Controlling Carbon Dioxide: An Analysis of Competing Marginal Effects

*By Peter Hartley and Kenneth B. Medlock III**

Introduction

When considering the control of carbon dioxide (CO_2) emissions, policy-makers are faced with a difficult decision. On the one hand, actions can be taken today to restrict the flow of emissions into the atmosphere, which by most accounts would result in a considerable economic loss. On the other hand, action can be delayed, which may or may not result in considerable social and economic loss at some point in the future. In principle, action should only be taken when the marginal costs of that action exactly offsets the marginal benefits (for the moment we are disregarding the effects of discounting in a dynamic setting). Therein lies the difficulty. There is considerable uncertainty about the potential costs and benefits of the problem at hand.

There exists a corollary to the problem of deciding when and if to enact CO_2 abatement measures in economic theory. The decision to abate CO_2 can be viewed as a problem of investment under uncertainty because it demonstrates some key characteristics of such a problem. First, once we decide to take abatement measures, the cost borne in the form of lost economic growth cannot be recovered, and is thus at least partially irreversible. Second, there is uncertainty over the future rewards of undertaking this investment project. And third, we have to make a decision about the timing of the investment. Thus, when analyzing the decision to abate CO_2, we must consider costs and benefits, and how costs and benefits change as time progresses.

Some scientists claim that the accumulation of CO_2 in the atmosphere will harm future generations by raising atmospheric temperatures. A number of factors, however, lend to a persistence of uncertainty concerning not only the possible effects of CO_2 on climates, but also concerning the natural forces that have produced substantial fluctuations in past climates. Delaying control of CO_2 emissions allows us to take advantage of future research. Evidence may show that CO_2 emissions are relatively harmless or even beneficial on net, and that people need not reduce their use of fossil fuels. Given our current understanding of the effects of CO_2, fear of global climate change does not justify an increase in the taxes on fossil fuel combustion and the concomitant adverse effects on economic growth and prosperity. Economic progress directly increases the welfare of future generations and provides resources necessary to developing new technologies and improving the environment. Technological change eventually will reverse the accumulation of CO_2 in the atmosphere without constraining energy demand or lowering economic growth.

Delaying action to abate CO_2 allows us to determine whether structural and technological changes that accompany economic growth will abate CO_2 emissions in amounts sufficient to alleviate concerns. As economies grow, consumption and output shift away from more energy-intensive industrial goods to less energy-intensive services. Moreover, current rates of technological advance in using alternative energy resources suggest that, within decades, fossil fuels are likely to provide a much smaller proportion of total energy requirements than they do now. By the middle of this century, innovations in solar and fuel-cell technologies could largely eliminate the use of coal, oil or natural gas to generate electricity. In addition, advances in the efficiency of fossil fuel combustion can reduce CO_2 emissions, even as such advances allow fossil fuels to remain price competitive. For example, gas-electric hybrid motor vehicles could increase private transportation efficiency by up to a factor of three, which, for a fixed number of miles driven, would reduce demand for gasoline by 67%. Such a development would greatly reduce fossil fuel consumption in industrialized countries, where energy demand for transport is currently a large proportion of total energy demand.

Delaying control also permits a more gradual adjustment to higher energy prices. There has been extensive research investigating the effects of oil prices on the macroeconomy. Rapid oil price increases are highly correlated with reductions in real GDP growth.[1] A large permanent rise in energy prices would make substantial amounts of otherwise usable capital obsolete. A gradual rise in energy prices would allow existing capital to continue providing productive services as it is phased out and replaced by more energy-efficient alternatives. Since only the gradual accumulation of CO_2 matters, future control at lower cost is an attractive alternative to current control at high cost.

Controlling CO_2 emissions can be viewed as an investment project. Up-front costs are incurred in order to deliver possible future benefits. We develop a simple framework in order to illustrate some of the important features of fossil fuel price increases brought about in order to reduce CO_2 emissions. Taxes on fossil fuels constrain economic growth by reducing the consumption of energy. A possible offsetting benefit, however, is that CO_2 emissions would be reduced. In weighing the costs and benefits of adopting a carbon reduction policy, one must sufficiently account for the marginal contributions of various beneficial and detrimental factors. For example, the modeling framework that we present indicates that if the net marginal effects of CO_2 on the biosphere and of fossil fuels as an energy source are positive at the optimal level of CO_2, then the marginal effects of additional CO_2 on the climate must be negative. Contrary to popular impressions, therefore, it would not be optimal to reduce CO_2 to a level where it has negligible harmful effects on the climate.

Some Sources of Uncertainty

Over the past 100 years, industrial activity, the demand for electricity, and the demand for transportation services have increased exponentially. The degree to which humans rely on fossil fuels to provide energy for these things is indicated by the fact that in 1997 fossil fuels provided about

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* Peter Hartley is Chair, Economics Department, Rice University and Kenneth B. Medlock III is Baker Institute Scholar, James A Baker III Institute for Public Policy, Rice University. The authors may be contacted at: Rice University, Economics Department MS-22, P.O. Box 1892, Houston, TX 77251-1892, phone: 713-348-2089, e-mail: medlock@rice.edu This is an edited version of their paper presented at the 24th Annual IAEE Conference in Houston, TX, April 25-27. It is best viewed as a summary paper. The companion paper entitled "Controlling Carbon Dioxide: Let's Wait and See" is available from the authors upon request.

