LESSONS FOR THE IMPLEMENTATION OF POLICIES

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TO MITIGATE CARBON DIOXIDE EMISSIONS

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INTRODUCTION

The analyses of greenhouse gas mitigation conducted for the twelfth Stanford Energy Modeling Forum (EMF 12) have produced a large body of results that is of great potential value for the formation of efficient climate policy. In this paper, we review some of these results, as well as the results of other research on the costs of mitigating emissions of greenhouse gases, in order to draw some lessons for the design and implementation of carbon dioxide (CO_2) mitigation policy.

The model simulations and analyses of the costs of abatement of CO_2 emissions performed for EMF 12 have, with few exceptions, focused on a single policy instrument: a tax on the carbon content of primary fossil energy. The focus of EMF 12 on carbon taxes is not unusual. Most analyses of CO_2 abatement focus on this policy tool. While there are many features of a carbon tax to recommend it, there are alternative policy tools that could be employed to reduce emissions. In this paper, we discuss some of the alternatives, such as carbon permit trading systems and command-and-control regulations, and examine some of the issues that might influence the choice of policy instruments.

We have learned that the uncertainty about the costs of specific mitigation measures that is evident in the various models, and the enormous amount of information required to implement cost-effective CO_2 controls through command-and-control regulations, suggest that market instruments offer potentially large cost savings relative to command-and-control regulations. Also, marginal costs of CO_2 abatement which increase at an increasing rate, and speculation that

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marginal damages from emissions may be flat over relevant ranges, suggest that a carbon tax may be a more efficient policy than a carbon permit market.

The most commonly considered tax for control of CO_2 emissions is the carbon tax. However, alternative taxes could also be used. We consider Btu taxes and ad valorem taxes on fossil fuels as alternatives for controlling CO_2 emissions. We have learned that a carbon tax is a far more efficient instrument for CO_2 mitigation than are other taxes on energy.

In addition to the problem of choosing between alternative policy tools, there is also the problem of allocating emission reductions over time. We examine the evidence on the sensitivity of control costs to the timing of CO_2 emission reductions. The evidence from the model simulations suggests that stabilizing emissions at a constant annual rate, a commonly proposed policy, is unnecessarily costly. The costs of achieving stabilization at current levels by a particular year can be reduced by easing restrictions in early years and tightening restrictions in later years.

These and other lessons that yield insights of value in crafting efficient climate policy are discussed below.

MARKET INSTRUMENTS V. COMMAND-AND-CONTROL INSTRUMENTS

The options for reducing emissions of CO_2 are numerous. Increases in energy efficiency, or reductions in energy input per unit of gross domestic product, can be achieved by the use of more energy efficient appliances, industrial motors, lighting, motor vehicles, and other end-use equipment. New construction can incorporate energy conserving measures and existing buildings can be retrofitted to reduce energy consumption. Production processes can be redesigned to substitute away from energy inputs. Energy efficiency can also be increased by shifting consumption patterns away from goods and services that have relatively energy intensive production processes. Fuel switching can also reduce emissions. Natural gas and oil can

substitute for coal. Nuclear and non-nuclear carbon free energy can be substituted for fossil energy. Finally, CO_2 emissions can be abated by reducing aggregate consumption of goods and services by reducing per capita consumption or by slowing population growth.

The various options can be implemented by the use of either market instruments or command-and-control regulations. Command-and-control regulations target selected end-uses for reductions of CO_2 emissions. For example, Senate Energy Bill S.2166 raises efficiency standards for industrial motors, space heating and cooling equipment, lighting, and selected appliances. Motor vehicle transportation is another end-use that is frequently suggested as a target for emission reductions through more stringent fuel economy standards. These traditional instruments rely on policymakers to select the options for emission reductions and to either mandate their implementation through command-and-control regulations or to encourage their implementation through other methods.

An alternative approach is to control all sources of CO_2 emissions through implementation of a single, broad based, market instrument such as carbon taxes or carbon permits. These market instruments send a price signal to all sources of CO_2 emissions that is equal for all sources. They rely on numerous private individuals to respond to the common price signal by selecting abatement options with costs per unit of abatement that are less than or equal to the price signal. Baring any market imperfections, the result is control of CO_2 emissions at the lowest possible cost.

There are a number of reasons to favor a broad based market instrument for CO_2 control. Emissions come from the combustion of a variety of fuels, using a wider variety of process technologies, for a myriad of end-uses, by millions of sources that are widely dispersed spatially. However, regardless of fuel, process technology, end-use, and spatial distribution, the emitted CO_2 has the same radiative forcing and effect on climate. CO_2 is not directly hazardous to human

health or the environment and so ambient concentrations of CO_2 are of no concern. Thus there is no environmental gain to the use of narrowly tailored policy instruments that focus on CO_2 emissions in particular geographic areas, from particular fuels, process technologies, end-uses, or sources. A reallocation of CO_2 emissions by the market will not alter the climate impacts.

A reallocation of CO_2 emissions by the market will, however, alter the costs of control. The cost advantage of market instruments relative to other policy instruments for emission abatement is well established theoretically, but the size of the potential cost savings will vary with the particular application. In the case of CO_2 control, the promise of cost savings from market instruments is large. The greater the variation in control costs across sources and control measures, the greater the potential cost advantages of a market instrument. The diversity of sources and options for CO_2 control suggest that there is a wide range of control costs for CO_2 mitigation. The implication is that control costs will be highly sensitive to the allocation of CO_2 emissions across sources and control options. Furthermore, the stringency of proposed CO_2 controls that have dominated international discussions, if adopted in the United States, would require abatement in the range of 50 to 250 million metric tons of carbon in the year 2000 and even more in subsequent years. Even with small variations in control costs across sources and options, the cost advantage of market instruments would be substantial at these levels of abatement.

