e-lab

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Carbon Dioxide Emissions Trading: Simplifying the Analysis

One of the hottest topics in recent climate-change negotiations has been emissions trading. Under the Kyoto Protocol, countries that face high costs to reduce emissions of carbon dioxide (CO_2) are allowed to pay countries with lower-cost opportunities to make the reductions for them. An Energy Laboratory team has developed an easy-to-interpret method of showing who would trade and how specific nations would be affected. Using output from standard models that simulate economic growth, energy use, and carbon emissions, the researchers form "marginal abatement curves" that show the cost to a given region of achieving cuts in CO_2 emissions. By superimposing curves for different regions, they can readily see which regions would trade and how their costs would be affected. Analyses show that, almost regardless of circumstances, all regions will benefit from trading. The savings are enormous when the lowest-cost reducers—the developing nations—participate. But costs drop considerably even when trading is limited to the major regions of the Organization for Economic Cooperation and Development (OECD). In every case, nearly all nations benefit some, and nations facing the highest costs benefit most. The researchers are now performing analyses involving different levels of economic and emissions growth and specific rules for trading currently being considered. These analyses show, for instance, that establishing ceilings on how much a nation can trade severely reduces the overall gains from trading.

Reducing carbon emissions is easier for some countries than for others. Developing nations, for example, can reduce emissions by improving their generally inefficient energy practices—a relatively low-cost approach not available to developed nations, where efficiency is already high. Even among the developed nations that signed the Kyoto Protocol, the cost of a one-ton reduction varies considerably. The United States, for example, can reduce emissions by switching from coal to

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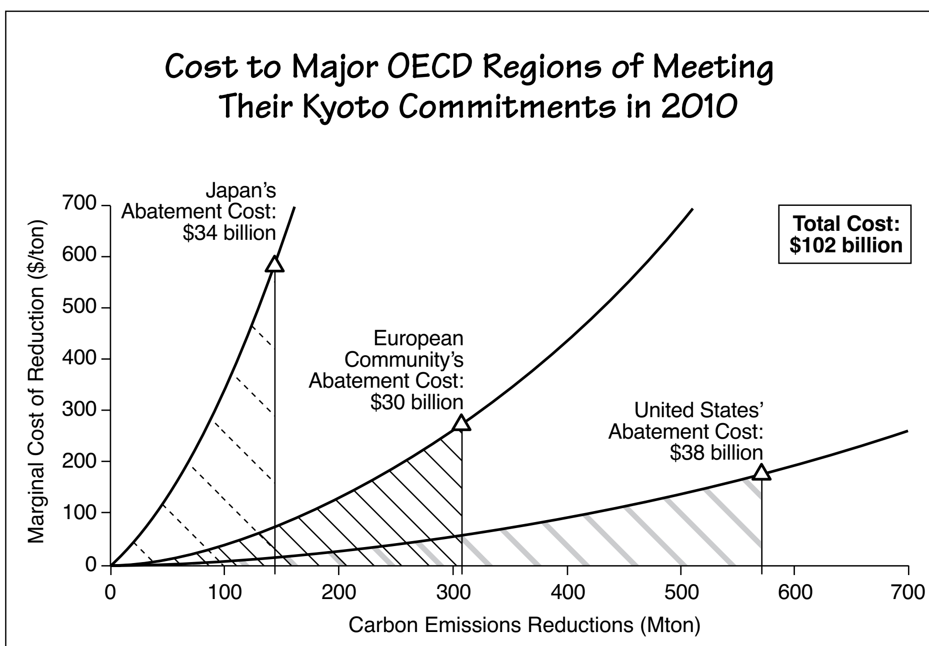


These marginal abatement curves show the cost to Japan, the European Community, and the United States of achieving a one-ton reduction in their emissions of carbon in the year 2010 as the total reduction in emissions changes. Not surprisingly, as the total reduction in emissions increases, the cost of cutting another ton increases. The triangle on each curve shows the reduction that that region must make in 2010 to meet its Kyoto commitment, and the hatched area under the curve equals the total cost of making that reduction.

natural gas—an option less available to Europe, where little coal is used. In light of those cost discrepancies, the Kyoto agreement allows countries to trade emissions "permits." Thus, a region that has only expensive opportunities to reduce can abate less by getting a region with less-expensive opportunities to reduce more in its place. The total reduction in global emissions is the same, and everyone comes out ahead. The "high-cost" region pays less to meet its restrictions by buying emissions permits from a "low-cost" region, and the low-cost region makes money by selling its permits for more than it spends on reducing the extra emissions. Under this arrangement, market-driven forces cause the least-expensive measures available worldwide to be pursued first, so the total cost of meeting the Kyoto constraints is minimized. (The location of emissions reductions is not critical because of the long-lived, well-mixed nature of atmospheric CO_2.)

Many experts believe that such trading may be the key to stabilizing atmospheric CO_2 at a tolerable cost—and perhaps the key to getting a meaningful climate-change agreement in place. But international negotiators have been unable to settle on acceptable rules for emissions trading. The issue is highly controversial, in part because the potential impacts of trading are so complex. An overall reduction in cost seems likely, but which countries will benefit and by how much? Will some countries be worse off? And do the benefits disappear in the absence of the developing nations, which have the lowest-cost reduction opportunities but the least-developed infrastructures for trading?

