1733 would be adjusted upwards 601 million tons (the difference between the 1.5 billion ton limit on domestic offsets and actual usage) from 0.5 billion tons to 1.101 billion tons. Now if domestic offset usage were to increase by one million tons from 899 to 900 million tons, then the limit on international offsets would fall by 601 million tons from 1.101 billion to 0.5 billion tons. In this situation a small change that would ordinarily lead to a small increase in allowance prices and small increases in offsets demand, has the potential to have a disproportionately large effect on allowance prices because of the discontinuous change in the international offsets limit. This issue also exists in H.R. 2454, but to a lesser degree as the 0.9 billion ton trigger for allowing extra international offsets is only 0.1 billion tons below the domestic offset limit, so the international offsets limit would only fall by 101 million tons in the analogous situation.

In EPA's analysis of H.R. 2454, estimated usage of domestic and international offsets are below the limits established in H.R. 2454, and below the limits established in S. 1733 in all scenarios that do not place constraints on technology. Thus the changed language on offsets limits will not impact the costs of the bill as estimated by EPA in scenarios that do not place limits on technology. However, in scenarios with limits on the availability of technologies such as nuclear, biomass, and CCS, the limits on international offset usage would be reached. In these scenarios, when the limit on domestic offsets is not met, H.R. 2454 adjusts the limit on international offset usage to allow approximately 1.5 $GtCO_2e$ per year, while S. 1733 adjusts the limit on international offset usage to allow 1.25 $GtCO_2e$ per year. The fewer international offsets allowed by S. 1733 compared to H.R. 2454 in these limited technology scenarios would require an extra 9.5 $GtCO_2e$ of abatement from covered sources cumulatively over the 2012 to 2050 time frame, and would result in higher allowance prices.

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why this is unlikely to be the case. First, even if covered emissions remain at reference levels, in the early years of the policy they will not be 2 billion tons over the cap level. Second, if firms bank allowances, their covered GHG emissions will be reduced, which will reduce the amount of offsets they are allowed to use. Third, in the later years when firms are drawing down their bank of allowances, it is possible for covered GHG emissions to be more than 2 billion tons above the cap, which means that the pro rata sharing formula can be in conflict with the overall 2 GtCO2e limit on offsets usage.

[70] S. 1733 sec. 722 (d)(1)(B) establishes the entity level limit on offsets as the product of 2 billion tons and that entity's share of covered emissions from the previous year.

[71] H.R. 2454 sec. 722 (d)(1)(B) and S. 1733 sec. 722 (d)(1)(B).

[72] H.R. 2454 sec. 722 (d)(1)(C) and S. 1733 sec. 722 (d)(1)(C).

International Offsets Modeling

In order to model international offsets, it is necessary to have information on both supply and demand for international greenhouse gas abatement. Since the United States is not acting unilaterally in any of our policy simulations, the price and availability of international offsets will be influenced by both the potential for GHG abatement, and the amount of GHG abatement demanded by other countries. This section discusses the reference projections of international greenhouse gas emissions and assumed international greenhouse gas policies, which together determine the international demand for greenhouse gas abatement. This section also covers the marginal abatement cost curves that represent the supply of greenhouse gas abatement available from various international sources at different carbon prices. Finally this section discusses how these projections of international GHG abatement supply and demand are integrated into the Intertemporal General Equilibrium Model (IGEM).

International Reference Emissions

The first part of projecting international demand for GHG abatement is projecting reference case GHG emissions internationally. Table C.7 describes the two broad country groupings used in this paper and in EPA modeling of H.R. 2454 and other legislative cap-and-trade proposals. Group 1 countries are those that are likely to adopt policies on climate change concurrently with the United States, and group 2 countries are those that are likely to delay their adoption of climate policies.

Figure C.18 depicts reference case GHG emissions for group 1 and group 2 countries as projected by the MiniCAM model. In this paper, and in EPA modeling of legislative cap-and-trade proposals, international reference emissions are based on the MiniCAM Climate Change Science Program Synthesis and Assessment Product 2.1a reference case (Clarke et al., 2007). As a sensitivity case, an alternate reference emissions projection is used based on the MiniCAM Energy Modeling Forum 22 (EMF 22) reference case emissions projection (Calvin et al., 2009).

While group 1 emissions are similar in the EMF and CCSP reference cases, group 2 emissions grow at a faster rate in the EMF reference case than under the CCSP reference case. The implication is that for equivalent cap levels, there will be greater demand for GHG abatement under the EMF reference case than under the CCSP reference case. The implications of this difference will be explored in a later section of this paper.

Assumed International GHG Policy—The G8 Agreement

With international reference emissions specified, the next step required to generate international demand for greenhouse gas abatement is to make an assumption about the climate policies adopted by other countries. The

TABLE C.7 Group 1 and 2 Countries

Group 1	Group 2
Canada	Former Soviet Union
Western Europe	Eastern Europe
Japan	China
Australia, New Zealand	Southeast Asia
	Korea
	India
	Middle East
	Africa
	Latin America

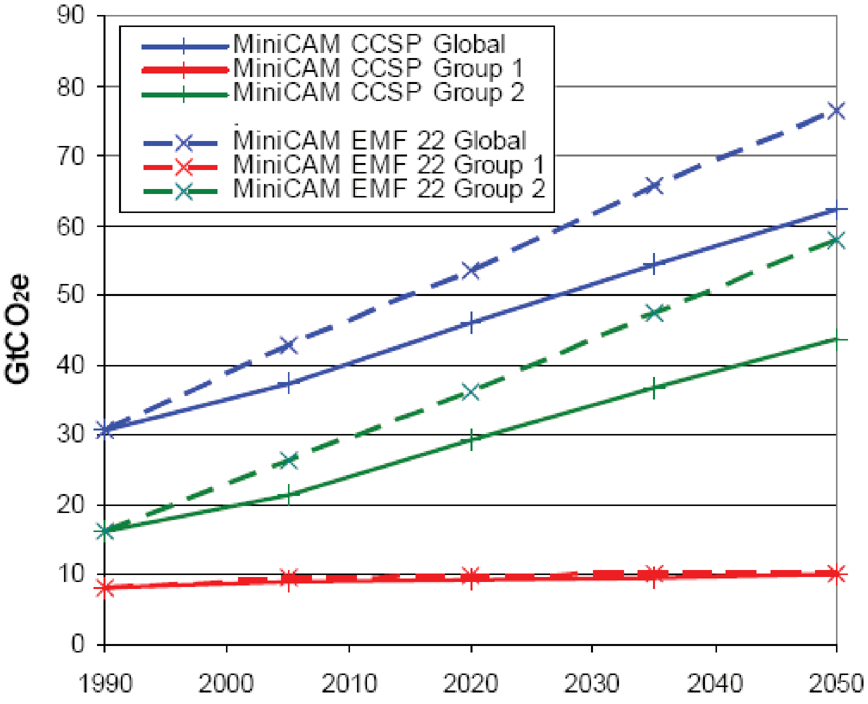

FIGURE C.18 International reference GHG emissions.

international policy assumed in EPA's January 29, 2010 supplemental analysis of H.R. 2454, and the policy assumed for this paper, is based on the July 9, 2009 Major Economies Forum, where "the G8 leaders agreed to reduce their emissions 80% or more by 2050 as its share of a global goal to lower emissions 50% by 2050." Specifically the international action assumed is as follows: group 1 countries follow an allowance path that is falling linearly from the reference emissions levels in 2012 to 83% below 2005 in 2050; group 2 countries adopt a policy beginning in 2025 that caps emissions at 2015 levels, and linearly reduces emissions to 26% below 2005 levels by 2050.

The combination of U.S., group 1, and group 2 actions cap 2050 emissions at 50% below 2005 levels. Figure C.19 depicts the cap levels consistent with the G8 agreement.

Marginal Abatement Cost Curves—Data Sources and Construction

A number of models are used by EPA to generate marginal abatement cost (MAC) curves for international offsets. The 2006 U.S. EPA report, "Global Mitigation of Non-CO_2 Greenhouse Gases," provides marginal abatement cost curves for the various sources of non-CO_2 abatement. The Global Timber Model (Sohngen and Mendelsohn, 2006) generates the marginal abatement cost curves for international forest carbon sequestration. And the GCAM model (formerly known as the MiniCAM model) generates the energy related CO_2 marginal abatement cost curves (Clarke et al., 2007). Table C.8 lists all of the mitigation categories along with model used to generate the data.

For each of these mitigation categories in Table C.8, marginal abatement cost curves are generated for two groups of countries: the first group, consisting of Annex I countries excluding the United States, is assumed to adopt market-based emissions policies immediately; and the second group, consisting of non-Annex I countries, is assumed to adopt market-based emissions policies in 2025 (see Table C.7 above).

An adjustment process is applied to the mitigation information from these models to represent the amount of abatement that would actually be available to the market either as an offset purchase or under a foreign market-

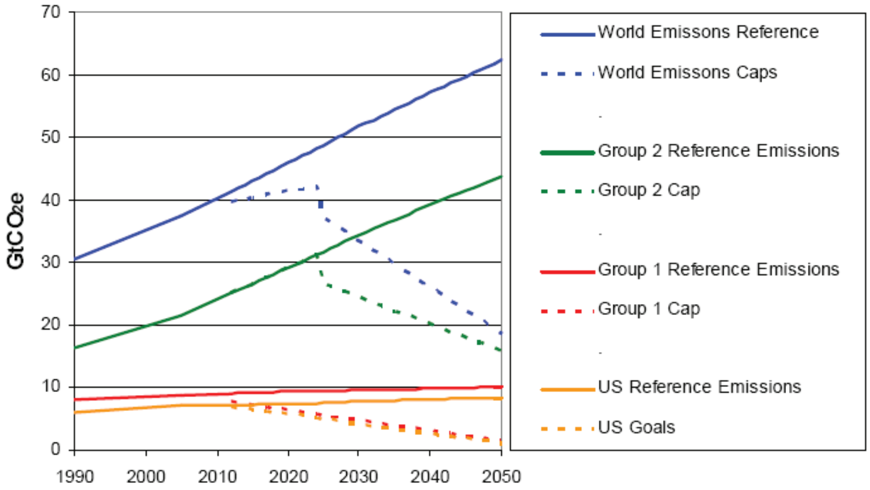

FIGURE C.19 G8 international assumptions.

TABLE C.8 Mitigation Categories and Data Sources for International MAC Curves

Mitigation Category	Data Source
CH_4 from landfills	U.S. EPA (2006)
CH_4 from coal mines	U.S. EPA (2006)
CH_4 from the natural gas sector	U.S. EPA (2006)
CH_4 from the oil sector	U.S. EPA (2006)
N_2O from adipic acid production	U.S. EPA (2006)
N_2O from nitric acid production	U.S. EPA (2006)
CH_4 and N_2O from livestock manure management	U.S. EPA (2006)
CH_4 from livestock enteric fermentation	U.S. EPA (2006)
CH_4, N_2O, and soil carbon from paddy rice	U.S. EPA (2006)
N_2O and soil carbon from cropland	U.S. EPA (2006)
F-Gases (11 source categories)	U.S. EPA (2006)
International forest carbon sequestration	Sohngen and Mendelsohn (2006)
International energy related CO_2	Clarke et al. (2007)

based emissions policy. For most of the above mitigation categories (excluding international energy-related CO_2, CH_4 from the natural gas sector, and CH_4 from the oil sector), each mitigation option within each mitigation category was evaluated and a determination was made if it should be eligible to provide abatement from a country with a market-based emissions policy, and if it should be eligible to provide abatement from a country without a market-based emissions policy.

A uniform adjustment was applied to all mitigation options within the CH_4 from the natural gas sector, and the CH_4 from the oil sector mitigation categories. For these mitigation categories, a 50 percent reduction was applied for international regions assumed to have a market-based emissions policy, and a 75 percent reduction was applied for the periods before a market-based emissions policy is assumed to be in place. For international energy related CO_2 emissions, no adjustments were made when a region is assumed to have market-based emissions policy in place. Before 2020, a 90 percent reduction is applied, and a 75 percent reduction is applied thereafter to

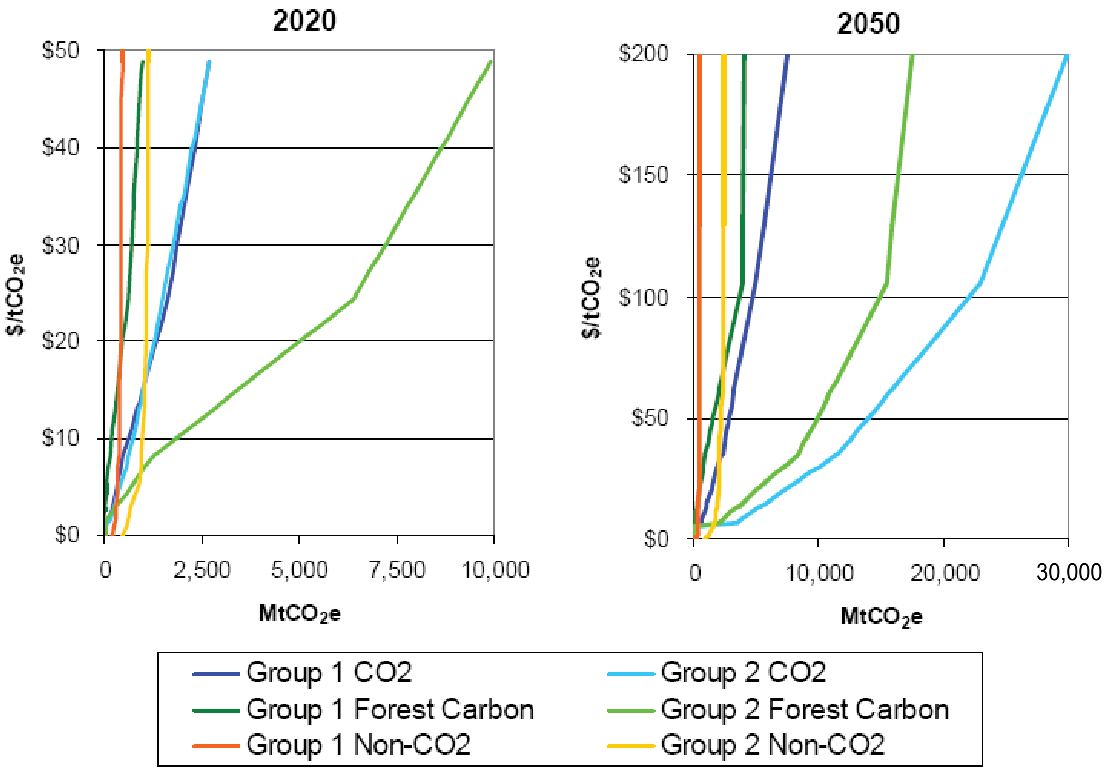

FIGURE C.20 2020 and 2050 marginal abatement cost curve comparisons.

the energy-related CO_2 abatement potential in countries that have not adopted market-based emissions policies. These adjustments were meant to take into account the difficulties in measuring, monitoring, and verifying offset reductions in countries without a market-based greenhouse gas emissions policy, as well as the lack of a clear market signal that the allowance price in the model run assumes (U.S. EPA, 2007).

Marginal Abatement Cost Curves—Characterization

It is useful to plot the various marginal abatement cost curves to see how different abatement sources compare to each other, how abatement sources evolve over time, and how they compare across the country groups. Figure C.20 depicts the energy-related CO_2, forest carbon sequestration, and the aggregate non-CO_2 MAC curves for group 1 and 2 countries in 2020 and 2050.[73]

At very low prices, below approximately \$5/tCO_2e, non-CO_2 abatement sources in group 1 and particularly in group 2 countries supply the majority of abatement. As prices increase, the non-CO_2 MAC curves become vertical, and forest carbon and energy-related CO_2 begin to dominate. In 2020, forest carbon sequestration in group 2 is the largest source of abatement at higer prices. The energy related CO_2 MAC curves for group 1 and 2 in 2020 are very similar, even though actual CO_2 emissions are much higher in group 2, due to the 75% reduction applied to the underlying energy-related CO_2 MAC curve for group 2 estimated by the MiniCAM model. In 2050, after all regions are assumed to have adopted market-based climate policies, energy-related CO_2 from group 2 is the largest source of abatement, closely followed by group 2 forest carbon sequestration.

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[73] Note, all prices for the marginal abatement cost curves in this paper are presented in 2000 year U.S. dollars.

