Economic Assessment of CO_2 Capture and Disposal

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A multi-sector multi-region general equilibrium model of economic growth and emissions is used to explore the conditions that will determine the market penetration of CO_2 capture and disposal technology.

1. The Study Design

One method for controlling CO_2 emissions is to capture the gas at the point of combustion, and store it for the long term. The potential for this approach will depend not just on its own technical performance and cost, but also on patterns of economic growth and their energy intensity, on the structure of international agreements to control greenhouse gases, and on the availability of low-carbon alternatives to fossil fuels. Here we use the MIT Emissions Prediction and Policy Analysis (EPPA) model to evaluate the prospects for this method of emissions mitigation.[1] The primary target for application of capture technology is large-scale electric power generation, and with a set of simulation experiments we explore its possible use in this sector. Uncertainties in the costs of both the capture and the disposal stages of this process are very great, of course, as are the future economic conditions that will influence its competitive position. Therefore the purpose of our inquiry is to illuminate the cost goals it will have to meet if substantial market penetration is to be achieved, not to try to predict the actual level of use.

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[1] The EPPA model has been developed with the support of a government-industry partnership including the U.S. Department of Energy (901214-HAR; DE-FG02-94ER61937; DE-FG02-93ER61713), U.S. Environmental Protection Agency (CR-820662-02), the Electric Power Research Institute (W02141-23), and a group of corporate sponsors from the United States, Europe and Japan.

The economics of market penetration are illustrated in Figure 1, which divides the likely sources of future electric generation into three categories: conventional plants, non-carbon “backstop” technologies, and fossil-fired generation with CO_2 capture and disposal. Today, the largest fraction of electricity supply is from conventional fossil-fuel-fired generation, which supplies electricity to a region at a cost C_f, and releases CO_2 to the atmosphere. (Existing sources of hydroelectric and nuclear power are accounted for in the analysis, but in the EPPA model future expansion of these sources are included in the non-carbon backstop technologies.) The CO_2 capture and disposal technologies under study here produce electricity at a higher cost, $C_{c\&d}$, but reduce the emissions per kWh generated by as much as 90%. In the future, these costs of fossil-fired generation will reflect any tax on CO_2 emissions, denoted T_{CO2} in the figure, or (equivalently) the price of any constraint on emissions which applies to the electric power industry.

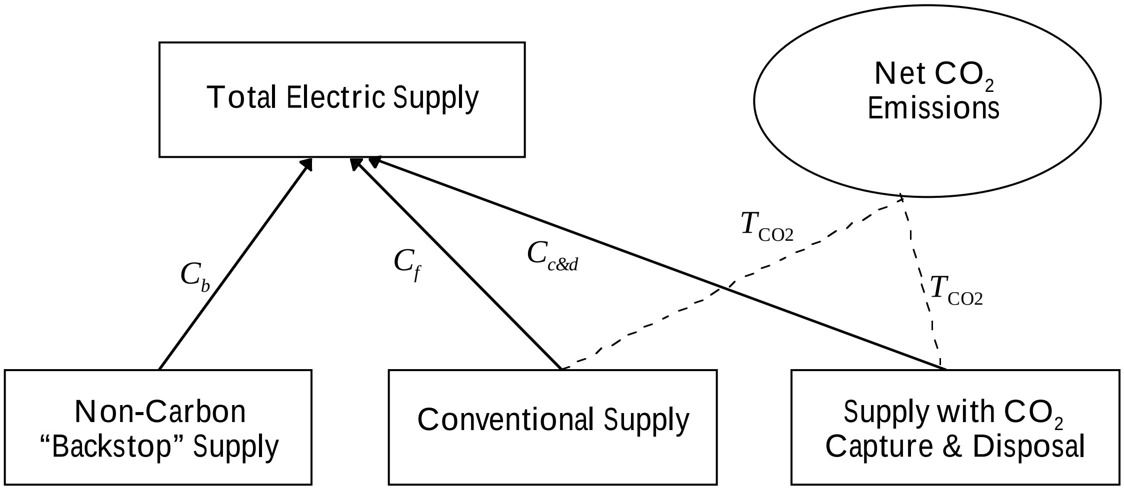

Figure 1. Alternative sources of regional electricity supply.

If $T_{\mathrm{CO2}} = 0$, capture and disposal methods will never be used. A positive carbon price will tip the relative economics away from conventional fossil generation, however, and toward generation with capture and disposal. If $C_{c\&d}$, including the shadow price of the residual emissions from the capture process, falls below C_f, including its carbon emissions penalty, then capture and disposal will begin to compete with conventional technology for market share. How either of these fossil-fired technologies fares will also depend on competition with other forms of low- or no-carbon electricity generation, which are represented in the EPPA model by a non-carbon electric “backstop” technology. In our analysis, this backstop technology represents the possible expansion of solar power, nuclear power (through the development of new, advanced, and socially acceptable reactor designs), and biomass-based systems.