A central authority might attempt to approximate the cost-effectiveness of market instruments by selecting options thought to be low cost and implementing policies that target the selected options. However, because of the enormous diversity of sources and control options, the information requirements for least cost allocation of control responsibility by a central authority are staggering. The task is complex and the economic stakes are high.

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If we examine the source of emission reductions projected as a response to carbon taxes across the models that have participated in EMF 12, we begin to see how difficult is the task of identifying the least cost options. In the Executive Summary of the EMF 12 report, CO_2 reductions to achieve stabilization of US emissions are decomposed into the broad categories of increased energy efficiency, fuel switching, and reduced gross domestic product for the period 1990 to 2010. The majority of reductions come from improved energy efficiency in four of nine models and from fuel switching in the other five. Improved energy efficiency ranges from 0 to 95 percent of the reductions across the models. Alternatively, fuel switching ranges from 5 to 100 percent. If we look at the fuel switching projected by the models, we find that some emphasize nuclear power and others emphasize a variety of non-carbon renewables.

These results display substantial uncertainty regarding the least cost mix of energy efficiency improvements and fuel switching for reducing CO_2 emissions. If there is this much uncertainty regarding the cost-effectiveness of different options even at this aggregate level, how can policymakers ever hope to identify and implement through command-and-control regulations the specific measures that are optimal? An important policy conclusion that is suggested by the range of uncertainty for the sources of low cost emission reductions is that picking least cost control options is best left to the market. Market instruments rely on those who have detailed knowledge of specific sources and who have strong incentives to identify and implement the least cost options to make the required choices.

So far the US No Regrets policy has relied primarily upon instruments that target narrow end-uses for CO_2 mitigation. For the modest reductions that are the goal of the policy, the inefficiency of this approach may not be great. However, if the US embarks on a course of more aggressive mitigation of CO_2 emissions, the potential losses of inefficiently allocating reductions across sources and control options will be large. Reliance on a broad based market instrument

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such as carbon taxes or carbon permits to allocate responsibility for emission reductions can reduce the costs of a CO_2 mitigation policy substantially.

THE TIMING OF CO_2 EMISSIONS REDUCTIONS

In addition to the problem of allocating CO_2 emission reductions across sources, there is also the problem of allocating emission reductions over time. The standardized policy scenarios examined for EMF 12 typically require stabilization of CO_2 emissions at 1990 levels or lower by a specified year. The intertemporal allocations of emission reductions represented by these scenarios are designed neither to maximize social welfare, nor to achieve emission reductions at the lowest possible cost. The motivation for the policy scenarios is to approximate the CO_2 emission policies that have been proposed, or committed to, by various governments.

These proposals, however, are not the product of careful weighing of how changes in the timing of emission reductions might influence the net benefits of abatement policy. The costs of CO_2 abatement and the potential damages of emissions will vary significantly with time. If these differences are investigated and exploited, it may be possible to significantly increase the efficiency of climate change mitigation policy.

An important policy question is whether the costs of CO_2 abatement will increase or decrease if emission reductions are deferred to the future. The answer to this question cannot be deduced *a priori* from theory alone. Because baseline emissions are projected to rise for many decades, stabilization of emissions would require ever increasing levels of abatement. If marginal costs increase with the level of abatement in each period, deferring a ton of emission control from the near term to a more distant time would raise costs, all else equal. Technological innovation and diffusion could either raise or lower the cost of abatement in future years, depending upon whether the cost differentials between carbon intensive and low or no carbon technologies

increase or decrease. Irreversible costs that have been sunk in building the existing stock of energy consuming and producing capital lower the costs of abatement in the distant future relative to abatement in the near term. Current capital investment decisions can either raise or lower future abatement costs. The depletion of oil and natural gas can also either raise or lower the costs of future abatement, depending upon whether the least cost substitutes are synthetics derived from coal or carbon free renewables. Discounting of costs of course favors future abatement relative to current abatement.

Cohan et. al. (1992), Manne and Richels (1992), and Kosobud et. al. (1992) employ models of energy supply and use that embody a variety of assumptions regarding the above factors to examine the control costs of alternative time paths of CO_2 abatement. The results of their model simulations suggest that deferring emission reductions, relative to a policy of stabilization, can reduce control costs substantially. Cohan et. al. and Manne and Richels investigate the sensitivity of control costs to changes in the selected date for stabilizing emissions. Cohan et. al. find that delaying the target date from 2010 to 2015 for stabilizing US emissions at 20% below 1990 emissions can reduce control costs by as much as 20%.[1] Manne and Richels find that delaying stabilization of global emissions at 1990 levels from a target date of 2000 to 2010 can reduce control costs 25%. Delaying until 2020 can reduce costs 40%.

The tradeoff in these scenarios is that delaying stabilization of CO_2 emissions increases cumulative emissions, the rate of emissions in the near term, and potentially the damages from climate change. Delaying stabilization of global CO_2 emissions at 1990 levels from 2000 to 2010 increases cumulative emissions through 2100 by 4% in the Global 2100 model simulations of Manne and Richels. Delaying stabilization to 2020 increases cumulative emissions by 9%. To control for this difference, Manne and Richels compare the abatement costs of two emission time paths that have identical cumulative emissions through 2100.[2] One scenario stabilizes emissions

by 2000 at 1990 levels and holds them constant for all subsequent years. The second scenario defers reductions by permitting "borrowing" of emissions in early years from later years. Emissions are allowed to exceed 1990 levels until 2030 and are subsequently reduced to levels below 1990 emissions. Manne and Richels estimate that control costs are 25% lower when CO_2 reductions are deferred to the future for a savings of $350 billion.