[1] See footnotes at end of text.

86% of primary energy requirements globally. Since carbon dioxide (CO_2) emissions are an unavoidable by-product of fossil fuel combustion, modern economic activity has resulted in an increase in the concentration of CO_2 in the atmosphere. From 1958 to present, the concentration of CO_2 in the atmosphere has risen about 14% and is now about 30% above pre-industrial levels. Furthermore, the Intergovernmental Panel on Climate Change (IPCC) currently estimates that future economic activity will cause CO_2 concentrations to rise during the next century to a level 90% above pre-industrial levels.

The accumulation of carbon dioxide (CO_2) in the atmosphere is purported by some scientists to cause a warming of the Earth's surface. Since about 1970, there has been a positive correlation between the atmospheric concentration of CO_2 and average global temperatures, which has led many to suggest that the relationship is causal. The hypothesis, referred to as the "greenhouse effect", is plausible because CO_2, as well as other greenhouse gases[2], absorb some of the infrared radiation that is emitted from the earth's surface after the sun warms it. This, in turn, warms the atmosphere thereby increasing the amount of water vapor. Increased water vapor can then amplify the effect of CO_2 to produce noticeable temperature increases.

Due to the extreme complexity of the Earth's climate, complicated computer models are necessary to predict the impact of future CO_2 accumulations. The global climate models (GCM's) vary considerably in their predictions. Not only does the global average temperature increase predicted by different models vary, but the regional predictions for rainfall and temperature also vary considerably. This variability in prediction only serves as a testament to the degree of uncertainty that exists in climate science. A general tendency, however, does emerge. Specifically, the coldest winter air masses in Siberia, North America and Antarctica are predicted to warm the most.[3] Therein lies a potentially major global problem. The melting of land-based polar ice, combined with thermal expansion of the world's oceans, could raise sea levels, flooding low-lying, coastal areas. Moreover, adjusting to rising sea levels could be difficult because the change could occur abruptly. Initially, warming may cause a gradual melting of ice, but if large chunks of land-based ice fall into the ocean, they will melt more rapidly. The resulting influx of fresh water into the oceans could also affect the circulation of ocean currents producing further changes in climates.

Many factors complicate the modeling of global climates. For example, the net effects of the initial increase in temperature produced by CO_2 are complicated by interactions between the atmosphere and the oceans. It is well known that the oceans serve to regulate climate, but the extent to which they act in such a manner is largely unknown. There is also much to learn about the effects of upper atmospheric disturbances, such as ozone depletion and changes in stratospheric winds. To complicate matters further, there is geological evidence that suggests the world's climate can change rapidly, but the amount of CO_2 that must accumulate before a catastrophic event would occur is unknown.

Other factors complicate the assessment of any damages that may result from warming. For example, increased CO_2 can stimulate plant growth and, more generally, biosphere productivity. Since carbon compounds form a large part of living organisms, an expansion of the biosphere would tend to reduce CO_2 concentrations in the atmosphere. When coupled with the uncertainty in climate modeling, this type of competing factor contributes to making the timing and severity of any potential damage very difficult to predict.

When the Intergovernmental Panel on Climate Change (IPCC) was established in 1988, the GCM's that formed the basis for that report were predicting a median temperature increase of 8 degrees Celsius by the year 2100. However, as the scientific understanding of climate mechanisms has grown, additional climate feedbacks have been incorporated into the GCM's, and subsequent predicted temperature increases have been reduced. For example, in 1990, the median predicted increase for 2100 was reduced to 3.2 degrees Celsius, and by 1995 the IPCC's median projection had fallen to 2 degrees Celsius. Just as with any other discipline, advances in climate science extend both our understanding of the climate system and our ability to predict future climate outcomes.

Despite the uncertainties surrounding the causes and ramifications of global warming, the severity of the purported damages of global warming has raised public awareness and governments are being urged to act. The Kyoto Protocol, an international agreement signed in 1997 but yet to be ratified by any of its signatories, calls for the reduction of greenhouse gas emissions. The protocol specifies a greenhouse gas emissions target of between 5% and 8% below 1990 levels by 2008-2012 for a group of industrialized nations (referred to as Annex I countries). Carbon taxes or direct controls could be used to achieve these targets, but they are likely to be very costly. Costs will also be higher the faster controls are enforced since reducing emissions in the short term generally requires reducing production causing some degree of capital obsolescence. Relatively low cost methods of control, such as land-use changes, the clean-development mechanism (CDM), and emissions permit trading, have been proposed, but methods of implementation have yet to be worked out.

Modeling the economic cost of taking CO_2 abatement measures is just as difficult as modeling the climate. Uncertainty pervades the exercise due a number of problems. The lack of clearly defined guidelines for reducing CO_2 emissions, an inadequate understanding of the potential of new technologies, and more conventional problems of projecting economic growth, the composition of fossil fuel use, and projecting energy prices each contributes to this uncertainty. Therefore, while we cannot be certain whether or not global warming is an immediate and serious threat, we also cannot be certain about the economic costs of taking steps to eliminate an uncertain threat.