The non-CO_2 MAC curves for group 1 and 2 in various years are presented in Figure C.21. The result of the adjustment process is evident in the group 2 curves. The 2015 and 2020 non-CO_2 MAC curves for group 2 contain considerably less abatement potential than the MAC curves for later years, due to the reduced number of mitigation options eligible to supply abatement before group 2 is assumed to have adopted a market-based climate policy. In general, the non-CO_2 MAC curves provide most of their abatement at relatively low carbon prices, and approach vertical at prices above approximately \$60/tCO_2e.

The forest carbon sequestration marginal abatement cost curves in Figure C.22 were generated by modeling a series of rising carbon price paths, as opposed to constant carbon price paths, in order to capture the important investment behavior associated with price expectations. In a dynamic model, the abatement potential available in 2050 at a carbon price of \$100/tCO_2e could be different depending on if the 2020 price were \$25/tCO_2e or \$100/tCO_2e. In all years, group 2 forest carbon sequestration abatement potential is considerably greater than the potential in group 1. In this set of MAC curves, reduced emissions from deforestation and degradation (REDD) are allowed from all regions in all years. In the policy experiments discussed below, the impact of not allowing REDD offsets is explored.

As with the forest carbon sequestration marginal abatement cost curves, the energy-related CO_2 marginal abatement cost curves depicted in Figure C.23 were generated using a series of rising carbon price model runs. The adjustment process that was evident in the group 2 non-CO_2 MAC curves is again evident in the group 2 energy-related CO_2 MAC curves. The full energy-related CO_2 abatement estimated by the MiniCAM model is reduced by 90% in the 2015 MAC curve and by 75% in the 2020 MAC curve. Starting with the 2030 MAC curve, the abatement potential is considerably larger for group 2 compared to group 1.

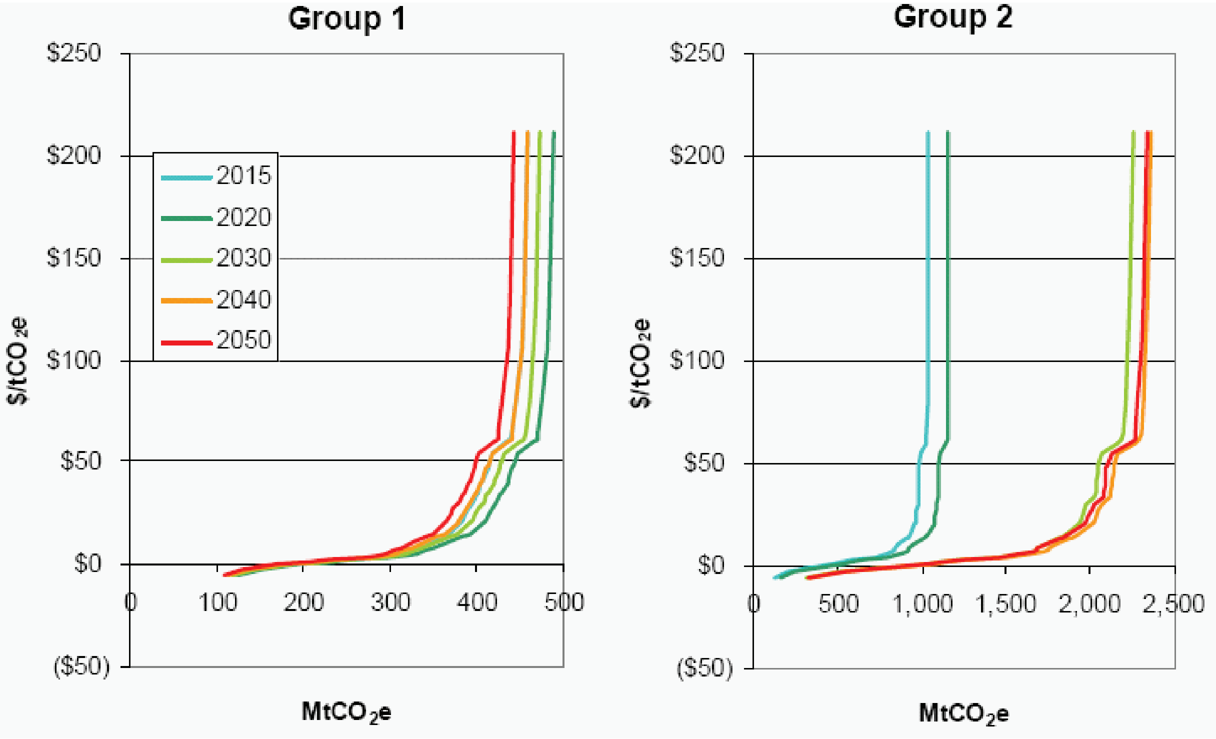

FIGURE C.21 Group 1 and group 2 non-CO_2 MACs.

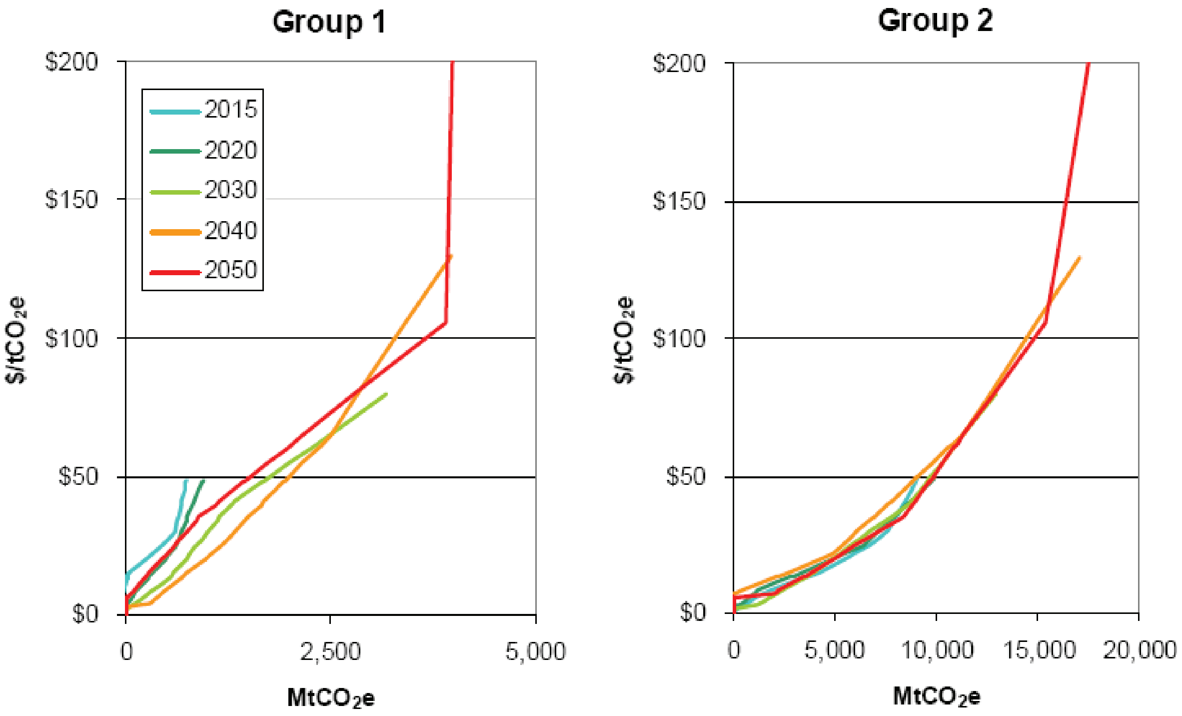

FIGURE C.22 Group 1 and group 2 forest carbon sequestration MACs.

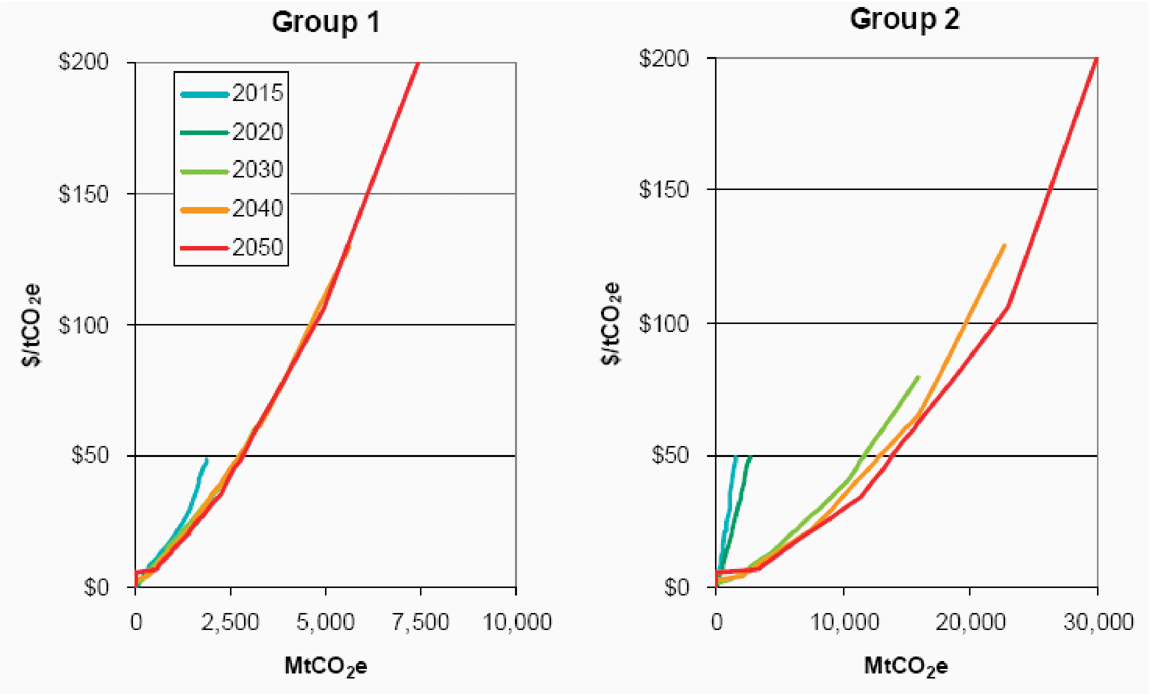

FIGURE C.23 Group 1 and group 2 energy-related CO_2 MACs.

Use of MAC Curves in IGEM

The reference international greenhouse gas emissions projections combined with the assumed climate policies for group 1 and group 2 countries generate the international demand for GHG abatement, but in order to fully represent the demand for international GHG abatement, we need an estimate of U.S. demand for international offsets. This is accomplished by using a reduced-form representation of the Intertemporal General Equilibrium Model (IGEM). IGEM is a dynamic computable general equilibrium (CGE) model of the growth and structure of the U.S. economy and has been used in a variety of efforts related to climate change and climate change policy (e.g., see Jorgenson et al., 2000, 2008, 2009; Goettle and Fawcett, 2009; U.S. EPA, 2009a; U.S. EPA, 2009b; and U.S. EPA, 2010). The reduced-form version of IGEM represents reference GHG emissions covered under H.R. 2454, the H.R. 2454 emissions caps, domestic offset marginal abatement cost curves, domestic covered non-CO_2 marginal abatement cost curves, a marginal abatement cost curve representing covered CO_2 abatement potential in IGEM, and a marginal abatement cost curve representing end-of-pipe abatement associated with carbon capture and sequestration from advanced coal-fired power plants.

The reduced form version of IGEM, representing the U.S. cap-and-trade system and the U.S. demand for international offsets, is combined with a simple spreadsheet model that includes the assumptions about international GHG abatement demand, as described above, and the international marginal abatement cost curves described above. This system can be solved iteratively to generate a U.S. allowance price, U.S. GHG emissions path, U.S. demand for international offsets, international carbon price (which may systematically differ from the U.S. allowance price if international offsets are subject to a turn-in-ratio as in H.R. 2454), and international supply of GHG abatement. The model assumes a constant growth rate for U.S. allowance prices and international carbon prices to represent the effect of banking. The U.S. allowance prices determined by the model can then be fed into the full version of IGEM in order to determine the full general equilibrium response to the policy.

Note that while this model uniquely determines the total amount of GHG abatement supplied by each source represented by the GHG marginal abatement cost curves, it is not possible to uniquely specify which country is purchasing the abatement. Therefore, the model does not determine the source of international offsets purchased by the United States. Additionally, while the amount of banking occurring globally is uniquely determined, the model does not specify where that banking takes place. For each region (group 1, group 2, and U.S. international offset purchases), the cumulative amount of abatement demanded over the entire time frame is solved for, and for each year the sum of abatement across the three regions is determined. The result is that multiple time paths of international offset purchases are consistent with the cumulative international offset usage determined by the model.

Projected U.S. Usage of International Offset Under H.R. 2454

Analyses of H.R. 2454 have universally shown that the availability of international offsets is one of the most important determinants of the cost of the policy (e.g. CBO, 2009; EIA, 2009; Paltsev et al., 2009; Ross et al., 2009; U.S. EPA, 2009; U.S. EPA, 2010). Some analyses handle offsets by exogenously setting the amount of offsets allowed in the model. For example the MIT analysis of H.R. 2454 using the EPPA model (Paltsev et al., 2009) presents three scenarios: no offsets; full offsets, allowing the full 2 billion tons of offsets each year; and medium offsets, which exogenously sets the path of offset usage to grow from zero in the first year to 2 billion tons by 2050. While this approach appropriately demonstrates the range of possible outcomes given the uncertainties about offset availability, it distorts how the model responds to other sensitivities that affect the cost of covered GHG abatement by not allowing corresponding changes in the offset market. This section of the paper examines the usage of international offsets under H.R. 2454 as analyzed in the EPA supplemental analysis of H.R. 2454 (U.S. EPA, 2010), how international offset usage varies in response to technology availability, and how different assumptions about international offset availability impacts the cost of H.R. 2454.

Non-Binding International Offsets Limits and Sensitivity Scenarios

The overall limits on offset usage in H.R. 2454 are set at two billion tons annually, or 78 billion tons cumulatively from 2012 through 2050, split evenly between domestic and international offsets. Because of the mechanism for sharing the offset limits among covered entities discussed in the "Legislation" section above, and the provisions for allowing extra international offsets when the domestic limits are non-binding, the actual limits are somewhat different. In the core IGEM scenario from EPA's supplemental analysis of H.R 2454, the limit on domestic offset usage ends up at 34.7 billion tons cumulatively from 2012 through 2050, and the cumulative limit on international offsets is 51.7 billion tons. These limits are non-binding in the core policy scenario.

Figure C.24 depicts reference and policy 2012–2050 cumulative covered U.S. GHG emissions, offset usage, and covered GHG abatement across five scenarios. The first scenario represents H.R. 2454 as modeled in scenario 8 of EPA's supplemental analysis of H.R. 2454. The next four scenarios vary the 2020 cap level from the 17% reduction specified in H.R. 2454 to either a 20% reduction as specified in the Kerry-Boxer bill (S. 1733), or a lower 14% reduction. These scenarios then either hold offset usage fixed to the level estimated in the first H.R. 2454 scenario, or endogenously determine offset usage.