The time path of emissions selected by Manne and Richels as an alternative to stabilization at 1990 levels is arbitrary. Kosobud et. al. (1991) conduct a similar analysis, but rather than specifying an arbitrary time path as an alternative, they allow the market to allocate emissions over time. They conduct a model simulation in which a fixed stock of carbon permits is issued to the market. The permits are valid for a 100 year time period. Suppliers of fossil fuels must acquire, and submit to a central authority, permits for the carbon content of the fuels supplied to the market. Energy suppliers have the flexibility to decide when to "consume" their permits and thereby determine the allocation of emissions overtime. Assuming perfect markets and perfect foresight, this intertemporal allocation of emissions by the market minimizes the costs of cumulative CO_2 reductions. The stock of permits is selected so as to result in the same concentration of CO_2 in 2095 as would result from stabilizing emissions by 2000 at 1990 levels.[3]

In their simulations, the market defers reductions from the near and intermediate term to the more distant future relative to a scenario of constant emissions. The time path of emissions selected by the market, and which achieves the cumulative CO_2 target at least cost, is one that allows emissions to grow initially and remain above 1990 levels until 2050. After 2050, emissions are reduced substantially so as to achieve the CO_2 constraint in 2095. The cost savings relative to the constant emission path is $900 billion.[4]

Kosobud et. al. (1991) also conduct the same experiment for more stringent restrictions on CO_2 emissions. In these experiments they note the same pattern: the market defers emission

reductions from early years to later years, relative to a scenario of constant emissions. The cost savings of these reallocations are even greater for the more stringent restrictions.

One of the results that stands out in their simulations is the difference between the time paths of the carbon permit prices, and thus marginal control costs, for the two emission paths. In the stabilization scenario, marginal control costs fluctuate widely over time, jumping to very high levels when stabilization is first imposed, then declining, and then rising again near the end of the time horizon. When the market is permitted to allocate emissions intertemporally as well as intratemporally, emissions are reallocated in time to take advantage of these cost differentials. The result is that the time path of marginal control costs is smoothed out over time until there is no abatement cost advantage to changing the timing of any unit of emission.

Of course, whether or not deferring emission reductions is an efficient policy depends also upon the damages caused by emissions. Two emission paths that yield identical cumulative emissions by a selected date are not likely to cause the same damages. Except for the terminal date, cumulative emissions, and thus atmospheric CO_2 concentrations and radiative forcing, will differ at each moment in time. If damages in each period are solely a function of the level of realized temperature change, then deferral of a unit of abatement to a later date reduces the benefits of abatement. This would decrease the net benefit of deferring emission reductions. If damages are primarily a function of the rate of temperature change, then the marginal benefit of a unit of abatement from baseline emissions will likely increase over time for several decades.[5] Whether the present discounted value of the marginal benefit increases or decreases will depend upon the discount rate and the rate of increase of the current value of the marginal benefit. Thus, deferral of abatement could either increase or decrease benefits if damages are a function of the rate of temperature change.

Peck and Teisberg (1992) consider the problem of the optimal time path of emissions when both costs and damages are considered. Using a variety of hypothetical damage functions, they simulate the optimal path of CO_2 emissions over the time horizon 1990 to 2200. The damage functions they consider include both linear and cubic specifications that model damages as dependent upon either the level of temperature or the rate of temperature change.[6] In none of their simulations is a time path of constant emissions found to be an optimal policy. For damage functions that are cubic functions of either temperature or the rate of temperature change, their simulations suggest that significant mitigation will be warranted, but not until the middle of the next century. For damage functions that are linear in either the level of temperature or the rate of temperature change, Peck and Teisberg find that little mitigation of CO_2 emissions is warranted.

The general pattern of optimal emission reductions is the same as the results from Kosobud et. al. that consider only control costs and a cumulative emission limit: significant emission reductions are deferred from the near term to later years. Peck and Teisberg also confirm the finding that, for an optimal mitigation policy, emissions follow an irregular time path and emission taxes or permit prices rise smoothly over time. Peck and Teisberg argue that the optimal carbon price rises smoothly over time because the marginal damages of a ton of CO_2 emitted is much the same from one year to the next.[7] The optimal emissions follow an irregular time path because the costs of emission reductions follow an irregular time path. Control cost functions shift over time due to newly available technologies, exhaustion of finite energy resources, and turnover of the stock of energy consuming or producing capital.

The evidence reviewed here suggests that CO_2 control costs can be reduced by deferring emission reductions rather than stabilizing emissions at or near current rates. However, the evidence comes from simulations of relatively few models. These models, of necessity, must make

assumptions regarding key relationships with little empirical support and about which there is considerable uncertainty. It would be desirable to see if the result holds up across more models and across a wider range of assumptions within each model.

It is also essential to give further study to the sensitivity of the optimal path of emissions to alternative assumptions regarding the damages of climate change. In the one study that models damages as well as control costs, consideration of damages does not alter the policy conclusion that stabilization of emissions is not an efficient policy. Marginal cost and marginal damage functions are not constant over time, implying that neither is the optimal rate of emissions. The net benefits of mitigation policy can potentially be increased by exploiting differences in costs and benefits of CO_2 abatement across time. The results of Peck and Teisberg imply that deferring abatement from early years to later years can increase net benefits relative to a policy of stabilization. This conclusion, however, is based upon hypothetical damage functions and is only illustrative of a possible outcome. Further study is needed to see if the result is robust across a wider range of assumptions for both damage functions and costs.