Technology is another major source of uncertainty that affects the prediction of future climate and the estimation of the economic costs of CO_2 abatement. Contrary to the predictions of many analysts, and despite continuing growth in energy demand, the price of energy has not risen significantly in real terms in recent decades. The real price of oil at the end of 1999 was about equal to the real price at the beginning of the 1970's. Significant advances in fossil fuel (oil, coal, and natural gas) recovery technology have extended the life of previously mined reserves and allowed new

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resources, such as deep water oil reservoirs, to be exploited. In addition, technological change in energy-using industries has reduced the amount of energy needed per unit of output produced. Finally, alternative energy sources, such as nuclear power, hydro-electricity, solar power, and fuel cells promise to provide alternatives to fossil fuels for meeting new energy demands. For example, while fossil fuels accounted for 96% of total energy requirements in the United States in 1970, by 1995 they provided only 84%. This process is likely to accelerate as alternative sources of power are developed. Solar power ultimately may supply much of the electricity to the interconnected grid. While solar power currently can compete with fossil fuels only in specialized and remote applications, future innovation and development may make solar generated power competitive with conventional forms of power, such as coal-fired electricity, in urban areas.

Controlling CO_2 as an Investment

Controlling CO_2 emissions can be viewed as an investment project. Up-front costs are incurred in order to deliver future benefits. The primary up-front cost of CO_2 abatement is forgone economic growth. For example, taxes on fossil fuels constrain economic growth by raising the cost of capital services, which reduces the utilization of capital and, hence, the consumption of energy. A possible offsetting benefit of fossil fuel taxes is that CO_2 emissions would be reduced. There is, however, substantial uncertainty about the consequences of changes in the atmospheric concentration of CO_2. Discounting is also important because the significant costs of global warming, should they occur, will be experienced decades into the future. Thus, the discounted present value of the net benefits of CO_2 abatement must be large enough to warrant the up-front costs.

Figure 1
Cost of Taxes on the Use of Fossil Fuel

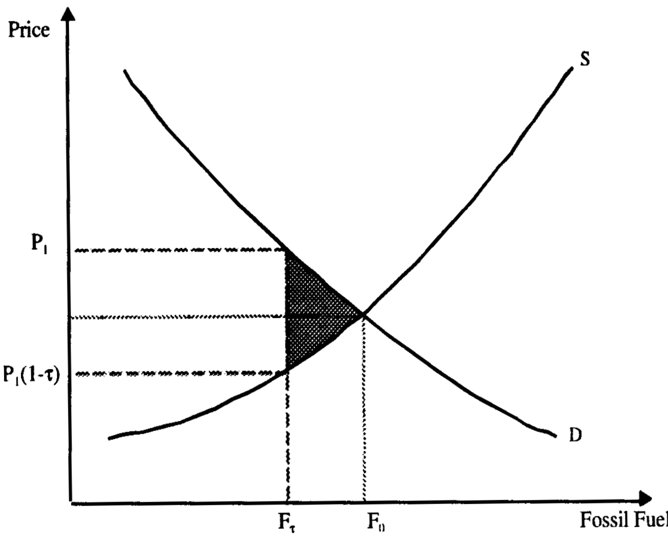

Figure 1 illustrates the effect of a tax on energy use, ignoring any beneficial effects such a tax might have on emissions of CO_2. The latter benefits are examined separately in Figure 2. In Figure 1, the curve labeled *S* represents the supply of fossil fuel, or the marginal costs of supplying fossil fuel energy, ignoring potential externalities from CO_2 emissions.[4] The curve labeled *D* represents the demand for fossil fuel, or the marginal benefits of fossil fuel energy consumption (the marginal value of transport services, electricity consumption and so forth). Equilibrium fossil fuel energy use in the absence of taxes is labeled F_0, while F_t represents energy consumption under an energy tax at rate t. The tax imposes efficiency losses by artificially discouraging the consumption of fossil fuel energy. The reduced production of fossil fuel energy saves costs equal to the area under the marginal cost curve between F_0 and F_t. The lost benefits equal the area under the marginal benefit curve between F_0 and F_t. The efficiency losses, therefore, equal the loss in benefits minus the cost savings, which is the shaded area in Figure 1. This area is proportional to the square of the reduction in fossil fuel consumption $(F_0 - F_t)^2$.