Furthermore, the relevant input prices depend not only on evolving conditions within the electric sector, but on developments in each national economy as a whole and (because of the influence of international trade) on economic conditions in all other world regions. Thus the competition between electricity generation with capture and disposal and other technologies depends on many factors, all of which are changing over time. These include the technical development of all these technologies (in terms of their required inputs of capital, labor, fuel and other inputs per kWh of output), the relative prices of these inputs, and the stringency and structure of the CO_2 control policy. It is because of this extensive interdependence that a multi-sector, multi-region model like EPPA is necessary for exploring the market potential of this new CO_2 control option.

To analyze the prospects for capture-and-disposal methods, we assume a policy environment which is as favorable to this technology as any now being discussed for adoption within the Framework Convention on Climate Change. Under it the OECD countries agree, by 2005, to limit their CO_2 emissions to 20% below their 1990 baselines. We explore two versions of such an agreement. In one case, each of the OECD regions agrees to meet this constraint on its own, and in the other a system of global trading in CO_2 emissions rights is agreed as well.

The structure of the EPPA model, and key assumptions that underlie the study, are summarized in Section 2 of the paper. Section 3 then explains how the capture and disposal option has been implemented in the model, and describes the way we formulate assumptions about its cost. The model is applied in a set of studies of market penetration by the new technology, testing the level of its use in different regions under alternative hypotheses about its cost in relation to conventional fossil generation. In Section 4 we probe the results for insights about the factors that will dominate the prospects for capture and disposal methods in decades to come. Some conclusions flowing from this preliminary analysis are offered in Section 5.

2. The MIT EPPA Model

2.1 Model Structure

The MIT Emissions Prediction and Policy Analysis (EPPA) Model (Yang, *et al.*, 1996) is a recursive-dynamic computable general equilibrium (CGE) model which is derived from the General Equilibrium Environmental (GREEN) Model developed by the OECD (Burniaux, *et al.*, 1992). It is a mathematical representation of multi-regional world economy, with supplies of input factors (*e.g.*, labor, capital, land and other resources), consumer demand functions, and production technologies for each region. It is referred to as a "general equilibrium" model because it finds a set of product and factor prices that balance supplies and demands for all markets in each period. The model is called "recursive" because it is solved by stepping forward one period at a time without anticipation of future changes in relative prices. It is “dynamic” in the sense that the capital stocks available in any period are, in part, an inheritance from decisions in previous periods.

The world is divided into 12 regions, shown in Table 1, which are linked by multilateral trade. This interconnected system is simulated in five-year time steps, and in this study we focus on the period to 2050. The economic structure of each region consists of nine fully-elaborated production sectors. Sectors 1, 2 and 3 are non-energy activities, Sectors 4 through 9 are components of energy supply. Fossil-fired electricity generation with capture and disposal of CO_2, which is the focus of the analysis, is Sector 9. There are four consumption sectors, shown in the table, plus one government sector and one investment sector (not shown).

Each of the nine production sectors is modeled by a nested set of constant elasticity of substitution (CES) functions. This formulation allows a flexible representation of the degree of substitution between inputs to the production processes (for details, see Yang, *et al.*, 1996). The output of each sector results from the combination of energy and intermediate goods (provided by other production sectors), and three primary factors: capital, labor, and a fixed factor. The fixed factor represents land in agriculture, reserves in the production of oil, gas and coal, and the role of existing sources of hydroelectric and conventional nuclear power within the electric supply sector. The EPPA model can handle various assumptions about vintages of capital. In the calculations shown here a “putty-putty” assumptions is made, which means that capital is treated as mobile among sectors from one period to another.

Table 1. Key dimensions of the EPPA model.

Production Sectors			
Non-Energy	Energy		
1. Agriculture	4. Crude oils	7. Coal	
2. Energy-intensive industries	5. Natural gas	8. Electricity, gas and water	
3. Other industries and services	6. Refined oil	9. Electric with CO_2 capture and disposal	
Backstop Technologies			
10. Carbon-free electric backstop[†]	11. Carbon liquids backstop[‡]		
Consumer Sectors			
1. Food and beverages	2. Fuel and power	3. Transport and communication	4. Other goods and services
Primary Factors			
1. Labor	2. Capital (by vintage)	3. Fixed factors for each fuel, and for land in agriculture	
Region Abbreviations			
1. United States: USA	5. Central and Eastern Europe	9. India	
2. Japan: JPN	6. The Former Soviet Union	10. Dynamic Asian Economies	
3. European Community: EEC	7. Energy-exporting LDCs	11. Brazil	
4. Other OECD[*]: OOE	8. China	12. Rest of the World	

[†] Carbon-free electricity derived from advanced nuclear, solar or wind, or biomass.

‡ Liquid fuel derived from tars, oil sands, and oil shale.
* Australia, Canada, New Zealand, EFTA (excluding Switzerland and Iceland), and Turkey.