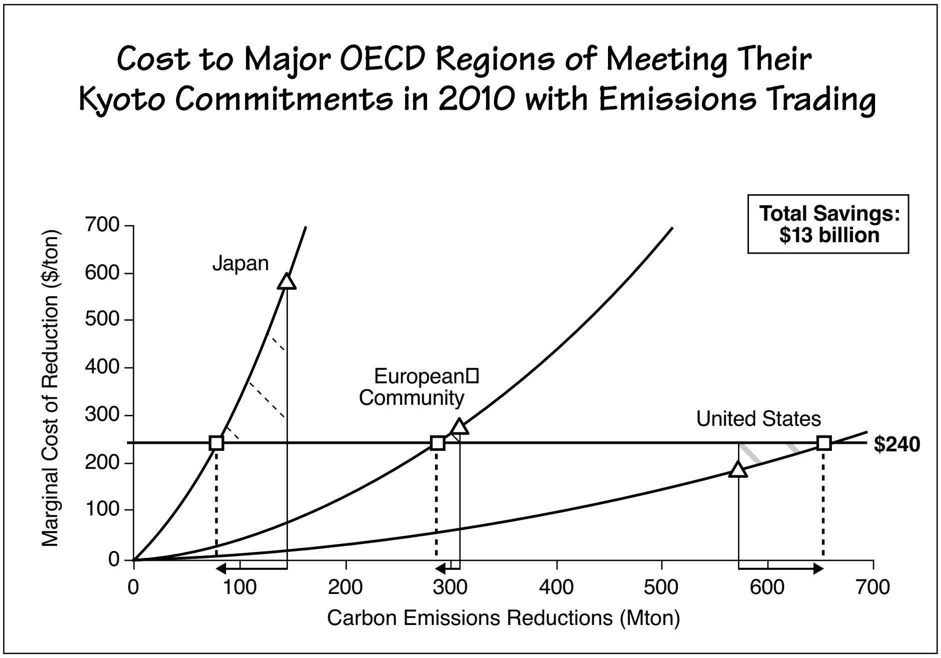
Energy Laboratory researchers led by Dr. A. Denny Ellerman have developed an approach to analyzing CO_2 emissions trading that not only quantifies the impacts of various trading conditions but also helps economists and non-economists alike understand why the market will behave as predicted. The data they use are not new but rather come from existing "computable general equilibrium" (CGE) models such as the Emissions Prediction and Policy Analysis (EPPA) model, developed by Professor Henry D. Jacoby and his colleagues at MIT. This complicated model simulates economic activity, energy use, and greenhouse gas emissions for many regions and economic sectors (see *e-lab*, January–March 1997). Based on those simulations, it forecasts future CO_2 emissions and the cost of reducing them.

However, CGE models can examine only one set of assumptions at a time. To understand the economic impacts of the Kyoto constraints, one needs to see not only the cost of abating a single ton of carbon given one set of assumptions but also how that cost changes as the reduction required in the future is greater or less, reflecting the intervening economic and emissions growth. (One performs the least-expensive emissions-reduction measures first and turns to increasingly expensive measures for further reduction. Thus, the per-ton cost will rise as the required reduction increases, and vice versa.) The needed data can be generated by running a CGE model many times with varying assumptions, but making sense of the results is difficult.

Dr. Ellerman and Annelène Decaux have developed and demonstrated a clear, easy-to-interpret method of presenting such data. To assemble the data, they use the EPPA model to perform systematic analyses of the cost to a region of reducing carbon levels by specific amounts (for example, 10%, 20%, 30%, and so on) in a specific year. Based on those results, they form a "marginal abatement curve" showing the cost of an additional one-ton reduction in carbon emissions at various levels of abatement. (One ton of carbon corresponds to 3.67 tons of CO_2.)

The figure on page 1 provides examples of marginal abatement curves and how they can be used. The curves shown, taken from a case study using the EPPA model, represent costs for varying levels of abatement for Japan, the European Community (EC), and the United States—the three biggest OECD regions—in 2010, the middle year of the first time period covered by the Kyoto agreement. As expected, within each region, the cost of reducing a ton of carbon emissions increases as more reduction occurs. But the cost of reducing emissions by a set amount differs substantially from region to region. For example, both the marginal cost and the total cost of abating 100 million tons (Mton) are many times higher for Japan than for the US. (Marginal cost is the cost of preventing the last ton of carbon from escaping. Total cost equals the hatched area below the curve.) Even when scaled as a percent of current emissions, the costs are higher for Japan than for the EC or the US because of the Japanese economy's greater energy efficiency.

Based on those curves, the researchers can estimate the costs to the regions of meeting their 2010 constraints. The triangle on each curve indicates how many tons of carbon the region must prevent from escaping into the atmosphere in 2010, based on a prediction of what emissions would be without the Kyoto constraint. (A region's reduction requirement equals the difference between its Kyoto constraint and its



This figure shows how the three regions would meet their Kyoto commitments if they were allowed to trade emissions permits. At their commitment levels (indicated by triangles), Japan and the European Community (EC) must pay much more per ton of reduction than the United States must. Therefore, Japan and the EC would pay the US to make their reductions for them—to a point. As the US reduces more, its per-ton cost goes up; and as Japan and the EC reduce less, their per-ton costs goes down. When seller and buyers are all paying $240/ton (marked by the dark horizontal line), trading stops. The level of abatement actually accomplished by each region is marked by a square, and the amount of savings (or earnings) is measured by the hatched areas. Under these assumptions, trading reduces total costs to the three regions by $13 billion.

expected emissions in the absence of abatement efforts.) Thus, Japan will have to reduce emissions by about 150 Mton, the EC by a little over 300 Mton, and the US by about 575 Mton. The total costs of achieving those reductions are shown on the figure.