Figure 2
Losses from an Excessive Level of CO_2 Accumulation

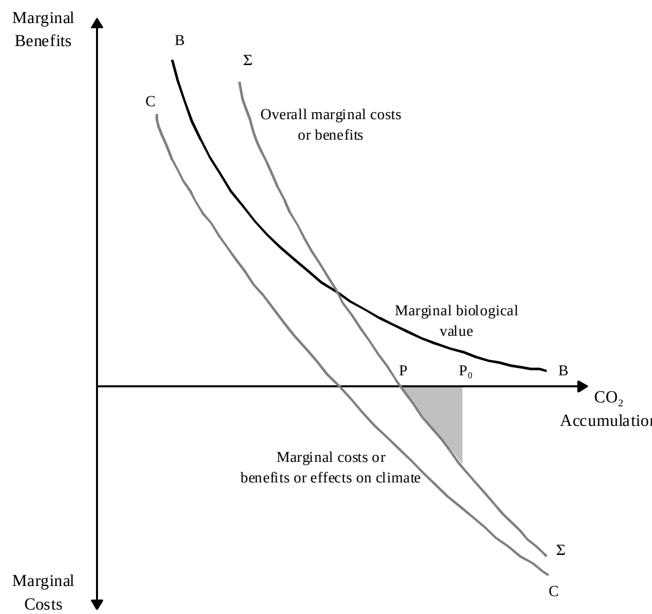

Figure 2 presents the efficiency losses accompanying an excessive, or insufficient, amount of CO_2, if we ignore the value of fossil fuels as an energy source. The latter was presented in Figure 1. Figure 2 contains two downward sloping curves labeled *B-B* and *C-C* and a third curve, labeled Σ-Σ, which represents the vertical sum of the other two curves. The curve labeled *B-B* in Figure 2 represents the marginal value of CO_2 to the biosphere, ignoring the effects of CO_2 on climate. These benefits arise as a result of the beneficial effects of CO_2 on plant growth. Plants (including plankton in the oceans) absorb CO_2 as part of the process of photosynthesis. Increased CO_2 has been shown to make most plants grow faster and bigger, make them more resistant to stresses such as drought or disease, allow them to photosynthesize with less nitrogen and water and at lower levels of light, and increase the production of fruits and grains.[5] Most life on earth is based on the production of carbohydrates by plants using CO_2, water and sunlight as inputs. Making plants more productive also allows the animal kingdom to expand on that food base. The productivity of agriculture and forestry (and perhaps also fishing) is likely to rise substantially as more CO_2 is added to the atmosphere (and oceans). Throughout the range represented in Figure 2, the "fertilizer" effect of CO_2 is positive, but the curve slopes down because the marginal benefits decline as the CO_2 level increases. With a relatively large amount of CO_2 already present in the atmosphere, a given increase has less of a stimulatory effect on plants.

The curve labeled *C-C* in Figure 2 represents the marginal effects of atmospheric CO_2 on the climate. At very low levels of CO_2, the climate models imply that additional CO_2 would be beneficial because it helps prevent the earth from being too cold.[6] The models imply, however, that as the CO_2 level increases, the average global temperature rises. Eventually, climates become undesirable for humans. Most of the models imply that the effect of CO_2 on the average global temperature is approximately linear. The curve *C-C* in Figure 2 need not be linear, however, because it represents the marginal cost of the temperature change and that need not be a linear function of the average temperature.

If we ignore the direct benefits obtained from fossil fuel consumption, the overall marginal benefits or costs of CO_2 are represented by the sum of the biological effects and the effects on climates. This is the curve labeled Σ-Σ in Figure 2. The efficient level of CO_2, labeled *P*, would be where the marginal climate costs of CO_2 just balance the marginal biological benefits. There is no presumption that P corresponds to either the current or the "pre-industrial" level of CO_2 in the atmosphere. If the biological benefits of CO_2 were large, and the effects on climates were small, CO_2 levels far above the current level would be optimal, even if we ignored the benefits from fossil fuel combustion.

An interesting implication of Figure 2 is that if the marginal biological effects of CO_2 are positive at the optimal level of CO_2 (ignoring the benefits of fossil fuels as an energy source), the marginal effects of additional CO_2 on the climate ought to be negative. Contrary to popular impressions, it would not be optimal to reduce CO_2 to a level where it has negligible harmful effects on the climate. At the CO_2 accumulation level labeled P_0 in Figure 2, there is too much CO_2. The total cost of the increase in the CO_2 level from *P* to P_0 are given by the area under the overall marginal cost curve Σ, or the shaded "triangle" in Figure 2. This area is proportional to the squared difference $(P_0 - P)^2$.

Suppose that the level of CO_2 initially exceeds *P* as illustrated in Figure 2. A tax on the use of fossil fuel will produce a triangle of efficiency losses in the fossil fuel energy market, but the resulting fall in the rate of accumulation of CO_2 in the atmosphere will reduce the efficiency losses illustrated in Figure 2. In principle, the tax rate should be chosen so that the losses in Figure 1 just balance the reduced losses in Figure 2. An implicit assumption underlying this analysis is that we can calculate the optimal CO_2 level *P*. In reality, we do not know enough about the likely effects of additional CO_2 in the atmosphere to enable us to do this. The extent of uncertainty about *P* should fall over time as we learn more about the effects of additional CO_2 on climate and the biosphere. Hence, any decision made in the future regarding optimal tax rates to reduce CO_2 emissions should be better informed.

The point here is worth reiterating. Efforts to reduce CO_2 emissions should only be taken when $P_0 > P$ by an amount in excess of the benefit to society from consuming fossil fuel. Then, and only then, are the costs of imposing a tax on fossil fuels justified. The difficulty in measuring these costs, however, presents a significant problem. We do not have a clear picture of where the curves *B-B* or *C-C* lie. Thus, with no knowledge of the optimal value of CO_2, we must somehow deal with the uncertainty. A typical firm, when faced with significant uncertainty, will delay an investment until more information can be obtained regarding potential returns. One can argue, therefore, that action should be delayed until some of the uncertainty can be eliminated. The cost of imprudent action is simply too high to be ignored.

