

**ENERGY EFFICIENCY AND PETROLEUM DEPLETION IN
CLIMATE CHANGE POLICY**

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Abbreviated Title

Energy Use, Depletion, and Climate Policy

I. Introduction

The standard practice for determining the empirical structure of economic models is to draw upon recent empirical history. This provides a good insight into the near future. However, as the analysis extends further into time, and especially into the far future, the variability around empirical and, perhaps, even structural assumptions necessarily increases. The researcher is, thus, forced to invoke some tangible representation of his or her particular world view and expectation regarding the evolution of economic societies.

In the case of climate change, there are several economic assumptions that are extremely tentative and yet vital to the results of the models currently in use.¹ An important subset of these relates to the evolution of technology. How will the global economy's use of energy as a factor input in the production process change over time? When will global oil resources be depleted? What energy source will replace it and for how long? The answers to these and related questions directly determine the future trajectory of greenhouse gases, particularly carbon dioxide, and hence the magnitude of the climate change problem and the economic response to it.

This paper examines the validity of standard technology assumptions commonly used in climate economy models for the far future, and explores the consequences of changing them to reflect actual as opposed to postulated trends. While the alternatives explored here might be interpreted as pessimistic, we consider them highly plausible. The significant policy conclusion is the need for an earlier and more aggressive implementation of climate policies than typically found in other work.

II. Energy Use and the Evolution of Technology

Economic models typically incorporate a simple representation of technology. Technology and technical change are represented by the form of the production function and the changes in the numerical values of exogenously specified parameters. For climate-economy models a key parameter is one that represents the efficiency with which the economic system uses energy as a factor in the production process. The evolution of energy technologies is typically represented through autonomous energy efficiency improvements (AEEI) which are exogenous to these models (Manne and Richels, 1992 and 1999, Kurosawa et al., 1999, Peck and Teisberg, 1995 and 1999, among others. Nordhaus, 1994, Nordhaus and Yang, 1996, and Nordhaus and Boyer, 1999, use autonomous decarbonization in place of AEEI.)

Improvements in energy efficiency are assumed to be quite rapid. For instance, Manne and Richels (1999) assume the annual AEEI rate to be 40% of the annual GDP growth rate. This translates into a continuous improvement in the efficiency of energy use in the global production process, though the growth rate declines from approximately 0.98% per year in 2000 to about 0.77% per year in 2100. This trend is assumed to hold not only for the world as a whole, but also for every region, including developing countries such as India and those in Africa and South East Asia.² Comparable assumptions are found in other integrated assessment models of climate change. Note this reduction in energy demand is independent of the impact of rising energy prices: it is an assumed pure technology effect at the global level.³

The implication of this assumption is that welfare as measured by gross economic product can be increased in the future without a corresponding increase in energy use and

carbon dioxide emissions. That is, the ratios of energy use and CO₂ to GDP decline steadily over time, regardless of prices, income, and population changes.

Data from the 1970s onwards do not support this assumption unambiguously. Figure 1 shows that global energy use per unit of economic output was, on average, higher in the early 1970s than in 1998, the latest year for which data are available. A similar trend is observed for high income countries (as defined by the World Bank, 2000). For the remaining countries, the trend is mixed. During the 1980s, energy intensity in the rest of the world showed a rising trend. However, the collapse of the Soviet Union and the subsequent economic crisis in South East Asia led to a decline in the energy intensity for this group of countries in the first half of the 1990s. From 1995 onwards, energy intensity has increased for both group of countries, as well as for the world as a whole.

Based on world data, we estimated a simple two-parameter econometric model. This asymptotic curve, shown in Figure 1, has a better fit than a simple exponential decay. The estimated growth rate falls from about 0.43 % per year in 2000 to around 0.02 % per year in 2100.⁴

FIGURE 1 ABOUT HERE

A priori, it is difficult to predict the outcome for the next century or so. Manne and Richels (1992, p. 34) ascribe the common assumption of a positive and high AEEI to the optimistic outlook of energy technologists. A more pessimistic outlook might be based on the generally slow spread of efficient production technologies to developing

countries, coupled with the lack of basic infrastructure, especially in rural areas where the bulk of the world's population lives. This view might conclude that, at least for the next 100 years or so, the energy intensity in these countries might rise slowly. Then, it is not unlikely that global energy intensity would stabilize somewhere around the current level for the course of the next century as predicted by our econometric model.

We consider this possibility equally likely to the commonly posited decline in the ratio of the global energy use to gross economic produce.

III. Optimal Petroleum Depletion

Data from the 1950s show world oil production rising steadily (EIA, 2000). Yet throughout the last decade, economic models of climate change have typically projected a monotonically declining oil production trajectory. Underlying this assumption is usually some type of resource depletion model loosely based on the Hotelling (1931) model for exhaustible resources. This traditional depletion model is typically based on static demand curves which ignore the growth in income and population, often assumes rising marginal extraction costs, and usually does not reflect the important geological concept of undiscovered resources. Consequently, this conventional model yields a monotonically declining equilibrium production trajectory, a result that was clearly discordant with 20th century global reality.

Chapman (1993, and with Khanna, 2000a) augmented the traditional Hotelling model to reflect the growth in income and population. In the absence of a backstop technology, this model yields an optimal equilibrium production trajectory that increases in the near-term, peaks, and then declines as the resource approaches exhaustion. The

historic trend of rising oil production is likely to continue over the next few decades. However, as oil resources are depleted and the rising user cost of extraction begins to dominate the positive impact of shifting demand curves, it is not unlikely that the oil production trajectory would eventually be on a downturn. Alternatively, in the presence of a backstop the global production trajectory might continue its monotonically increasing trend till prices rise to the level of backstop, a result that is also yielded by the Chapman model.

Another conspicuous feature of many current integrated models is the omission of cross-price effects as a direct determinant of fossil fuel use (Khanna and Chapman, 1997). From a policy perspective, this could have serious implications. Market based CO₂ abatement instruments typically operate by changing the relative prices for different fuels based on the differential carbon content of each fuel. As relative fuel prices change, there are cross-substitution effects which would affect the ability of an instrument to achieve any given emissions trajectory.

Here we extend the augmented Chapman model to include multiple exhaustible resources whose markets are linked through cross-price effects. This more complex depletion model yields a parabolic production trajectory (rather than an always-declining path), and an equilibrium price trajectory which may show stable prices in the near term (rather than always-rising prices).⁵

Suppose there are M fossil fuels, $m \in \{1, \dots, M\}$, each of which has a finite stock of remaining resources, S^m . Each faces a marginal cost of extraction, C_t^m , that varies over time. Suppose also linear demand curves that shift over time in response to a growing world population, L_t , rising per capita incomes, y_t , and the price of the substitute fuel,

Under perfectly competitive markets the Hamiltonian for the above problem is:

$$H^m = \frac{[P_t^m(\bullet) - C^t(t)] q_t^m}{\prod_{t=1}^t (1 + r_t)} - \mathbf{I}_t^m q_t^m \quad (2)$$

$$\frac{\partial P_t^m}{\partial q_t^m} \equiv 0$$

where δ_t^m is the costate variable representing the change in the discounted NPV^m due to a small change in the quantity of remaining resources for fuel m . The optimal production trajectory, q_t^{m*} , is found by solving the first order conditions and the constraints, simultaneously. The solution is:

$$q_t^{m*} = \mathbf{b}_{3_t}^m + \frac{\prod_{t=1}^t (1 + r_t)}{X^m(r_t)} (S^m - \mathbf{b}_4^m)$$

$$\mathbf{b}_{3_t}^m = \frac{\mathbf{b}_2^m L_t^{\mathbf{h}_1} y_t^{\mathbf{h}_2} (P_t^{subs,m})^{\mathbf{h}_3} - C^m(t)}{\mathbf{b}_1^m} \quad (3)$$

$$\mathbf{b}_4^m = \sum_{t=1}^{T^m} \mathbf{b}_{3_t}^m$$

$$X^m(r_t) = \sum_{t=1}^{T^m} \left(\prod_{t=1}^t (1 + r_t) \right).$$

where $X^m(r_t)$ is the compound discount factor.

