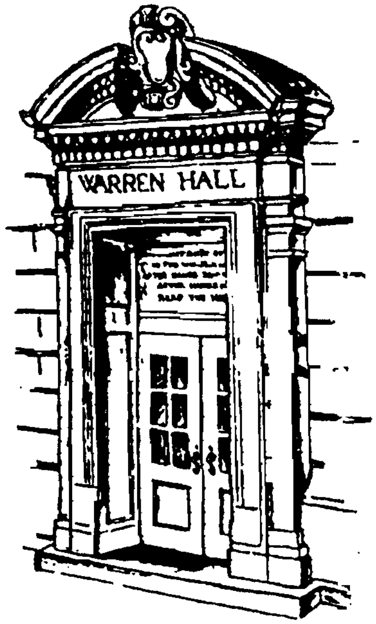


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## Climate Policy and Petroleum Depletion in an Optimal Growth Framework

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# CLIMATE POLICY AND PETROLEUM DEPLETION IN AN OPTIMAL GROWTH FRAMEWORK

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## Abstract

This paper presents a model framework and results that combine resource depletion with optimal economic growth and climate change in a macro-geoeconomic model. In doing so, the authors build upon the Nordhaus DICE model to include the demands for coal, oil, and natural gas. These demands depend upon own price, prices of substitute fuels, per capita income, and population. The resource depletion model captures the effect on oil depletion of upward shifting demand curves which respond to population and income growth. A methodological advantage of including price, income, and population sensitive energy demand functions is that it allows substitution possibilities in the "production" of emissions. Furthermore, it allows the analysis of energy tax regimes in an environment of growing world population and income, non-decreasing energy and carbon intensity, and future, declining petroleum availability.

*Our future lies not in the stars, but in our models.*

*(William Nordhaus, 1994, p. 6)*

## 1. An Analytical Framework for Optimal Resource Depletion in a Growing World Economy

The Dynamic Integrated Climate Economy (DICE) model developed by William Nordhaus represents a new genre of economic analysis in the context of climate change. It has been widely discussed (Nordhaus 1991, 1992, 1994). In subsequent work, Nordhaus and Zili Yang (1996) expanded this approach to encompass several world regions which may work cooperatively, or each may work in pursuit of maximum benefit for itself. Similar model configurations were developed by Manne and Richels (1992), Manne *et al.* (1995), and Peck and Teisberg (1992, 1995) in the 1990s.[1] The pioneering contribution of these models, often referred to as integrated assessment models of climate change, lies in combining the standard tools of optimal economic growth with climate modeling. The interaction between these two facets is established via greenhouse gas (GHG) emissions, ocean storage, and climate induced damage that links temperature rise to loss in world output.

The concatenation between optimal economic growth and climate modeling forms the starting point of the current analysis. We present an analytical framework that combines an augmented model for optimal resource depletion with the macro-geoeconomic growth model developed

[1] The special issue of *Energy Policy* (Vol. 23, # 4/5, 1995) on integrated assessment models of climate change provides an excellent review of model structures and issues. Dowlatabadi's paper in the same issue provides an overview. The Nordhaus-Yohe work (National Academy of Sciences 1983) foreshadows the path-breaking DICE methodology.

by Nordhaus (1994). The traditional resource depletion model utilizes demand assumptions which typically ignore rising per capita incomes and population growth, often assumes constant marginal costs of extraction which may not be consistent with observed data, and does not reflect the important geological concept of undiscovered resources. Consequently, this conventional model yields a monotonically declining equilibrium production trajectory, a result clearly discordant with global reality.

The augmented depletion framework presented here models demand curves that respond to population and income growth, and also the price of substitute fuels.[2] This allows for solutions with near-term growth in optimal consumption. Furthermore, in estimating the stock of remaining resources, we take account of undiscovered resources in addition to identified reserves.