Concluding Remarks

In order to stabilize greenhouse gas concentrations, anthropogenic global emissions cannot exceed 40% of their 1996 levels (6.518 billion tons of carbon), which amounts to 2.6 billion tons of carbon. An emissions reduction on the order of ten times the level proposed in the Kyoto agreement would be required. Calculations using the climate models suggest that full implementation of the Kyoto Protocol will decrease the predicted increase of average world temperatures in 2100 by only 0.07 degrees Celsius. This difference is so small that it could not be detected reliably by ground-based thermometers. Moreover, if controls are imposed sooner rather than later, technology will be less advanced, the life of more capital equipment will be prematurely shortened, and fewer resources will be available to compensate for losses. Cost estimates of fully implementing the provisions of the Kyoto Protocol range from $US5-180 billion annually in the United States alone.[7] To justify spending such large amounts to reduce CO_2 emissions, reliable evidence of significant and dangerous global warming is imperative.

Processes affecting climates are not well understood. While the costs of delaying action on CO_2 emissions may be small, the benefits could be large. The determinants of global climates are not fully understood. Uncertainty persists not only concerning the possible effects of CO_2 on climates, but also concerning the natural forces that have produced substantial fluctuations in past climates. Delaying control of CO_2 emissions allows us to take advantage of future research. Evidence may show that CO_2 emissions are relatively harmless or even beneficial, and that we need not compel people to reduce their use of fossil fuels.

Ten more years of research and observations are likely to tell us a great deal about the accuracy of predictions from computer simulations of the earth's atmosphere. The most sensible approach, therefore, is to wait and see how our understanding of the effects of CO_2 emissions develops over the next decade. In fact, most of the anticipated costs of CO_2 accumulation are predicted to occur decades in the future. The incremental costs of delaying control, therefore, would also be incurred in the distant future, making them quite small in present value terms. In addition, economic growth will raise the living standards of future generations, and make the sacrifice needed to adjust to a climate change easier to bear in the future than in the present.

Footnotes

[1] See, to name a few, Bohi (1991), Hamilton (1983), Lee, Ni, and Ratti (1995), and Mork, Olsen, and Mysen (1994).

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THE COSTS OF THE KYOTO PROTOCOL: A MULTI-MODEL EVALUATION

Edited by John P. Weyant
(Energy Modeling Forum, Stanford University)

This Special Issue represents the first comprehensive report on a comparative set of modeling analyses of the economic and energy sector impacts of the Kyoto Protocol on climate change. Organized by the Stanford Energy Modeling Forum (EMF), the study identifies policy-relevant insights and analyses that are robust across a wide range of models, and provides explanations for differences in results from different models. In addtion, high priority areas for future research are identified. The study produced a rich set of results. The 448-page volume consists of an introduction by John Weyant and a paper by each of the thirteen international modeling teams. More than forty authors provide richly illustrated descriptions and of what was done and concluded from the model runs that were undertaken.

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ABOUT THE EDITOR: John P. Weyant is a professor of engineering-economic systems and Director of the Energy Modeling Forum (EMF) at Stanford University. His current research focuses on analysis of global climate change policy options and models for strategic planning.

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Risk and the Reserve/Production Ratio

*By Douglas B. Reynolds**

Risk is a factor in oil exploration and development that has not been fully incorporated into our analysis of OPEC and world oil market. Robin and Thaler (2001) show that an individual's marginal utility for wealth-gains decreases exponentially and that for wealth-losses increases exponentially. In other words, people are normally highly risk averse. But if an individual person, who is an economic agent, is highly risk averse, then an economic entity such as an oil company can also be risk averse. Each OPEC country has a National Oil Company (NOC) or a national bureaucracy, which controls all oil exploration and development. Since an NOC is an economic entity and could be highly risk averse, then we might see not only high reserve to production ratios for that country, but also very little new exploration or development.

Adelman (1986) shows that Saudi Arabia has less exploration and development than the United States even though oil reserves and potential oil production are greater in Saudi Arabia than in the United States. Reynolds (2000) suggests that the reason oil exploration and development investments are lower for some oil producer countries than for the United States is due to risk aversion. NOCs are risk averse to oil investment and, therefore, have lower oil production and in turn higher reserve to production ratios. Investments tend to be less aggressive and the pace of oil exploration and development is much slower than under a competitive environment. This, however, should not be interpreted as a bad thing. It is to the world's advantage that oil be conserved for the future. Oil is the most valuable energy commodity on earth and always will be. Therefore, any market environment that conserves oil should be applauded.

In contrast to OPEC producers, the United States has a well adjudicated property rights system and a competitive market, with many wildcat drillers. These wildcat drillers tend to have little to lose and are extremely risk loving. They push oil exploration to the limits of marginal cost. Oil supply models that compare a competitive U.S. market environment, with greater risk taking, to a risk averse market environment, such as OPEC countries operate in, can lead to the wrong oil supply forecast. It is important to incorporate the idea of risk loving and risk averse behavior into a model of oil supply. I will do that by using a modified Hubbert curve model, which is one of the most important models for oil supply.