A striking feature of the curves is the variation in the cost of reducing a ton as each region approaches its constraint. At this level of abatement, marginal cost is far lower in the US than in either Japan or the EC (even though the number of tons reduced is far higher in the US). The US pays only $186 to abate the last ton, while Japan must pay $584 and the EC $273. If emissions trading were limited to these three regions, Japan and the EC could save money by paying the US to reduce on their behalf.

The figure to the left shows emissions trading among the three market participants and the savings that would accrue. The curves themselves are unchanged. (The cost for a region to reduce a ton of carbon emissions is the same whether the region performs the reduction to sell to another region or to meet its own requirement.) The triangles are also in the same locations as before, indicating the required Kyoto reductions. The squares on the curves show how much each country would abate, given the opportunity to trade. Because the US faces the lowest costs among this group of regions, it can reduce more than it has to and become an exporter of emissions permits. But there is a limit to the amount of abatement it exports. As the US reduces more (see the right-facing arrow under the horizontal axis), the per-ton cost of reduction gradually goes up. And as Japan and the EC reduce less (see the left-facing arrows), their per-ton costs of reduction gradually go down. At a certain point, the marginal cost in the US will no longer be less than the marginal costs in Japan and the EC. Cheaper abatement will no longer be available from the US, and the other regions will perform the balance of their required reductions themselves.

Under the assumptions made here, when the reduction costs for all participants converge at $240/ton, trading is no longer beneficial. At that cost—marked by the dark horizontal line—the US abates 83 Mton more than required, and Japan abates 65 Mton less and the EC 18 Mton less. Everybody benefits economically. The US earns $2 billion by exporting permits, while Japan saves $10 billion and the EC about $1 billion by importing permits rather than performing their own reductions. Under these circumstances, all three regions can meet their obligations for a total of

$89 billion rather than the $102 billion they must spend when trading is not allowed.

These results demonstrate several important points. First, even if only the three major OECD regions trade, their cumulative savings are significant. Second, although all regions benefit to some extent, the gains from trade are greatest for those regions whose marginal cost is farthest from the market price of emissions permits. Finally, when trading occurs, the disparity among countries in the cost burden of achieving the Kyoto commitments is diminished—a condition that encourages adherence to the commitments and the subsequent upholding of the agreement.

Of course, the market for emissions permits may involve more than just the three major OECD countries. The "Annex B" countries that have agreed to limit their emissions under the Kyoto Protocol include other OECD countries (Canada, Australia, and New Zealand), eastern Europe, and the former Soviet Union (FSU). When those regions are also involved in trading, the picture changes significantly, largely because of the involvement of the FSU. According to most predictions, the FSU's commitment made at Kyoto will not result in a constraint on its carbon emissions in 2010 because the commitment corresponds to an emission level higher than the one predicted for that year. The difference between the committed level and the predicted level translates into emissions permits that the FSU can sell—a feature known as "hot air" because no actual reductions occur. In addition, the FSU's marginal abatement curve suggests that performing a certain level of actual abatement in order to export permits would make economic sense.

Magnitude and Distribution of Gains from CO_2 Emissions Trading

Trading Among Japan, the European Community, and the United States

Region	Imports (%)	Savings (billion $)*
Japan	45	10
European Community	7	<1
United States	—	2

Trading Among All Annex B Regions

Region	Imports (%)	Savings (billion $)*
Japan	66	19
European Community	35	7
United States	19	2

Global Trading

Region	Imports (%)	Savings (billion $)*
Japan	92	31
European Community	76	24
United States	68	27

*** Savings compared to costs in the absence of trading (for Japan, $34 billion; for the European Community, $30 billion; for the United States, $38 billion). See the figure on page 1.**

By creating marginal abatement curves for all of the Annex B regions, the researchers determined which regions would buy and sell emissions permits and how costs would change. With all Annex B regions trading, the market price of emissions permits settles at $127/ton—well below the $240/ton when only the three OECD regions trade. At that permit price, the US becomes an importer rather than exporter, and Japan and the EC increase the fraction of reduction requirements met with imports (see the summary table to the left). Japan again reaps the most economic benefit, now saving $19 billion by trading. The biggest winner, however, is the FSU. By providing 98% of all exports (through hot air and low-cost reductions), the FSU earns $34 billion.

Broadening the market to non-Annex B regions worldwide brings in many more low-cost abatement providers, notably China and India. Analysis of the economic behavior of all participants shows that with global trading the market price of permits drops to $24/ton. As shown in the table, Japan now imports fully 92% of its abatement, the EC 76%, and the US 68%. Costs for each region drop, with the total cost for the three regions falling to about $20 billion. With other low-cost providers participating, the FSU is no longer as big a winner. It captures only 37% of the market; and its net gain in the global market drops to $4 billion.

Using their global data, the researchers calculated the total costs of implementing the Kyoto agreement, not just for the major OECD regions but for all of the Annex B regions. Without trading, the cost to the Annex B regions is $120 billion. When trading occurs but is limited to the Annex B regions, the cost drops to $54 billion. When nations worldwide participate, the total cost of achieving the Kyoto goals is only $11 billion.

Such findings shed light on one frequently heard argument: that the gains from trading will be limited because only the developed nations will trade. Concerns that potential suppliers of low-cost permits may not trade are valid. Some developing nations may not participate because their governments are unfamiliar with trading as a concept; China and India have objected to emissions trading on principle; and some negotiators are demanding that the FSU have stricter abatement constraints so that it cannot sell emissions permits without making real reductions. However, the MIT case studies suggest that even a subset of traders can make a significant difference. A wider market brings lower-cost permits, greater benefits to the constrained regions, and lower costs for implementing the Kyoto agreement. The wider the market, the better; but even a narrow market is better than none at all.