As applied below, the EPPA model incorporates two “backstop” energy supply technologies, represented as Leontief functions of labor and capital. We first consider the prospects for capture and disposal on the assumption that these alternatives do not materialize on large scale, and then discuss the difference in results if they are considered to be a real option. If assumed to be available at all, the Carbon-Free Electric Backstop (Production Sector 10 in Table 1) can be used in any of the twelve EPPA regions. Sector 11, the Carbon Liquids Backstop, represents the industry producing liquid fuels from heavy oils, tar sands and shale, and it can be developed only in the three regions now known to have substantial amounts of the necessary resources. These are the Energy Exporting Countries (*e.g.*, Venezuelan tars and heavy oils), the Other OECD countries (*e.g.*, Canadian and Australian tar sands) and the United States (*e.g.*, Western oil shales). This sector produces a perfect substitute for refined oil (the output of Sector 6). Because of extensive processing requirements, CO_2 is emitted when fuels are produced using this technology, and these emissions are credited to its regions of origin. Sector 9, electricity production using CO_2 capture and disposal technology, is available in all regions, but in this analysis it only shows up only in OECD regions, which are assumed to accept restrictions on CO_2 emissions.

All goods are traded among regions. With the exception of crude oil and natural gas, where the supplies of each are treated as perfect substitutes anywhere in the world, imported goods are imperfect substitutes for the equivalent domestic ones, and goods imported from alternative foreign regions are imperfect substitutes for one another. All relative prices are calculated within the model, including the wage rate and the return to capital. The returns to capital, along with the level of aggregate income, determine aggregate savings and the level of capital formation.

In the calculations below, emission quotas are imposed on individual regions of the OECD, and in some cases these quotas are tradable among all world regions. These emissions restrictions depress the demand for output from the more carbon-intensive energy sectors, and shift the equilibria in the economy away from the no-policy baseline conditions. The adjustments are complex and may include substitution among sources of energy supply, substitution in production among inputs of energy, capital, labor, and fixed factor, changes in the mix of goods consumed, and shifts in international trade, both in energy and non-energy goods.

2.2 Key Assumptions

The most important exogenous inputs to the EPPA model are population change, the rate of productivity growth (stated in terms of labor productivity), and a rate of autonomous energy efficiency improvement which reflects the effect of non-price-driven technical change on the energy intensity of economic activity. The rate of capital formation, which is another important influence on economic growth, is endogenous to the model. Finally, a key determinant of the carbon intensity of economic growth, which also has an important influence on the competitive position of the capture and disposal option, is the assumed costs relative to conventional sources of the backstop technologies (Sectors 10 and 11 in Table 1). In the calculations reported below, the base-year (1985) cost of the carbon-free electric backstop is $0.15 per kWh, and the cost of the carbon fuels backstop is set at 1.4 times the 1985 cost of refined oil in each producing region. These costs change over time, relative to other energy sources, as input prices vary in response to changing economic conditions.

Figure 2 shows the trajectory of carbon emissions for the OECD and Non-OECD regions over the period from 1990 to 2050, for the reference case with no backstops. Results are shown both with no policy of carbon restraint, and with our sample policy of restriction in the OECD. The effect of OECD stabilization is clearly seen, as is the carbon "leakage" (*i.e.*, Non-OECD emissions are higher when the OECD is cutting back). These results are for the case without backstop technologies. In the reference case with no policy the two backstops partially cancel one another (the carbon-free electric activity reducing emissions *vs*. carbon-intensive fuels increasing them), leaving the case with backstops with less carbon in total than is the case shown in Figure 2.

The challenge for CO_2 capture and disposal, then, is to reach a level of cost performance where this technology can take a role in the OECD emissions reductions shown in the figure.

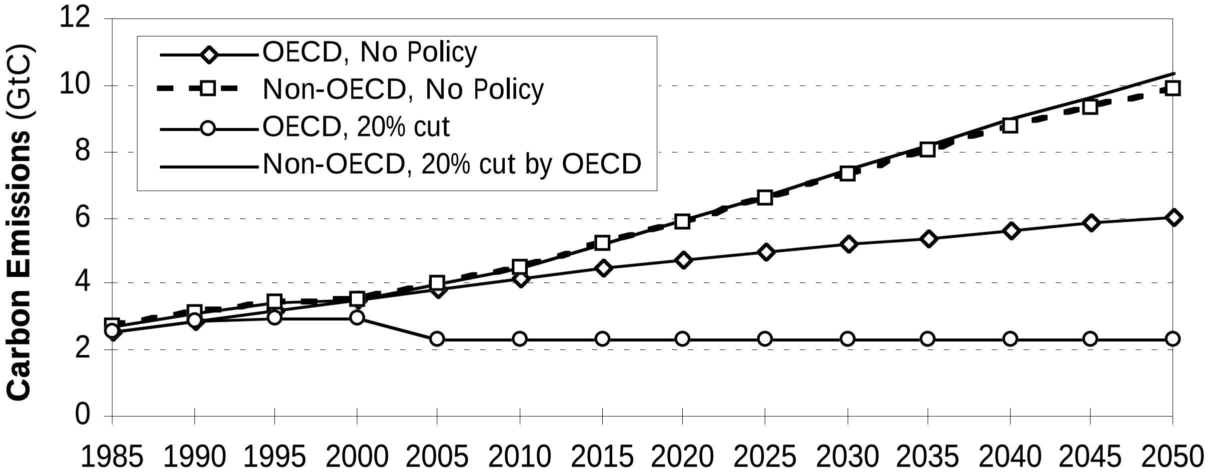

Figure 2. Carbon emissions by the OECD and Non-OECD regions, with and without AOSIS-like emissions restriction on the OECD, and with no emissions trading. Backstop energy supply technologies assumed not available.