In 1962 M. King Hubbert created a mathematical logistics curve, often called the Hubbert curve, which could be used to project future trends in oil discovery and production. Cleveland (1991), Reynolds (1999), Slade (1982), and Uhler (1976) give theoretical reasons for why the Hubbert curve works. Cleveland and Kaufmann (1991), Moroney and Berg (1999), and Kaufmann (1991), incorporate economic principles into Hubbert's equations. Pesaran and Samiei (1995), Campbell and Leherrere (1998), Edwards (1997), Campbell (1997), and Cleveland and Kaufmann (2001) use Hubbert's equations to forecast oil supplies for the United States and the world. On the other hand, Wiorkowski (1979), Ryan (1965), and Lynch (1994) have criticized Hubbert for not accounting for economic, technological and political changes in the oil market. The claim that in many instances it is not possible to forecast oil supplies using the Hubbert curve. Nevertheless, even with as much criticism as Hubbert received, his 1962 forecast for the peak in oil production for the U.S. lower 48 was only off by one year. Hubbert also theorized that his curve does take into account technological trends.

Since Hubbert's work has been resurrected as a viable forecast model, forecasters are starting to use it more. For example Campbell and Leherrere (1998) predicted a world oil shortage in the near future. The U.S. Energy Information Administration (EIA) also uses what looks to be a Hubbert curve analysis for their world oil supply forecast. The EIA, (EIA 2000), forecasts that oil production will not peak until at least 2030 and maybe into the 22nd century. I will also use a Hubbert curve to forecast world oil supplies and add a risk factor to take into account OPEC countries risk averse behavior. However, in order to better use the Hubbert curve it needs to be made into a cumulative production model rather than a time dependent logistics curve.

One of the problems with Hubbert's oil discovery and production logistics curve has been that it is time dependent. Because of this, if the demand for oil goes down or even increases more slowly, then the time path of production changes substantially from Hubbert's logistics curve. Once oil production goes below Hubbert's logistics curve it becomes difficult to track where the production limit is. An alternative Hubbert curve uses a simpler quadratic equation. This equation is derived by using the Hubbert time dependent oil production logistics curve and the time dependent cumulative oil production logistics curve and subsuming the time variable. The quadratic Hubbert curve is no longer time dependent but cumulative production dependent. The equation for the curve is:

$$QP = a \times CQP - (a/URR) \times CQP^2$$

where

QP = Quantity of Oil Produced during each year, i.e. the rate of oil production.
CQP = Cumulative Quantity of Oil Produced up to each year.
URR = Ultimately Recoverable Reserves.
a = a size parameter, which determines the height and width of the Hubbert curve.

Note, that QP is statistically independent of CQP because they have different units of measurement, one is a rate and the other is a quantity. The independence of QP from CQP, similar to the independence of QP from time, allows a statistical analysis using the quadratic Hubbert curve similar to his logistics curve. The new quadratic Hubbert curve has characteristics that make it easier to use. For example, if actual oil production is below the quadratic Hubbert curve, it is easier to see where consumption falls relative to the limits of supply. Plus it is easier to see how far demand can increase before it reaches the Hubbert limit. Therefore, this new Hubbert curve is the supply limit. Putting both supply and

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* Douglas B. Reynolds is an Assistant Professor at the University of Alaska Fairbanks, his new book *Scarcity and Growth Considering Oil and Energy: An Alternative Neo-Classical View* should be out in April 2002. This is an edited version of his paper presented at the 24th Annual IAEE Conference in Houston, TX, April 25-27.

Risk and the Reserve/Production Ratio *(continued from page 31)*

consumption (demand) on the same graph will allow us to see how far away the Hubbert curve supply limit is from demand.

Campbell and Laherrere use a Hubbert curve to estimate total world oil supplies at 1.8 trillion barrels and a peak in oil production before 2005. If they are right, in less than five years oil prices will increase to spectacular heights. An oil crisis of immense magnitude will ensue. However, even if the URR is much larger than what Campbell and Laherrere predict, we may still reach a Hubbert curve limit sooner than expected due to OPEC countries' risk averse natures. When risk aversion is included into a Hubbert analysis then Campbell and Laherrere's prediction may turn out to be much truer than expected. First consider an alternative Hubbert analysis using the EIA's world oil supply forecast. The EIA estimates a medium URR using geological data and scientific methods at 3 trillion barrels. The EIA's medium estimate for increases in oil demand is 2% per year. Putting together supply and demand, the EIA's best estimate is that world oil supply will peak in 2037. An alternative estimate forecasts the peak in 2030. If the EIA's estimated URR is correct and the world follows a U.S.-type Hubbert curve, then we can see where supply and demand were relative to each other in the past. Figure 1 shows the EIA model in terms of a quadratic Hubbert curve. The assumption is that reserve to production ratios will be at 10 to 1 as it has been in the United States for many decades.