Deciding which regions would actually buy or sell emissions permits is only one of many uncertainties encountered in trying to predict the impacts of emissions trading. For example, different levels of emissions changes and economic growth for certain regions significantly change the emission reductions required by the Kyoto Protocol. For instance, a recent forecast from the Energy Information Administration predicts less emissions growth overall but relatively more rapid economic and emissions growth for the US than for Japan or the EC. This particular forecast implies that the US would face the highest marginal cost and therefore import permits from Japan and the EC.

The researchers have also examined possible impacts of proposed rules for trading. One proposal put forth by the European nations and rejected by the US involves placing a "ceiling" on the degree to which a single nation can meet its commitment by buying emissions permits from other nations. Analyses using marginal abatement curves suggest that the imposition of such a ceiling would have perverse impacts. The analyses show that adoption of an import ceiling increases the global cost of meeting the Kyoto requirements and transfers most of the gains from trade from exporters to importers. Marginal abatement curves are thus proving a useful tool for investigating not only economic uncertainties but also proposed policy options and their potential impacts on the magnitude and distribution of gains from emissions trading.

A. Denny Ellerman is a senior lecturer at the Sloan School of Management and executive director of the MIT Joint Program on the Science and Policy of Global Change. Annelène Decaux received her SM degree from MIT's Technology and Policy Program in 1999. She is now employed by ABB Energy Information Systems. Henry D. Jacoby is the William F. Pounds Professor Management and co-director of the MIT Joint Program on the Science and Policy of Global Change. *This research was supported by a group of corporations in the United States, Europe, and Japan; by the Electric Power Research Institute; and by agencies of the Norwegian and US Governments.* *Further information can be found in references 1 and 2.*

Capturing Carbon Dioxide from Power Plants: Cost-Effective Carbon Management?

One way to reduce emissions of greenhouse gases is to capture and permanently store the carbon dioxide (CO_2) emitted by electric power plants burning fossil fuels. However, current methods of capturing CO_2 are expensive; so a critical concern with CO_2 "capture and sequestration" is cost. Energy Laboratory researchers have performed a methodical study of projected costs for capturing CO_2 from three types of power plants, two fueled by coal and one by natural gas. According to their analyses, capturing CO_2 could push up the cost of generating electricity from 3.3¢/kWh to 5.2¢/kWh at a natural gas plant and from 4.6¢/kWh to 6.0¢/kWh at a coal plant based on gasification. At those costs, carbon capture promises to be a less-expensive near-term option for carbon mitigation than switching to solar and perhaps nuclear power. With technological advances expected by 2012, incorporating capture could add less than 1¢/kWh to the cost of electricity. Increasing power plant efficiency could reduce the cost of capture substantially as it would lower both the cost per kWh generated and the amount of CO_2 emissions to be captured. Interestingly, if carbon capture and sequestration are practiced, coal plants may become more competitive with natural gas plants as restrictions on carbon emissions tighten. The researchers are now using MIT's Integrated Global System Model to perform more rigorous analyses of how CO_2 capture compares to other carbon-mitigation options under various assumptions about the future.

The world meets more than 85% of its energy needs using fossil fuels, and sufficient fuel supplies exist to continue that practice well into the 21st century. But there is a catch. Combustion of fossil fuels generates about 80% of all anthropogenic emissions of CO_2, the single greatest contributor to potential global warming. Continuing our dependence on fossil fuels requires reducing those emissions, and an obvious target for change is the electric power industry. Within the United States, electric power plants generate fully a third of all anthropogenic CO_2 emissions. In addition, power plants occur at limited locations so are more controllable than are other major sources of CO_2 (transportation, space heating, and industrial processing). Strategies to reduce emissions from power plants include increasing fuel efficiency and developing non-fossil energy sources such as solar and nuclear power. But those strategies alone may not be sufficient, so international attention has also been focusing on a less-familiar approach: capturing the CO_2 that comes out of fossil fuel-fired power plants and sequestering it, that is, recycling it or storing it to keep it out of the atmosphere. While a long-range strategy of decreasing dependence on fossil fuels is attractive, short-term major disruptions in our energy infrastructure have adverse economic consequences. Carbon capture and sequestration may be an effective transitional strategy.

For more than a decade, Energy Laboratory researchers led by Howard J. Herzog have been studying CO_2 capture and sequestration. In early work they assessed the economic, technical, and environmental aspects of various methods of capture and sequestration (see *e-lab*, April–September 1989 and October–December 1992). One critical issue they identified is what to do with the huge quantities of captured CO_2. Commercial uses for CO_2 are limited, so the researchers have been examining methods of permanent storage, including injection into geological formations such as depleted oil and gas wells and into the deep ocean. Their analysis of the environmental impacts of deep ocean injection was described in the January–March 1996 issue of *e-lab*, and recent participation in ocean-injection field trials and other activities are discussed in the box on page 9.

Another issue the Energy Laboratory team has been addressing is cost. Some people believe that the cost of capturing and storing CO_2 emissions would be exorbitant, largely due to the high cost of separating and capturing the CO_2 prior to storage. Whether that conclusion is warranted is not obvious. For one thing, determining the cost of capture is tricky. Cost varies from one type of power plant to another and depends on many assumptions about plant design, performance, fuel use, and so on. Cost calculations are further complicated by the "energy penalty" associated with CO_2 capture. The capture process uses energy, in some cases enough to reduce a plant's net output of electricity by 20%. Moreover, the energy used in the capture process creates additional CO_2 emissions that must be captured. The decline in power output and the increase in CO_2 emissions to be cleaned up must be reflected in the cost calculations. Finally, most cost estimates are based on today's CO_2-capture technology, which was developed decades ago as a means of removing unwanted acid gases such as CO_2 from process streams. The design and cost of a capture technique optimized for controlling power plant emissions may be quite different.