MARKET INSTRUMENTS: PRICE V. QUANTITY RULES

A carbon tax sets the price of a unit of carbon and allows the market to determine the quantity of carbon, and thus CO_2 emissions. A carbon permit market sets the quantity of carbon and allows the market to determine the price. If the costs of CO_2 control are known with certainty, and markets function perfectly, then identical results can be achieved with either instrument. However, the costs are not known with certainty and the two instruments will not perform identically in application.

A primary difference in the performance of the two instruments is the degree of certainty that the central authority has over the costs of emission reductions versus the quantity of

reductions. By setting the level of a carbon tax, the central authority sets the upper limit for the cost per ton of the marginal emission reductions. However, the quantity of emissions that can be abated at a cost per ton that is equal to or less than the carbon tax is uncertain. The central authority will therefore be uncertain of the quantity of emissions that will result from a chosen tax rate. Alternatively, the central authority can set the quantity of emissions by selecting the quantity of carbon permits to issue or auction. However, the costs of the chosen level of reductions will not be known with certainty.

Weitzman (1974) has examined the conditions under which one type of rule might be preferred to the other when costs and benefits are uncertain. He showed that, if the marginal damages from emissions are more sensitive to changes in the level of emissions than are marginal abatement costs, then the expected net benefits of a quantity rule are greater than for a price rule. If expected net benefits is accepted as the criterion by which an instrument is to be chosen, then a quantity rule is to be preferred. If, alternatively, marginal abatement costs are more sensitive to changes in emissions than are marginal damages, then a price rule is preferred.

Current evidence on CO_2 control costs suggest that they are highly sensitive to the level of abatement. Results from the standardized policy scenarios analyzed by modelers participating in EMF 12 find that marginal costs increase at an increasing rate for reductions in annual CO_2 emissions. In some models the difference in marginal costs for stabilizing annual emissions at 1990 levels and cutting them 20 percent below that level exceeds 100 dollars per ton of carbon.

Unfortunately, we know very little about the potential physical and economic damages caused by CO_2 emissions. There is wide agreement that anthropogenic emissions of CO_2 are raising the atmospheric concentration of CO_2 and that continuing this trend will lead to increases in mean global temperature with a high degree of probability. However, there is considerable uncertainty about future emissions of CO_2, the timing and magnitude of warming that will result

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from emissions, changes in other climate variables, regional variations in climate variables, and the physical effects of changes in climate. Valuation of potential effects to estimate economic damages is hampered by uncertainty regarding economic variables and human responses (such as adaptive responses in anticipation of, or reaction to, climate change), and by methodological problems for valuation of many of the non-market effects. The problem is made even more difficult by the long time horizon over which CO_2 emissions will influence climate and our meager abilities to predict how societies and natural environments will change over time, either with or without changes in climate.

When CO_2 abatement policy is viewed as a single decision for a very long time horizon, Weitzman's analysis cannot help us to choose between a carbon tax and a carbon permit market. Damages might be highly nonlinear, or exhibit discontinuities, at temperatures and rates of temperature change that might be experienced in the next century and beyond. We cannot say whether marginal damages are more or less responsive to changes in emission levels than marginal costs over the very long term. However, we need not decide today on a tax or emission path for the next century or longer. In fact, it is not rational to do so. A better strategy is to approach CO_2 abatement policy as a sequential decision process in which choices are made for shorter time horizons and reevaluated periodically in light of new information and circumstances.[8] For example, we might consider the problem of selecting an abatement policy for the next ten years. If we decide that abatement of emissions is prudent over the coming decade, should these reductions be implemented via a carbon tax or a carbon permit market?

The marginal contribution of ten years of emissions to atmospheric concentrations of CO_2 and to mean global temperature is relatively small. Even deep reductions in emissions in the coming decade will have little impact on future temperature. It may be reasonable then to postulate that the marginal damages avoided per ton of CO_2 abatement would be roughly

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constant over the range of plausible abatement that might be undertaken over the course of a decade.

To see this, consider an emission path that leads to a doubling of CO_2 from preindustrial levels to 560 ppm in year t. Along this path, emissions of CO_2 over the coming decade are 100 gigatons of carbon (GtC). Assuming that a doubling of CO_2 raises equilibrium temperature 4.5° C, and that 50% of emissions in the next decade remain airborne in year t, abatement of 10% of CO_2 emissions will reduce equilibrium warming less than 0.03° C in year t. Abatement of 30% of CO_2 emissions over the decade will reduce equilibrium warming in year t by approximately 0.08° C.[9]

The estimated difference in the avoided warming for a 10% and 30% reduction in the ten years of CO_2 emissions is 0.05° C. The marginal warming avoided per gigaton carbon abatement is virtually constant at less than 0.003° C over the postulated range of emission abatement. If damages are a function of the level of temperature, the damage function would have to be *highly* non-linear in temperature for marginal damages per ton of carbon to vary significantly over the range of 70 to 100 gigatons of emissions for the decade.[10]

If, as we speculate, marginal damages are roughly constant for the range of abatement that might be targeted over a decade, the expected loss of making an error in the selection of a tax path would be relatively low. If the tax rates for the decade are set too low, the excessive warming for future periods would likely be small, and so too, presumably, would be the excessive damages. In contrast, the expected economic loss of making an error in the selection of a quantity rule capping CO_2 emissions for the decade is relatively high. If the quantity of permits issued for the decade is too low, the excessive level of control that would be enforced could be very costly given the sensitivity of marginal control costs to levels of abatement.[11]

The US reluctance to commit to targets and timetables for greenhouse gas emission abatement is consistent with these observations. Such targets have the characteristic of quantity rules which pose uncertain costs. If the costs of abatement are underestimated, adherence to an emission target may cost substantially more than bargained for and cause significant hardship. If the costs are overestimated, opportunities to reduce large quantities of emissions cheaply may be foregone.