3. Representation of CO_2 Removal Technology

3.1 The Technical Options

Various methods have been developed for the capture of dilute CO_2 from gas streams, and many others are proposed (*e.g.*, US DOE, 1993; IEA, 1992; Hendriks, 1994). Examples of the possibilities include:

> **Chemical stripping**, which involves a reversible chemical reaction of the gaseous CO_2 with some material, to produce a solid or liquid species that can be collected and which, upon heating, will release the CO_2 and regenerate the collector material.
>
> **Membrane systems**, which use one or more stages of a porous or semi-porous structure, through which some chemical species permeate more easily than others.
>
> **Cryogenic fractionation**, which involves the compression of the gas stream, and cooling it to a temperature low enough to allow separation by distillation. The resulting liquid CO_2 may then be removed for disposal.
>
> **Physical absorption** of CO_2, in which a solid absorbent (such as activated carbon) is passed through the gas stream, and the CO_2 is held on the surface of the particles by (non-chemical) surface forces. Once collected, the particles are heated, releasing (desorbing) the CO_2.
>
> **Physical absorption**, whereby organic or inorganic liquids are passed through the gas stream, preferentially absorbing some gases from the mix. The collected gases are released, and the absorbant regenerated, by temperature or pressure changes.

Each of these technologies may be combined with various methods for fuel pre-processing and combustion. For example, the removal process may be applied directly to the flue gas from a conventional power plant; it may be combined with a coal gasifier as an add-on to an integrated coal gasifier combined cycle facility; or it may be integrated into a system based on fuel cells. The precise form of the separated CO_2 (purity; solid, liquid or gaseous state; and the temperature and/or pressure) is a function of the total system design, including the disposal method. The costs of each of these individual technical approaches are highly uncertain, particularly at the scale of a modern fossil power plant. Moreover, costs estimates may differ greatly depending on the type of fossil fuel used.

The uncertainty in the technical feasibility and cost of large-scale CO_2 disposal is even greater than that for the capture stage. A number of possible means and locations of disposal have been considered (US DOE, 1993; Ormerod, 1994):

> **Discharge into depleted natural gas reservoirs.** Where power plants are near appropriate geological structures, this likely is the cheapest of the options, and indeed the much of the needed technology is in place as a result of the use of this technology for enhanced oil recovery.
>
> **Discharge into aquifers.** The approach is similar to that for natural gas reservoirs, but again its application depends on the fortuitous location of power plant and aquifer. Further, the behavior of aquifers under CO_2 change is poorly understood.

> **Discharge deep into the ocean.** Here the capacity is essentially unlimited. However, it is uncertain how deep the disposal point must be to insure that the CO_2 does not return too quickly to the atmosphere.
>
> **Convert to solid state and store in insulated warehouses.** Though technically possible, this method is prohibitively expensive.
>
> **Convert the CO_2 back into useful organic compounds.** This is a "re-use" option, usually with solar energy to drive the conversion (*e.g.*, using the CO_2 to fertilize algae ponds). Little is known of these alternatives, except that they also appear to be prohibitively.

Aside from the discharge into underground reservoirs, where there is extensive experience in the oil and gas industry, the costs of these options are highly uncertain. Moreover, they differ substantially from one another in their capacity to absorb large quantities of CO_2. Underground discharge may be the cheapest alternative, and it offers a way to test pilot installations, but only the oceans could absorb the quantities that substantial market penetration of CO_2 capture and disposal methods would imply.

Because of these uncertainties and the widely differing disposal options faced by the various OECD countries, and the degree of regional and sectoral aggregation of the EPPA model, we do not conduct the analysis in terms of detailed designs of specific capture and disposal facilities. Rather, as shown in the next section, we formulate capture and disposal in terms of a single set of fuel, capital and M&O cost premia, over and above the cost of conventional generation. In this way we can explore the cost conditions that must be met by *any* combination of these technologies if it is to penetrate electricity markets.

3.2 Implementation in the EPPA Framework

Conventional Fossil-Fired Electric Supply

As noted earlier, each of the first nine production sectors in Table 1 is represented by a nested set of CES production functions. Figure 3 shows a collapsed version of this structure for the sector that represents electric supply. (The figure omits the details of the several-layer nesting, which allows for different degrees of substitutability between the various inputs.) Electricity is provided by a process that combines inputs of capital, labor, energy in the form of fossil fuels, intermediate goods other than fuel (primarily output of the Other Industries and Services sector and electric power itself), and a fixed factor. The cost of electricity supply (at the top of the nesting in Figure 3) is a function of the quantities of the inputs used and their relative prices. These input prices evolve over time, as a result of a set of interdependent dynamic processes, including the growth of the twelve regional economies, technological change, depletion of oil and gas reserves, and the effects of CO_2 control policies. As a result, the relative price of conventional electricity also changes, as indeed it has done in most world regions over the *past* century, in a process driven by many of the same forces.