We assume that there is a set of fossil fuels, $M$, where $m \in M$, each of which has a finite stock of remaining resources, $S^m$, and each faces a slowly rising marginal cost of extraction, $C_t^m$. (The assumed extraction cost incorporates the internalization of environmental protection costs into production costs.) In addition, the exogenously specified, linear demand curves shift over time in response to a growing world population, $L_t$, and rising per capita incomes, $y_t$, and also the price of the substitute

[2] Also see Chapman (1993) which compares monopolistic, competitive, and mixed solutions, with and without backstop substitute technologies. Usually, Hotelling models have fixed demand curves which, in the absence of a backstop, define a monotonically declining consumption trajectory. In future work, we plan to investigate the impact of declining and/or constant marginal costs of extraction for future periods.

fuel, $P_t^{subs,m}$.[3] For exhaustible fuels, the price of the backstop, $P_t^{back,m}$, sets the upper bound on their respective price trajectories. Producers in each market maximize the net present value ($NPV^m$) of competitive profits by choosing the optimal duration of production, $T^m$, and the quantity produced in each time period, $q_t^m$, given the demand and cost schedules, and remaining resources. Following Chapman (1993) this can be written as:

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[3] Note that in the case of a linear demand curve, the shifting intercept implies that the own-price elasticity of demand varies from period to period. The expression for the own-price elasticity corresponding to the demand function in equation 1 is:

$$\mathrm{E} = - \frac{P_t^m}{\beta_2^m L_t^{\eta_1} y_t^{\eta_2} (P_t^{subs,m})^{\eta_3} - P_t^m} .$$

Maximize $NPV^m$ *w.r.t.* $[q_t^m, T^m]$, where

$$NPV^m = \sum_{t=1}^{T^m} \left( \frac{[P_t^m(q_t^m, L_t, y_t, P_t^{subs,m}) - C^m(t)]\, q_t^m}{\prod_{\tau=1}^{t}(1 + r_\tau)} \right)$$

$$P_t^m(\cdot) = \beta_2^m L_t^{\eta_1} y_t^{\eta_2} (P_t^{subs,m})^{\eta_3} - \beta_1^m q_t^m$$

$$C^m(t) = C_0^m (1 + \phi^m)^t \tag{1}$$

$$\sum_{t=1}^{T^m} q_t^m \le S^m$$

$$P_t^m \le P_t^{back,m}$$

$$P_t^m,\ q_t^m,\ P_t^m - q_t^m \ge 0$$

$P_t^m$: price of fuel $m$ at time $t$

$q_t^m$: production of fuel $m$ at time $t$

$C^m(t)$: marginal cost of extraction for fuel $m$ at time $t$

$L_t$: population at time $t$

$y_t$: per capita income at time $t$

$r_\tau$: real interest rate

$S^m$: stock of remaining resources

$\beta_1^m$: slope of the demand curve

$\beta_2^m$: calibration constant

$\eta_1$: population sensitivity parameter

$\eta_2$: income sensitivity parameter

$\eta_3$: cross-price sensitivity parameter

$\phi^m$: growth rate of extraction cost

Note that the real interest rate, $r_\tau$, 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:

$$r = \mu + \theta g \tag{2}$$

where $\mu$ is the pure rate of time preference, $\theta$ is the elasticity of marginal utility *w.r.t.* per capita consumption, and $g$ is the growth rate of per capita consumption.[4] The trajectories for per capita consumption and per capita income are also determined via the optimal economic growth model.

The Hamiltonian for the above problem, under perfectly competitive fuel markets, is:

$$H^m = \frac{[P_t^m(\cdot) - C^m(t)]q_t^m}{\prod_{\tau=1}^{t}(1 + r_\tau)} - \lambda_t^m q_t^m$$

$$\frac{\partial P_t^m}{\partial q_t^m} \equiv 0 \tag{3}$$

where $\lambda_t^m$ 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 equilibrium production trajectory, $q_t^{m*}$, can be found by solving the first order conditions and the constraints, simultaneously. The solution is:

[4] In the case of the DICE model, and also for the present analysis, $\mu$ = 3% per year and $\theta$ = 1. Khanna and Chapman (1996) investigate the policy implications of alternative numerical values for these parameters.