The current *No Regrets* policy of the US shares a characteristic with a price rule. Rather than target a specified quantity of emission abatement, these policies seek to achieve whatever quantity of abatement that can be had at or below a selected price.[12] We may be displeased and discover that less abatement than anticipated is forthcoming at the chosen price. But we will not go broke as we make this discovery. Alternatively, we may be pleasantly surprised to learn that more abatement than anticipated is purchased and that the bill is not onerous. In either case, the committed warming after ten years of such policies would not be much different than if we chose a quantity rule with the same *ex ante* cost. If the marginal damages are roughly constant over this narrow range of warming, then damages will not vary dramatically across outcomes.

Our tentative conclusion is that the expected net benefits of a short-term CO_2 abatement policy are greater if implemented with a carbon tax than if implemented with a carbon permit market. We say tentative because of our ignorance of the damages that might be caused by climate change. A number of uncertain factors such as threshold effects and high sensitivity to the rate of warming could produce marginal damages that are more responsive than we have speculated. These issues need to be studied further, both to aid us in deciding how much mitigation is prudent and in choosing the proper policy instrument. However, even if these concerns prove true, it may still be the case that, in the neighborhood of current temperatures

and rates of temperature change, a carbon tax is the more efficient instrument for implementing CO_2 abatement in the near term.

LEVEL OF THE MARKET

A carbon tax or permit market can be implemented at a number of points in the market. For example, energy consumers could be taxed or required to obtain permits for the carbon content of the energy they consume. Alternatively, taxes or permit requirements could be imposed upon energy suppliers. This could be done at the level of primary production, secondary processing, or distribution to end-users. The question of what level of the market is the most cost-effective for implementation of these market instruments has been examined by Heister and Michaelis (1991), Scheraga and Leary (1991,1992), Smith et. al. (1992), and Leary and Scheraga (1992).

Heister and Michaelis argue that liability for permits should be placed upon suppliers of fossil energy. Because consumers of fossil energy far outnumber suppliers, administrative costs and opportunities for cheating would be lower if liability is placed with suppliers. Smith et. al. also conclude that the administrative costs of a carbon permit market that places the liability for permits with all consumers is prohibitive. As an alternative, they also investigate a consumer permit market that limits participants to only industrial energy consumers from the sectors emitting the most CO_2. This would reduce the number of market participants from millions to under 20,000 in the US and greatly reduce administrative costs. However, they reject this strategy because it would neglect many opportunities for low cost reductions from residential, commercial, and transportation end-uses and would not be cost-effective. These other sectors contribute 40 percent of total CO_2 emissions in the US.

Smith et. al. (1992) also examine alternative levels of the market on the supply side for implementation of a carbon permit market. They consider implementation at the levels of primary production, secondary processing, and distribution to end-users. Each of these options has three characteristics in common. First, the number of market participants would be less than 10,000, implying much lower administrative costs than a carbon permit market for consumers. Second, nearly all emissions are subject to control so that there are few low-cost emission reductions that would escape coverage. And third, concentration in the permit market is not expected to create market power problems. Smith et. al. conclude that these characteristics suggest that any one of the three supplier permit markets would be more cost-effective than a consumer permit market. However, their analysis does not unambiguously point to any one of the various levels of the supply chain as the optimal level for permit trading.

Their analysis does, however, identify factors that would influence the relative cost-effectiveness of the different options. One of the factors is the cost of failing to exempt feedstock uses of energy that do not result in emissions for carbon permits and the administrative costs of exempting these feedstocks for different market designs. A second factor is the cost of failing to include the emissions from secondary processing and the administrative costs of including these emissions for different market designs. A third factor is the cost of monitoring carbon to verify permit liabilities at different levels of the vertically integrated energy market. These same problems are also relevant for the cost-effectiveness of carbon taxes implemented at the various levels of the market.

In Scheraga and Leary (1991,1992), we examine the cost-effectiveness of carbon taxes and carbon permit markets at two different levels of the market using simulations from the Gemini model. The levels of the market we examine are primary production and distribution to end-users. In our simulations, the costs of reducing emissions are 20 to 40 percent lower when carbon

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taxes or permits are implemented at the primary producer level than when they are implemented at the distribution level.

The reason for the higher costs when permits or taxes are implemented at the distribution level is that emissions from secondary energy processing escape liability. Because the Gemini model baseline projection includes relatively large quantities of synthetic fuels derived from coal, these fugitive emissions are significant. Emissions from petroleum refining are also relatively large. The leakage of these emissions from liability for permits or taxes implies that greater reductions from other sources are required to reach a chosen emission path. This raises the cost of hitting the target. This effect seems to be more important than the inclusion of all feedstocks in liability for permits and taxes when these policies are implemented at the level of primary production.

Our results suggest that the level of primary production is the most cost-effective point at which to implement a carbon tax or carbon permit market. However, more evidence is needed before a conclusion can be drawn. The cost simulations for implementation at different levels of the market come from a single model. It would be useful to see if other models and methods either verify or contradict our findings. Further investigation of the monitoring problems posed at different market levels is also needed.[13]

ALTERNATIVE TAX INSTRUMENTS FOR CONTROL OF CO_2

The most commonly proposed and analyzed tax for control of CO_2 emissions is the carbon tax, but alternative taxes could be used to accomplish the same goal. Two taxes on fossil energy that have received some attention for reduction of CO_2 are a Btu tax and an ad valorem tax. Btu and ad valorem taxes have been considered for selected forms of energy and for broad application to all forms of energy for a variety of other policy goals. These taxes, when applied to fossil

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energy, can also reduce CO_2 emissions by raising the price of fossil energy and reducing fossil energy consumption.