In Figure C.24, the total height of each bar represents the 246 $GtCO_2e$ of cumulative 2012–2050 covered GHG emissions in the IGEM reference scenario. The bottom segment of each bar represents the cumulative number of GHG allowances that must be held by covered entities. This is equal to the cumulative cap, or the cumulative amount of covered GHG emissions after subtracting offset purchases. The next two segments of each

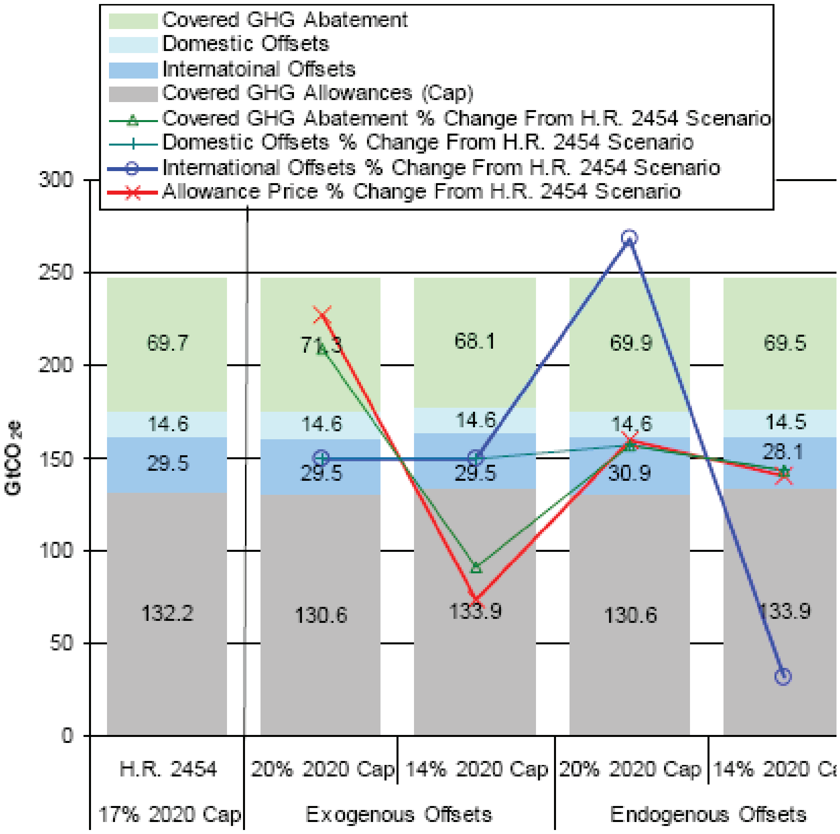

FIGURE C.24 IGEM 2012–2050 cumulative covered U.S. GHG emissions and abatement—cap level and exogenous offset sensitivities.

bar represent international and domestic offset purchases, which are well below the limits placed on offset usage in all scenarios. The sum of the bottom three segments of each bar is the cumulative covered GHG emissions in the policy case. This amount exceeds the cap because of the availability of offsets. The topmost segment of each bar represents the cumulative amount of GHG abatement from covered entities. Each of the lines represents a percentage change from the core H.R. 2454 scenario. The red line represents the percentage change in the allowance price, and the other lines represent percentage changes in the various sources of abatement compared to the core H.R. 2454 scenario.

Figure C.24 demonstrates that the impact that changes to the cap level have on allowance prices is dependent on how offsets are treated. Changing the 2020 cap level from a 17% reduction from 2005 levels to a 20% (or 14%) reduction represents a 1.2% (or –1.2%) change in the cumulative cap. If offset purchases are not allowed to change, then these changes to the cap will raise allowance prices by 3% (or –3%), as required covered sector GHG abatement is raised by 2.3% (or –2.3%). Alternatively, when offset usage is endogenously determined, then the marginal cost of abatement will equalize across covered sectors and domestic and international offsets. The result is that changing the 2020 cap to a 20% reduction (or 14%) results in a 0.4% (or –0.4%) increase in allowance prices, as international offset usage increases by 4.7% (or –4.7%), domestic offset usage increases by 0.3% (or –0.3%), and covered GHG abatement falls by 1.2% (or –1.2%).

The effect of endogenous offsets with non-binding offset limits shown here on cap level sensitivities also applies to any sensitivity that alters the marginal cost of abatement within covered sectors. For example, a technology sensitivity that limits the availability of nuclear and CCS will show a smaller impact on allowance prices if offsets are allowed to endogenously adjust to equalize the new marginal cost of covered sector abatement with the marginal cost of offsets abatement. Similarly, non-cap-and-trade policies such as a renewable portfolio standard or energy efficiency subsidies will change the marginal cost of abatement within covered sectors and show a smaller impact on allowance prices if offset usage is allowed to endogenously adjust.

Impacts of Limiting U.S. Purchases of International Offsets

As discussed in the section above, "Use of MAC Curves in IGEM," the model solves for the cumulative amount of international offset usage, but the exact time path of international offset usage is not uniquely determined. Previous EPA analyses of H.R. 2454 have generally assumed a relatively constant amount of international offset usage; however a path that gradually ramps up international offset usage over time, resulting in the same cumulative amount, is equally valid so long as the annual limits on international offset usage are not exceeded. Figure C.25 presents the results of several sensitivities that limit the ability of the United States to purchase international offsets. The limitation on international offsets is formulated as a delay in the date at which the United States is allowed to purchase international offsets, after which international offsets are allowed to be purchased up to the limit. The impact on the model is primarily due to the reduction in the cumulative international offsets allowed.

Not allowing international offset purchases for the first 10 years of the policy has a relatively modest impact, because international offset usage can be increased in subsequent years, and cumulative international offset usage only falls by 4%. Domestic offset usage increases by 2% and covered GHG abatement increases by 1% to make up for the decline in international offsets, and allowance prices increase by 4%.

A 20-year delay in international offset availability has a slightly greater impact, decreasing cumulative international offset usage by 12%. This increases domestic offset usage and covered GHG abatement by 4% each, raising allowance prices by 5%.

Delaying international offset availability 30 years to 2042 has much larger effects. Cumulative international offset usage falls 62%, forcing a 25% increase in domestic offsets and a 21% increase in covered GHG abatement. Allowance prices in this scenario increase by 31%.

Completely eliminating international offsets has the largest impact, as domestic offsets increase by 42% and covered GHG abatement increases by 33% to make up for the 29.5 billion tons of lost international offsets. Allowance prices must increase by 54% in order to induce this extra domestic GHG abatement. It is important to note that the impact of eliminating international offset on allowance prices is dependent on how many international offsets are used in the first place. In EPA's supplemental analysis of H.R. 2454, the Applied Dynamic Analysis of

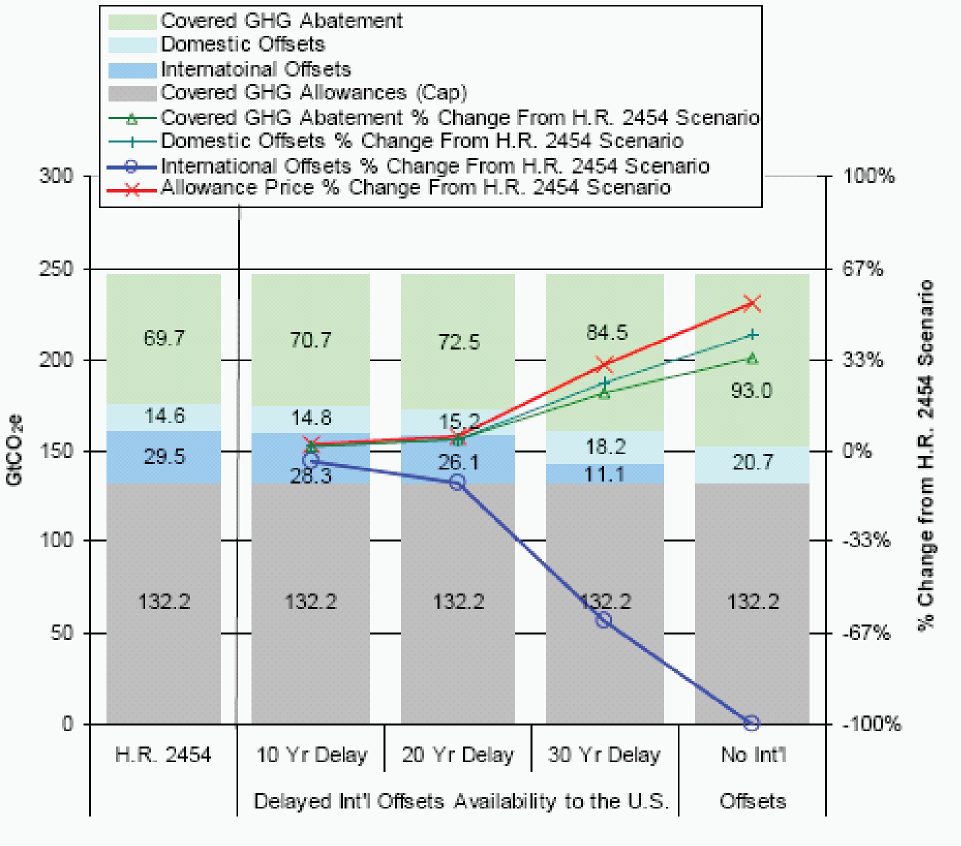

FIGURE C.25 IGEM 2012–2050 cumulative covered U.S. GHG emissions and abatement—international offset availability sensitivities.

the Global Economy (ADAGE) model estimated that eliminating international offsets would increase allowance prices by 148% instead of the 54% estimated by IGEM. This was in part due to the greater usage of international offsets in the core ADAGE H.R. 2454 policy scenario, which meant that covered GHG abatement had to increase by a greater amount in response to the removal of international offsets.

Banking and International Offsets

The previous section discussed how delaying the availability of international offsets affected other sources of GHG abatement and allowance prices. This section examines how international offset availability affects allowance banking. H.R. 2454 allows for unlimited banking of allowances. As a result the allowance prices in both models grow at the exogenously set 5% interest rate. In all modeled scenarios, a bank of allowances is built up in early years, and drawn down in later years so that the cumulative covered emissions (net of offsets) over the 2012–2050 period is equal to cumulative emissions allowed under the cap.

Before exploring how delayed international offset availability impacts banking, it is important to note again that the reduced form IGEM model used in this paper solves for the cumulative amount of international offsets required, but does not distinguish between alternative pathways of international offset usage that add up to that cumulative amount, so long as the annual limits are not exceeded. Figure C.26 depicts the cumulative GHG allowance bank from the primary IGEM scenario in EPA's supplemental analysis of H.R. 2454, which assumed international offset

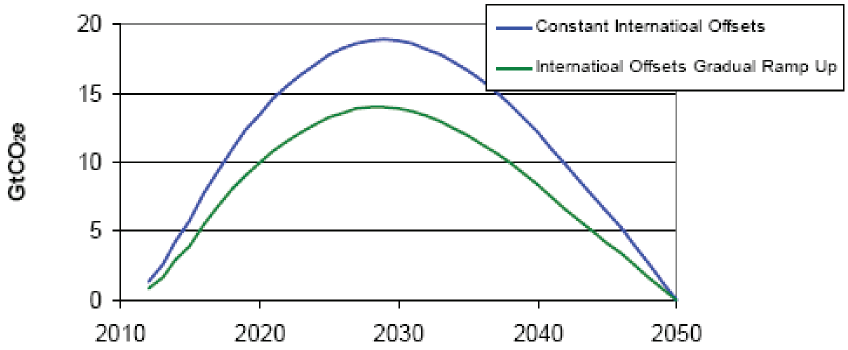

FIGURE C.26 Cumulative GHG allowance bank—constant versus gradually increasing international offsets.

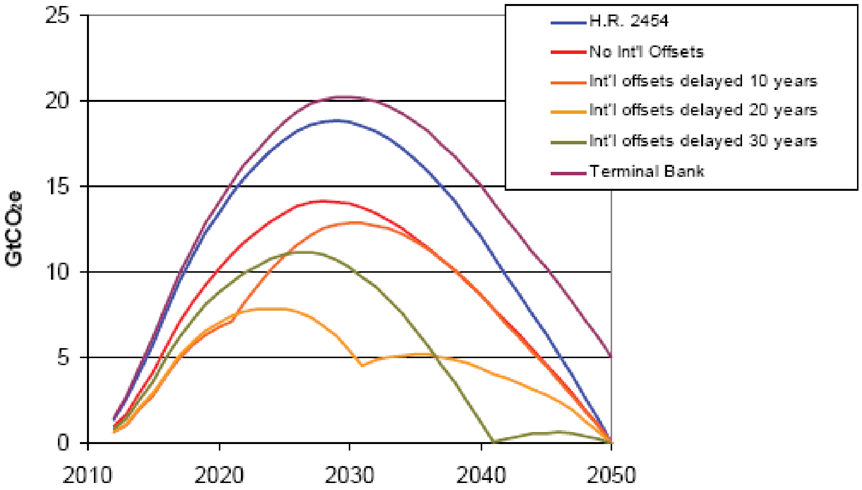

FIGURE C.27 Cumulative GHG allowance bank—international offsets delay and terminal bank.

usage was constant over time at 757 $MtCO_2e$ per year; and an alternative scenarios in which international offset usage increases linearly from 265 $MtCO_2e$ in 2012 to the limit of 1,273 $MtCO_2e$ in 2050. These two scenarios are identical in allowance prices, cumulative international offset usage, and abatement pathways for covered GHG's and domestic offsets. The only impact of changing the international offsets pathway is to change the amount of allowances that are banked. In the constant international offsets scenario, the extra international offsets available in the early years are submitted for compliance, freeing more allowances to be banked. If instead international offset usage ramped up gradually, then fewer allowances would be banked in the early years, and with a smaller bank to draw down in later years, more international offsets would be used for compliance.

The allowance banks in the scenarios delaying international offset availability are depicted in Figure C.27. All scenarios that limit international offsets reduce the amount of banking in early years. When international offsets are delayed, more allowances must be used for compliance in the early years, and international offset usage can increase in the later years to make up for not having a large bank to draw down. When international offsets are completely eliminated, the increased allowance price induces more abatement in the early years and a larger bank compared to the scenarios where international offset availability is simply delayed.

The last scenario represented in Figure C.27 is one that requires the model to hold a terminal bank of allowances in 2050. The allowance bank in the scenarios discussed to this point all go to zero in 2050. However, H.R. 2454 specifies a constant emissions cap past 2050. The banking behavior predicted by the models is dependent on the complete credibility of the caps. Firms bank allowances beginning in 2012 in anticipation of rising allowance prices that are driven in part by the out-year caps. If firms believe that Congress may revise the caps upward, then the incentive for banking is diminished, as an upwardly revised cap would reduce the value of banked allowances. However, if the post 2050 caps are credible, then a positive bank would still be held in 2050 at the end of the model run, and allowance prices would accordingly be higher than without a terminal bank.

As a proxy for constant post 2050 caps, domestically and internationally, we run a scenario in the reduced-form version of IGEM that requires a positive terminal bank in 2050. In order to determine the size of the terminal bank needed, we extrapolate U.S. and international policy case emissions past 2050, and calculate the cumulative amount by which the post-2050 cap is exceeded before emissions fall to the cap level. We then iteratively solve the reduced-form IGEM model to converge on a new allowance price path and required 2050 bank. This process results in the following terminal banks: in the United States the required 2050 bank is 5.1 $GtCO_2e$. The bank is exhausted and the post-2050 cap is met exactly by 2061; in the international market the required 2050 bank is 5.3 $GtCO_2e$. The bank is exhausted and the post 2050 cap is met exactly in 2055.

Requiring the U.S. and the international market to hold these banks in 2050 increases the allowance price by 2% over the IGEM allowance price estimated for H.R. 2454; and international offsets usage in the United States increases by 13%. After the bank is exhausted, the allowance price would be expected to grow at a rate less than 5% per year as the caps are met exactly in each year and there is no longer any incentive to bank allowances.

The Market for International GHG Abatement

While the previous section focused on U.S. usage of international offsets, and how the availability of international offsets impacts the cost of climate policy in the United States, this section explores the global market for GHG abatement. Specifically, this section examines how the international GHG abatement market is impacted by altering assumptions about reference emissions, policy, and abatement potential.

It is not possible to specify the mix of GHG abatement sources that supply international offsets to the United States; however, it is possible to specify the amount of abatement each source supplies to the global market for GHG abatement. Figure C.28 depicts supply and demand of international GHG abatement in the core policy scenario, as projected using the reduced-form IGEM model, assuming international reference emissions based on the CCSP (see Figure C.18), and assuming that the United States adopts H.R. 2454 and other countries adopt climate policies consistent with the G8 agreement (see Figure C.19).

Each bar in Figure C.28 is divided into segments representing the various sources of abatement characterized by the marginal abatement cost curves described above. The size of each segment represents the amount of abatement supplied by that source at the market-clearing price. The dots in Figure C.28 represent demand for GHG abatement calculated as the difference between reference emissions and the cap level.[74] The difference between the height of each bar and the height of the dot representing total world demand for GHG represents allowance banking.