$$q_t^{m^*} = \beta_{3_t}^m + \frac{\Pi_{\tau=1}^t (1+r_\tau)}{X^m(r)} (S^m - \beta_4^m)$$

$$\beta_{3_t}^m = \frac{\beta_2^m L_t^{\eta_1} y_t^{\eta_2} (P_t^{subs,m})^{\eta_3} - C^m(t)}{\beta_1^m} \tag{4}$$

$$\beta_4^m = \sum_{t=1}^{T^m} \beta_{3_t}^m$$

$$X^m(r) = \sum_{t=1}^{T^m} \left( \Pi_{\tau=1}^t (1 + r_\tau) \right)$$

The optimal production trajectory, $q_t^{m^*}$, is made up of two components. The first, $\beta_{3t}^m$, is the equilibrium production trajectory in the absence of a resource constraint. It is the locus of the intersection over time between the shifting demand curves and the steadily rising marginal cost of extraction. The second part represents the present value of the scarcity arising due to the finite stock of remaining resources. It is based on the difference between remaining resources, $S^m$, and the cumulative production in the absence of a resource constraint, $\beta_4^m$.

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

$$\begin{aligned} T_1^m &= T \ni \beta_2^m L_T^{\eta_1} y_T^{\eta_2} (P_T^{subs,m})^{\eta_3} = C^m(T) \\ T_2^m &= T \ni P_T^m = P_T^{back,m} \end{aligned} \tag{5}$$

where $T_1^m$ 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.

$CO_2$ emissions are determined via exogenously specified coefficients, $\upsilon^n$, that translate energy units to billion tons of carbon. Unconstrained emissions at time $t$ are represented as:

$$E_t = \sum_n \nu^n q_t^n \tag{6}$$

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

The macro-geoeconomic model and the optimal resource depletion models operate iteratively until they converge to a solution, thereby determining the optimal trajectories for capital stock and $CO_2$ emissions reduction, and also the optimal production horizons and production quantities for all exhaustible fossil fuels. The optimal production trajectory is such that remaining resources are exhausted when the rising equilibrium price passes the cost of the backstop. The model developed by Nordhaus is summarized in appendix 1.

## 2. Greenhouse Gas Emissions and the Existence of Decarbonization

Carbon intensity, the relationship between carbon emissions and economic product, is a key parameter determining results in macro-geoeconomic models. In his model, Nordhaus projects uncontrolled GHG emissions as proportional to world economic output.[5] The evolution of technology brings two additional forces into play. First, total factor productivity, $A(t)$, increases so that the production isoquant shifts inward over time. This implies that the same physical quantities of capital and labour produce an increasing output over time. Second, the emissions to output ratio, $\sigma(t)$, decreases monotonically. That is, the ray defining the relation between emissions and output rotates towards the output axis with time.[6] Nordhaus assumes this decline in $\sigma(t)$ on the grounds that it is consistent with historical data and with the results of some energy models. At the same time, he notes that there is a great deal of uncertainty and speculation here, and acknowledges that there is no correct assumption regarding the future trend in the $CO_2$-GNP ratio. According to his perspective, in the long term this ratio could fall by as much as 1.5% per year or by as little as 0.5% per year (Nordhaus 1994, pp. 66-70). The key factors determining the total level of uncontrolled emissions in DICE are, thus, the level of world output and autonomous technological change.

While these factors are important, they are not the only determinants of the emissions profile of the global economy. Total emissions depend not only on the amount of output produced, but also on how it is produced. In other words, the fuel mix and factors affecting it:

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[5] Only carbon dioxide ($CO_2$) and chloroflorocarbons (CFCs) emissions are proportional to output. All other GHGs are determined outside the model and are independent of the level of gross world product.