The optimal production trajectory is made up of two components. The first, $q_{3_t}^m$, is the equilibrium production trajectory in the absence of a resource constraint. It is the intertemporal locus of the intersection between the shifting demand curves and the changing marginal extraction cost. The second part represents the impact of scarcity arising due to the finite stock of resources. It defines the distance between the actual equilibrium, q_t^{m*} , and the hypothetically unconstrained equilibrium, $q_{3_t}^m$, and is based on

the difference between remaining resources, S^m , and the cumulative production in the absence of a resource constraint, $\$4^m$.

The optimal production horizon, T^m , is the minimum of T_1^m and T_2^m :

$$T_1^m = T^m \ni \mathbf{b}_2^m L_{T^m}^{\mathbf{h}_1} y_{T^m}^{\mathbf{h}_2} (P_{T^m}^{subs,m})^{\mathbf{h}_3} = C^m(T^m) \quad (4)$$

$$T_2^m = T^m \ni P_{T^m}^m = P_{T^m}^{back,m}$$

where T_1^m is defined as the period when the marginal cost of extraction rises to the level of the intercept of the demand curve, and T_2^m is the period when the equilibrium price of the exhaustible fuel rises to the price of the backstop.

An obvious extension of the above framework is to assume reserve dependent extraction costs. In the present context, however, this might not be appropriate since it would yield rapidly rising marginal costs. In fact, there is some evidence to indicate that extraction costs for petroleum have been slowly declining (Fagan, 1997, Adelman, 1992 and 1994). The current model structure allows the flexibility of determining the growth rate of extraction costs exogenously, and testing the sensitivity of model results to the numerical values assumed. Despite the evidence of stable or even declining extraction costs over the last few decades, we believe it is reasonable to assume a positive though slow growth in extraction costs in the context of a climate change model whose horizon extends up to 400 years into the future. This would incorporate the interaction of technological improvement and depleting resources.

Two issues remain. The first relates to the geological concept of remaining resources. Remaining resources refers to the total conventional crude oil available for recovery. It is the sum of both undiscovered resources and identified reserves (Masters,

1991, Chapman, 1993). The undiscovered resources concept is adapted from geology: it is probabilistic, based upon the geological extrapolation from known formations and petroleum occurrence. Identified reserves are similar to an inventory concept. It refers to the economically recoverable crude oil at known reservoirs and fields with expected technology.

Over time, the USGS has provided a shifting probability distribution of the world's original endowment of oil resources.⁷ Between 1983 and 1991, there was a greater shift in the distribution at the higher probability levels, while the distribution remained almost unchanged at the lower tail (Masters, 1991, summarized in Chapman, 1993). At the median 50% probability, the growth in the estimates of original endowment has exceeded the growth in cumulative production over this period. In both 1983 and 1991, there was only a 5% probability that the original resource endowment exceeded 2600 billion barrels.

According to Manne and Richels (1992: see pp. 38-39 for discussion), the 95th percentile constitutes the practical upper bound for undiscovered resources as it allows for technological improvements such as those that might affect the costs of deep drilling. Chapman (1993) is also in favor of this approach. Thus, we use the 5% probability estimates as the preferred economic guideline for remaining resources.

A final issue pertaining to the resource depletion model relates to the backstop technology. Many climate-economy models assume that petroleum would be replaced by a liquid synthetic fuel such as coal or shale oil, which is quickly replaced by a carbon-free energy form such as solar or ethanol from biomass. Often, the dates of introduction and maximum rates of expansion or decline are specified exogenously based on the

researchers' expectation of the future development of these technologies and their ability to penetrate energy markets (see, for instance, Manne and Richels, 1992 and 1999, and Peck and Teisberg 1992, 1995, and 1999).

Based on cost assumptions and other considerations, Manne and Richels point out that in the absence of a global carbon constraint, a highly carbon intensive liquid fuel would place an upper bound on the future cost of non-electric energy. In our perspective, this is not unreasonable. There are approximately 15 trillion tons of remaining coal resources (Chapman, 2000). By current rates of consumption, this implies enough coal to meet demand for the next 3000 years or so. What, then, provides the incentive for a shift to a carbon-free alternative whose cost per energy unit might be an order of magnitude higher?

In the analysis that follows, we explore the consequences of the possibility that a coal based liquid fuel replaces petroleum as the backstop. Realistic options are coal powered rail transport and liquefied coal as personal vehicle transportation fuel. Given the huge remaining resources, we assume that the cost of this energy source increases very slowly over time, such that carbon-free alternatives to liquid fuels do not become economically attractive over our model horizon.

IV. Integrated Assessment: Discussion and Results

In this section, we examine the implications for climate policy of the preceding discussion regarding the evolution of energy use and technologies. In order to do so, we incorporate the resource depletion model and other assumptions into an existing model and examine the changes in the results obtained.

Nordhaus (1999, 1996, 1994) provides a convenient framework and starting point. The advantage of this model is its compact representation of a fairly detailed, global climate-economy model, accompanied by a candid discussion of model structure, assumptions, and results. The logic of this model is summarized in the Appendix. Further details are available in the references cited, therein.

In the present analysis, there are four carbon based fuels – coal, oil, natural gas, and a coal-based synthetic fuel that is the backstop. It is assumed that the oil market is, in the near future, the driving force of the energy economy and the first resource that may reflect economic scarcity in the future. The resource depletion model is, therefore, operated for oil only. The demands for coal and natural gas are determined by population, per capita income, own prices, and the prices of all other fuels. Oil is ultimately replaced by the synfuel, whose demand is also determined through a similar function of prices and income.⁸ The substitutability between fuels is captured by the cross-price elasticities. Based on the discussion in section II, no exogenous improvements in energy or carbon intensity are imposed. Changes in carbon and energy intensity are determined by the model in response to relative price changes. CO₂ emissions are determined through exogenously specified coefficients, L^n , that translate energy units to billions of tons of carbon. That is:

$$E_t = \sum_n \mathbf{n}^n q_t^n \quad (5)$$

where $N: n \in N$ and $M \in N$, is the set of fossil fuels, and q_t^n refers to the aggregate consumption of all fossil fuels, including the exhaustible fuels and backstop, at time t .

The macro-geoeconomic model and the optimal resource depletion model operate iteratively until they converge to a solution. Per capita income and the interest rate from

the economic growth model serve as inputs in the energy module and which determines the optimal trajectory of oil and other fossil fuels.⁹ CO₂ emissions are based on equation (5), and feed back into the climate-economy model via changes in equilibrium temperature and the resulting loss in global economic output. The energy module parameter values are summarized in the Appendix (see Table A). All other parameter values are consistent with the DICE model.

The model is operated under two scenarios: the base case with no CO₂ control, and the case where the control rate for CO₂ is optimized (the “optimal case”). The basic results are shown in Figures 2-6, with the latter four showing comparative paths with the Nordhaus work.¹⁰

In Figure 2, the global transition to synthetic fuel takes place towards the first quarter of the next century. Since the synthetic fuel releases a much higher amount of carbon per unit of energy than either oil or conventional coal, carbon emissions shift upward and accelerate relative to the DICE projections (see Figure 3).¹¹ This Figure highlights the implications of assumptions regarding the backstop technology. In the case of a carbon-free alternative, there would be a decline in emissions of a similar magnitude, which would have the opposite impact on the optimal carbon control rates shown in Figure 6.