Figure C.29 compares the market for international GHG abatement as depicted in Figure C.28 under the core policy scenario using the CCSP reference international GHG emissions, with a scenario that assumes identical policies, but uses the EMF reference international GHG emissions (see Figure C.18). Cumulative 2012–2050 group 1 GHG emissions are 4% higher, and cumulative group 2 GHG emissions are 28% higher in the EMF reference scenario compared to the CCSP reference scenario. The increase in cumulative global GHG emissions is 19%, and the resulting cumulative global demand for GHG abatement rises by 24%. The United States use of international offsets falls by 69% and the U.S. allowance price increases by 35% due to the greater demand for global GHG

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[74] Except for the U.S. international offset and set-aside demand, which represents the actual U.S. demand in that year as calculated by the reduced-form IGEM model. Note that this includes the full amount of GHG abatement purchased for use as an offset, which is 25% greater than international offset usage due to the four-to-five turn-in-ratio for international offsets in H.R. 2454; and this includes U.S. demand for forest sequestration associated with allowances set aside in H.R. 2454 to fund international forest sequestration activities outside of the international offset program.

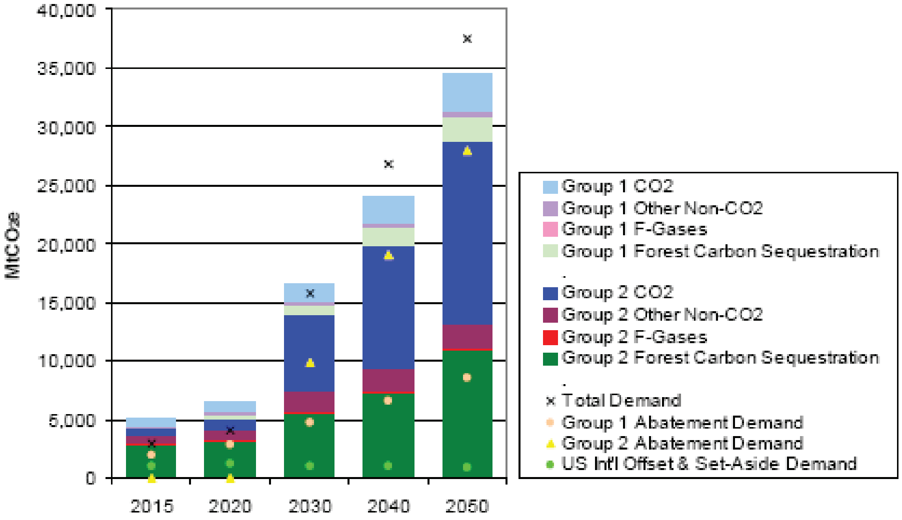

FIGURE C.28 International supply and demand of GHG abatement—core policy scenario.

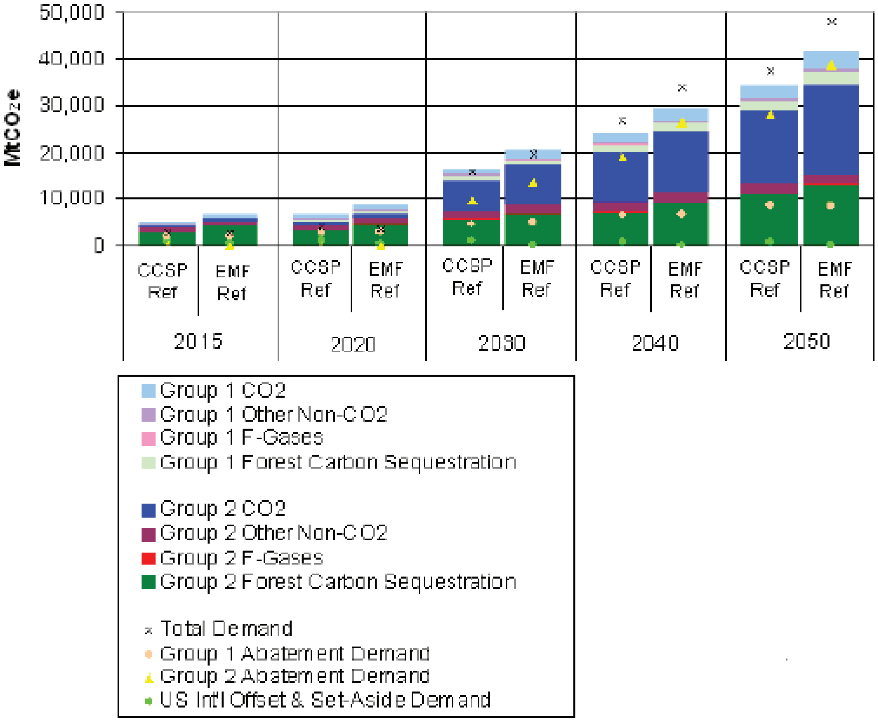

FIGURE C.29 International supply and demand of GHG abatement—the effect of alternative international reference emissions projections.

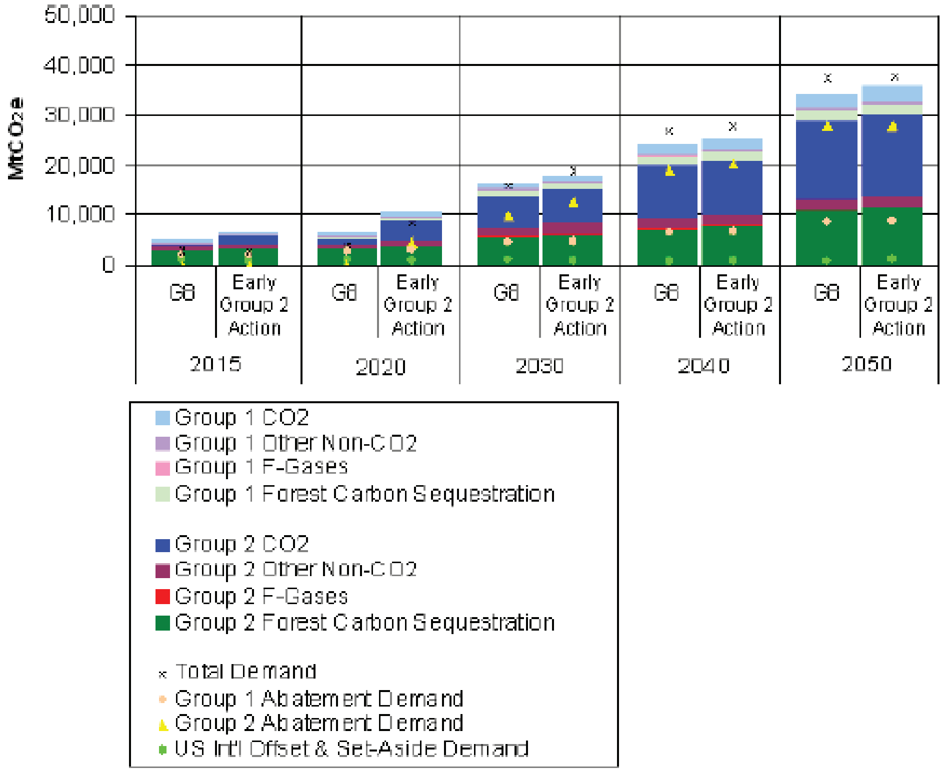

FIGURE C.30. International supply and demand of GHG abatement—the effects of alternative assumptions about international GHG caps—early group 2 action.

abatement (see Figure C.34 below).[75] With the higher price of carbon, all GHG abatement sources supply more abatement in this scenario.

As with the sensitivity above, the next sensitivity examines increased international demand for GHG abatement, but instead of varying the reference emissions, this sensitivity varies the assumed policy. Figure C.30 shows the result of assuming that group 2 countries adopt climate policy in 2020, setting cap levels equal to 2015 GHG emissions levels, and linearly reduce emissions to the same 2050 target as in the G8 international assumptions used in the core policy scenario.

The early group 2 adoption of climate policy decreases the cumulative emissions allowed under the group 2 cap by 8%, which increases global demand for GHG abatement by 9%. This increase in the demand for GHG abatement from group 2 countries results in an 8% increase in U.S. allowance prices, and a 16% reduction in cumulative U.S. use of international offsets (see Figure C.34 below). The supply of GHG abatement from all international sources increases slightly in response to the higher carbon prices.

The next sensitivity case again varies the assumed group 2 climate policy, this time assuming that group 2 does not cap GHG emissions before 2050 (see Figure C.31). Without group 2 caps on GHG emissions, the global demand for GHG abatement falls by 56%. This has profound effects on the international carbon market. First, without a market-based climate policy in group 2 countries, their marginal abatement cost curves are subject to a stricter adjustment process, as described in the section "Marginal Abatement Cost Curves—Data Sources and

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[75] Due to the four-to-five turn in ratio for international offsets in H.R. 2454, the U.S. allowance price is always 25% higher than the international carbon price when the limit on international offset usage is non-binding.

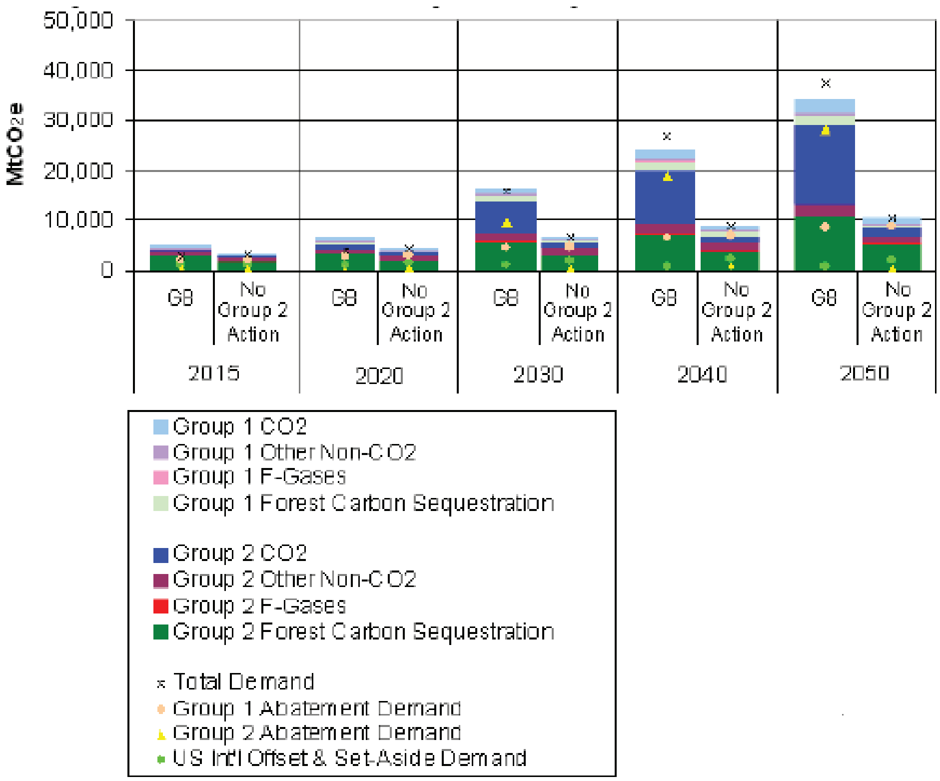

FIGURE C.31 International supply and demand of GHG abatement—the effects of alternative assumptions about international GHG caps—no group 2 action.

Construction" above. This inward shift of the GHG abatement supply curve is overwhelmed by the reduction in demand, and the price of carbon falls globally.

In the United States, the demand for international offsets increases by 73% up to their limit. The substantial increase in international offset usage reduces abatement required from covered GHG emissions by 26%, and results in a 32% fall in U.S. allowance prices (see Figure C.34 below).[76]

The changes in the assumed climate policies and reference GHG emissions levels in the previous sensitivities all examined changes to the demand for GHG abatement. The final sensitivity scenario in this section looks at a change to the supply of GHG abatement. Figure C.32 depicts the marginal abatement cost (MAC) curves generated by the Global Timber Model (GTM) for group 2 countries with and without reduced emissions from deforestation and degradation (REDD). The largest differences arise in the 2015 and 2020 MAC curves, which do not provide GHG abatement at any price when REDD is not available. In years after group 2 is assumed to have adopted climate policy, options such as afforestation and forest management begin to provide some forest carbon sequestration abatement in the MAC curves without REDD. At high prices in the later years (above \$80/tCO_2e in 2040, above \$65/tCO_2e in 2050), GTM indicates that more abatement is available when REDD is not allowed. This is the case because the afforestation that occurs in the early years at high prices in scenarios without REDD

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[76] Because the international offset limit is binding in this scenario, the marginal cost of abatement in the U.S. is no longer equalized (subject to the four-to-five turn in ratio) with the marginal cost of abatement on the international market. The price of carbon on the international market falls by a greater amount. Additionally, without group 2 as a demander of abatement, group 1 would borrow allowances in the early years instead of banking, if they were allowed. If borrowing is not allowed, as is assumed here, then GHG abatement supply will exactly equal demand in each year, and the price will grow at a rate slower than assumed 5% banking price path.

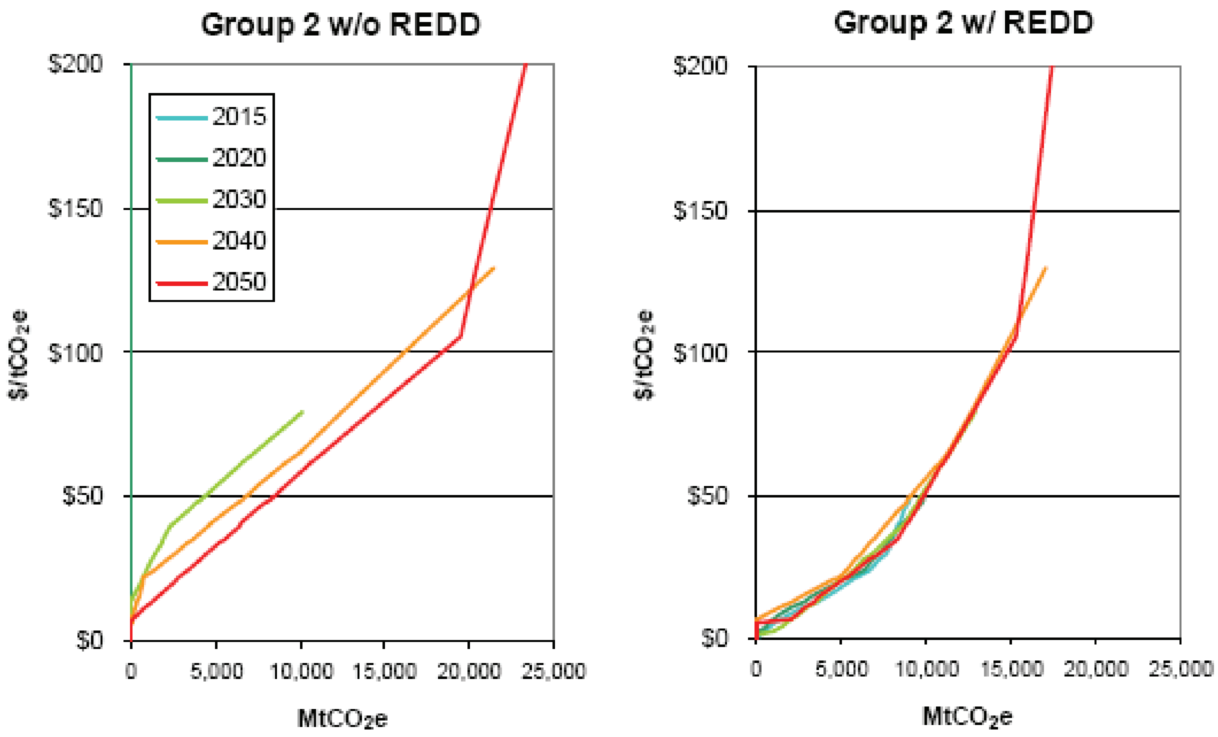

FIGURE C.32 Group 2 forest carbon sequestration MAC with and without REDD.