[6] For both parameters $A(t)$ and $\sigma(t)$, the rate of change declines by a numerically identical amount.

energy prices, per capita income, resource availability, and substitutability, for example, are equally significant factors. At the same time, the carbon intensity of the global economy depends on the relative future growth of presently developing and developed economies. The emissions to output ratio can decline only if, *ceteris paribus*, the observed decline in the carbon intensity of the developed countries more than outweighs the possible increase in the carbon intensity of developing countries, or if both decline. Exactly what will happen is not clear, *a priori*. This is apparent from table 1 which shows the global carbon intensity between 1929 and 1989. While the carbon-GNP ratio is lower at the end of the period, it is instructive to consider two component time periods separately. Between 1929 and 1960, carbon intensity declined sharply. However, the period from 1960 onwards experienced a slight increase, possibly indicating the growing importance of developing countries in the global energy-economy.

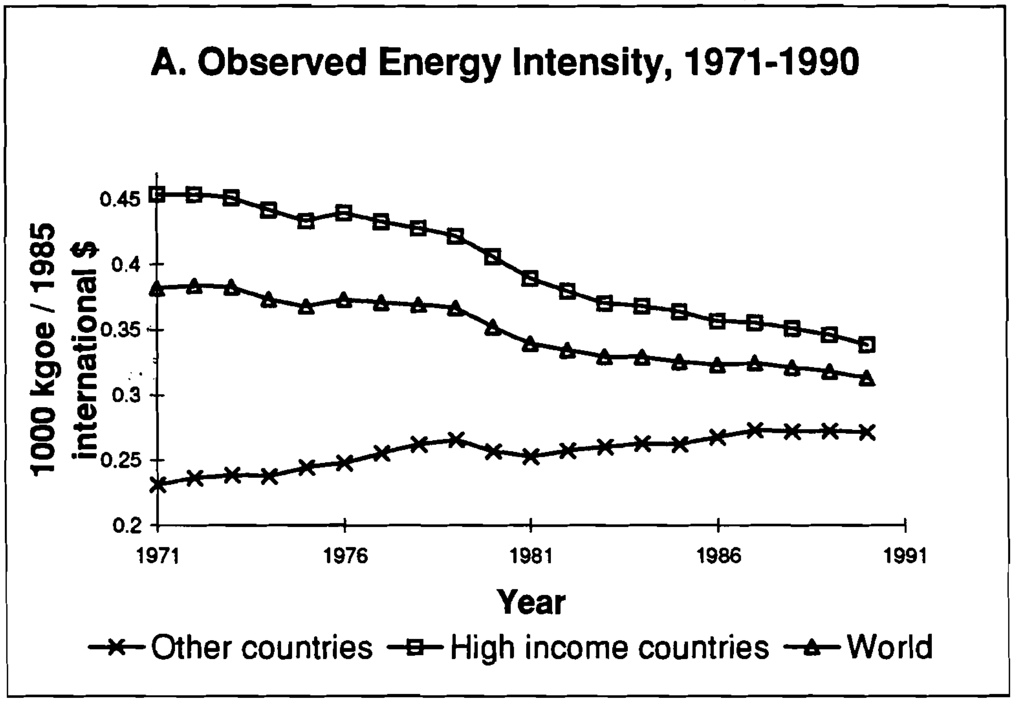
**Table 1**
**Global Carbon Intensity, 1929-1989**

| Year | Tons of C / 1000 1989 US $ |
|---|---|
| 1929 | 0.409 |
| 1938 | 0.366 |
| 1950 | 0.343 |
| 1960 | 0.219 |
| 1970 | 0.219 |
| 1980 | 0.241 |
| 1989 | 0.232 |

*Source*: Nordhaus (1994, p. 67)
*Note*: "Ton" refers to the metric rather than the U.S. ton.

This trend in global carbon intensity is influenced by underlying trends in the patterns of energy consumption of high income and other countries. Panel A in figure 1 shows energy use per unit of economic output from 1971 to 1992 for 101, countries grouped as high income countries and as the rest of the world (ROW) or other countries.[7] While there is a slight upward trend in the energy intensity of the countries comprising ROW during this period, energy intensity for the entire

[7] GDP data for this analysis were obtained from the Penn World Tables (version 5.6). Details of this data base are available in Summers and Heston (1991). Energy consumption data were obtained from World Bank (1995). Countries were categorized according to the World Bank's definition of countries by income class (World Bank, 1995). For countries included in our sample see Khanna and Chapman (1997), pp. 27-28.