For the past year, Mr. Herzog and Neda Vukmirovic have been examining data from diverse sources to answer several key questions. First, what would the cost of electricity be if we incorporated CO_2 capture capability into different kinds of power plants? Is there a clear winner in terms of plant design and fuel? How might costs change after a decade of research progress? And where are the greatest opportunities for making cost-reducing technological improvements?

The first task was to determine the cost of electricity and the levels of CO_2 emissions for specific types of power plants, with and without CO_2 controls. The researchers considered three types of CO_2-capture plants.

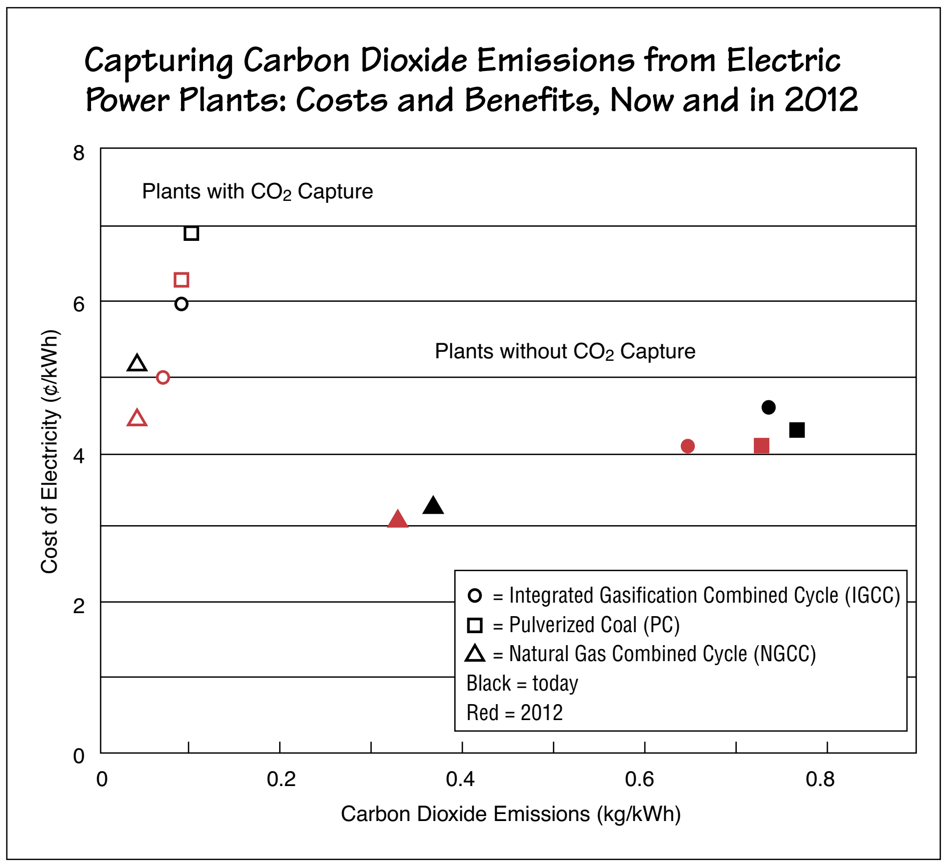
Integrated Gasification Combined Cycle (IGCC): In this power plant, coal is gasified and reacted over a catalyst to form a mixture of CO_2 and hydrogen. The CO_2 is removed, and the remaining hydrogen powers a gas turbine combined cycle—an efficient source of electricity.

Pulverized Coal (PC): This conventional plant burns pulverized coal to raise steam, which drives an electricity-generating steam turbine. CO_2 is removed from the exhaust gas using a scrubbing process involving the solvent monoethanolamine (MEA).

Natural Gas Combined Cycle (NGCC): In this plant, natural gas drives a gas turbine combined cycle, and CO_2 is removed from the exhaust gases using the MEA scrubbing process.

The researchers used data from ten recently published studies that analyzed the economics of CO_2 capture. All were based on commercially available equipment; all assumed effective controls on emissions of nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulates; and all included the cost of compressing the captured CO_2 for pipeline transportation. But critical assumptions such as fuel costs and discount rates differed from study to study. Therefore, the researchers developed a computer model that could adjust the various results so all were based on consistent economic assumptions. The model then synthesized the adjusted data from the individual studies to yield representative electricity cost and emissions data for each type of CO_2-capture plant. For comparison, the model also calculated electricity cost and emissions data for conventional (non-capture) versions of the same types of plants based on data from the same ten studies and from the Coal Utilization Research Council (CURC).

Results from the researchers' analyses are shown in the figure below. The solid black symbols show the emissions level and electricity cost for each "reference" (non-capture) plant today. (Cost estimates are for generation only and exclude the cost of transmission and distribution. Today, a residential customer in the United States pays about 8¢/kWh for delivered electricity.) The hollow black symbols show what happens to those cost and emissions estimates when capture, separation, and compression are added to the plants.



This figure shows Energy Laboratory estimates of electricity costs and carbon dioxide emissions at three types of power plants, based on data from various studies. The solid black symbols show data for a basic, non-capture plant of each type. The hollow black symbols show how adding capture would reduce emissions and increase costs. The red symbols show similar data for the year 2012, assuming expected improvements in both power plant design and CO_2 capture technology. In all cases, the natural gas combined cycle (NGCC) plant is most economical, with an electricity cost in 2012 comparable to costs at today's non-capture coal plants. The incremental cost of capture is lowest with the integrated gasification combined cycle (IGCC). If likely improvements in the basic IGCC technology come to fruition, the IGCC could be the capture plant of choice.