FIGURES 2 AND 3 ABOUT HERE

The exogenous decarbonization imposed in the Nordhaus model, and other similar analyses implies that the carbon intensity declines steadily. In our analysis, this is

not the case. Initially, the carbon intensity increases, rising sharply when the synfuel replaces crude oil. Thereafter, the ratio remains more or less stable (see Figure 4). This is an intuitively appealing result. For the next few decades, while a large proportion of the world's population in developing countries strives to meet its basic energy needs, the global energy and carbon intensity is likely to rise. Once these nations have acquired some minimum level of energy consumption, and as energy prices rise world-wide, there may be an increased effort to reduce energy consumption per unit of economic output, resulting in the subsequent stabilization of energy and carbon intensities.

FIGURE 4 ABOUT HERE

The paramount importance of the AEEI assumption, and future oil depletion, is evident in Figure 5 with a higher trajectory for global mean surface temperature. Note that because of the lags in the transfer of heat between the layers of the atmosphere and the ocean, the difference in the temperature becomes much greater after the mid-21st century. As a consequence, our optimal control rates for carbon emissions (Figure 6) are much higher than the Nordhaus projections.

FIGURES 5 AND 6 ABOUT HERE

Our conclusion is that a less optimistic assumption regarding energy use in developing countries, and the continued growth in oil use followed by the use of

synthetic liquid fuel, can result in a much higher carbon emissions trajectory and global temperatures than is typically found in similar work.

V. Sensitivity Analysis

How dependent are our results on the petroleum-linked parameter values? We investigate this question with a sensitivity analysis.

In the first sensitivity case, A1, we allow the marginal extraction cost to grow very slowly at 0.5% per year, as compared to 1.61% per years in the base case. In the high growth case, A2, we shift in the opposite direction with the marginal cost of extraction growing rapidly at 2.5% per year. This might partially reflect higher production costs associated with environmental protection. The implications for the optimal oil production trajectory are shown in Figure 7.

FIGURE 7 ABOUT HERE

In the base case, we assume that oil resources are at the 95th percentile of the frequency distribution. This implies that there is a 5% probability that resources exceed the estimated amount. In scenario B1, we use the 50th percentile of the frequency distribution for petroleum resources. The remaining resources corresponding to this level are 2150 billion barrels. In the more optimistic case, B2, remaining resources are 2650 billion barrels, corresponding to the 97.5th percentile. This case allows for breakthrough technological developments that might increase the amount of economically recoverable reserves in the future.

The sensitivity results in Figure 8 have an obvious interpretation. The optimal carbon emissions trajectory as well as the optimal control rate are not very sensitive to the assumptions used in the current analysis. However, note that scenario B1 (lesser remaining oil resources) results in visibly higher CO₂ emissions and optimal control rates.

FIGURE 8 ABOUT HERE

VI. A Tax Policy Simulation

Since the introduction of the Buenos Aires Action Plan in 1998, climate economists have focused their research on the potential carbon permit prices under various emission trading scenarios. The optimal carbon tax rates furnished by our model correspond exactly to the optimal permit price under a global emissions trading regime. However, even under such a regime, there is likely to be some differential impact on fossil fuel prices due to their different carbon contents.

In this section we simulate the effectiveness of changing relative fossil fuel prices in lowering the emissions trajectory towards the optimal level.¹² Under the first two scenarios, we impose taxes at rates that are ranked according to the relative carbon intensities of the fossil fuels, with the tax rates in the second case being twice as high as in the first case. The third scenario is designed such that the resulting emissions trajectory approximately tracks the optimal emissions trajectory obtained earlier. The tax rates used for the analysis are shown in Table 1. Note that the tax on oil is levied on the marginal cost of extraction.

TABLE 1 ABOUT HERE

The impact of an energy tax on the emissions trajectory depends on the simultaneous interplay of several forces. First, as the marginal cost of oil extraction increases due to the imposition of an exogenous tax, the optimal production horizon changes, and therefore, the optimal price and quantity trajectories change. Second, the introduction of synthetic fuels, the most carbon intensive of all the fuels considered, depends on the optimal production horizon for oil. Third, there are substitution possibilities between the various fuels. As the price of a fuel rises there is not only the decline in emissions due to the negative own price effect on demand, but also a partially offsetting increase in the emissions level due to the positive cross-price effect on the demand for substitute fuels.

As evident from Figure 9, the first two scenarios have limited success in reducing the emission levels to the optimal trajectory. For this to be achieved, extremely high tax rates are required, an example of which is shown in scenario three, which raises energy prices by as much as 300%.

FIGURE 9 ABOUT HERE

VII. Conclusions

The modeling of the far future necessary for the analysis of climate change raises challenging economic issues. Ultimately, the empirical structure of a climate-economy model is based on an expectation regarding the development and spread of technologies

and their impact on the economic system. This necessarily involves some amount of informed and educated guessing. The current paper examines the implications for climate policy of some technology related assumptions regarding future energy use.

One can only conjecture what will happen when oil becomes relatively scarce. A common approach is to assume that a carbon-free backstop, such as hydrogen produced by electrolysis, or solar and nuclear power, will take its place.¹³ The result is the presumption of a concave carbon trajectory: in the near term CO₂ emissions rise, but then continuously decline as the carbon-free backstop replaces a larger and larger fraction of the traditional fossil fuels (Chapman and Khanna, 2000b). This presumption is important in the global warming context because, it is, in a sense, the “don’t worry, be happy” approach: if you wait long enough, the problem will solve itself because the very source of the problem will begin to disappear through the postulated AEEI and the shift to carbon-free fuels.

In this analysis, we consider the problem from a different, more pessimistic perspective, where oil may be replaced by an even more carbon intensive but proven energy form, such as a coal or shale based synthetic fuel, for an appreciable length of time. This is accompanied by rise in the energy intensity in presently developing countries such that the frequently posited decline in global energy and carbon intensity is not realized.

Our model yields a much higher level of carbon emissions accompanied by a higher optimal control rate relative to that obtained in other work. The bottom line is the need for greater, quicker, and consequently, more expensive abatement efforts. Furthermore, we find that in the presence of cross-price effects between fossil fuels, high

levels of energy taxation would be required to reduce carbon emissions to their optimal level. (There may be opportunity cost equivalents such as CAFE fuel economy standards, and building insulation code requirements.) In the current economic and political setting it seems unrealistic to expect these to be implemented. Yet, any delay in their implementation might warrant even higher taxation in the future.

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Appendix

A. Estimating Future World Energy Intensity

The econometric model underlying the predicted energy intensity shown in Figure 1 is Model 1. All estimated coefficients are significant at the 1% level.

Model 1 (figures in parenthesis are standard errors):

$$E_t = 11.99 + 46.5 \left(\frac{1}{trend} \right) - 29.65 \left(\frac{1}{trend^2} \right) + error$$

(0.44) (4.07) (4.18)

$$R^2 = 0.9273$$

where E_t = energy intensity in year t

$trend$ = trend variable, measured in terms of calendar years.

An alternative model, Model 2, was also estimated.