In the EPPA model, releases of CO_2 are accounted for within the sectors that produce each of the fossil fuels (Production Sectors 4, 5, 6, and 7 in Table 1). Thus, for example, the CO_2 from coal consumed in the generation of electric power shows up in a calculation based on the total amount of coal produced in Sector 7. (The are no inventories in this model, so the total coal produced in any period is the same as that burned.) This method of emissions accounting then influences the way that credit is given for the capture and disposal process, discussed next.

Electricity Supply with Capture and Disposal

Applying the technology choices discussed above, the economic structure of capture and disposal is conceived as a two-stage process, as shown in Figure 4. The supply and generation stage has the same CES input structure as conventional generation, only it produces two products: electricity and the CO_2 that has been captured and prepared for pipeline transport. Then, in a second stage, the captured CO_2 is transported to the location of the disposal facility, and placed in long-term storage. In the software language used for the EPPA model (see Yang, *et al*., 1996) the two stages are implemented in a single nested CES function.

Because of the power requirements of the CO_2 recovery equipment, and the process steps required to bring the captured gas to the level of purity and pressure required for shipment, the fuel

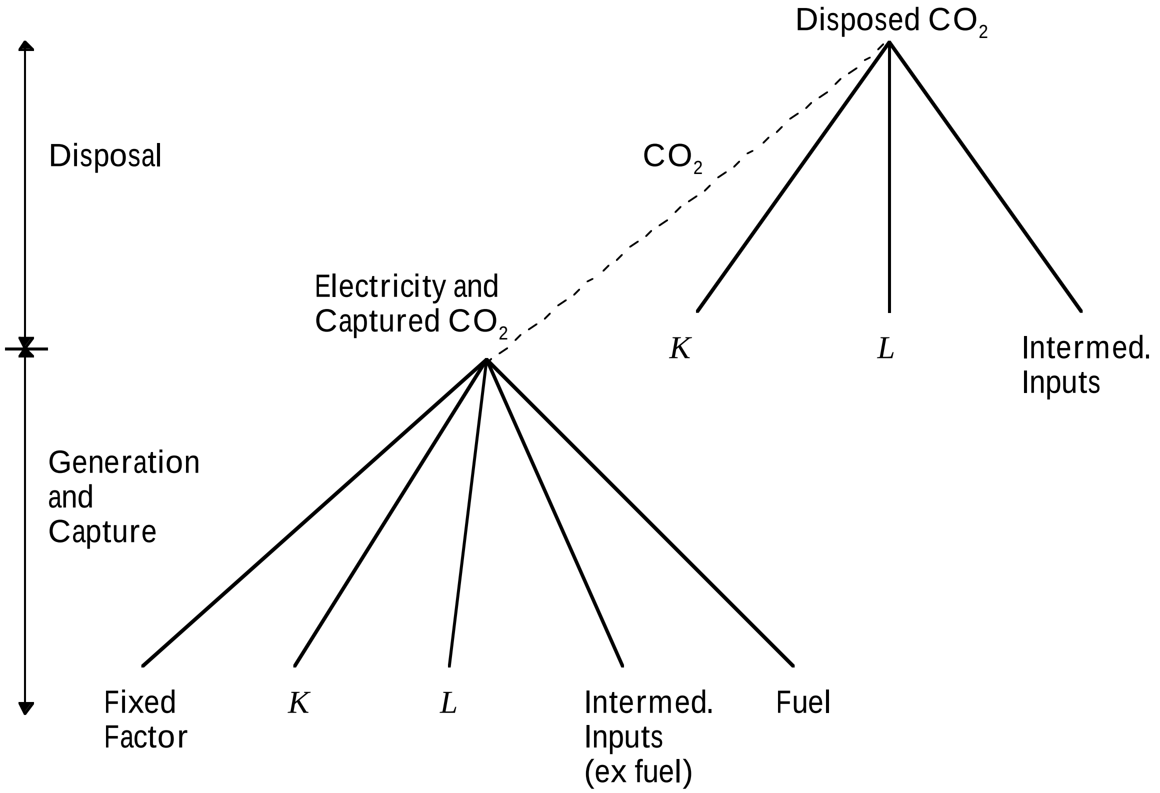

Figure 4. Formulation of electric supply with CO_2 capture and disposal in the EPPA model.

efficiency of a facility with CO_2 capture will be lower than for a conventional power plant. If this efficiency loss is denoted *EL*, for example, then the fuel multiplier is:

$$Multiplier = \frac{1.0}{1.0 - EL},$$

so that a 20% degradation in fuel efficiency per kWh sent out requires 25% more fuel input. This fuel penalty varies according to the technology assumed. For example, the percentage loss is generally estimated to be less for an integrated coal gasifier combined cycle plant than for a conventional coal-fired facility. Given the historical data base of the EPPA model, the factor proportions (*i.e.*, capital, labor, fuel, other intermediate inputs) which are implicit in its representation of the electric supply sector are closest to those of conventional fossil-fired generation. For this underlying generation technology, estimates of the loss in fuel efficiency for CO_2 capture range from around 20% (*e.g.*, Hendriks, 1994) to as high as 35% (*e.g.*, EPRI, 1991). In the calculations reported here we use multipliers of 1.25 and 1.33 (efficiency loses of 20% and 25%), because we are exploring the domain that these technologies must attain if they are to see use as part of a response to the climate change threat.