With today's technology, the NGCC performs best on both measures. The two coal plants emit about twice as much CO_2 as the NGCC does; and the cost of electricity is higher, with the IGCC cost highest. With the CO_2-capture process in place, emissions from all three plants drop substantially. Electricity still costs least at the NGCC plant. However, the cost of adding capture is lowest at the IGCC; and with capture installed, the IGCC plant becomes the more economical of the two coal plants.

Extensive research is now under way that promises to improve power plant designs and capture technologies. Therefore, the MIT investigators performed additional analyses assuming advances likely to be made by the year 2012. Based on information from the CURC, they assumed higher fuel efficiency and lower capital costs for the three basic plant designs. They also assumed improvements in today's capture technology, notably a decrease in energy required—a change that reduces both fuel costs and added emissions of CO_2 due to the capture process.

The red symbols on the figure reflect results for the 2012 scenario. The solid red symbols show electricity cost and emissions for the three reference plants. The open red symbols show the effects of adding the optimized CO_2 capture capability to the 2012 plants.

Technological improvements generally make the 2012 reference plants somewhat less expensive and cleaner than today's reference plants, with the IGCC technology making the greatest gains. Adding capture technology brings a similar reduction in CO_2 emissions as in today's plants. But the cost of adding capture is lower in the 2012 plants. Even with the capture technology, the cost of electricity from the three types of plants is not exorbitant. In fact, the cost of electricity from the NGCC capture plant in 2012 is close to the cost of electricity from today's coal plants without capture technology.

Those results bring into question two attitudes that now prevail. First is the idea that CO_2 capture and sequestration would be much more expensive than switching to non-fossil sources such as solar and nuclear power. While the MIT research is still in progress, the findings thus far suggest that carbon capture and sequestration may be a less expensive way to lower CO_2 emissions than switching to technologies based on renewable energy sources. In particular, most projected solar electricity costs are well above the costs cited here.

The second prevailing attitude is that building new power plants that use natural gas rather than coal is the economically and environmentally sound choice. The analyses reported above support that belief, but there are several factors that could make coal competitive. For example, the cost of including capture capability is lower with the IGCC than with the NGCC. If the IGCC reference plant became less expensive, the coal capture plant could become a less-expensive source of electricity than the natural gas capture plant is. Also, if the price of natural gas rises by 30% and the price of coal remains the same, the cost per kWh becomes about equal with the two capture technologies. Both of those changes are feasible. Current research on the IGCC technology could lead to significant decreases in capital costs, and the electric power sector's expanding use of natural gas rather than coal will drive up demand for natural gas and hence perhaps its price.

Working with members of the Joint Program on the Science and Policy of Global Change, Mr. Herzog and Sean D. Biggs are now incorporating data from the CO_2 capture analyses into MIT's Integrated Global System Model. This climate-change model combines descriptions of processes including economic growth, technological change, emissions growth, climate chemistry and physics, and ecosystem biology (see *e-lab*, January–March 1997). Using the Integrated Model, the researchers will perform rigorous analyses of how possible technology advances, fuel prices, carbon restrictions, and other policies and conditions would affect the economic viability of the different CO_2 capture plants. In addition, they will see how the performance of those plants compares to that of other strategies, including switching to solar and nuclear power.

Mr. Herzog and his colleagues are now involved in a variety of other studies relating to CO_2 capture. For example, they are performing sensitivity studies to see how much the cost of capture would be affected by increasing the power plant's efficiency and by decreasing the energy consumed in the capture process. Results thus far show that research priority should be placed on achieving efficiency gains. Increasing efficiency decreases not only electricity cost but also CO_2 emissions. With CO_2 emissions reduced, subsequent efforts to capture and sequester CO_2 are less costly. According to their analyses, increasing the efficiency of today's IGCC power plant by 50% would make it possible to capture CO_2 and reduce electricity cost simultaneously.

In other work, Mr. Herzog and his coworkers are examining different technologies for capturing CO_2; they are considering possible methods for integrating CO_2 capture with controls for other emissions; and they are looking at opportunities for retrofitting existing plants for CO_2 capture. They are also continuing their work on CO_2-storage methods and are planning systems analyses of how to coordinate capture and separation with transportation and storage to minimize overall costs. Finally, they are looking beyond 2012 at innovative technologies including new types of power plants and power cycles that may bring even larger reductions in the cost of capturing and sequestering CO_2.

Howard J. Herzog is a principal research engineer in the Energy Laboratory. Neda Vukmirovic is a master's degree candidate in the Department of Chemical Engineering. Sean D. Biggs is a master's degree candidate in MIT's Technology and Policy Program. This research was supported by the US Department of Energy. Further information can be found in references 3 and 4.

Energy Laboratory Researchers Investigate Ocean Sequestration of Carbon Dioxide

The largest potential sink for carbon dioxide (CO_2) captured from electric power plants is the ocean. The world's oceans now absorb about a third of our CO_2 emissions, and they have the capacity to absorb far more. But the transfer of CO_2 to the ocean is slow. Developing a faster and more direct means of moving CO_2 into the ocean could potentially prevent dangerous spikes in atmospheric concentrations. However, the physical, chemical, and environmental effects of such actions are not well understood.