The problem with using a U.S.-type Hubbert curve or assuming a low reserve to production ratio is that the United States has a competitive market with a large number of risk loving agents. As explained above, the United States is unique in its competitive marketplace. In many of the largest world oil producing regions, only one NOC is allowed to look for oil, or to determine who will and who will not explore for and develop oil within the country, and at what profit. Having a single economic entity in charge of all oil activities will normally reduce risk taking and create a very risk averse environment. Clearly with a single entity in charge, the Hubbert curve model, or any model, must take into consideration that risk averse behavior, which will radically reduce oil exploration, development, and production for any given region.

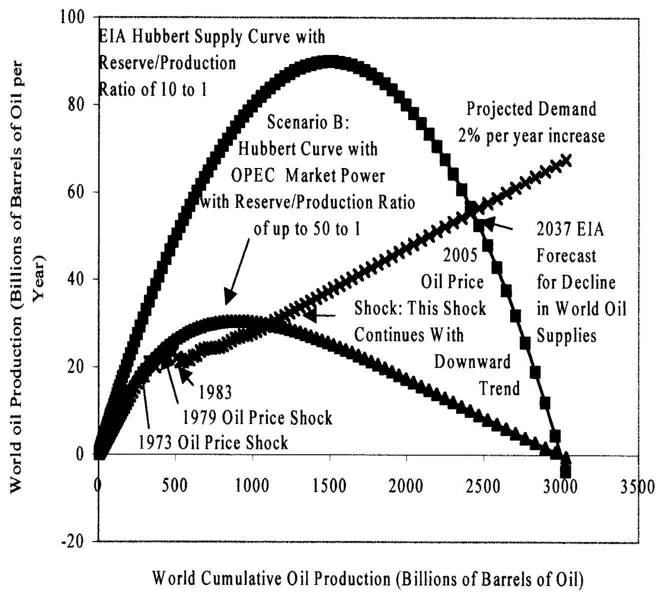
If a normal U.S.-type Hubbert curve cannot be used to analyze world oil supplies because actual supplies will be much lower than a 10 to 1 reserve to production ratio would allow, then how can world oil supplies be modeled? The best model for world oil supplies may simply be to track the maximum supply points in the past and forecast that path to the estimated URR. Looking at 1973 and 1979, we see extremely sudden declines in demand. The changes occurred because oil prices suddenly shocked upward. However, was it the price changes that caused the demand trend to change, or was it a supply limit that forced prices to increase and demand to fall. It is surprising to find oil prices rising so suddenly when oil consumption was well below the EIA modeled Hubbert curve limit. Indeed, the very fact that oil prices suddenly skyrocketed and stayed high suggests that the Hubbert curve at a 10 to 1 reserve production ratio is not in fact the limit of oil production, but that the Hubbert curve limit is much lower. Remember, many oil producing countries in the world produce oil at a 50 to 1 or even a 100 to 1 reserve/production ratio. This is a level of oil production 80% lower than for a 10 to 1 ratio. This means that a standard Hubbert curve should not be used to forecast world oil supply potential.

Figure 1 shows an alternative Hubbert curve called Scenario B. The Scenario B curve is created by finding a formula that fits the 1973 high point of oil production, the 1979 high point of oil production, and the currently estimated URR. The equation used for this curve is

$$QP = [a\times CQP - (a/URR)\times CQP]^2 \times 0.78[(CQP/URR) + 1]^{-ex}$$

Where ex = 2.5

Figure 1
Forecast OPEC Supply and World Oil Demand As a Function of Cumulative Production



Other exponents for *ex* less than or greater than 2.5 do not fit the 1973 and 1979 high points as well. Scenario B assumes that the maximum world oil production is lower than what a 10 to 1 ratio would give. One way to look at Scenario B is to assume that political or other economic factors have caused it. I believe it is OPEC countries risk averse environment that caused NOC's to have lower exploration and development efforts that caused Scenario B. Therefore, it is the Scenario B Hubbert curve that caused the 1973 and 1979 oil price shocks rather than the oil price shocks causing Scenario B. Note that although the second price shock was slightly lower than Scenario B suggests, this was due to Iran's slight reduction in production and Saudi Arabia's reductions thereafter. The most striking thing about Scenario B is that demand will reach and exceed supply in the next five years creating an oil price shock, even with URR at three trillion barrels. If URR is even higher at say six trillion barrels, Scenario B can be redrawn and the price shock is only delayed by another five years. Therefore, we should not expect higher URR estimates to delay for long the inevitable world oil price shock.

The reason the Scenario B curve is so much lower than a regular Hubbert curve is because of the inherent risk averse nature of NOCs. No matter how much an NOC is cajoled, reorganized or provided with internal incentives, it will still be a single entity making oil exploration and development decisions one project at a time. The company will by nature be risk averse because each individual oil project it decides on will be judged a gamble in isolation from all other considerations. In other words, the NOC does not judge individual project decisions by comparing it to other risks in the economy or by comparing it to the countries overall wealth. Rather the entity judges each risk in isolation and becomes very risk averse to make any move. This makes the oil entity, just like many individuals, very hesitant to expand its activities and investment.