Model 2:

$$E_t = E_0 \left(\exp(\mathbf{a} * trend + \mathbf{b} * trend^2) \right) + error$$

where E_0 refers to the observed energy intensity in year 0 (1973 in our case)

Econometrically, it is hard to distinguish between the two models. Both models seem to fit the data equally well, and with all coefficients statistically significant at the 1% level. The significant difference between the two models in our context is that Model 2 predicts a u-shaped curve for global energy intensity. However, given the discussion in the text, Model 1 has a greater intuitive appeal.

Both models were estimated using energy data from the EIA (1979, 1987, 1997). Economic data were obtained from the World Bank (2000). World GNP in current US \$ was converted to constant 1996 US \$ using the US GDP deflator (ERP, 2000). This methodology is preferred over the standard GNP in constant US \$ series provided by the World Bank due to the known under-reporting of inflation rates by national governments for political reasons. See Suri (1997) for details.

B. An Overview of the DICE Model, and Some New Developments

The DICE model comprises a representative agent, optimal growth model with an intertemporal objective function which maximizes the present value of utility. The decision variables are the rate of investment and the fraction by which GHG emissions are reduced. The model has a 400 year horizon starting from 1965, and operates in time steps of one decade. The pure rate of time preference is 3% per year.

The world economy produces a composite economic product using a constant returns to scale, Cobb-Douglas production function in capital and labor with Hicks neutral technical change. Production is associated with the emissions of GHGs. The model assumes that only CO₂ and chlorofluorocarbons (CFCs) are controlled. Other GHGs are determined exogenously. The uncontrolled level of emissions in any period is proportional to the level of output. The transformation parameter is assumed to decline over time, according to the growth in total factor productivity.

The accumulation of GHGs in the atmosphere depends not only on the emission levels, but also on the rate at which carbon diffuses into the deep ocean. The ambient atmospheric carbon level in any period, therefore, depends on two, time invariant

parameters - the atmospheric retention ratio and the rate of transfer to the deep ocean.

The accumulation of GHGs results in the rise of global mean surface temperature. The relation between GHG emissions and increased radiative forcing has been derived from empirical studies and climate models. The link between increased radiative forcing and climate change is established by another geophysical relation that incorporates the lags in the warming of the various layers in the climate system, such that a doubling of ambient CO₂ emissions increases radiative forcing by 4.1 Wm².

The economic impact of climate change, represented by the fraction of output lost, is a quadratic function in the increase in atmospheric temperature. The cost of reducing emissions is also assumed to increase with the rise in temperature through an empirically determined relationship. Damage and cost relations come together through an additional shift parameter in the production function.

Details of the model, including the GAMS code are available in Nordhaus (1994). The model has also been developed at a regionally disaggregated level (Nordhaus and Yang, 1996). Howarth (1996) has interpreted the representative agent model in the context of an overlapping generations framework.

Hall (1996) questions the use of such models to obtain optimal climate policies. He argues that the correct framework for analyzing climate policy is based on the concept of geoeconomic time which incorporates the interaction between the economic system and the earth's geophysical system.

Recently, both the 1994 and 1996 Nordhaus models were updated. The most significant change includes a multi-reservoir climate model calibrated to existing climate models (Nordhaus and Boyer, 1999). In addition, the regionally disaggregated RICE

model incorporates carbon-energy as a factor input in the production process. While this is an improvement over the simple two factor production function used in the earlier DICE and RICE models, the formulation is subject to the same criticisms applicable to other models mentioned in the text. The new RICE-98 model assumes a long-run carbon supply curve. The supply price of carbon is determined by the ratio of cumulative consumption to remaining resources. The model does not distinguish between the different fossil fuels. A generic carbon-free backstop is assumed to be available at a high cost.

None of these changes would affect the qualitative results of our analysis.

C. Integrating the Energy Module with the DICE Model

The integrated energy-DICE model is run in three steps. (Copies of the corresponding GAMS code are available from the authors.)

- 1) The pure Ramsey growth model is run to obtain initial values for the gross economic output and the discount rate. The Ramsey model is obtained as a subset of the DICE model, excluding the emissions, concentrations, forcings, temperature change, damage, and cost equations. Since there are no climate effects in this model, the damage coefficient in the production function is set at 1. The discount rate is obtained as the rate of return on capital.
- 2) The equilibrium per capita economic output and the discount rate obtained in step1 are used as the starting values for the energy model, which simulates the demand for oil, coal, natural gas, and the synfuel. The per capita demand for coal, natural gas, and the synfuel are modeled as Cobb-Douglas functions of per capita

output, own prices, and prices of substitute fuels. The optimal production horizon for oil production as well as the equilibrium production trajectory are obtained using equations (3) and (4) in the text.

The total demand for each energy type determines CO₂ emissions through emission coefficients (see equation (5) in the text, and Table A in this Appendix). The emissions are then used to determine optimal temperature change and its economic impacts using the climate change equations of the DICE model. In turn, these determine the optimal net economic output, i.e., economic output after taking account of climate impacts.

- 3) Finally, steps 2 and 3 are repeated using the net economic output and the corresponding discount rate till the integrated energy-economy model converges to a steady state.

D. Parameter Values for the Energy Module

TABLE A ABOUT HERE

Footnotes

- 1 For an overview of recent literature, see Weyant and Hill (1999) and the 1999 Special Issue of the *Energy Journal*.
- 2 In the case of India, Manne and Richels (1999) assume a much lower AEEI in the early years of 2000 and 2010 due to the shift from non-commercial to commercial energy use.
- 3 At the national level, energy consumption may also decline due to the effect of policies, and the shift from manufacturing to services that occurs as the economy matures.
- 4 Details of the econometric model and data are provided in the appendix.
- 5 Chapman (1993) also developed the model under cartel monopoly-like assumptions and a combination of competition and monopoly, both with and without a backstop technology.
- 6 Note that in the case of a linear demand curve, the shifting intercept implies that the responsiveness of demand to own-price varies from period to period. The expression for the own-price elasticity corresponding to the demand function in equation (1) is:

$$+ \rho + \frac{P_t^m}{\beta_2 L_t^{\beta_1} y_t^{\beta_2} (P_t^{subs,m})^{\beta_3} + P_t^m}$$

- 7 Original endowment is defined as the sum of undiscovered resources, identified reserves, and cumulative production (Masters et al., 1991).
- 8 Computationally, per capita demands for coal, natural gas, and the synfuel are modeled as linearly homogenous Cobb-Douglas functions in per capita income and prices. Aggregate demand is the product of rising per capita demand and population.
- 9 The real interest rate in equation (1) is determined from the optimal economic growth model as the real rate of return on capital, and varies from period to period. At the steady state equilibrium, it is numerically equal to the discount rate:

$$r = \rho + g$$

where ρ is the pure rate of time preference, β_2 is the elasticity of marginal utility w.r.t. per capita consumption, and g is the growth rate of per capita consumption (Khanna and Chapman, 1996).

This relationship is modified if climate change impacts have a direct negative impact on utility. In that case, the pure rate of time preference might be lower than 3% per year as assumed in this analysis. (We thank an anonymous reviewer for pointing this out.) Khanna and Chapman (1996) have argued for a zero pure rate of time preference in the case of climate change models. However,

- the original Nordhaus assumption of 3% per year is retained here so as to focus on the impacts of technology assumptions on climate policy. Chapman et al. (1995) explore the sensitivity of optimal climate policy to changes in the pure rate of time preference.
- 10 The model generates results for a 400 year horizon. However, for ease of presentation, we present results through the year 2110 only. The only exception is Figure 5.
 - 11 In Nordhaus (1994) “emissions” refer to the sum of CO₂ and CO₂-equivalent CFC emissions. Our model considers only the former, as does the later work by Nordhaus and Yang (1996) and Nordhaus and Boyer (1999).
 - 12 Note that this is a simulation and not an optimization exercise. The base case trajectory of per capita income is treated as an exogenous variable for this section of the analysis.
 - 13 A contrasting view is presented by Drennen et al (1996). They argue that even after including externality costs, solar photovoltaics are unlikely to be competitive and available for widespread adoption without significant technological breakthroughs.