Of course, to meet the parasitic power demand of the capture equipment, the generation facility must be larger per kWh sent out (and thus more costly) than a conventional plant. Then, to the additional costs of the generation plant itself must be added the capital and M&O costs of the capture process facilities. For this analysis, all these additional costs (the generation plant and all ancillary facilities) are combined into a single premium applied to inputs of capital, labor and intermediate inputs, over and above the cost of an equivalent (in terms of kWh sent-out) conventional fossil-fired power plant.

As with the fuel multiplier, we do not span the whole range of implied capital and M&O cost premia in our calculations, because above certain levels the technology has no potential whatever. Rather, we explore that portion of the cost range where the capture and disposal option might possibly begin to take a significant role. Since it is unlikely that economies of scale, in cost per kW for the larger generation plant, are so strong as to overwhelm the additional costs of capture and disposal, the smallest capital and M&O premium we study is 25%, which is the lowest fuel (and therefore generation plant scale) multiplier. Then we also investigate generation premia of 33%, 50% and 58%. (EPPA models electric supply at the consumption level, so these cost premia at the generation stage are converted into overall sector-level cost penalties on the assumption that generation is 60% of total electricity supply cost, including transmission, distribution, and overhead costs.)

We assume that the capture technology removes 90% of the CO_2 produced. If there is no constraint on CO_2 in a particular period, or no carbon tax assumed to be in effect, then this shadow price (denoted T_{CO2} in Figure 1) is zero. If $T_{CO2} > 0$, then the carbon accounting for the capture and disposal activity occurs in two places in the calculation. The appropriate fossil-fuel supply sector incurs a cost for the CO_2 content of the fuel sent to the Electricity With Capture and Disposal activity (Sector 9 in Table 1), and the disposal activity gets credit for the 90% of this CO_2 which it is preventing from going into the atmosphere. The net result is that supply from Sector 9 incurs the CO_2 shadow price on emissions from 10% of the fuel burned, which actually is released.

4. Patterns of Market Penetration

We consider first a case where the backstop technologies are assumed not to be available. Also, no emissions trading is allowed, so each of four countries or aggregate regions that make up the OECD must meet the 20% emissions reduction on its own. The price of carbon in the resulting simulations is shown in Figure 5.[2] For the USA, the European Community (EEC) and the Other OECD (OOE), the carbon price rises to somewhere between \$200 and \$300 per ton (in \$1990) by 2050. For Japan, the carbon price required to keep the economy on the reduced-emissions path is higher, around twice what it is for Europe. The difference results from the fact that, as modeled within EPPA, the Japanese economy operates at a higher level of energy and carbon efficiency from the start of the simulation period, and stringent internal measures are required to achieve and maintain the assumed emissions reduction. One way of thinking about the economics of CO_2 capture and disposal is in reference to this carbon price: in order to begin to take market share in a particular region, the technology must achieve emissions reductions at cost (per ton C) equal to or below the levels shown in the figure.

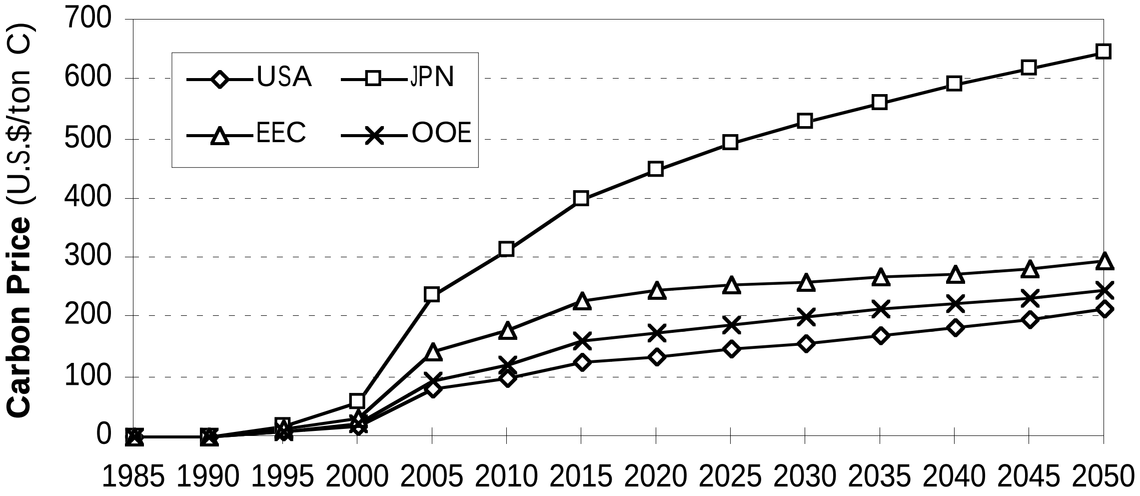

Figure 5. Carbon price under an AOSIS-like protocol (CO_2 reduction by OECD to 20% below 1990 levels by 2010), with no backstops and no trade in emissions permits.