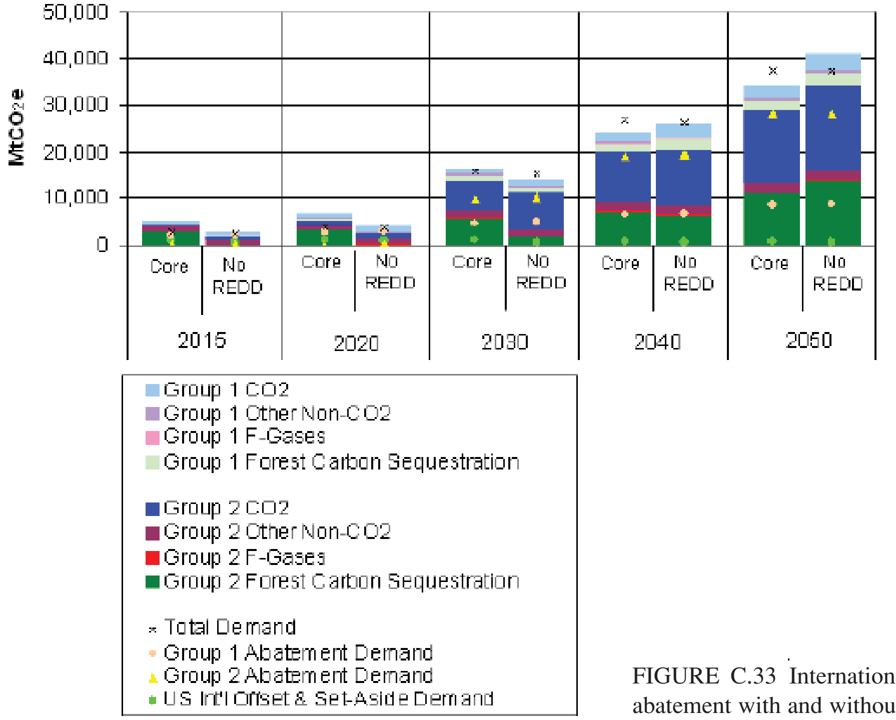

FIGURE C.33 International supply and demand of GHG abatement with and without REDD.

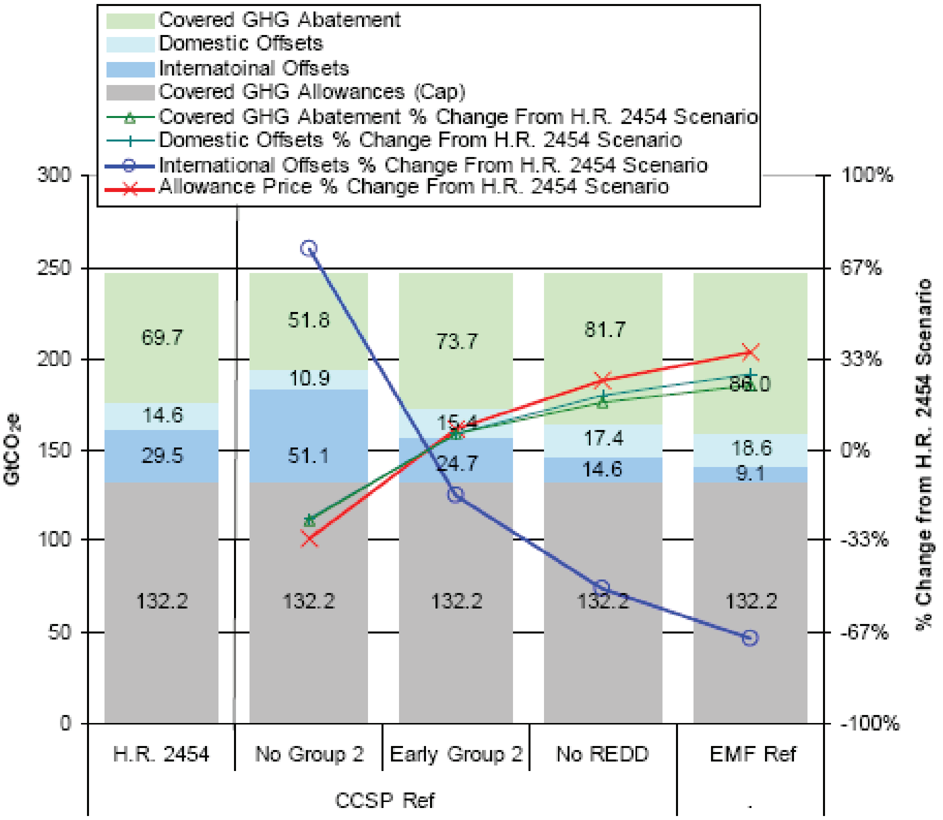

FIGURE C.34 The effects of alternative assumptions about the international GHG market on the United States.

as an option sequesters more carbon in the later years after those trees mature. In the scenario with REDD and all other options available, the net present value of the market and carbon offset returns are greater than the scenario without REDD, even if carbon sequestration is not greater in each year.

Figure C.33 shows the effect that removing REDD from the forest sequestration MAC curves has on the composition of international GHG abatement supply. Compared to the core policy scenario, in 2015 and 2020, total GHG abatement is sharply reduced as forest carbon sequestration from group 2, which had been the largest source of GHG abatement, no longer supplies any GHG abatement. By 2030, some forest carbon sequestration has returned in the scenario without REDD, and by 2040 and 2050, prices have risen to the point that forest carbon sequestration provides a similar amount of abatement in the scenarios with and without REDD. Within the United States, the allowance price increases by 25% in the scenario without REDD abatement, as shown in Figure C.34. In order to equalize the marginal cost of abatement across sources, cumulative international offset usage falls by 51%, domestic offset usage increases by 20%, and domestic covered GHG abatement increase by 17% when REDD abatement is not available.

Conclusion

International offsets are one of the most important cost containment features of both the House-passed American Clean Energy and Security Act of 2009 (H.R. 2454), and the Clean Energy Jobs and American Power Act of 2009 (S. 1733), which was passed out of the Senate Environment and Public Works Committee, as both of these bills potentially allow the use of over one billion tons of international offsets each year. Estimates of the cost and availability of international offsets are one of the most important factors determining estimates of the cost of these bills. This paper has described how international offset usage was modeled in EPA's analysis of H.R. 2454, and how assumptions about available sources of greenhouse gas abatement, reference case greenhouse gas emissions, and climate policies in other countries can have major impacts on the cost of the bill. This highlights the importance of future research to update and improve estimates of marginal abatement cost curves for international sources of greenhouse gas abatement; to revisit the difference in greenhouse gas abatement potential from countries with market-based climate policies versus abatement in the form of offsets or sectoral credits from countries without market-based climate policies; to continually update reference greenhouse gas emissions projections; and represent the broad range of climate policies that could be adopted in the future.

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THE POLITICS AND ECONOMICS OF INTERNATIONAL CARBON OFFSETS

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Offsets are the "sleeper" issue in climate policy. Most public attention concentrates on headlines such as the exact level of emission cuts promised in legislative proposals such as the 2009 Waxman-Markey bill (H.R. 2454) or the bill taking shape in the Senate. In reality, the rules that govern the use of offsets are likely to be much more important in determining the cost and efficacy of a U.S. climate policy. A wide array of studies suggest that offsets are the single largest factor in determining the overall cost of climate legislation such as the Waxman-Markey bill of 2009.[78] The studies presented at this conference point in similar directions. The analysis by Fawcett (2010) reinforces EPA's earlier results showing the important role for offsets in determining compliance costs. Using a different model, Blanford (2010) also shows the total compliance costs will be especially sensitive to offset rules, notably the rules that govern which types of offsets will be allowed into the market. Forestry is proving to be one of the largest wildcards in the supply of offsets. Sohngen (2010) shows that there are, in theory, large supplies of low-cost forestry offsets, but they are difficult to monitor and verify; high transaction costs and poor policy design could make it hard to utilize forestry offsets. Indeed, numerous studies have suggested that poorly designed offsets schemes could undercut the efficacy of emission limits while also creating perverse incentives that make it harder to engage developing countries in meaningful emission controls.[79]

Over the last 1-2 years the community of economic modelers that study climate change have begun to focus on offsets. Their studies are rightly looking at an array of important technical questions, such as quantifying supply curves for offsets, potential demand for offsets in different compliance markets, and transaction costs. This paper offers a complement: politics. I look at the origins of the world's largest carbon offset market: the Kyoto Protocol's Clean Development Mechanism (CDM).[80] Then I explain the political forces that have shaped the design and administration of the CDM. I concentrate on the question that looms over most offsets schemes: whether offset credits are truly "additional" in the emission reductions they supposedly represent. Finally I explore how offsets might influence the dynamics of carbon markets. In each part of the analysis I suggest some implications for the community of modelers that are looking at the economics of climate change, along with implications for the emerging U.S. strategy in this area.

Throughout this analysis, I will make four arguments. First, there is much to be learned from the CDM because its history reveals the political forces that will shape offsets in the real world. Too much of the debate over offsets has imagined ideal schemes that function perfectly; the CDM illustrates how politics and administration can yield outcomes that are radically different from the ideal vision.

The CDM finds its political origins in a "second best" policy strategy. Economically, the first best policy strategy would have seen developing countries adopt meaningful commitments to control their emissions; in the absence of that approach, the CDM offered a market-like mechanism for engaging developing countries. While most of the U.S. policy debate about offsets today is focused on offsets as a means of lowering compliance costs, the CDM experience is a reminder that perhaps the most important role for offsets is as part of a strategy for engaging developing countries. Engaging developing countries may require massive transfers of resources, and the only politically feasible way to mobilize and channel those resources is through mechanisms such as offsets that keep the full cost hidden and away from public budgets. Within such constraints, the CDM was an expedient choice. But it has created perverse incentives that are making it harder to engage credibly with developing countries

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[78] For example, without international offsets, the allowance price would be 89% higher than the base scenario in the EPA study (EPA, 2009). Studies by Paltsev et al (2009) and CBO (2009) point to similar conclusions.

[79] For example, Wara (2007); Schneider (2007); Wara and Victor (2008); Victor (2009).

[80] I use the term "carbon" as a shorthand for all the warming gases, including carbon dioxide (CO_2), that are typically considered under international offsets schemes. And I use the term "offsets" with a focus on international offsets, but most of the analysis here probably applies equally to domestic offsets.

because it pays those countries to avoid strict emission control policies. Future studies of the economics of climate change should look at offsets not just for their impact on compliance costs but also for their influence on strategic interaction between industrialized and developing countries. The analytical questions are not just whether offsets are "additional" but whether they produce positive (or even negative) leverage on the emissions from developing countries. Over the long term the largest leverage that the industrialized countries have on the global warming problem will come from their strategy to engage developing countries. Because of perverse incentives embedded in any offsets scheme, one element of that strategy must be a credible sunset for offsets.

Second, the design of CDM rules has been highly political, which is hardly surprising since it is mobilizing and allocating large amounts of capital and the other benefits that flow alongside investment. At present, the CDM pipeline is probably worth several tens of billions of dollars. By 2020, the Copenhagen Accord envisions that the CDM and other offsets markets might annually channel $100 billion to developing countries, which would exceed total current annual spending on official development assistance from all sources for all purposes. Politically organized interest groups have favored some technologies (e.g., small hydropower) while abhorring others (e.g., nuclear power). Those forces are evident in the current and prospective flow of CDM credits.

The most important effect of politics on the design of the CDM has been the strong political pressure to generate high volumes of offset credits at the expense of quality. Firms and governments in industrialized countries seek offset credits to assure that they will be able to comply with strict emission targets. Developing countries that host projects want to maximize the revenues that are linked to the flow of credits. By contrast, the interest groups that would press for higher quality and strict administration, which would lead to much lower and more uncertain flows of emission credits, are much less well organized and influential. A similar constellation of political forces is now mobilizing around U.S. policy on offsets. There are well-organized industrial forces that favor generous offsets rules. (Those forces are not wrong—indeed, if well administered, an unfettered offsets system would be a good policy.) But the crucial administrative questions have been left vague and are most deferred until the future. Interest groups that would favor strict administration are much less coherently organized. One remedy for these pressures is to set a credible safety valve on emission prices, which would remove the incentive for purchasers of offsets to seek high offset volumes as their only means of managing compliance costs.

Third, many of the troubles in the CDM arise because it was designed by committee with very little attention to political economy. A much more strategic approach to the design of offsets is feasible and badly needed.

In theory, most of the power in the creation of an offsets market originates with the largest purchasers of offset credits—today the EU and Japan (via the CDM) and eventually the United States, once a U.S. emissions policy is reliably in place. So far the EU and Japan have ceded much of their potential power to the Executive Board created under the Kyoto Protocol to manage the CDM. That Board is a cumbersome and largely ineffective system for administration. This is not news to the governments of the EU and Japan, but these countries have not pressed harder for such reforms nor created their own, better parallel system because they had no other alternative means of meeting the Kyoto targets.

The United States has the luxury of starting over. The United States should use its market power more wisely by setting rules for price offsets according to quality, creating a system of buyer liability, and adopting other rules that will create stronger private incentives to identify and reward (with higher prices and better delivery terms) high quality projects. As such, U.S. rules could create a competition for quality rather than a race to the bottom. This is a hypothesis that merits some modeling effort since it suggests that the United States could have inordinate leverage on the quality of worldwide efforts to engage developing countries through the rules it sets in its home market.

Fourth, the studies presented at this conference suggest that the offsets supply market will not be competitive. A few activities—forestry in Brazil and possibly Indonesia as well as the electric power sector in China—are likely to be the largest suppliers of offsets.[81] All are dominated by government-owned corporations or government

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[81] The actual supply of forestry credits will depend on the combination of available forestry projects as well as the systems for administering those projects. Brazil combines large potential supply of such projects with decent public administration and could be the dominant supplier in forestry. In energy-related offsets, see Blanford (2010) for a striking set of supply curves suggesting that perhaps half of the supply of offset credits from developing countries would come from the Chinese electric sector. See also Victor (2009) for an argument why most of the non-electric activities in developing countries are much more difficult to include in crediting schemes—because monitoring of emissions and government control over the electric sector is usually much more decisive than in most other segments of the economy.

administrative bodies. The market is ripe for collusion, especially if demand for offset credits is strong and inelastic. Large purchasers of emission credits, notably the United States, can strengthen their hand by setting rules that encourage a diversity of supplies as well as safety valves that avoid the need to negotiate for offsets supplies from a position of weakness. Contingent offers of access to the U.S. offsets market could also create more elasticity and make it easier to negotiate with offset oligopolies.

The Political Origins of International Offsets

At its core, international climate diplomacy suffers from a problem of incompatible incentives. Some countries, mainly in the industrialized world, are deeply worried about global warming and willing to spend their own resources (such as money, jobs, and political effort) to address the problem. Emissions from the enthusiastic nations are roughly flat; emissions from the more reluctant nations are growing like a weed. How can the enthusiastic nations convince the reluctant to change their behavior?

Such problems are not new to international environmental diplomacy, and historically they have been solved by using carrots to realign incentives. In the Montreal Protocol on the Ozone Layer, notably, a large (about $5 billion to date) multilateral fund pays developing countries the "agreed incremental cost" of controlling their emissions. That big fund thus transformed a problem of incompatible incentives into one of compensation. And where compensation didn't work the threat of coercion sat in the shadows. For developing countries that refused despite the generous offer, the Montreal Protocol threatened trade sanctions against ozone-depleting—a threat never carried out because the carrots were so effective.[82]

In global warming the stakes are a lot larger, and thus bigger carrots would be needed. That posed a huge problem for the diplomatic talks leading to the Kyoto Protocol; three solutions were explored. One solution would just pay the extra cost from a huge fund akin to the Montreal Protocol's Multilateral Fund. A second would set emission targets for all nations and leave "headroom" for developing nations to sell extra credits and earn cash.

These solutions were interesting to analysts but politically and practically impossible for real governments to adopt. A big government-to-government fund raised questions about whether governments really knew how to spend such resources, for cutting warming emissions was quite unlike the discrete technological projects involved in shifting away from ozone-depleting substances.[83] Moreover, the sums would be huge—perhaps on the scale of $10 billion to $100 billion per year—which made theorists of international justice happy but politicians wince.[84] Much of that money would have gone to China, and even in the boom times of the late 1990s finding tens of billions of public dollars for subsidizing economic competitors was an invitation to political suicide back at home.

The "headroom" idea was equally impractical since all the developing countries abhorred targets.[85] And even if that toxic political problem could have been overcome there remained the practical difficulty of setting headroom targets for developing countries. Developing countries were averse to the economic costs of honoring strict targets and thus they would demand caps far above their highest emission scenario—thus assuring that under any scenario they would not be harmed by the cap. The resulting negotiations would have been "negative sum"—for every new country added to the negotiation the share of emissions left for industrialized countries would shrink faster than

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[82] See Parson (2003) and Benedick (1998) for histories of the ozone talks and the crucial role (among other factors) of the ozone layer fund.

[83] The ozone fund was remarkably well administered, probably for two reasons. One is that administrative decisions were deferred to teams of experts (with modest political oversight), which would be hard to assure when much bigger amounts of money were at stake. The other is that projects were relatively easy to identify and technologies relatively easy to cost, and thus in practice it was not too onerous to agree on the meaning of "agreed incremental cost." See de Sombre and Kaufman (1996).