Table 1: Tax Rates and Levels Under Alternative Tax Scenarios

	Scenario 1 Low Tax			Scenario 2 Medium Tax			Scenario 3 Optimal Control		
	Rate (%)	Tax Level		Rate (%)	Tax Level		Rate (%)	Tax Level	
		1995	2015		1995	2015		1995	2015
Oil (\$/bl) ^A	20	2.2	-	40	4.3	-	100	10.8	-
Coal (\$/ton)	30	6.8	7.6	60	13.5	15.1	200	45.1	50.4
Nat. Gas (\$/1000 cf)	10	0.3	0.4	20	0.6	0.7	100	3.1	3.5
Synfuel (\$/bl) ^B	40	-	23.6	80	-	47.2	300	-	177

The tax rate refers to the percentage by which energy prices are raised. The tax level is the absolute level of the energy tax (units are shown in the first column).

A: The tax is levied on extraction.

B: The tax is levied once synfuel production begins in the decade of 2005.

Table A

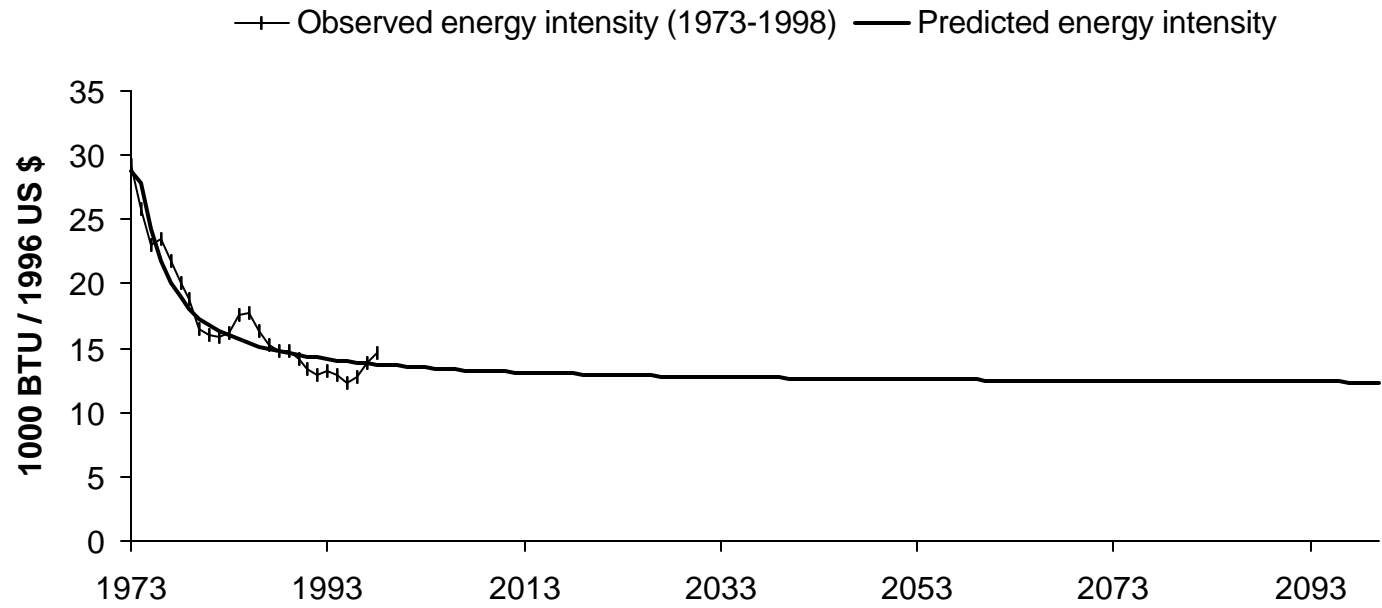
Parameter	Value	Data Sources
Energy Demand Elasticities		Drennen (1993)
Own-price	-0.5	
Cross-price	0.25	
Income	1	
Energy Prices: 1965, 1995		
Coal (price to utilities, \$/ton)	21.82, 22.56	EIA (1994 and 1996, respectively)
Natural gas (\$/1000 cf)	2.27, 3.14	AGA (1981), EIA (1996)
	0.1	
Growth Rate (% per year)		
Per capita energy consumption: 1965		Based on energy data from Brown et al. (1995) and population data from Nordhaus (1994).
Coal (mbtu)	15.58	
Natural gas (mbtu)	7.14	
Cost of backstop		
Initial value (\$/bl)	55	
Growth rate (% per year)	0.1	
Cost of extraction		Based on Chapman (1993)
1965 value (\$/bl)	6.71	
Growth rate (% per year)	1.61	
Remaining oil resources: 1965 (trillion barrels)	2.5	Based on 95 th percentile of distribution for 1990 and cumulative production from 1965-1990. See text also.
Carbon coefficients (BTC/quad)		Based on Manne and Richels (1992)
Coal	0.0254	
Oil	0.0210	
Natural gas	0.0144	
Synfuel	0.0421	

Note:

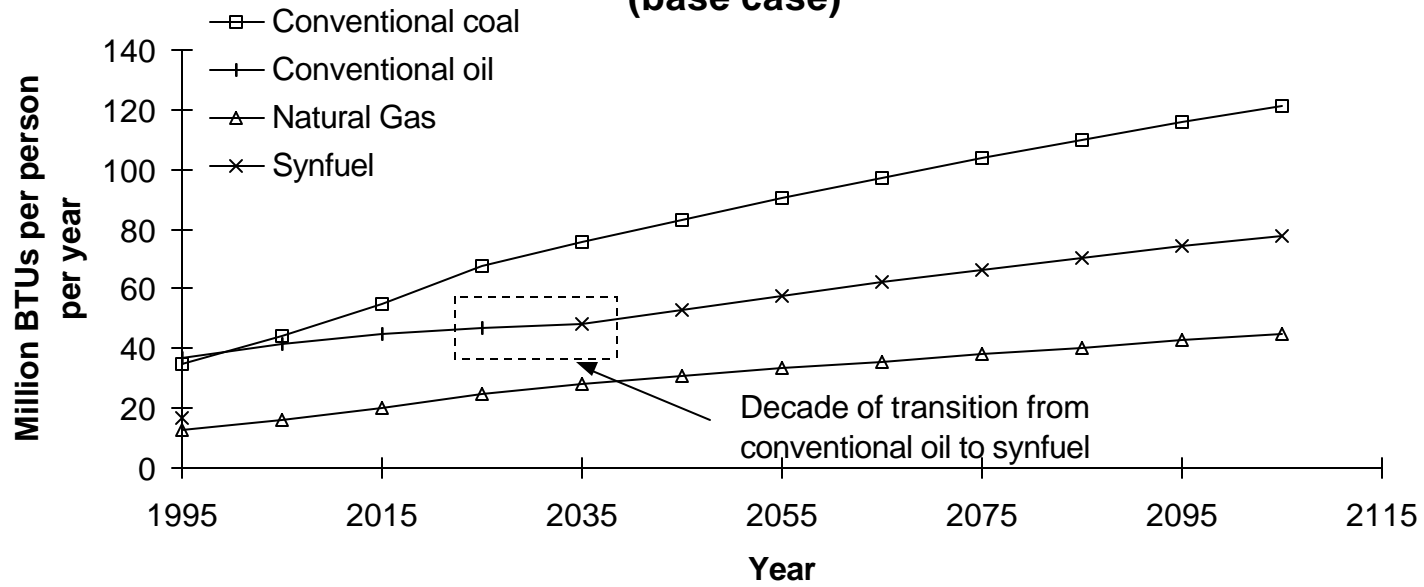
1. Data are in 1989 \$ where applicable. The base year was changed using the implicit GDP deflators obtained from EIA (1994) and BEA (1996).