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[2] These shadow prices differ only slightly among cases with different assumed costs of capture and disposal. They differ more substantially if both backstops are assumed to be available, or if trading is allowed, as discussed below.

Table 2. Market penetration in 2050 by capture and disposal technology, under CO_2 reduction by the OECD to 20% below 1990 levels by 2010. No backstops and no emissions trading. Year of first penetration shown in parentheses.

Fuel Multiplier per kWh Sent-Out	Premium on Generation Capital and M&O Cost 25%	33%	50%	58%
1.25	Moderate (2015)	Moderate (2015)	Small (2020)	Zero
1.33	N.A.	Small (2020)	Zero	Zero

Definitions: Zero = No penetration anywhere in 2050. Small = Penetration in only one region, at less than 15%. Moderate = Penetration in 2 or more regions, none over 20%. Large = Penetration in all regions at over 20%. N.A.= Not applicable.

Under these conditions, the market penetration of capture and disposal technology is as shown in Table 2. With a fuel multiplier of 1.33 (25% efficiency loss) or more, and a premium on capital and M&O of 50% or above, this technology does not enter at all between now and 2050 (nor in the period to 2100 either). With the smaller fuel multiplier, and a cost premium as low as 50%, the technology does take some role, achieving entry in the European Community in 2020. As can be seen in Figure 5, under these cost conditions a carbon price of around $250 is required to bring this technology on line in the European Community. It does not penetrate first in Japan, despite the high carbon price there, because the cost of conventional electric power is high in Japan, relative to the other OECD regions, so a capture and disposal option that is some multiple of conventional plant cost has a hard time competing with other ways of reducing carbon emissions.

If the cost premium is lower, say 33% or 25%, the penetration is greater, first entering in the European Community in 2015, and in other regions some five to 15 years later. At the higher fuel penalty of 1.33, the prospects are poor: there is some introduction in the European Community in 2020 but, as noted earlier, a case where the premium on capital and M&O costs is no larger than the fuel multiplier is unlikely. The case where the cost penalty is even lower than the adjustment in plant size (required to compensate for the efficiency loss) is not applicable, as discussed earlier.

It is interesting to note that, even if the capture option enters and takes some role in electric generation, its market share may not grow steadily over time, and indeed it may be lost as cost conditions change. For example, Figure 6 shows the entry of the capture option in the case with a fuel penalty of 1.25 and a cost premium of 33% (classified as “moderate” penetration in Table 2). The technology enters in the European Community in 2015, as noted above, followed by Japan and the Other OECD in 2025. But note that, by 2045, the capture option is beginning to lose market share. This change occurs because the relative prices of the inputs are changing over time, constantly revising the relative competitive position of alternative ways to reduce carbon emissions. Indeed, in this case the capture option continues to decline in market share through the century.

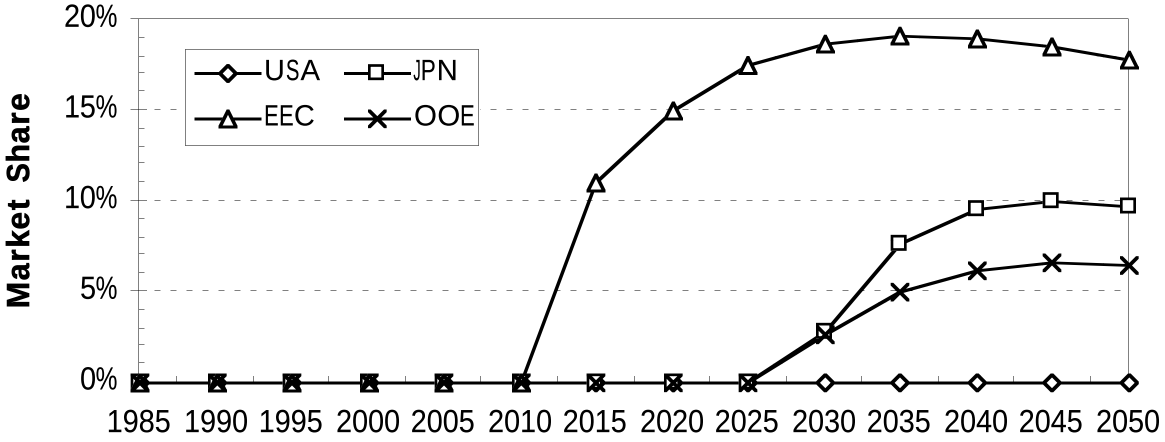

Figure 6. Market shares of capture and disposal technology, by region for a fuel multiplier of 1.25 and a premium of 33% on generation capital and M&O.

Next, we contrast this "no backstops" case with one where both of the backstop technologies (non-carbon electricity and carbon-based fuels) are assumed to come into play if justified under the cost assumptions specified above. The availability of the carbon-free electric source will tend to lower overall emissions, and the new carbon-fuels source will tend to increase them. Under the particular cost assumptions imposed here, the carbon-free electric backstop has the greater influence, so that, in the case with no emissions restrictions, global CO_2 emissions in 2050 are 11% lower than in the no-backstop case. Further, because these baseline emissions are lower, the carbon prices needed to achieve the prescribed 20% reductions in OECD emissions also change. They are lower in three of the regions, but somewhat higher in the Other OECD.