[84] It is hard to pin down exactly what scale of international transfer would be required, in part because that depends on the overall level of abatement. The scale of $10 billion annually is at the upper end of what was discussed in Kyoto and the $100 billion annual spend is written into the Copenhagen accord for the sum of public and private resource transfers by 2020.

[85] In 1998 Argentina suggested setting a voluntary target for itself, in part because it was hosting the Conference of the Parties that year and wanted the event to be a success. Its action was pilloried by all other developing countries for breaking ranks and violating the maxim that developing countries don't agree to targets. In the years since that maxim has thankfully eroded, but the wariness to setting binding targets—which is what would be required for a full blown emission trading scheme to operate—remains acute.

the benefit of having a new negotiating partner.[86] The Kyoto talks offered an instructive test of the negative sum theory. Russia was formally an industrialized nation and urged to accept a cap in Kyoto, but the nation was little worried about warming. The result was a cap identical to the highest emission scenario that Russian diplomats could imagine. Actual emissions from Russia, of course, were much lower, which gave the nation a huge surplus of "hot air" credits. If the Kyoto talks had had many more Russia's sitting around the table the negative sum bargaining would have produced even more hot air. The NGOs called this "tropical hot air," and they were right to oppose it. Analysts invented many clever schemes to solve the problem of tropical hot air, but none of them would work reliably in the real world and this strategy for engaging the reluctant developing countries would never work.

With those other two options dead, the CDM emerged as a third option. It was a way to achieve (in theory) the economic advantages of global emission trading while avoiding the toxic problem of setting emission targets for developing countries. It was a way to encourage those countries to join on a volunteer basis—project by project—while avoiding the need for large government-to-government funds.

The emergence of offsets in the U.S. policy debate has taken a very different track. It has originated through pressure from firms concerned about compliance costs and about the impact of U.S. regulations on economic competitiveness. Those are worthy concerns, but the U.S. debate has given strikingly little attention to how a large system of offsets will influence the willingness of developing countries to engage in mitigation of climate change. An offsets scheme such as the CDM isn't the only way to engage developing countries. I have suggested some alternative answers that are based on the model of accession to the WTO—where complex accession deals engage reluctant countries rather than just payments of cash or credits (Victor, 2009). Over the last two administrations the U.S. government has pursued an approach that relies on bilateral deals with key developing countries—such as the U.S.-India nuclear partnership or the various U.S.-China deals on clean energy that are taking shape. The relationship between such ventures and the U.S. offsets market has remained strikingly vague.

The conventional wisdom is that an offsets scheme will make it easier to engage developing countries because it will put more money on the table. The experience with the CDM suggests that exactly the opposite outcome may be unfolding. More money is available, but many of the offsets projects do not represent real reductions. Worse, the existence of an offsets scheme such as CDM creates perverse incentives. The problem in any such scheme is determination of the baseline against which offsets will be offered, and the experience with most offsets schemes—including the CDM—is that once the scheme is in place the baseline is endogenous. In gaming the baseline, host countries have strong incentives to avoid clear policies that would result in a lower emissions baseline.[87]

A full-blown solution to this problem is beyond the scope of this essay, but such a solution is likely to involve at least two elements. One is a credible sunset for offsets. With a sunset provision—written into national law in the United States and other large purchasing countries, which will make it more difficult to roll back and thus more credible—it will be easier to avoid endogenous baselines because developing countries will know that they face the need to reduce emissions at their own expense over the long haul. Some preliminary modeling work that I have done with Valentina Bosetti suggests, in fact, that in a world where such policy signals have high credibility the result will be large efforts of self-financed emission reductions by developing countries (Bosetti and Victor, 2009). In tandem with the sunset is the need for a sunrise on credible sticks—ultimately, trade sanctions. So far, most of the U.S. debate about trade sanctions has focused only on the sticks, which has made such proposals particularly unwelcome overseas. (The lack of a credible U.S. policy to control its own emissions has also played a role.) But it is hard to see how a full-blown system of emission controls that includes all major economies and makes a serious dent in total world emissions will function without a complementary system for enforcement.

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[86] The ways that negative sum logic would unfold and why this spelled doom for global emission trading are detailed in Victor (2001).

[87] There are ideas for solving such problems—such as negotiated baselines, standard international baselines, and such—but those approaches rarely work in practice because each host country's situation is so different. It is hard to avoid the need to tailor baselines to each country—or even individual projects or sectors within countries. And it is hard to avoid the problem that plagues most systems based on complex counterfactuals, which is that administrators rarely have enough accurate information to set the baseline.

Design of Offsets

In the ideal world, an offset scheme—like any performance-based instrument—should be designed to allow firms maximum flexibility to achieve the objective. A carbon offsets scheme should allow credit for any source of carbon reductions, leaving market participants to find the least costly way to meet that goal. The real political world is different. Markets channel resources that affect interests, and thus the design of offset rules is prone to become highly politicized.

The most glaring example of political control over design in the CDM is the exclusion of nuclear power. That decision reflects that the best organized advocates for climate policy in the late 1990s when the CDM was taking shape also generally abhorred nuclear power. The nuclear industry was concentrated on other policies, less well organized and faced the particularly debilitating problem that the EU (which had emerged as the largest market for CDM credits once it was clear the United States would not join the Kyoto protocol) had decided it would not purchase any CDM credits from nuclear power projects.

Such choices are hardly limited to nuclear power. Large hydro projects are all but banned from the CDM, although small hydro is a favored technology. Carbon capture and storage has struggled to gain approval even as renewable energy projects that are more costly, yield a lesser impact on emissions, and are probably not truly additional have readily earned CDM credits. From its formation, the CDM has been steeped in a particular vision of decarbonization based on small projects involving renewable energy and efficiency. Those projects are often the most costly way to decarbonize an energy system and they are particularly difficult to administer—a topic to which we turn in the next section. One sign that the political forces are wired in favor of such projects is the current effort to adopt special administrative rules to lower the administrative burdens for small projects and to allow "sectoral CDM" that would allow clusters of projects and policies to earn credits. None of these rules would be needed for crediting of large projects such as nuclear power, carbon storage, or efficiency upgrades at coal-fired power plants.

It is hardly surprising that a scheme generating rents will be steered to the advantage of politically powerful groups. Analysts lament this because a more pure policy would give every comer an equal opportunity to earn credit for emission reductions. But in the real world that won't happen—not just because some technologies have better organized interest groups but also because once the rents start flowing there are strong incentives for beneficiaries to remain well-organized and to block new types of emission projects from earning credit. My expectation is that the forestry community will soon learn this lesson. One of the few bright spots from the Copenhagen meeting was the adoption of the "REDD+" scheme. But if that scheme ultimately works by generating carbon credits that are fungible with emission credits earned under the CDM (so-called "CERs") then success of REDD + will mean failure for other rent-seeking technologies. We should expect that CDM incumbents will soon be raising questions about the integrity of REDD+ investments and lobbying for rules that will lower the credits available from such activities.

When creating new offsets systems, as in the United States, policy makers can fix these problems in two ways. First, they can create offsets schemes that allow all viable technologies to compete from the outset, which will reduce (but not eliminate) the flow of rents to hallowed projects and raise the odds that the offsets scheme will work like a real market. This seems like an obvious point, but it was a difficult point to apply when creating the CDM. U.S. policy makers should expect similar difficulties when they create a U.S. offsets scheme. U.S. policy makers should not underestimate the power of political interests that will try to control the rents that will flood into an attempt to torque the administration of an offsets system.

Second, policy makers should not assume that offsets work best through monopoly. The Kyoto vision was for a single offsets market—the CDM—in part because that would yield the largest and most credible market. That choice has concentrated political fervor on the CDM and made it harder for the system to evolve because it faces no legitimate competition. A series of parallel markets could be better because that would allow for more experimentation and learning. Obviously some common floor standards would be needed to avoid the plague of Gresham's Law. This kind of thinking has been abhorred in the diplomatic talks on global warming because the UN system does not welcome competition and because firms rightly fear the chaos of multiple standards. At this stage, however, a multiplicity of offsets schemes would be much more useful than a single system that is prone to gridlock. The United States has an opportunity, when it creates its own offsets scheme, to put this insight to work.

For economic modelers, one implication is the need to look at scenarios where only certain technologies are eligible for offsets and where transaction costs vary with technology type. Looking beyond the exclusion of nuclear power in the CDM, the exclusion of certain options will play a large role in the use of CDM credits for advanced coal projects. Studies such as Blanford (2010) show the huge potential for reducing emissions from the power sector—notably through improved efficiency in the coal fleet. So far, however, no coal efficiency upgrades have ever gained CDM approval; some of the CDM's most ardent supporters are also in the midst of a global campaign against coal. Despite compelling economics, the politics of awarding emission credits to coal upgrades (and the administrative challenge of determining which efficiency upgrades are truly additional) suggest that the CDM and other offsets schemes will find it difficult to include whole swaths of coal-related projects. As the economic modeling community looks at possible designs for a U.S. offsets scheme it should look more closely at political economy scenarios that exclude coal, nuclear and other such projects. My guess is that the economics of offsets are a lot less attractive in those worlds, and that would be an important message to the designers of U.S. offsets systems.

Administration and Additionality

By far the biggest debates around offsets have concerned the question of additionality. Do offsets projects represent "genuine" reductions or are they just a shell game? I have worked on this question for a long time and am convinced that there are some offsets projects that are genuine but that the market is awash in bogus credits.[88] This is not simply a matter of fraud but is probably unavoidable once a decision has been made to deploy offsets as a policy instrument. Policy makers select offsets as a policy instrument when they are unable to regulate all pollution sources because such regulation would be politically or administratively impractical.[89] In this second-best setting, the task for administrators is never easy. They must obtain information about the hypothetical "true" investment patterns in the offset host and compare that counterfactual with actual investments. Offset credit is awarded for the difference. Analysts have known long ago—such as by studying the offset schemes under the 1977 Amendments to the Clean Air Act—that such schemes often sink under the weight and uncertainty of their administrative burdens.[90]

The administration of the CDM program has faced a nearly unsolvable problem: the counterfactual. Administrators—which in the case of the CDM is a function divided between a central administrator (the CDM Executive Board) and supposedly independent verification agencies—must gather information that is essentially unobtainable. The counterfactual can't be measured, and for many projects it is nearly impossible even to estimate the counterfactual credibly.

One standard approach for solving this problem is to calculate the financial return on a project in the absence of CDM credits and then compare that with the value of the credits. Other approaches have been tried as well—such as assigning standard baselines, which is attractive in theory yet nearly impossible to implement in the real world—but for most of the investments that are relevant to global warming it is hard to avoid an approach that relies on some form of financial counterfactual. And that approach suffers two fundamental flaws.

First, an offsets system creates strong incentives for host governments to keep irrational policies in place. Put differently, a financial counterfactual makes policies in the host country endogenous to the CDM. If a host country behaves strategically it will pretend not to adopt policies that might otherwise make sense—for example, adopting incentives like local pollution mandates that encourage firms to switch away from high carbon fuels that also cause local pollution—because with offsets there is a large financial advantage to keeping old policies in place. When administrators of the offsets scheme don't have perfect information on unobservable local prefer-

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[88] Wara and Victor (2008). Michael Wara and I are hardly the only people to work on this question. For others see, notably, Schneider (2007).

[89] I will discuss this decision as a "second best" outcome, but there are some circumstances when case-by-case opt-in approaches are more efficient than attempting to include all emission sources. So far, international global warming diplomacy has not been dominated by those situations. Instead, the political forces for avoiding developing country caps have been the main factor at work.

[90] Hahn and Hester (1989).

ences then the host country can get paid for the switch. Consider China, which has been particularly strategic in its policy behavior and not surprisingly is the largest world supplier of CDM offset credits. Late last year the CDM Executive Board rejected 10 Chinese wind projects (after a string of similar projects had earned approval) in part on the logic that Chinese wind policy had become endogenous to the CDM.[91] Some see the crackdown on these projects as evidence that the CDM administration can identify situations where local policy has become overly endogenous. If that were true then we should be encouraged that better administration is feasible such that only genuine projects are rewarded. In reality, the cats and the mice are both learning. The CDM Executive Board is in no better position today to identify such troubles than it was when it opened its doors for business. Over the long term local hosts will always have the advantage because policy endogeneity is nearly impossible to detect, and in countries where local policy is shrouded in opacity—which is often true when state enterprises with soft budget constraints play a large role in investment decisions, as is true in most developing country energy systems—it is particularly difficult for outsiders to determine the counterfactual.

Second, financial additionality encourages investors and host countries to conspire in an effort to find investments that look as irrational as possible. In many settings irrationality is just a fiction, for policies are endogenous. But often the real outcome includes a tinge (or more) of irrationality, which means that projects that earn support under the CDM do not scale or sustain themselves. Rather that offering a nudge down a different, lower-carbon development trajectory the CDM instead creates a dependency relationship that is hard to shake.

These fundamental flaws suggest that any offsets system will include large numbers of bogus permits. My guess is that somewhere between one-third to two-thirds of the CDM pipeline fails the additionality test, although I must underscore that nobody knows the answer to this question and no amount of research probably will produce a robust answer since counterfactuals are impossible to observe.[92] Put differently, linking a cap and trade system to a poorly administered offsets scheme is the carbon equivalent of Gresham's law. It lets the players in the offsets market print money. Another implication is that the presence of an offsets scheme will create deeply perverse incentives for host countries and investors.

Such troubles might be reduced with better administration, but what is striking in the U.S. policy debate is how little attention has been given to exactly how to administer a large offsets system (as envisioned in essentially all draft legislation working through Congress). This fact reflects that there isn't much of a political constituency for strict administration. Firms that are worried about compliance with a national cap and trade system comprise an understandably strong constituency for generous offsets rules. Their keen interest in offsets might be dampened if, for example, a U.S. trading scheme included a price cap, which would dampen fears that compliance will be onerous and reduce the need to rely on international offsets as a cost control mechanism. (I favor such a price cap—for that reason and because a price-like instrument is a better way to slow global warming.)

One of the puzzles in the CDM debate is why environmental groups have not been better organized to press for stricter administration. On this I can only speculate. One reason is that the gains from better administration are diffuse and abstract, and the cost of mobilizing to press for better administration are probably high. Moreover, a poorly administered CDM has channeled benefits to favored technologies—notably renewables and energy efficiency. Now that new industrial gas projects are coming to an end the next largest source of CDM credits is from renewable power projects.

For U.S. policy makers this logic suggests that administration of an offsets scheme should be a bigger part of the policy debate. At present, all the main legislative proposals would vaguely delegate these functions to administrative agencies, notably the EPA. Yet many of the administrative problems, such as the problem of baselines, are essentially unsolvable. Delegating them won't fix that. I am particularly worried about two things. One is the inevitable fact that large numbers of bogus permits will be emerge and that will reduce confidence in the system. A second is the fact that EPA will be performing delegated functions—such as negotiating baselines—with near-monopoly suppliers, such as the Chinese electric sector.

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[91] Morse and He, 2010, "Making Carbon Offsets Work in the Developing World: Lessons from the Chinese Wind Controversy," Program on Energy and Sustainable Development, Working Paper #90.

[92] A big part of the answer depends on the accounting for industrial gas projects, which are an oddball feature of the CDM that I will address in the next section.

There is no magical strategy for solving these problems. One starting point is clearer statutory guidance to EPA—including the power to adjust the size of the U.S. market that is linked to offsets, which would diminish the leverage of potential monopoly suppliers. Another, as mentioned above, is an explicit price cap so there are fewer pressures on the offsets scheme to provide a de facto price cap. The experience with the EU, where there is no meaningful price cap, suggests that international offsets, in practice, are an unreliable price cap because the exact timing of the crediting mechanism has been hard to predict; there is some evidence that the CDM may actually make prices more volatile.