Energy Laboratory researchers are now taking part in two major programs that bring together experts from various organizations to develop that understanding. Howard J. Herzog, principal research engineer in the Energy Laboratory, is participating in the US Department of Energy's Center for Research on Ocean Carbon Sequestration, or "DOCS." DOCS will receive a total of $3 million over three years to perform research on the feasibility, effectiveness, and environmental acceptability of two methods of ocean carbon sequestration. One method involves injecting CO_2 into the deep ocean; the other calls for fertilizing marine organisms living on the ocean's surface so that they absorb more CO_2. Research will combine observations and experiments in the ocean with computer modeling of ocean currents and the diffusion of CO_2.

DOCS is led by a consortium of the Lawrence Berkeley and Lawrence Livermore National Laboratories. Other participants are Moss Landing Marine Labs, the Pacific International Center for High Technology Research, Rutgers University, and the Scripps Institution of Oceanography. DOE formed DOCS and another center focusing on sequestration of CO_2 in terrestrial ecosystems during the summer of 1999 as part of its program of research on global climate change.

In other work, Mr. Herzog and Dr. E. Eric Adams, senior research engineer and lecturer in MIT's Department of Civil and Environmental Engineering, are taking part in an international field experiment that involves injecting small amounts of pure liquid CO_2 into the deep ocean. Data gathered in the vicinity of the CO_2 injection point will improve the basic understanding of underlying physical phenomena and will increase the accuracy of predictive computer models that are needed to evaluate the environmental impacts of CO_2 injection.

The CO_2-injection experiment will take place on the Kona coast of the island of Hawaii during the summer of 2001. About 40 hours of daytime testing will occur over a period of about two weeks. Liquid CO_2 will be injected at different flow rates through a small steel pipeline following the sea floor to an injection depth of nearly 3,000 feet.

The experiment is being managed by the Pacific International Center for High Technology Research. Mr. Herzog and Dr. Adams are members of a technical committee that is supervising the design of the experiment and is responsible for the data collection and analysis. Other technical committee members include scientists and engineers from the United States, Japan, Norway, Canada, and Australia. The experiment is being sponsored by government agencies from the United States, Japan, Norway, Canada, and Australia and one private organization, ABB Corporate Research. For further information, go to the CO_2 Ocean Sequestration Field Experiment Web site at <http://www.co2experiment.org/>.

News Items

John B. Heywood, the Sun Jae Professor of Mechanical Engineering and director of the Sloan Automotive Laboratory, is the 1999 winner of the **Soichiro Honda Medal**. The award is presented by the American Society of Mechanical Engineers for outstanding achievement in improving the field of personal transportation. Professor Heywood was cited for his "pioneering research contributions in the field of internal combustion engines, particularly emissions control, and distinguished leadership at the largest university-based automotive laboratory in the United States." Professor Heywood leads Energy Laboratory research relating to automotive engines and future transportation technology. Much work focuses on the operation, combustion, and emissions characteristics of internal combustion engines and on their fuels requirements.

Subra Suresh, the R.P. Simmons Professor of Materials Science and Engineering, has been named one of five new **Fellows** of the **Minerals, Metals, and Materials Society** (TMS). TMS has a worldwide membership of about 8,000 professionals and 2,000 students. Of those members, only about 100 are given the special title of Fellow of the Society. Dr. Suresh, the youngest of all the Fellows, was elected "for pioneering contributions to the understanding of mechanical behavior and mechanics of materials, and for leadership in materials education." Dr. Suresh leads Energy Laboratory research on new methods of measuring the mechanical properties of materials (see *e-lab*, April–June 1999).

Marija Ilić, senior research scientist in the Department of Electrical Engineering and Computer Science and an active Energy Laboratory researcher, has been appointed by the **National Science Foundation** (NSF) as **Program Director for Control, Networks, and Computational Intelligence** in the **Division of Electrical and Communications Systems**. Her main responsibility in this half-time position is to help the NSF's Engineering Systems Research Program define its long-term education and research goals in the area of power and energy systems. Due to electric sector restructuring, transmission networks and the electric service sector in general are important new areas of research and education. Dr. Ilić's NSF activities coincide well with her current teaching and research activities at MIT, which focus on competitive power systems. She currently heads two Energy Laboratory programs: a multi-sponsored consortium entitled "New Concepts and Software for Competitive Power Systems: Operations and Management," started in fall of 1998, and a new initiative entitled "Distributed Power Industry of the Future," sponsored by ABB Power T&D Company and begun in September 1999. Both programs focus on technical, institutional, and regulatory aspects of a restructuring electric sector and seek to bridge the real-time operation aspects of the industry to longer-term technological and investment factors. Former and current graduate students supported through these programs are in high demand by many types of market participants, including technology companies, grid operators, power brokers, and consulting firms.

In June, **Elisabeth M. Drake**, associate director of the Energy Laboratory, served on a panel that was convened by the Under Secretary of the US Department of Energy (DOE) to analyze **DOE's Energy Resources R&D Portfolio** using a new strategic planning methodology. Specific objectives were to assess the adequacy of the energy R&D portfolio in addressing six national strategic goals and to identify any gaps or opportunities that exist. The panel included thirteen representatives from DOE, the DOE national laboratories and energy technology centers, and universities. The final report describing the methodology used and the conclusions reached has just been released.