A carbon tax can be expected to be a more cost-effective instrument for CO_2 control than the Btu and ad valorem taxes on theoretical grounds. Cost minimization requires that the marginal costs of CO_2 reductions be equated across all sources. Because CO_2 emissions are very nearly proportional to the carbon content of fossil fuels burned, a tax on the carbon content of primary energy would satisfy this condition. Btu content of primary fuels is less well correlated with CO_2 emissions. A Btu tax therefore imposes a different tax per ton of CO_2 across the different fuels and results in different marginal costs of CO_2 reductions across fuels. An ad valorem tax results in an even wider divergence of marginal costs per ton of CO_2 abatement across the different fuels.[14] Because Btu and ad valorem taxes fail to equate marginal costs across fuels, they are not cost-effective instruments for CO_2 control. Jorgenson and Wilcoxen (1992) and Scheraga and Leary (1992) provide estimates of the efficiency losses of choosing these alternative taxes in place of a carbon tax. The estimated losses suggest that selection of a policy instrument other than a carbon tax, or carbon permit, may be very costly.

Jorgenson and Wilcoxen compare the impacts of carbon, Btu, and ad valorem taxes when they are used to stabilize US CO_2 emissions at 1990 levels. In their simulations the taxes are imposed at the primary level of production. They find the carbon tax to be the least disruptive of the three taxes in terms of its impact on gross national product (GNP). They estimate that a carbon tax that stabilizes emissions at 1990 levels would reduce GNP by 0.5 percent in 2020. In comparison, the GNP loss of a Btu tax is 0.6 percent, 20 percent greater than for a carbon tax. An ad valorem tax reduces GNP 1.0 percent, twice the loss of a carbon tax.[15]

Scheraga and Leary (1992) also found a carbon tax to be substantially less costly for CO_2 control than Btu or ad valorem taxes. The annualized cost of stabilizing CO_2 emissions with a

carbon tax is estimated to be $123 billion. The annualized cost of achieving the same emissions goal with a Btu tax is $173 billion, or 40 percent more. The cost of stabilizing emissions with an ad valorem tax is estimated at $450 billion, or more than three times the cost of stabilization with a carbon tax.[16]

THE EFFICIENCY VALUE OF CARBON TAXES

In addition to creating an incentive to reduce CO_2 emissions, a carbon tax also generates revenues. These revenues might be used to fund new public spending, reduce government borrowing, or to reduce revenues raised by other tax instruments. How the revenues are used can significantly alter the economic impacts of a carbon tax.[17]

The various taxes used to collect government revenues create distortions that result in substantial efficiency losses. If revenues from a carbon tax are used to reduce the more distortionary taxes, some of the efficiency losses of the existing tax structure might be offset. Shackleton et. al. (1992) examine this issue and conclude that the efficiency value of carbon taxes is potentially large. In simulations conducted with a variety of models of the US economy, they find that the efficiency gains from reducing taxes on capital with the revenues raised by a carbon tax may be more than enough to offset the direct negative impact of the carbon tax on GNP. Using carbon tax revenues to reduce taxes on labor or income, or to reduce the federal budget deficit, also provide efficiency gains, though the gains are more modest. Shackleton et. al. conclude that, if carbon tax revenues are used to offset some of the distortions of the existing tax system, the cost of a carbon tax, measured as a loss of GNP, can be reduced to zero. The cost might even be negative if the revenues are used to cut taxes on new capital formation.[18]

The use of revenues is clearly an important component of any carbon tax policy and the use of these revenues to reduce or eliminate other distortionary taxes may be a desirable policy.

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However, the value of a carbon tax as an instrument to reduce the efficiency losses under the current tax system must be interpreted cautiously. Abatement of carbon emissions is not costless. It will require changes in the production and use of energy that will raise the costs of energy services and the costs of producing other goods and services.

As discussed in Scheraga et. al. (1992), it would be inappropriate to argue for a carbon tax purely on the basis of its environmental impact if it is not justifiable on the basis of conventional cost-benefit analysis. In the assessment of joint policies that involve both environmental programs and tax reform, it is reasonable to require that consideration be made of whether proposed environmental programs make sense by themselves, whether they be implemented as part of a more comprehensive, integrated policy package or not, and to require that we implement only such programs as meet conventional -- or at least purely environmental -- cost-benefit analyses.

However, if it is decided that a carbon tax is justifiable as a tool to internalize environmental externalities, then we should aggressively seek out the best use for the revenues it would generate. The results of Shackleton et. al. suggest that one possibility, reducing taxes on capital, may yield high returns.

A COMPREHENSIVE GREENHOUSE GAS POLICY V. A CARBON EMISSIONS POLICY

Cristofaro and Scheraga (1991) have argued that the most cost-effective approach to mitigating climate change is one which considers anthropogenic emissions of *all* greenhouse gases. If mitigation policy is limited in scope to the control of CO_2 emissions, many potentially low-cost options for controlling other radiatively important gases will be neglected. The result of such a policy would be an inefficiently high cost of achieving any chosen climate change goal. By widening the scope of mitigation policy to include all radiatively important anthropogenic gases, it is possible to reduce the costs of climate change mitigation. The concept of a comprehensive

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greenhouse gas policy can be extended to include not only emission controls for all greenhouse gases, but also development and enhancement of sinks to remove gases from the atmosphere.