The lower carbon prices would be expected to greatly diminish the prospects for the capture and disposal options, but there is a countervailing effect. The penetration of the backstop electric source tends to lower price pressure on the inputs to both conventional generation and generation with capture and disposal, and to enhance the attractiveness of the latter approach to carbon reduction. These factors combine to produce a picture similar to that without backstops in Table 2, only now it is the Other OECD that is the first place of entry. Indeed, only in the lowest-cost case studied (fuel multiplier of 1.25, cost premium of 25%) does the technology take market share in any other region. The timing of first entry is delayed by 15 to 20 years, as compared with the case with no backstops.

Finally, we consider the prospects for capture and disposal methods if some form of Joint Implementation or "Activities Implemented Jointly" is adopted on a substantial scale. We approximate this case by assuming that the policy of 20% reduction in the OECD is supplemented by an agreement to full global trading in emissions rights. After 2010, each OECD region receives an annual allocation equal to its 1990 emissions *minus* 20%, and non-OECD regions receive an allocation equal to their emissions in the absence of policy,[3] and trading in these rights is allowed. In this case the implicit carbon price rises only to about $50 per ton by 2050, because under the EPPA analysis there are so many low-cost ways to reduce carbon if the task is approached on a worldwide basis. An EPPA-type model, which assumes an efficient trading system with no transactions costs, very likely overestimates the gains from trading, but even taking this factor into account, the implied cost target is far below any level now being discussed for capture and disposal technology.

5. Conclusions

The use of a computable general equilibrium model like EPPA offers insights into the prospects for capture and disposal that would not appear in a project-level engineering analysis, or even in a partial equilibrium analysis of a country's electric power sector. Our assessment starts with a hypothesized emissions control agreement involving restriction by OECD countries, and then explores the cost barriers to market penetration. The results reveal important factors bearing on the future competitiveness of this technology, and they provide a guide to those features of the electricity market that should be kept in mind in planning future R&D on the various components of the capture and disposal technology.

First, it is reasonable to assume that nations will seek the lowest-cost ways to meet emissions targets, and therefore that capture and disposal methods will have to compete with other ways of reducing carbon in all different sectors of the economy. The intensity of this competition is summarized most simply in the carbon price, region by region, that is associated with possible future agreements to restrict CO_2 emissions. Because the capture and disposal of CO_2 from central-station electric power would in any case be only one component of regional carbon restriction, the calculated carbon price is not much influenced by different degrees of penetration by this technology. Therefore, a rough cost goal can be drawn from any study of the general-equilibrium response to policy, without the need for modeling the role of capture and disposal technology itself within the regional or global equilibrium.

Further, even with this single measure, one can see that the challenge faced by capture and disposal technology is dramatically increased if international agreements include cost-saving measures, such as emissions trading. In the calculations discussed here, it is assumed that the trading scheme is global, involving all regions. As shown by Jacoby, *et al.* (1996), substantial cost reductions (and, therefore, reductions in the carbon price) are attainable from trade in emissions

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[3] This assumption is in the spirit of the Berlin Mandate (United Nations, 1995), which specifies that no emissions reductions for non-Annex I countries are to be discussed in the current round of negotiations.

permits even if only a subset of nations participate. Thus, in the face of even limited emissions trading, the cost goals for generation with capture and disposal are very likely beyond reach, at least under policy conditions like those assumed here.

If a nation is under emissions restraint but does not have the opportunity to trade in emissions rights, then another important is the future performance of the so-called “backstop” technologies. Here we considered a carbon-free source (*e.g.*, solar, advanced nuclear, or biomass), and a carbon-fuels source based on shales, tar sands and heavy oils. If these backstops are assumed to be available, the time of first penetration of the capture approach is delayed by 15 to 20 years, as compared to a world without them. Also, the regions where the new technology first becomes economic are different in the two cases. This latter result has implications for research on disposal methods. If different approaches to CO_2 disposal are likely to be preferred in different regions (*e.g.*, some countries have extensive underground reservoirs, or some ocean regions are more stable than others), then the allocation of R&D effort should consider which world regions would be most likely to see first penetration if costs could be reduced, and attention should be focused on the approaches favored there.

Finally, the timing and degree of penetration of capture and disposal technology will be influenced by the general stringency of CO_2 emissions targets which nations accept. We have tested this technology in conditions about as favorable as can be expected in the next couple of decades, but of course future developments in the scientific understanding of climate change could lead to stronger political commitments. If there were no emissions trading, and commitments to speed development of the low-carbon backstop technologies were believed to be unaffected by an increasing stringency of emissions controls, then such developments would brighten the prospects for capture and disposal option. However, as made clear by this analysis, studies of the influence of policy stringency on the prospects for this technology need to take account of the effects of increased climate concern on the design of control policies (*i.e.*, the inclusion of emissions trading), and of the pace of improvements in technologies competing with capture and disposal.

Given the importance of these various general-equilibrium adjustments, it is evident that R&D on capture and disposal should be accompanied by continuing efforts to extend and improve our understanding of how this technology might fit within a future energy supply sector, with its evolving structure of costs and prices.

6. References

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