The panel concluded that the R&D portfolio adequately addresses three strategic goals: to improve the economic efficiency of the energy supply and end-use systems to enhance the overall performance of the US economy; to reduce the vulnerability of the US economy to disruptions in oil supply; and to reduce pollutants. Two goals were deemed inadequately addressed: to ensure energy systems reliability, flexibility, emergency response capability, and risk management; and to enhance sustainable global economic development. The adequacy of the portfolio with respect to the last goal—reducing greenhouse gas emissions—was uncertain. The panel identified gaps in the R&D portfolio in the following areas: electric and natural gas infrastructure reliability, security, and integrity; advanced separations membranes; on-board hydrogen storage systems for vehicles; carbon sequestration; efficiency improvements in commercial buildings; maintenance of a viable nuclear energy option; sensors and controls for a variety of applications; methane hydrates; and international collaborative R&D on advanced energy technologies, particularly for developing countries. The panel also identified opportunities for improving the effectiveness of the R&D portfolio through better coordination of related R&D efforts. Copies of the final report (*Energy Resources R&D Portfolio Analysis*, August 1999) are available from Patricia Scharnberg, Sandia National Laboratories, PO Box 5800, Albuquerque, New Mexico 87185-0160 (telephone: 505-845-8086).

Jefferson W. Tester, director of the Energy Laboratory and Meissner Professor of Chemical Engineering, is now serving on several committees relevant to Energy Laboratory interests and activities. Last spring he began a two-year term as the first chairman of the newly formed **National Advisory Council** of the **National Renewable Energy Laboratory** (NREL). This 20-member committee was established to provide external, independent counsel to the director of NREL concerning the laboratory's R&D portfolio, including its relevance to the energy mission of the DOE, to national trends and goals, and to selected strategic directions of the laboratory. The council is expected to comment on the technical quality of the R&D effort; recommend new areas of research; identify opportunities for NREL participation in collaborative RD&D activities; and evaluate NREL's five-year plan and technology portfolio.

Since spring of 1999, Professor Tester has also been a member of a **National Research Council committee** that is performing a broad review of the programs in **DOE's Office of Power Technologies** (OPT). OPT focuses on the development and adoption of renewable energy and energy-efficiency technologies for electric power production and use. The ten-member committee is considering the goals of OPT and its programs; processes for developing program plans, choosing R&D projects, and monitoring research progress; the appropriateness of the technical directions being pursued, including the balance of near-term and long-term R&D; and strategies for leveraging and coordinating activities within and outside OPT.

Professor Tester is now spending his second year as a member of the **Plenary Research Committee** of the **Paul Scherrer Institute** (PSI), the national research institution of Switzerland. This committee consists of eight internal and eight external members who support the directorate in matters concerning the institute's research, with special emphasis on assessing the quality of both existing and planned research activities. The committee helps to ensure that PSI is engaged in topical and relevant fields and identifies additional important areas in which the institute would be qualified to carry out research.

PUBLICATIONS AND REFERENCES

The following publications of Energy Laboratory and related research were released during the past period or are cited as references in this issue. **MIT theses** may be ordered from the Library Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from Energy Laboratory Publications, MIT, Room E40-473, Cambridge, MA 02139-4307, *only* if a price is assigned and *only* if prepaid by check payable to "MIT Energy Laboratory." Prices are postpaid surface mail. For air delivery, add 15% to US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

Publications marked by an asterisk (*) can be found on-line via the following addresses:
Energy Laboratory:
http://web.mit.edu/energylab/www/publications.html
Center for Energy and Environmental Policy Research:
http://web.mit.edu/ceepr/www/
Joint Program on the Science and Policy of Global Change:
http://web.mit.edu/globalchange/www/

Instructions for ordering paper copies of the reports and working papers are also available at the above listed sites or by telephoning 617-258-0307 for Energy Laboratory publications, 617-253-3551 for Center publications, and 617-253-7492 for Joint Program publications.

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NEW AND RENEWED PROJECTS, JANUARY–MARCH 1999

Topic	Donor or Sponsor	Investigators *(Department)*
GIFTS AND CONTRIBUTIONS		
CEEPR membership	BP-Amoco; Exxon; Repsol, SA; Tennessee Valley Authority	
Joint Program on the Science and Policy of Global Change membership	BP-Amoco; Exxon; Ford Motor Co.; Mobil Corp.; RWE/Rheinbraun; Tennessee Valley Authority; G. Unger Vetlesen Foundation	
NEW PROJECTS		
SO_2 Emissions Trading	CEEPR	A. Ellerman *(Sloan School)*
Development of Ceramic Membrane/Metal Joints and Optimization of the Membrane	University of Alaska, Fairbanks	T. Eagar G. Ceder H. Larson H. Tuller *(Materials Science and Engineering)*
Research on Ocean Carbon Sequestration	Lawrence Livermore National Laboratory (under prime contract to US Department of Energy)	H. Herzog *(Energy Laboratory)* B. Trout *(Chemical Engineering)*
Distributed Power Industry of the Future	ABB Power T&D Co.	M. Ilić *(Electrical Engineering and Computer Science)* S. Connors *(Energy Laboratory)*
Production of Aluminum and Magnesium Metal by Reduction of Their Oxides with Light Hydrocarbon Gases	Norsk Hydro	W. Peters *(Energy Laboratory)* J. Howard *(Chemical Engineering)*

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NEW AND RENEWED PROJECTS, CONTINUED

Topic	Donor or Sponsor	Investigators *(Department)*
CONTINUING PROJECTS		
Airborne Organic Compounds: Sources, Transformation, and Control (in collaboration with New Jersey Institute of Technology and California Institute of Technology)	US Environmental Protection Agency	J. Howard *(Chemical Engineering)*
Computer-Generated Kinetic Models for PAH Formation	above	W. Green *(Chemical Engineering)*
Numerical Tools for Large-Scale Kinetic Models	above	P. Barton *(Chemical Engineering)*
Synthesis and Optimization of Chemical Processes	US Department of Energy	P. Barton *(Chemical Engineering)*

CEEPR = Center for Energy and Environmental Policy Research

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