2. Natural gas price is the volume weighted average for all consumers.

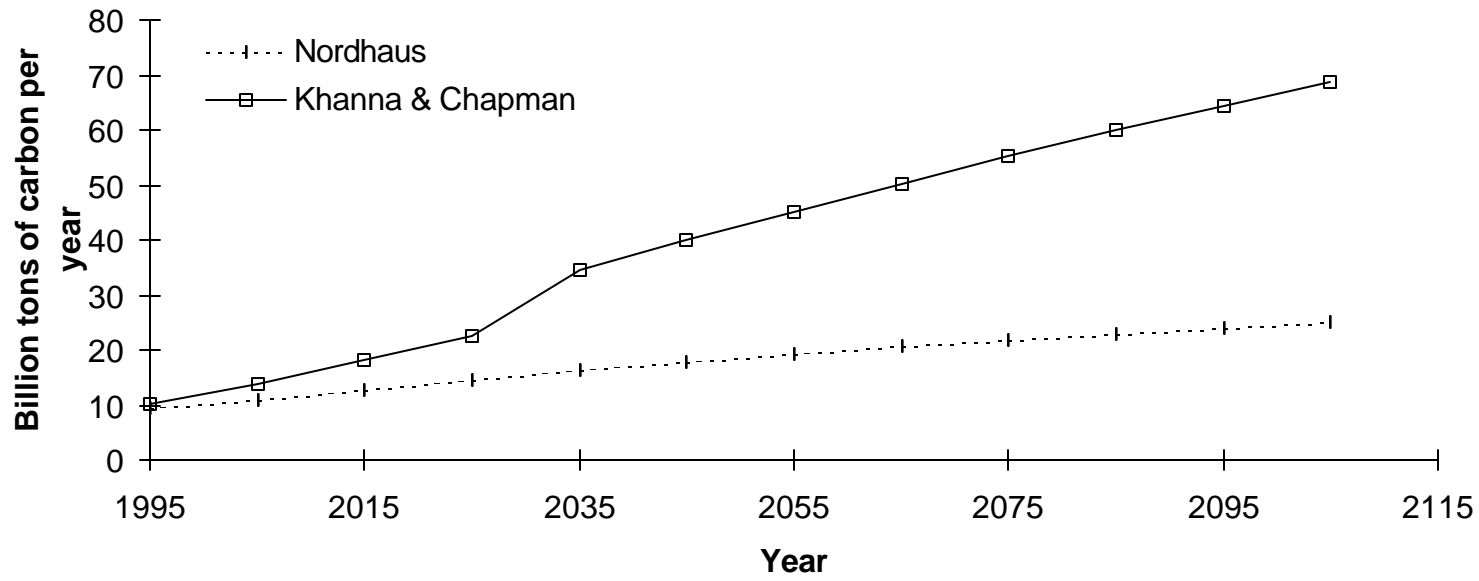
Figure 1: Observed and Predicted Energy Intensity



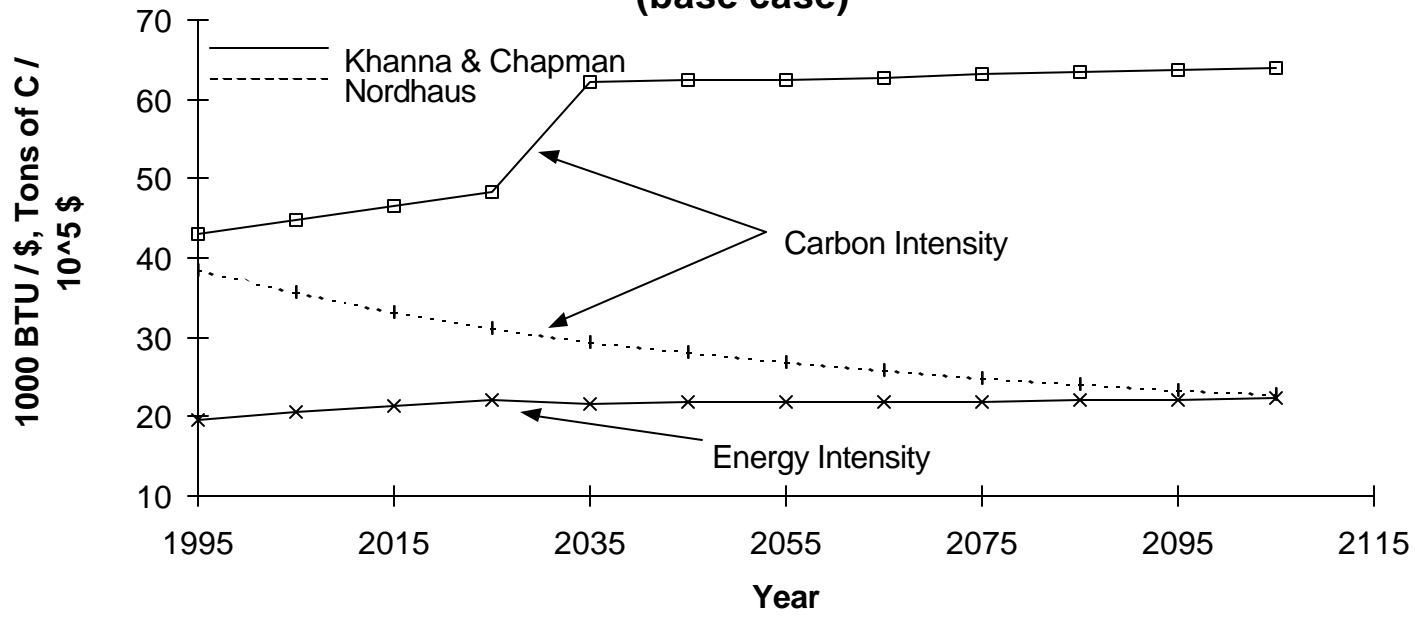
**Figure 2: Per Capita Energy Consumption
(base case)**