So far, my impression is that we have not had a serious debate about how an offsets scheme would be administered. Draft legislation working through Congress sees a large role for offsets and defers administrative questions until later and imagines that they can be solved. The few ideas for improving the quality of offsets, such as negotiated baselines, are unlikely to work. For example, one idea is to cap the quantity of offsets allowed inside the U.S. market. That approach, in theory, would limit exposure to poorly conceived offsets policy. In reality, it almost guarantees that the worst quality offsets will be used.[93]

For modelers I suggest efforts on three fronts. First, more work is needed to look at compliance costs and efficacy when offsets schemes yield large numbers of bogus permits. Second, more work is needed to model transaction costs. I have already suggested that transaction costs probably vary by project type; other formulations, rooted in political economy, could be useful to explore as well. The transaction costs for first-of-a-kind projects are dramatically higher than successors, for example, and it might be useful to explore whether that is a strong deterrent to investors for certain types of projects. Overall, transaction costs could have high absolute values and in the early stages of international offset trading could be a large fraction of the total cost of securing offset credits. Third, there would be utility in looking at the bogus factor and transaction costs in tandem, for there may be a relationship akin to the Laffer curve that could be a useful guide for policy. With no administration and with highly aggressive administration the supply of genuine offsets is probably zero. In between is an interesting space that is prone to optimization, with the optimal choices depending probably on the prevailing value of credits.

Market Dynamics

In the middle 1990s as nations were crafting what became the Kyoto Protocol the prevailing view was that a global system of emission trading would be desirable. A single market with a single price would prevail. I have never subscribed to that view because I never understood why all countries would adopt policies that produced the same marginal effort (price). Moreover, the political and financial consequences of allowing carbon markets to equilibrate would be unmanageable. I also doubted that countries keen to spend large resources controlling emissions would tolerate unfettered links to countries whose willingness to pay was zero or negative. How would countries that had costly and well administered regulatory systems in place respond when a country with lax regulations flooded the global market? How would countries that adopted hybrid policies—for example, emission trading schemes connected to direct regulation or to price caps—integrate their national trading systems with nations that had different kinds of hybrids? As governments got serious about controlling emissions there was no reason to think that every nation would adopt the same national regulatory approach. Yet a global emission trading market would require a large degree of commonality as well as exceptionally high confidence that all players were honoring the rules. One hiccup and the whole system could quickly crash.[94]

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[93] Under the CDM nearly the entire pipeline for several years was filled with projects to reduce emissions from industrial gases. Such projects generated massive quantities of credits at very low cost and with dubious additionality—especially since the prospect of credits encouraged investors in industrial gas facilities to avoid using the latest technology so they could get paid with credits. More complex projects that would have represented more genuine additional efforts were squeezed from the market because they could not compete with the industrial projects that had tiny investment and transaction costs. Capping the use of offsets doesn't fix administrative problems.

[94] My skepticism was outlined in some detail in Victor (2001) and Victor et al. (2005). The former explained why global trading would never work as envisioned and the latter predicted the emergence of bottom-up fragmented trading systems due to the huge variation in national willingness to spend resources on climate change and ability to administer what is, in effect, a new form of money. Anyone who needed more evidence that common currencies only work when there is a massive alignment of interests and administration need look no further than the travails of the European Monetary Union and now the European common currency.

The imagined ideal world of the Kyoto Protocol has not happened for more or less those reasons. Instead, the real world has evolved to produce highly fragmented carbon markets. Different rules govern different markets, and international trading is evolving very slowly and "bottom up." That real world is a lot less efficient economically, but it exists because political and administrative decision-making rests mainly at the national level and nations differ wildly in their interests and capabilities.

The fact of fragmented markets has important implications for international offsets because these credits could, in effect, become the trading hubs that integrate different national markets.[95] For policy makers this point suggests that offsets policy could become a central element of international strategy. At present, most of the discussion around international strategy focuses on diplomacy. But diplomacy, especially global diplomacy in the wake of the debacle at Copenhagen, is over-rated. Much more influential are facts on the ground, the draw of market forces, and real patterns of finance and investment. For the United States this creates a tremendous opportunity. If a U.S. offsets program sets the standard for quality then, through arbitrage, it can also set prices and quality for the global market. And if the United States avoids one of the central errors in the UN system—which has been to regulate offsets as a gatekeeper rather than creating price-based signals about offset quality—then it can also generate market forces that will use prices as a way to signal quality.[96] In effect, the United States can unilaterally use its market power to set rules that will spread more widely. That would have the benefit of encouraging international offsets to "trade up" towards higher quality rather than "race to the bottom." And it would put efforts to engage developing countries with payments—which was the original goal in crafting the CDM—on a footing that links those payments to real actions.

For analysts, this line of thinking suggests two clusters of work that will be needed. One is to start modeling how offsets affect price formation in global carbon markets. That offsets would become pricing hubs is a likely outcome but hardly assured, and the capacity to model this would help guide U.S. policy on offsets. For example, policy makers might ask us how large an offsets pool is needed and what kinds of pricing rules would allow the United States to encourage a flight to quality driven by the U.S. market rules. These will be hard questions of immediate practical importance that can't be answered without simulation. Carbon legislation in the United States that included offsets might include explicit instructions to administrators to perform such analyses so that the huge U.S. market is used as part of an explicit international strategy to encourage higher quality international regulation through offsets worldwide.

A second area for analytical efforts concerns hybrid national regulations. For too long we have analyzed policies that are convenient for models—such as global emission taxes or simple globally-integrated emission trading schemes—rather than policies that are convenient for politicians. Yet political convenience usually dominates in policy market. So far, the conventional wisdom is that political convenience favors emission trading. But upon close inspection the real outcome is likely to be what I have called "Potemkin trading," which is emission trading that looks like your economics textbook on the surface yet behind the façade isn't anything like a pure market. It is trading coupled to direct regulation, in part because many interest groups favor regulation as a way to diffuse and hide costs while channeling benefits to well-organized groups. Much of the regulation around renewable energy and energy efficiency in the United States takes this form, for example. Even in the EU, which has the world's largest emission trading system, much of the real leverage on industrial emissions has come from regulatory standards rather than price incentives. And more than half of European emissions are excluded from the trading scheme in favor of direct regulation. As more countries look to auctioning emission credits even the presumption that emis-

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[95] There is a small but growing literature on this important question—variously called "docking," "linkages" and "hubs." See for example, Wagner et al (2009) and Jaffe and Stavins (2008).

[96] I do not have space here to delve into the details on the errors of CDM administration, but the central point is that a rule of seller liability prevails. Thus once a methodology for generating CDM credits is approved then risk plummets. The result is that project brokers spend most of their efforts on gaining approval, which is what I am calling here the "gatekeeper" approach to administration, and *ex post* there is very little attention to project quality except in verifying that the project actually proceeds as approved in the methodology. And once credits are issued (which requires another gatekeeper step) buyers are essentially not liable for project performance. The enthusiasm for seller liability reflects a view, widely held especially as the CDM was taking shape, that buyers would avoid the market if they faced buyer risks. That view, I am suggesting here, is completely wrongheaded because it is buyers who have most of the power in the relationship and thus they need to face a price incentive to favor quality. Of course, there are risks to buyers and some of them are related to quality—for example, delivery risk—but the CDM administration has generally not aligned those risks and pricing mechanisms in a coherent manner.

sion trading is politically favored will come under scrutiny as more firms look to taxes (or tax-regulation hybrids) because they offer easier ways to control regulatory exposure and channel rents.[97]

Modelers probably should build the ability to analyze these real world policy outcomes—at least in a stylized fashion—because they suggest that emission caps and prices may not always be the binding constraint. When other constraints are more binding—for example, a strict renewable power standard coupled with emission trading in the power sector—then emission markets will generate scarcity and surplus that bears no relationship to the underlying costs of abatement. If those markets are coupled internationally then the coupling mechanisms between markets—that is, international offsets—could come under severe stress. It may be useful to anticipate that stress so that governments that want to preserve high quality efforts to regulate emissions have a sense of when and how to intervene.

Conclusions

For too long we have looked at international offsets as a technical matter. This essay suggests that they lie at the center of global warming politics. Moreover, the political forces, although complicated, are amenable to some simple analysis and prediction. Those predictions can help policy makers design better international offsets markets, and demand for those designs may be acute in the next few years as the United States devises its greenhouse gas regulatory program. They can also help analysts develop models and scenarios that allow scrutiny of politically realistic outcomes.

The largest international offsets market, the CDM, has not worked well. Yet it survives and has proven difficult to reform because the CDM rests on two political choices. One was the need to engage developing countries with a scheme that generates reliable income flows. The other was the need to dampen fears in the countries and firms that undertake the most aggressive regulatory efforts at home that costs will not spiral out of control. The political pressures that inspired the CDM also help explain the resistance to reform. There are powerful and well-organized constituencies that thrive on the rents that flow from the CDM. The constituency that would have been most likely to press for a better administered system has also found reform inconvenient because the CDM channels resources to a particular cluster of technologies and excludes technologies, such as nuclear power, that these groups abhor.

The U.S. international offsets rules are still virgin territory, but it is hard to believe that they will not come under similar pressures. Some careful analytical work on those political pressures and attention to mitigating them will be essential lest the U.S. scheme follow the similar, tortured path of the CDM.

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[97] For more on Potemkin markets see Victor (2009b).

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DEVELOPING NARRATIVES FOR NEXT-GENERATION SCENARIOS FOR CLIMATE CHANGE RESEARCH AND ASSESSMENT[98]

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The implications of anthropogenic climate change for the environment and society depend not only on the response of the Earth system to changes in atmospheric composition and land cover, but also on human responses. These responses are often classified into “adaptation”—changes in activities, infrastructure, or systems tailored to new climate conditions—and “mitigation”—actions to reduce net greenhouse gas emissions. Increasingly, analysts and researchers are examining adaptation and mitigation together, as both will involve changes in technology, economies, lifestyles, and policy that will interact in important ways geographically and sectorally. All of these processes—across socioeconomic, environmental, and climatic domains—are subject to extensive uncertainties.

Scenarios are used by researchers and other analysts to evaluate how human choices about mitigation and adaption to future climate change will fare under uncertain future socioeconomic and climate conditions. Scenarios used in climate research and analysis cover a wide range of topics including human activities and systems, emissions of greenhouse gases and other pollutants, land use change, future climate conditions, environmental factors such as sea level rise and air/water quality, and attributes of society that influence vulnerability and resilience to climate change.

This paper provides a brief overview of a new “parallel process” for developing and applying scenarios for climate change research and assessment. This parallel process was developed through a series of meetings and research papers from 2006-2010 and is described in the report of an expert meeting of the Intergovernmental Panel on Climate Change (IPCC) and a research article.[100, 101] The new process is still evolving but is already improving research on interactions between climate change and human choices about responses. It begins with a broad range of potential future radiative forcing—a measure of human impact on the climate system—not with detailed socioeconomic narratives or projections, as in the past. The new process is intended to provide greater flexibility in analysis of socioeconomic dimensions of mitigation and adaptation, specifically to encourage exploration of alternative socioeconomic futures that could give rise to different levels of climate change.

The paper briefly reviews the new process and points to resources for additional information on the current status of a range of related modeling activities. It focuses on challenges in developing socioeconomic scenarios for exploring future mitigation of net emissions and the interactions of mitigation with adaptation to changing climate conditions. The paper highlights a research need to develop narratives of potential institutional, demographic, eco-

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[98] Prepared for “Modeling the Economics of Greenhouse Gas Mitigation,” National Research Council, the National Academies, Washington, DC, April 15-16, 2010. Comments by workshop participants are gratefully acknowledged.

[99] This paper is based on a presentation given at a workshop on “Modeling the Economics of Greenhouse Gas Mitigation,” National Research Council, the National Academies, Washington, DC, April 15-16, 2010. It draws on an article that appeared in the February 11, 2010 issue of *Nature* on the next generation of scenarios for climate change research and assessment, as well as on results from a meeting on socioeconomic scenarios convened jointly by the Climate Research Committee and the Committee on the Human Dimensions of Global Environmental Change of the National Research Council on February 4-5, 2010. I am indebted to the co-authors of the *Nature* article and the presenters and participants in the joint workshop on socioeconomic scenarios. Comments by workshop participants are gratefully acknowledged. Information release: PNNL-SA-75225.

[100] Moss, R.H., Mustafa Babiker, Sander Brinkman, Eduardo Calvo, Tim Carter, Jae Edmonds, Ismail Elgizouli, Seita Emori, Lin Erda, Kathy Hibbard, Roger Jones, Mikiko Kainuma, Jessica Kelleher, Jean Francois Lamarque, Martin Manning, Ben Matthews, Jerry Meehl, Leo Meyer, John Mitchell, Nebojsa Nakicenovic, Brian O’Neill, Ramon Pichs, Keywan Riahi, Steven Rose, Paul Runci, Ron Stouffer, Detlef van Vuuren, John Weyant, Tom Wilbanks, Jean Pascal van Ypersele, and Monika Zurek. *Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies*. IPCC Expert Meeting Report, 19-21 September, 2007, Noordwijkerhout, The Netherlands. Intergovernmental Panel on Climate Change, Geneva, Switzerland (2008).

[101] Moss, R.H. Jae A. Edmonds, Kathy Hibbard, Martin Manning, Steven K. Rose, Detlef P. van Vuuren, Timothy R. Carter, Seita Emori, Mikiko Kainuma, Tom Kram, Gerald Meehl, John Mitchell, Nebojsa Nakicenovic, Keywan Riahi, Steven J. Smith, Ronald J. Stouffer, Allison Thomson, John Weyant, and Tom Wilbanks. “The Next Generation of Climate Scenarios.” *Nature* 463, 11 February 2010 doi:10.1038/nature08823.

nomic, cultural, and other factors that are essential for understanding the potential to reduce emissions and adapt to changed climate conditions. These factors are currently underrepresented in integrated assessment models of emissions and consequences of climate change and mitigation policies.

Scenarios

Scenarios are tools for analyzing situations in which outcomes are uncertain. The goal of working with scenarios is not to predict the future but to better understand uncertainties in order to reach decisions that are robust under a wide range of possible futures. Space constraints do not allow a full review of scenario development, but such reviews exist in the literature.[102]

In climate change research, scenarios describe plausible trajectories of different aspects of the future that are constructed to investigate the potential consequences of anthropogenic climate change. Over time, an increasingly broad array of scenarios has been developed to address different components of the issue. Scenarios currently represent major driving forces, processes, impacts, and potential responses important for informing climate change policy. See Box C.1 for a detailed description of types of scenarios used in climate change research.

A variety of techniques have been used in developing scenarios. For *climate* scenarios, these approaches include analogues of anticipated future conditions (both temporal and spatial), and model-based scenarios produced with general circulation models (GCMs—both global and regional) “forced” with scenarios of emissions.[103] *Emissions* scenarios are developed primarily using integrated assessment models (IAMs), which are comprehensive representations of quantifiable socioeconomic (e.g., demographic, economic, and technological) and environmental (e.g., land use) drivers of emissions and, increasingly, impacts. [104] A variety of *environmental* scenarios (e.g., sea level rise, hydrology, land cover, air quality) are produced with specialized hydrological, agricultural, ecological, and other models that incorporate both human and environmental processes—these, along with climate scenarios and socioeconomic assumptions are commonly used in evaluating potential consequences of climate change for a variety of human and natural systems. [105] Quantitative approaches to scenarios do not adequately account for political, cultural, and institutional influences that are important in understanding innovation, technological change, and the ability of societies to effectively implement policies. These factors are most often represented in qualitative *narratives* or *storylines*, which are used by analysts in a variety of ways to coordinate scenarios across scales or subject matters.[106, 107]

Many different groups have used scenarios at different spatial scales. At a global scale, the IPCC has used emissions and climate scenarios as a central component of its work of assessing climate change research. The IPCC has commissioned several sets of emissions scenarios for use in its reports, convening authors and modelers, providing terms of reference, and approving the scenarios through an intergovernmental process that took several

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[102] Parson, E.A. et al. Global Change Scenarios: Their Development and Use (Sub-report 2.1B of Synthesis and Assessment Product 2.1, U.S. Climate Change Science Program and the Subcommittee on Global Change Research, Department of Energy, Office of Biological and Environmental Research, Washington DC (2007).

[103] Mearns, L.O. *et al*. Climate Scenario Development. In *Climate Change 2001: The Physical Science Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change,* eds J.T. Houghton, Y. Ding, and D.J. Griggs. Cambridge University Press, Cambridge, UK. 739-768 (2001).

[104] For an excellent review of emissions scenario methods and literature, see Nakicenovic, N., et al. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change (Cambridge Univ. Press, 2000).

[105] For an overview of the use of different types of scenarios in assessment of impacts, adaptation, and vulnerability, see Carter, T.R. *et al*. Developing and Applying Scenarios. In *Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change* Eds J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, and K.S. White. Cambridge University Press, Cambridge, UK. 145-190 (2001).