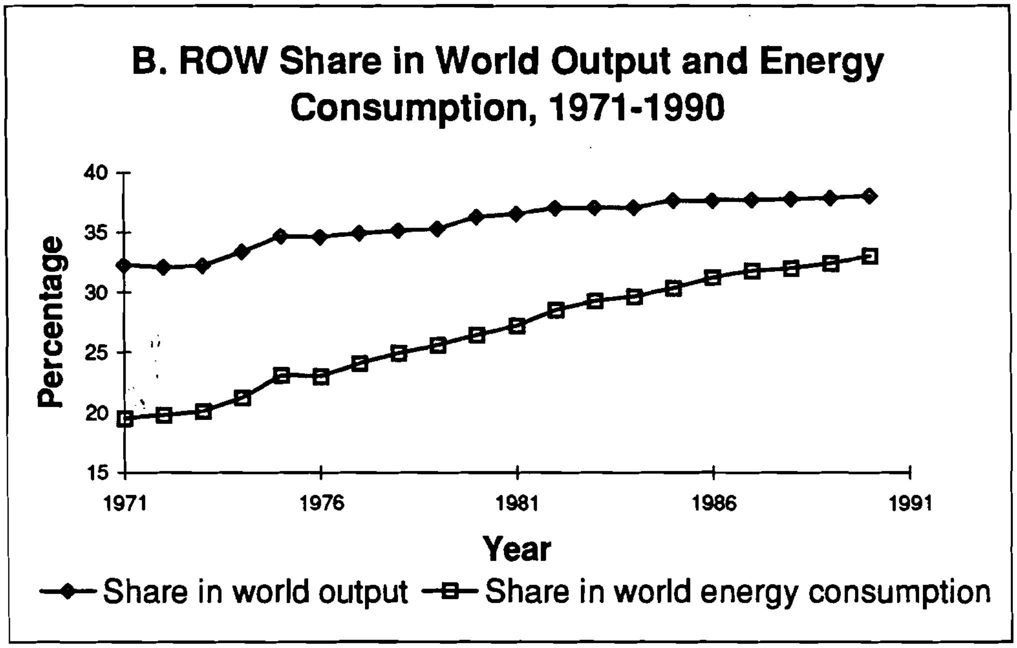




**Figure 1**

**Energy Intensity and Share in World Output and Energy Consumption**

sample declined by almost 18%, closely following the strong trend for high income countries. This is because high income countries dominated world energy consumption and output in the past: in 1971 they accounted for 80.4 % of total commercial energy consumption, and 67.7 % of the world's economic product. However, this highly skewed pattern of consumption and output is being slowly eroded with the ROW's share rising steadily (see panel B figure 1).[8] If this trend continues the future global trend in energy intensity will be dominated by the growth in energy consumption in the ROW countries, and would reduce or halt the historic decline in global energy intensity. This is contrary to the standard assumptions of many prominent macroeconomic energy and climate change models (see Peck and Teisberg 1992 and 1995, Nordhaus 1994, Nordhaus and Yang 1996, and Manne *et al.* 1995).

Manne and Richels (1992, pp. 32-34) review the literature on this issue, and conclude that there is no econometric evidence of autonomous energy efficiency improvements (AEEI) in post 1947 USA. They claim that the reason for the common assumption of positive AEEI is possibly the optimistic outlook of energy technologists. In their own modeling, they followed the existing practice and hypothesize a positive global AEEI. The postulated decline in carbon intensity through the AEEI is a highly significant, unresolved issue in climate change policy analysis.

[8] In figure 1 "world" refers to the aggregate for the 101 countries in the sample. This is different from the data in table 1 which presents global data on carbon intensity. Note that the sample of countries excludes the former centrally planned countries of East Europe that typically were large consumers of coal.