**Figure 3: Carbon Emissions
(base case)**



**Figure 4: Projected Energy and Carbon Intensity
(base case)**



**Figure 5: Rise in Mean Surface Temperature
(base case)**

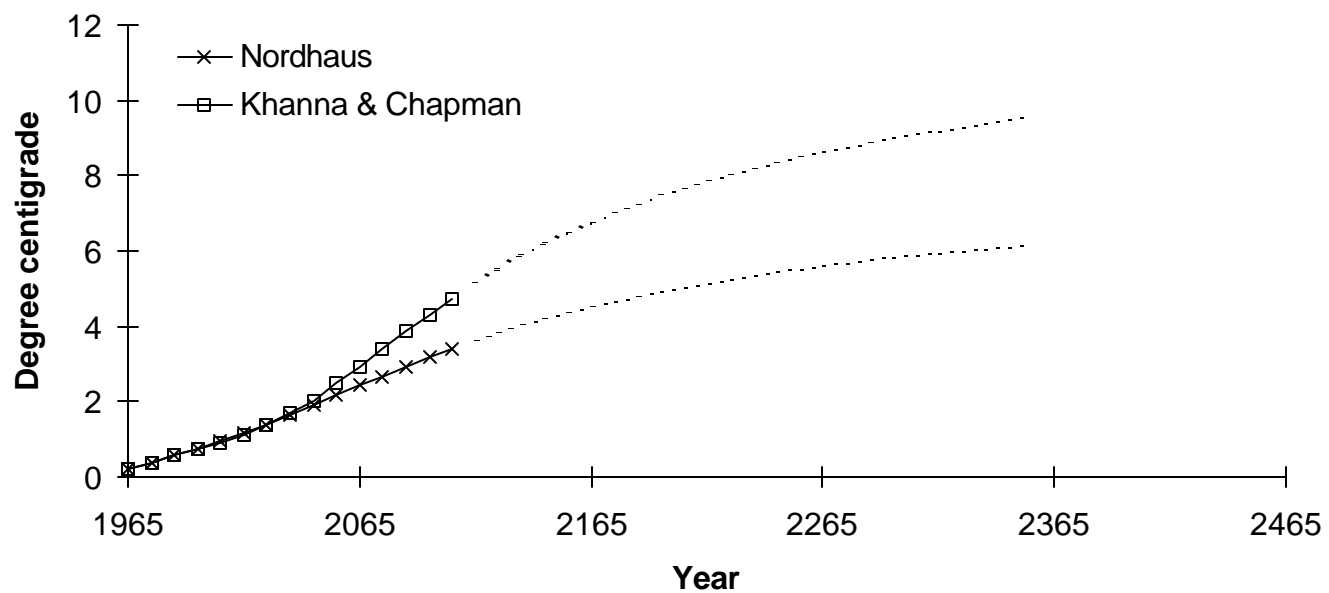


Figure 6: Optimal Control Rate for Carbon Emissions

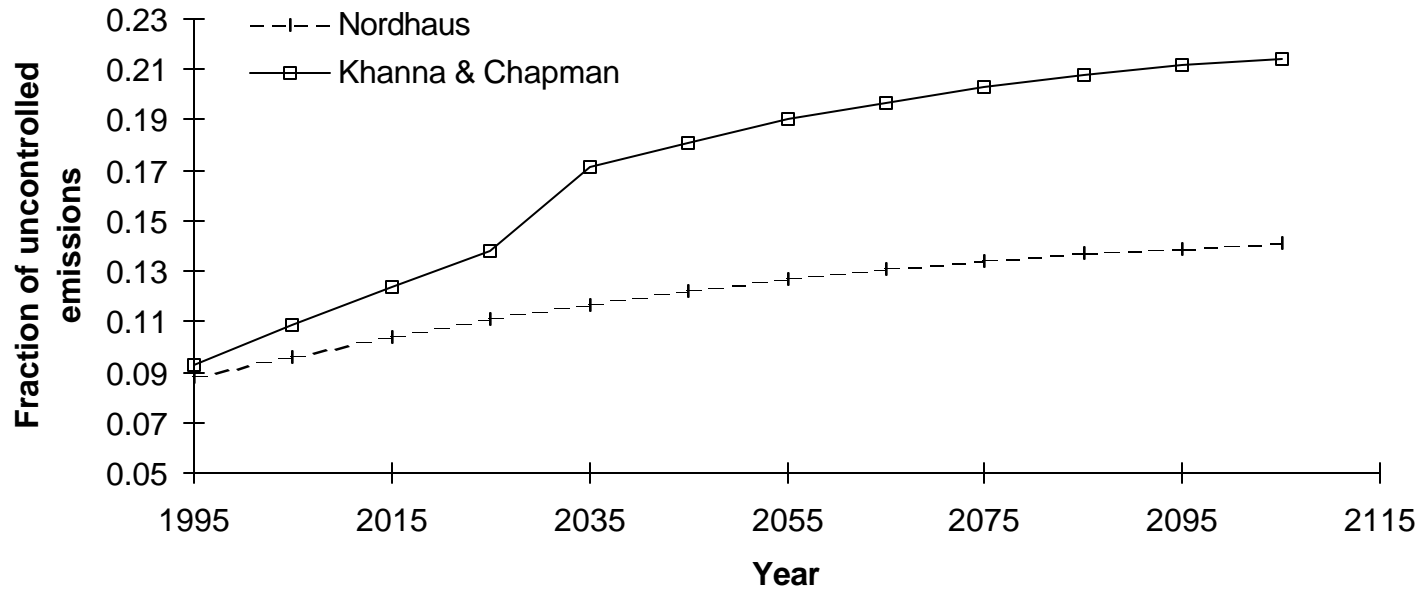
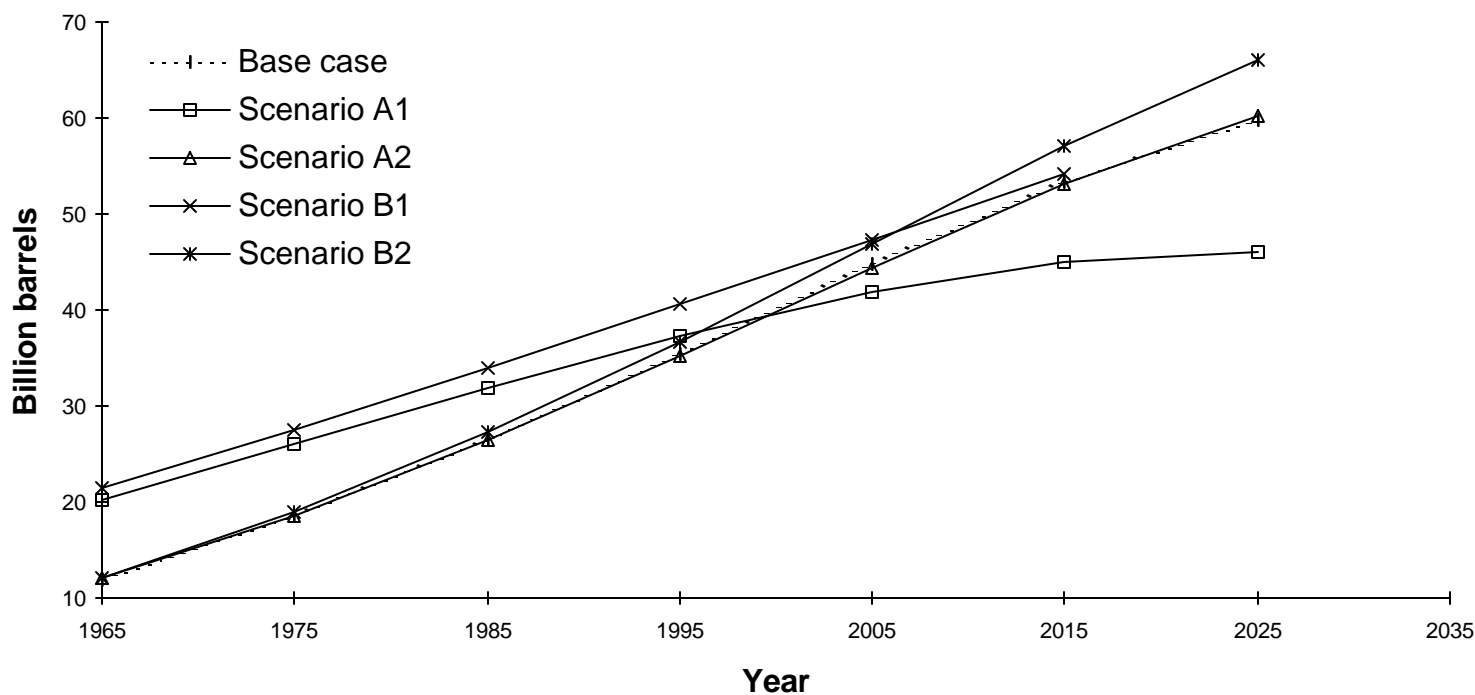