In this paper we have limited our focus to the control of CO_2 emissions from fossil fuels. This is not necessarily at odds with the prescription for a comprehensive climate change mitigation policy. A comprehensive mitigation policy does not imply that all mitigation measures be implemented via a single market instrument. Extending the scope of a market instrument to encompass more mitigation options can help to reduce the control costs of a mitigation policy by providing a common price signal across more options. However, it also adds to the administrative complexity and costs of the instrument. It is plausible that an efficient, comprehensive mitigation policy is one that is a composite of instruments targeted to different greenhouse gases.

Control of emissions of CO_2 from all domestic fossil fuel combustion is a good candidate for implementation via a single market instrument. Emissions have identical global warming potential regardless of their sources and all control options can be reduced to a single, common element: reduction of carbon input. Regardless of source, monitoring emissions of CO_2 from fossil fuels can be performed with accuracy and relative ease by monitoring the carbon content of fuels consumed. All of these factors simplify the administration of a market instrument that would constrain all CO_2 emissions from fossil energy consumption.

Extension of a market instrument for control of CO_2 emissions to encompass additional gases or carbon sinks is not a simple matter. Monitoring emissions of other greenhouse gases, or net uptake of carbon sinks, may be less accurate and require more complex and costly efforts that may vary by gas, process technology, and source. In the case of ozone, assigning liability for contributions to specific sources is an intractable problem. The Montreal Protocol already restricts the production and use of CFCs and inclusion of CFCs in a market with CO_2 is likely to meet with resistance. Inclusion of multiple gases in a single market would require fixing

exchange rates between gases based upon relative contributions to warming. However, the contributions of different gases to warming are uncertain and estimates of global warming potentials (GWPs) change with new scientific knowledge. Expectations of changes in GWPs and exchange rates introduces uncertainty to a market for multiple gases which may reduce the efficiency of the market. It is possible that segmented markets for each gas might perform more efficiently by insulating transactions for one gas from uncertainty regarding the value of emissions of other gases. Each of these factors can create problems for implementing a climate mitigation policy with a single market instrument.[19]

Because of the difficulties of encompassing all mitigation options under a single market instrument, it may be optimal to deal with CO_2 emissions from fossil fuels separately via a carbon tax or carbon permit market and to target other instruments at other mitigation options. A drawback to a mitigation policy that is a composite of instruments targeted to individual gases is that policymakers cannot rely on a single price system to guide atomistic choices toward a least cost mix of emission controls for the various gases and sink enhancements. If policymakers wish to achieve mitigation goals at the lowest possible cost, they will need to explicitly weigh the costs of different categories of options and attempt to assemble a cost-effective package of policy instruments. This promises to be a challenging task. A carbon tax or a carbon permit market would be a good start for assembling a cost-effective package.

CONCLUSION

The ongoing research on the costs of CO_2 mitigation has begun to yield insights that can be of value in crafting an efficient CO_2 mitigation policy. Some of the lessons we have learned are that the costs of mitigation are highly sensitive to the time path of emissions and that marginal control costs increase at an increasing rate with respect to the level of CO_2 abatement.

We have learned that Btu and ad valorem energy taxes are substantially more costly instruments for CO_2 control than is a carbon tax and we have some evidence to suggest that a carbon tax is least costly when applied at the level of primary energy production. We have learned that the costs of a carbon tax can be compensated by gains from use of the tax revenues to offset distortionary existing taxes. We have also learned that we cannot identify the least-cost options for CO_2 mitigation with a high degree of certainty given the information available to us.

From these lessons we are beginning to bring into focus a picture of an efficient CO_2 mitigation policy. The enormous information burden for implementing cost-effective CO_2 controls through command-and-control regulations dictate reliance on a broad based, market instrument. Because they create a common price signal per ton of CO_2 abatement, a carbon tax or carbon permit market are the optimal market instruments. Although the potential damages of climate change are poorly understood, there are reasons to speculate that a carbon tax, at least for the near term, would yield greater expected net benefits than would a carbon permit market. A carbon tax, if adopted, should be imposed upon suppliers of energy and not consumers. The lessons also suggest that a policy of stabilization of CO_2 emissions is not an efficient policy. If we increase our understanding of intertemporal differences in the costs and benefits of CO_2 abatement, and exploit the differences, the potential welfare gains of mitigation might be increased dramatically. We still have much to learn, but the picture is getting clearer.

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ENDNOTES

1. Cohan et. al. (1992) also examine alternative time paths of emissions that satisfy the condition that emissions in 2010 be 20% less than 1990 emissions. They find that a time path that defers most of the reductions until after 2000 is 30% less costly than a time path that forces most of the reductions to occur prior to 2000. They also find that delaying the start date for phasing in reductions by five years, as well as the target date for a 20% reduction, will significantly lower costs. A primary reason is that the delay allows greater reliance on renewable technologies and more energy efficient technologies that are not projected to be commercially available until after the year 2000.

2. This does not guarantee that the avoided damages of climate change will be identical. .

3. Carbon taxes can also allow the market to determine the time path of emissions. In the emission permit market analyzed by Kosobud et. al., a central authority sets a limit on cumulative emissions over a selected time horizon and lets the market determine the emissions in each period and the marginal control cost in each period. Alternatively, a carbon tax path can be specified, and thereby a marginal control cost path, and emissions allowed to adjust to the tax rates in each period. If there is no uncertainty regarding control costs, a carbon tax path could be selected to yield emissions that are identical to those of a cumulative emission permit market. The results of Kosobud et. al. suggest that, to approximate least cost control of cumulative emissions, the selected carbon tax path should rise smoothly over time so as to hold constant the present discounted value of the marginal cost of CO_2 emission abatement.