## 3. Discussion and Results

In the present Khanna-Chapman analysis (KCA) there are four carbon based fuels - coal, oil, natural gas, and a coal-based synthetic fuel that acts as the backstop. We operate the above analytical framework for a single exhaustible resource, *viz.*, oil, assuming that the oil market is the driving force of the energy economy and the first resource that may reflect future scarcity.[9]

The demands for coal and for natural gas are determined by population, per capita income, own prices, and prices of all other fuels.[10] Oil is ultimately replaced by a synthetic liquid fuel backstop, whose demand is also determined through a similar function in prices and income. This substitutability between fuel types, captured by cross-price elasticities, is an important assumption and is itself reflected in the changing fuel shares in total emissions production. In addition, it endogenizes the change in energy and carbon intensity that occurs in response to changes in relative prices. We do not impose exogenous improvements in future carbon and energy intensity. This is in concert with the discussion, and the data presented in table 1 and in figure 1.

Several other studies, most notably Manne and Richels (1992), Manne *et al.* (1995), and Peck and Teisberg (1992, 1995), incorporate a fairly detailed specification of the energy sector. These models also take

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[9] Future research will include natural gas, in addition to oil, among the set of exhaustible fossil fuel resources.

[10] Compuatationally, per capita demands for coal, natural gas, and the synfuel (unlike oil) are modeled as linear homogenous Cobb-Douglas functions in per capita income and prices. Aggregate demand is the product of per capita demand and population.

account of the depletion of oil resources using a framework that is loosely based on a Hotelling-type model for exhaustible resources. However, the optimal trajectories obtained from these models are monotonically declining, a result that is inconsistent with actual production data over the last three decades. The present analysis attempts to reconcile model results with observed data. In addition, none of the aforementioned studies incorporate cross price effects between the different fossil fuels.

KCA uses DICE parameter values in the macro-geoeconomic model to maintain consistency. The energy model parameter values are summarized in appendix 2.

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, p. 334). The undiscovered resources concept is adapted from geology; it is probabilistic, based upon the geological extrapolation from known formations and petroleum occurrence. Our assumption of total remaining resources of 2.5 trillion barrels in 1965 is derived from the ninety fifth percentile point on the frequency distribution for original resources developed by the U.S. Geological Survey in 1991.[11] A similar estimate has been used by Manne and Richels (1992: see pp. 38-39 for discussion). According to Manne and Richels, the ninety fifth percentile constitutes a practical upper bound on undiscovered resources. By using this value we allow for the possibility that technology improvements and future price

[11] The 1991 USGS frequency distribution (Masters 1991, summarized in Chapman 1993) provides estimates for 1990 remaining resources. To this figure, we added the cumulative production of crude oil from 1965 and 1990 to obtain the estimate for 1965. Data for crude production from 1965 to 1990 were obtained from Chapman (1986).

increases will lead to large quantities of economically recoverable oil.

The Khanna-Chapman model is operated under two scenarios: the base case with no $CO_2$ control, and the case where the control rate for $CO_2$ emissions 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. In figure 2, the global transition to synthetic liquid fuel takes place toward the first quarter of the next century. Since the synthetic fuel releases a higher amount of carbon per unit of energy than either oil or conventional coal (see appendix 2), KCA carbon emissions (figure 3) shift upward and accelerate relative to the Nordhaus projections.[12]

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[12] A qualification about the comparability of the results from the two models: in the Nordhaus (1994) model "emissions" refer to a combination of $CO_2$ emissions and $CO_2$-equivalent CFC emissions. Our model considers only the former, as does the latest work by Nordhaus and Yang (1996).