Figure 7: Equilibrium Oil Production Under Alternative Scenarios



Scenario A1: growth rate of marginal cost of extraction for oil = 0.5% per year

Scenario A2: growth rate of marginal cost of extraction for oil = 2.5% per year

Scenario B1: remaining oil resources estimated using 50th percentile in the frequency distribution for original resources

Scenario B2: remaining oil resources estimated using 97.5th percentile in the frequency distribution for original resources

Note: In all cases, the optimal oil production trajectory terminates in the decade of 2025

Figure 9: CO2 Emissions Under Alternative Tax Scenarios

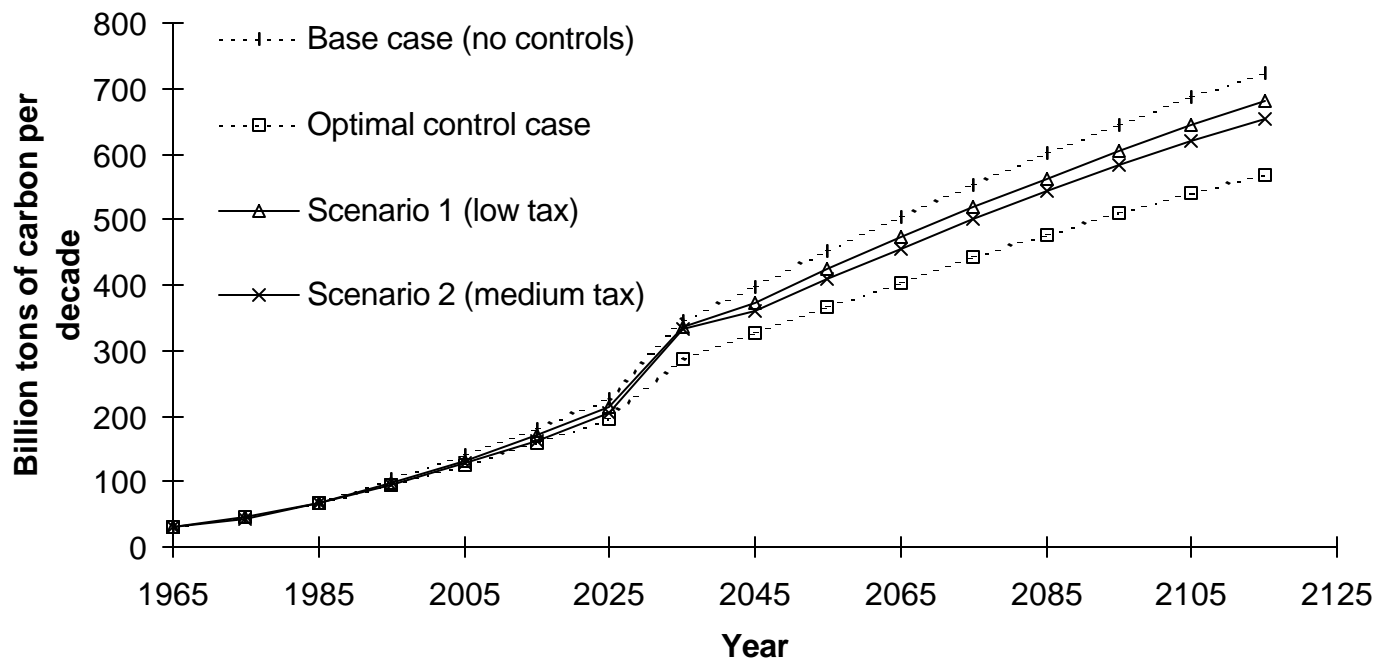
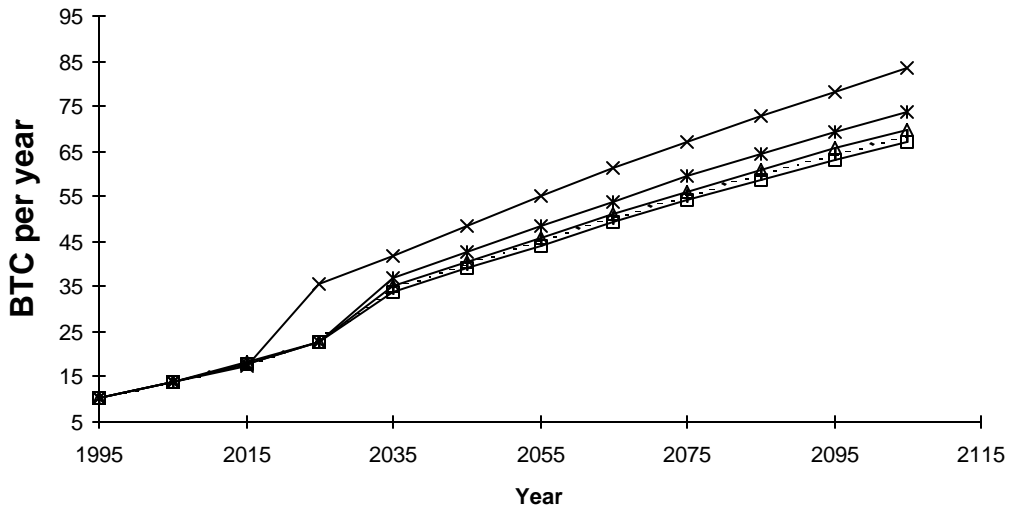
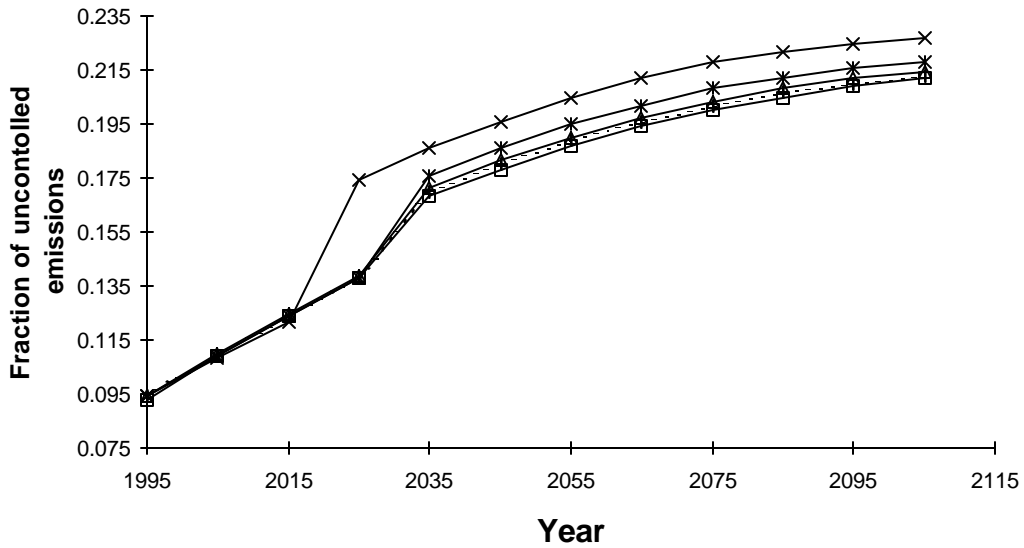


Figure 8: Sensitivity Analysis

CO2 Emissions Under Alternative Scenarios



Control Rate Under Alternative Scenarios



..... Base case —□— Scenario A1 —Δ— Scenario A2
—x— Scenario B1 —*— Scenario B2