4. Intertemporal allocation of CO_2 emissions by a market instrument can help to minimize the control costs of cumulative emission abatement. However, holding fixed the quantity of cumulative CO_2 emissions while allowing emissions to be reallocated over time does not hold fixed the damages from emissions. Different emission time paths will yield different time paths of temperature and other climate variables, and therefor a different time path of damages from climate change.

In Section II we argued that CO_2 is a good candidate for control by a market instrument because intratemporal allocation of emissions across sources would reduce control costs while not altering the environmental damages. This is not the case for intertemporal allocation by the market. Whether or not allocation of emissions across time by the market is an efficient policy when the potential damages of climate change are considered needs further study.

5. If the damages of climate change are a function of the rate of temperature change, marginal benefits of abatement can be expected to increase over time for two reasons. First, baseline emissions are expected to grow for several decades, implying an increasing rate of temperature change over time. Assuming that marginal damages are an increasing function of the rate of temperature change, the marginal benefit of abating a unit of CO_2 in a future year, when the rate of emissions will be greater, is greater than the marginal benefit of abating a unit in the present. Also, marginal damages are likely a positive function of income. As incomes increase over time, the marginal damage avoided by a unit of abatement increases.

6. Nordhaus' upper bound estimate of potential damages for the US of 2 percent of gross domestic product for a 3° warming is used as a benchmark for calibrating the various damage functions. Peck and Teisberg extrapolate this to the rest of the world.

The damage functions employed by Peck and Teisberg specify damages to be smooth functions of either the level of mean global temperature or the rate of change of mean global temperature. However, temperature is not the only climate variable that may influence damages, and may not even be the most important variable.

7. As Peck and Teisberg (1991) point out, a ton of CO_2 emitted this year raises temperature over a time span of one or two centuries that is nearly identical to the time span for a ton emitted the following year. This implies that the marginal damage from warming caused by a ton emitted in one year must be nearly the same as for a ton emitted in an adjacent year.

Another reason for smoothly rising marginal damages in the simulations is the assumption that there are no discontinuities or thresholds in the damage functions. Marginal damages are assumed to be smoothly differentiable in temperature or the rate of temperature change. There is considerable scientific uncertainty regarding possible thresholds for temperature or rates of temperature change. These uncertainties can have important implications for climate policy.

8. Hammitt and Lempert (1992) examine sequential policies for abating CO_2 emissions.

9. These calculations are based upon the simplified relationship:

$$\Delta T = \Delta T_d / \ln 2 * \ln [CO_2(t)/CO_2(0)]$$

where ΔT is the equilibrium, global average change in surface air temperature, ΔT_d is the equilibrium temperature change predicted for a doubling of CO_2, $CO_2(t)$ is the atmospheric concentration of carbon dioxide at time t, and $CO_2(0)$ is the initial concentration of CO_2 (National Research Council, 1983). The calculations ignore the possibility of any feedback effects that might release large quantities of carbon, for example from the ocean, to the atmosphere.

10. There is considerable scientific uncertainty regarding potential thresholds in the carbon cycle, the climate system, or physical responses of the environment to climate change. If such thresholds are approached, the damages of surpassing them may be extraordinarily high. There is also uncertainty about the sensitivity of natural environments and managed resources to the rate of climate change. If damages are a nonlinearly increasing function of the rate of temperature change, then it is possible that marginal damages can vary importantly with changes in the rate of emissions over a single decade. These factors could produce marginal damages that are more sensitive than we have speculated to changes in emissions over short time horizons.

11. Of course it is also possible to set tax rates too high or to cap emissions at too high of a rate.

12. In the case of the *No Regrets* policy, the implicit price is zero. An underlying presumption of the No Regrets policy is that market imperfections raise barriers to abatement options that would otherwise be implemented by self interested parties. If the barriers are removed or diminished, then some of these options might be implemented at zero or negative cost.

13. Smith et. al. (1992) examine other issues in addition to cost-effectiveness that might be relevant to the choice of market level for implementation of carbon permits or carbon taxes. For example, they examine the distribution of costs across energy consumers and suppliers and the geographic distribution of costs.

14. In simulations with the Gemini model, stabilization of CO_2 emissions at 1990 levels is achieved with a carbon tax of $120 per ton of carbon, a Btu tax of $3.30 per MMBtu, and an ad valorem tax of 125 percent at the distribution level. A Btu tax of $3.30 per MMBtu imposes implicit taxes per ton of carbon of $122 for coal, $154 for oil, and $228 for natural gas. Based upon 1990 prices, an ad valorem tax of 125 percent imposes implicit taxes per ton of carbon of $117 for coal, $367 for oil, and $412 for gas.

15. In each of the tax policy simulations, the revenues from the energy taxes are rebated as a lump sum by lowering the average tax on labor so as to hold the budget deficit constant.

16. The carbon tax is implemented at the level of primary production, while the Btu and ad valorem taxes are implemented at the distribution level. Each tax is implemented at the market level at which it is most cost-effective.

17. If carbon permits are auctioned by the government, the same analysis applies.

18. These results were obtained for a carbon tax that starts at $15 per ton in 1990 and grows at 5% annually to $39.80 per ton in 2010. However, if higher carbon tax rates are employed, diminishing returns would likely weaken the results.

19. Some of the problems presented by integrating all greenhouse gases and sinks into a single permit market are discussed by Heister and Michaelis (1991) and Smith et. al. (1991).