[106] National Research Council. *Describing Socioeconomic Futures for Climate Change Research and Assessment: Report of a Workshop*. Panel on Socio-Economic Scenarios for Climate Change Research and Assessment, Committee on the Human Dimensions of Global Change, Division of Behavioral and Social Science and Education. Washington, DC: The National Academies Press (2010).

[107] Arnell, N.W. *et al*. Climate and socio-economic scenarios for global-scale climate change impacts assessments: Characterising the SRES storylines. Global Environmental Change 14, 3-20 (2004).

BOX C.1 Types of Scenarios in Climate Research and Assessment

Emissions Scenarios

Emissions scenarios describe future releases to the atmosphere of greenhouse gases, aerosols, and other pollutants and, along with information on land use and land cover, provide inputs to climate models. They are based on assumptions about driving forces such as patterns of economic and population growth, technology development, and other factors. In addition to their use as inputs to climate models, emissions scenarios are used in research on mitigation to explore the economic, environmental, and climatic implications of alternative energy and technology futures. For example, numerous studies evaluate the changes in technologies, economic development, policy, or other factors that would be required to shift emissions from a baseline to a lower path, for example keeping greenhouse gas concentrations (or global average surface air temperature increases) below a specified level (see, for example, Clarke, L. et al. *Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations*). They do not track "short-term" fluctuations such as business cycles or oil market price volatility but instead focus on long-term (e.g., decades to centuries) trends.

Climate Scenarios

Climate scenarios are plausible representations of future climate conditions (temperature, precipitation, and other climatological phenomena). They can be produced using a variety of approaches including: incremental techniques where particular climatic (or related) elements are increased by plausible amounts; spatial and temporal analogues in which recorded climate regimes that may resemble the future climate are used as example future conditions; other techniques such as extrapolation and expert judgment; and techniques that use a variety of physical climate and earth system models including regional climate models. There is a notable increase in interest in regional-scale climate scenarios and scenarios of climate extremes and surprises, which are especially for impact and adaptation assessment.

Environmental Scenarios

These scenarios focus on changes in environmental conditions other than climate that may occur regardless of climate change. Such factors include water availability and quality at basin levels (including human uses), sea level rise incorporating geological and climate factors, characteristics of land cover and use, and local atmospheric and other conditions affecting air quality. The potential impact of climate change and effectiveness of adaptation options cannot be examined without understanding these interactions.

Vulnerability Scenarios

Scenarios of demographic, economic, policy, cultural, and institutional characteristics are needed for different types of impact modeling and research. This information is crucial for evaluating the potential to be affected by changes in climate, as well for examining how different types of economic growth and social change affect vulnerability and the capacity to adapt to potential impacts. Many of the same socioeconomic factors that affect emissions also affect vulnerability and adaptive capacity of different societies, and thus the underlying socioeconomic modeling must be coordinated.

Narratives

While some socioeconomic factors affecting emissions and vulnerability are modeled quantitatively, political, institutional, cultural and other qualitative factors are not effectively incorporated into quantitative model-based scenarios. For this reason, qualitative narratives (also referred to in the literature as "storylines") are developed to describe developments in these factors and how they could influence future forcing and responses. Narratives can be used as the foundation for quantitative scenarios, describing the general logic and developments underlying a particular quantitative set of scenarios. For example, the IPCC SRES scenarios were based on a set of four narratives that described a range of different development pathways for the world. Narratives can also facilitate coordination across spatial scales and substantive domains.

years.[108, 109, 110] The World Energy Council and the International Energy Agency, among other groups, have both commissioned scenarios that include greenhouse gas emissions and their interactions with socioeconomic and environmental systems as a way of analyzing the potential implications of different economic, industrial, energy, and research and development policies for future levels of emissions. [111, 112] The Energy Modeling Forum has played a substantial role in shaping the development of socioeconomic and emissions scenarios, convening a variety of intercomparisons of the results of IAM-based projections.[113] The Millennium Ecosystem Assessment, building on work in the IPCC, created a comprehensive set of scenarios covering a range of human, climate, and environmental changes relevant to assessing potential future changes in ecosystem goods and services.[114] There is increasing interest in developing scenarios at finer spatial scales, for example focusing on states/provinces or even metropolitan regions. Approaches for developing finer scale scenarios that are coupled to global or national scenarios to varying degrees are under development.[115] A challenge is representing the different socioeconomic and environmental processes at work at different scales, and nesting these scenarios in a way that adequately incorporates cross-scale interactions.[116] Further research on this issue is essential.

A New Process

Scenarios were typically developed and applied sequentially, in a linear causal chain that extended from the socioeconomic factors that influence greenhouse gas emissions to atmospheric and climate processes to impacts. This sequential process involved developing emissions scenarios based on different socioeconomic futures, estimating concentrations and radiative forcing from emissions and land use change, projecting the ensuing climate, and then using the resulting climate scenarios in impact research. As a result of this sequential process, there were frequently long delays in handing off information on emissions to climate modelers, and scenarios of climate change to researchers investigating impacts. This complicated the synthesis of results on issues such as costs and benefits and created challenges when comparing feedbacks across different types of models. In addition, climate futures appeared to be tied to only a single socioeconomic future when in fact a single climate future could result from a wide variety of development pathways (varying demographic, economic, technological, institutional, policy, and cultural conditions).

A new process and new scenarios were developed by researchers working on integrated assessment modeling, climate modeling, and modeling and analysis of impacts to respond to a variety of needs and opportunities. These included:

- A decade of new data on socioeconomic, environmental, and technological trends;
- New information needs of users, including a need for more information on the feasibility and implications of very low emissions scenarios and "overshoot" scenarios in which radiative forcing peaks and then declines to a target level;
- An increasing interest in scenarios which focus on the next two to three decades with higher spatial and temporal resolution and improved representation of extreme events to support adaptation studies;

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[108] Response Strategies Working Group. in Climate Change: The IPCC Scientific Assessment (eds Houghton, J. T., Jenkins, G. J. and Ephraums J. J.) 329-341 (Cambridge Univ. Press, 1990).

[109] Leggett, J., Pepper, W. J. and Swart, R. J. in Climate Change 1992: The Supplementary Report to the IPCC Scientific Assessment (eds Houghton, J. T., Callander, B. A. and Varney, S. K.) 69-95 (Cambridge Univ. Press, 1992).

[110] Nakicenovic, N., et al., op. cit.

[111] Deciding the Future: Energy Policy Scenarios to 2050 (World Energy Council, 2007).

[112] World Energy Outlook (International Energy Agency, Paris, 2009).

[113] See http://emf.stanford.edu/.

[114] Millennium Ecosystem Assessment. Ecosystems and Human Well-being: Scenarios, Vol. 2 (eds Carpenter, S. R. et al.) xix-551 (Island Press, 2005).

[115] The U.S. National Park Service is developing capacity for application of scenarios at a variety of spatial scales. See http://www.nps.gov/climatechange/docs/ScenarioPlanningBrief.pdf for an overview of this approach.

[116] Zurek, M., and Henrichs, T. Linking scenarios across geographical scales in international environmental assessments. Technological Forecasting and Social Change Volume 74, Issue 8, (2007) 1282-1295, doi 10.1016/j.techfore.2006.11.005.

- More information to support analysis of factors that affect vulnerability and resilience, which requires a process that promotes linked but flexible analysis across geographical scales;
- Scientific advances including advances in climate modeling (incorporation into climate models of the oceanic and terrestrial carbon cycle, aerosols, atmospheric chemistry, ice sheets, and dynamic vegetation);
- Increasing overlap in the substantive domains of climate, impact, and integrated assessment models which creates increased demand for harmonization of assumptions and data.

In addition to responding to these new information needs and opportunities, a new process for developing scenarios was stimulated by the IPCC's decision not to commission another set of emissions scenarios but instead to limit its role to assessing scenarios developed in the literature.

The new parallel process developed in response to these factors is shortening the time to develop different types of scenarios and transfer them from one set of researchers to another. Conceptually, the process begins with pathways of radiative forcing (the change in the balance between incoming and outgoing radiation to the atmosphere caused primarily by changes in atmospheric composition), not detailed socioeconomic narratives or scenarios. Central to the process is the concept that any single radiative forcing pathway can result from a diverse range of socioeconomic and technological development scenarios.[117] Among other issues, the new process facilitates exploration of the question "What are the ways in which the world could develop in order to reach a particular radiative forcing pathway?" To jump start the process, four RCPs were selected, defined by their total radiative forcing in 2100. The selection process for the RCPs was based on a detailed set of criteria and included an open peer review.[118] The RCP data and information on their intended uses and limits is freely available elsewhere.[119]

In the "parallel phase" of the new process, climate and integrated assessment modelers will work simultaneously rather than sequentially. Climate modelers will conduct new climate model experiments using the time series of emissions and concentrations from the four RCPs. These experiments will explore carbon cycle feedbacks, atmospheric chemistry interactions, and the response of the climate system, including a set of short-term experiments to 2035 at higher resolution in an effort to provide more information for adaptation studies.[120] Further information on these research activities, which are coordinated through the Climate Model Intercomparison Project, Phase 5 (CMIP5) is available.[121] Integrated assessment modelers will develop an ensemble of new socioeconomic and emissions scenarios that explore a variety of issues including alternative baselines and approaches to reach the various radiative forcing targets. IAM researchers will also work with researchers interested in impacts and adaptation to develop new socioeconomic narratives and scenarios to inform research on these topics. Many of these activities are being conducted through a newly-formed Integrated Assessment Modeling Consortium.[122] This paper will now turn to examining development of socioeconomic scenarios in some greater detail.

Development of Socioeconomic Scenarios

There are a variety of techniques and approaches for creating and applying socioeconomic scenarios that have been used in research and assessments. These have been developed to meet the needs of various user communities. Two major groups can be distinguished: (1) modelers and researchers who need the scenario outputs of one type of research as inputs to their analysis; and (2) resource managers, urban planners, or decision makers who need to incorporate climate change concerns into their decision processes.

In the traditional sequential approach, most of the focus has been on serving the needs of modelers and researchers, particularly the climate modeling community, which has required emissions scenarios as inputs to model experiments. The substantive focus of this work was primarily on developing centennial scale projections of

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[117] Ibid.

[118] Moss, R.H., *et al*., (2008), op. cit.

[119] http://www.iiasa.ac.at/web-apps/tnt/RcpDb.

[120] Hibbard, K.A., Meehl, G.A., Cox, P. and Friedlingstein, P. A strategy for climate change stabilization experiments. EOS 88, 217, 219, 221 (2007).

[121] http://cmip-pcmdi.llnl.gov/cmip5/.

[122] Further information is available at http://iamconsortium.org/.

emissions based on analysis of trends in fields as diverse as demography, economic development, and a full range of energy and agricultural technologies. Previous scenario efforts such as the SRES performed extensive reviews of the current state of science on scenario "driving forces" in relevant fields of socioeconomic research and used IAMs to develop quantitative projections for an increasingly comprehensive set of atmospheric constituents at the global scale.[123]

The significant achievements of this approach notwithstanding, there were limits to its ability to serve the needs of impacts-oriented researchers as well as resource managers, urban planners, or decision makers who focus on impacts, adaptation, and vulnerability and evaluating the robustness of potential decisions under uncertainty. These end users would benefit from improved approaches to develop locally or sectorally oriented scenarios embedded within broader climate and socioeconomic scenarios. Initial efforts at developing such nested scenarios were carried out using the SRES, and these were facilitated by use of the narratives of storylines that served as the foundation for the SRES.[124] However, the initial focus on emissions, coupled with the time pressure to produce the scenarios relatively quickly so that climate modelers could apply them, meant that issues important to vulnerability assessments were not incorporated systematically into the global scenarios themselves. One of the motivations behind the new scenarios process is to provide more time and flexibility to develop storylines that are relevant to a broader range of concerns including vulnerability assessment. There is also the potential to develop mitigation-oriented narratives and scenarios at the scale of the globe or large regions (e.g., continents) that are broadly consistent with the RCPs but that are oriented toward needs for analysis of specific sectoral or regional issues.

Taking advantage of the potential in the new scenarios process will require advances in research methods and process. These include:

- Coupling specific decision support scenarios relevant to regions/sectors to global scenarios: This is an issue that is particularly important for large scale assessments such as the IPCC and the U.S. National Climate Assessment (U.S. NCA) which need to coordinate assumptions and activities distributed across a wide range of specific regions and sectors. Processes affecting vulnerability and mitigation potential differ across geographic scales, and much work is required to better understand the key global determinants of mitigation and adaptation potential at finer scale in order to systematically include those factors in the design of scenarios. A second component of this work will examine the effects of local conditions and choices on vulnerability. A nested approach to scenario development links (i) global scenarios, which provide broad bounding conditions within which local/regional actors will have to operate and (ii) more specific decision support scenarios, which when coupled to global scenarios enable users to examine the robustness of specific options/decisions against a broad range of future conditions. Such an approach would enable users to tap into knowledge about global scale processes/conditions and relate that information to their own decision making. Work carried out by Robinson and colleagues focuses on approaches for relating stakeholder-driven concerns in the context of future levels of climate change and broader socioeconomic conditions.[125]
- Relating qualitative narratives to quantitative scenarios: Scenarios of socioeconomic change need to focus not only on quantifiable factors such as demography, economic development, and emissions or cost characteristics of different technologies, but also on a variety of qualitative factors that are essential for understanding the potential for innovation and adaption. These include a variety of institutional factors such as intellectual property regimes, international agreements, the effectiveness of enforcement of legal agreements, the functioning of markets, and the quality of public health, education, and other public services. Additional research is required to understand how to characterize uncertainty in potential outcomes in these areas, and to evaluate how a typology of future qualitative conditions could influence mitigation and adaptation potential.
- Evaluating the plausibility of combinations of future socioeconomic conditions: this is an important input into identifying a small number of strategically-important global scenarios to inform mitigation and vulnerability

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[123] Nakicenovic, N., et al., op. cit., Chapter 3.

[124] UK Climate Impacts Programme, *Socio-economic scenarios for climate change impact assessment: a guide to their use in the UK Climate Impacts Programme.* UKCIP, Oxford (2000). See http://www.ukcip.org.uk/images/stories/Pub_pdfs/socioeconomic_tec.pdf.

[125] Alison Shaw, et al. Making local futures tangible—Synthesizing, downscaling, and visualizing climate change scenarios for participatory capacity building. Global Environmental Change 19 (2009) 447-463, doi:10.1016/j.gloenvcha.2009.04.002.

assessments. Initial statistical evaluation of population trends, economic development, and other factors indicate that a very wide range of socioeconomic conditions can be associated with any of the RCPs. Clearly, there are relationships among socioeconomic conditions (e.g., demographics are not independent of the other variables, for example rates of urbanization will depend on economic development paths) that will make some combinations of conditions unlikely to occur. The full range of potential conditions presents too broad an array of futures to consider systematically. Research is needed to develop characterizations of a smaller number of potential futures that represent plausible combinations of conditions but that span important uncertainties, for example futures that give rise to greater levels of vulnerability or in which mitigation is more difficult. The new process provides new opportunities to consider potentially undesirable futures (e.g., global pandemics, failure of development in some countries) that governments have been reluctant to consider.

- Delivering and supporting use of scenarios: scenario data are becoming increasingly available through a wide variety of websites. In many cases, the proper uses and limits of the information provided in scenarios is not acknowledged, potentially leading to misapplication of information. In addition, the new scenario process itself calls for creation of a scenario "library" with guidance for users on how to integrate climate, socioeonomic, and environmental scenarios in a consistent fashion. Support for users, especially in developing countries where access to scenario information can be limited, is especially important.

Concluding Thoughts

The new parallel scenario process presents opportunities but remains a still evolving and imperfect approach for coordinating across research communities and providing tools that meet the needs of various user communities. It has the potential to be more open and flexible, especially for socioeconomic scenario development; to increase collaboration across distinct research communities; and improve synthesis and coordination across multi-scale assessments. More attention to the development of socioeconomic scenarios that address both mitigation and adaptation can lead to improved understanding of the interactions of these distinct approaches in managing risks from anthropogenic climate change. Because of the inherent potential of scenario techniques to evaluate decision making under conditions of deep uncertainty, it is especially important to develop tools for a wider range of users that facilitate examination of regional or sectoral decisions in the context of a wide range of future climate and socioeconomic conditions.