What Scenario B suggests is that the world is in danger of an upcoming oil supply shock of epic proportions. What is more, there will be confusion over why such an oil shock will happen. Oil price shocks in the past occurred during or around significant political evens such as a war. However, I must stress that in no way could a one month Arab/Israeli war or a six month Iranian revolution cause an oil price increase of such a sustained magnitude as what happened in 1973 and 1979. The price increases were caused by fundamental economics. They were caused independently of political events and were due to the risk averse nature of OPEC's NOC's. However, political events do tend to push markets into chaos a little faster than they normally would. In today's highly charged political and terroristic environment, there will no doubt be future significant events as great as the World Trade Center horror. These events will not be the cause of future oil price increases but they will exacerbate them. Political and economic events that happen simultaneously will be interpreted as being cause and effect. Political events will be judged the cause rather than the underlying economic reality. Plus political events will exacerbate the economic events. What we can assume, though, is that there will be a huge oil price adjustment within five years. Oil prices of upwards of $200 to $300 per barrel are not out of the question. We need to prepare now for that event.

References

For references contact the author.

Student Conferences *(continued from page19)*

ics, presented a paper on "Deregulation in the North American Natural Gas Industry: what lessons for Mexico?"

At the second and final session on *The Electricity Sector,* Virginie Pignon, Ph.D. Student in Economics discussed "Electricity Transmission Tariffs in the Nordic Countries: An Assessment of Pricing Rules," Marie Laure Guillerminet, Ph.D. Student in Economics, discussed "Investment and Financing in an Institutional Environment in Mutation: the Case of an Electronuclear Equipment," Pierre Taillant, Ph.D. Student in Economics, discussed "Technological Competition and Lock-in in the Photovoltaic Solar Electricity Production" and Stine Grenaa Jensen, Ph.D. Student in Economics discussed "A Simple Integrated Power Market Model Including Tradable Green Certificates and Tradable Emission Permits."

The abstracts of the presentations from the Mexican student conference will be in the next issue of the newsletter of the Mexican Association for Energy Economics. In order to obtain free proceedings of either one of the student conferences please contact Alberto Elizalde Baltierra (elizaalb@hotmail.com) or Stine Grenaa Jensen (stine.grenaa@risoe.dk).

Controlling Carbon Dioxide *(continued from page 29)*

[2] Greenhouse gases, as defined by the United Nations Framework Convention on Climate Change (UNFCCC), are "those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and re-emit infrared radiation." These are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC's), perfluorocarbons (PFC's), and sulfur hexafluoride (SF_6). Each gas is assigned a "global warming potential," which is a value that allows for comparison in terms of carbon units. The most important constituent of global warming models, in terms of its impact, is water vapor.

[3] Since water is far more effective at absorbing outgoing infrared radiation than is CO_2, most of the temperature increase predicted by the models arises from increased water vapor in the atmosphere triggered by CO_2 rather than the CO_2 itself. A slight warming of the coldest air masses allows them to hold substantially more water vapor and greatly increases their insulating effect. By contrast, more water vapor at tropical latitudes, and in the summer months, increases cloud cover. Clouds reflect incoming solar radiation, however, and this tends to have a cooling effect. Another factor making CO_2 more potent at warming higher latitudes is that CO_2 absorbs a greater proportion of the longer wavelength radiation emitted from colder surfaces.

[4] Figure 1 simplifies the analysis by ignoring the role of the OPEC cartel in the world fossil fuel energy market. The Appendix (to the companion paper) shows how the discussion in this section can be extended to allow for the actions of OPEC in setting the price of oil and thus indirectly of coal and other energy resources. The analysis of this section applies to the case where the supply chosen by OPEC is independent of the tax rate on fossil fuel. More generally, the analysis in this section under-states the efficiency costs of taxing the use of fossil fuel. Monopoly pricing by OPEC would already reduce the consumption of fossil fuel below the efficient level. Additional taxes on fossil fuel consumption would only exacerbate the efficiency losses resulting from monopoly pricing.

[5] If average temperatures do increase, laboratory experiments have shown that the stimulatory effect of CO_2 on photosynthesis is likely to be enhanced.

[6] Sir Fred Hoyle (1996) has noted the difficulties this creates for people concerned about current projected levels of global warming (K stands for degrees Kelvin, or degrees above absolute zero):

"Given the choice, I imagine nobody would opt for a world without any greenhouse, that is a world with a mean temperature of about 259K. And probably few would opt for an ice-age world with a mean temperature of 275K to 280K. To this point, the greenhouse is seen as good. Further still, a clear majority continues to see the greenhouse as good up to the present-day mean of about 290K. But, at the next 1.5K a drastic change of opinion sets in: the greenhouse suddenly becomes the sworn enemy of environmental groups, worldwide, to the extent that they rush off to Rio and elsewhere and make a great deal of noise about it. I find it difficult to understand why. If I am told that computer calculations show immensely deleterious consequences would ensure, then I have a good laugh about it. In private, of course, since I am always careful to be polite in public." (p. 185)

[7] These cost estimates derive from the survey of a number of models presented in a special issue of *The Energy Journal* (Weyant, (1999)).

Bibliography

For bibliography contact the authors.