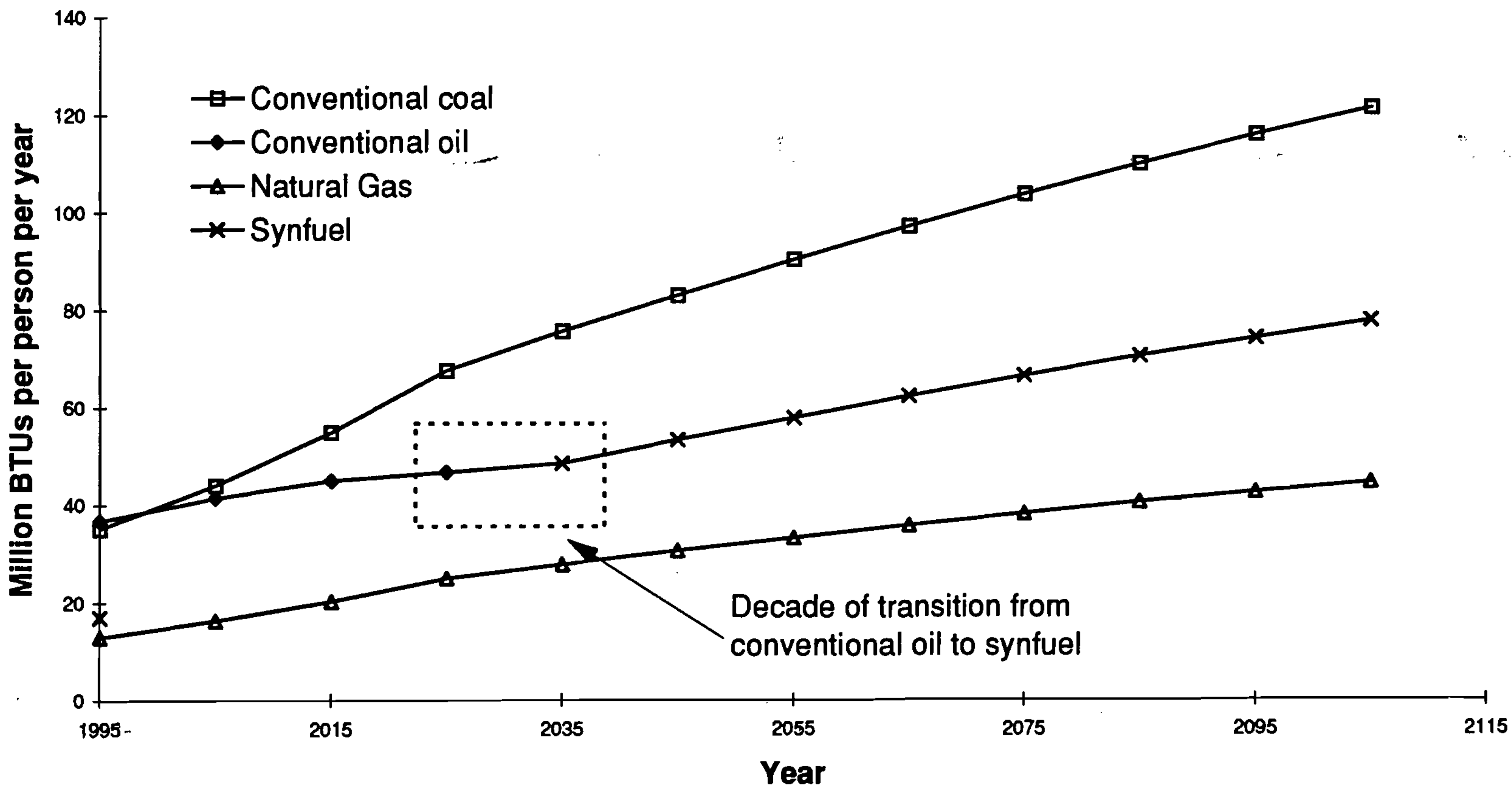


**Figure 2.2**
**Per Capita Energy Consumption**
**(base case)**

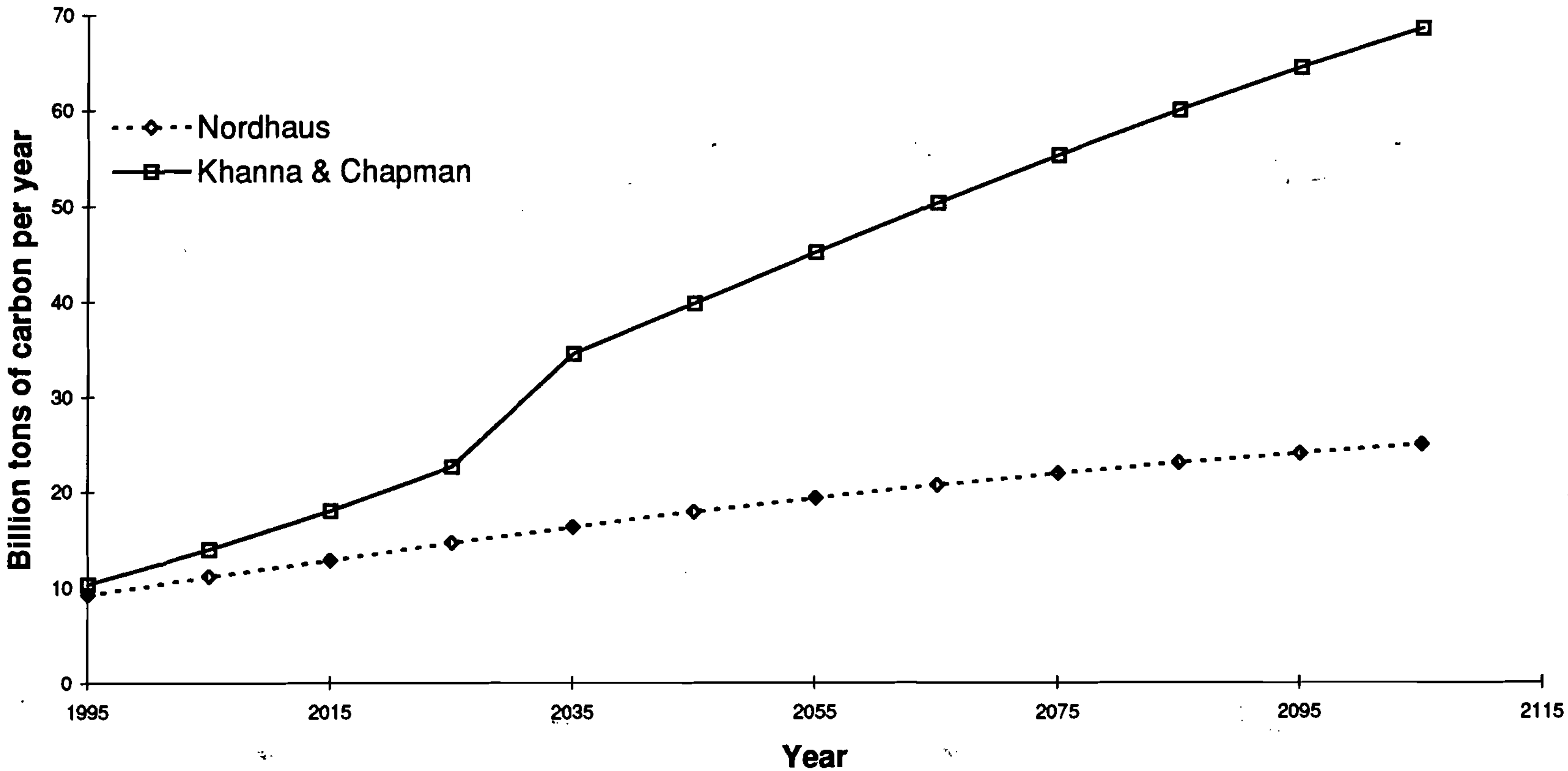


**Figure 2.3**
**Carbon Emissions**
**(base case)**

The exogenous decarbonization imposed in the Nordhaus analysis implies that the carbon intensity declines steadily. In the KCA, this is not the case. Initially, the carbon intensity increases, rising sharply when the synfuel comes on-line to replace 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 energy and carbon intensity of the global economy is likely to increase. Once these nations have acquired some minimum level of per capita income and energy consumption, and as energy prices rise world-wide, there will be an increased effort to reduce energy consumption per unit of economic output, resulting in the subsequent stabilization in energy and carbon intensities.

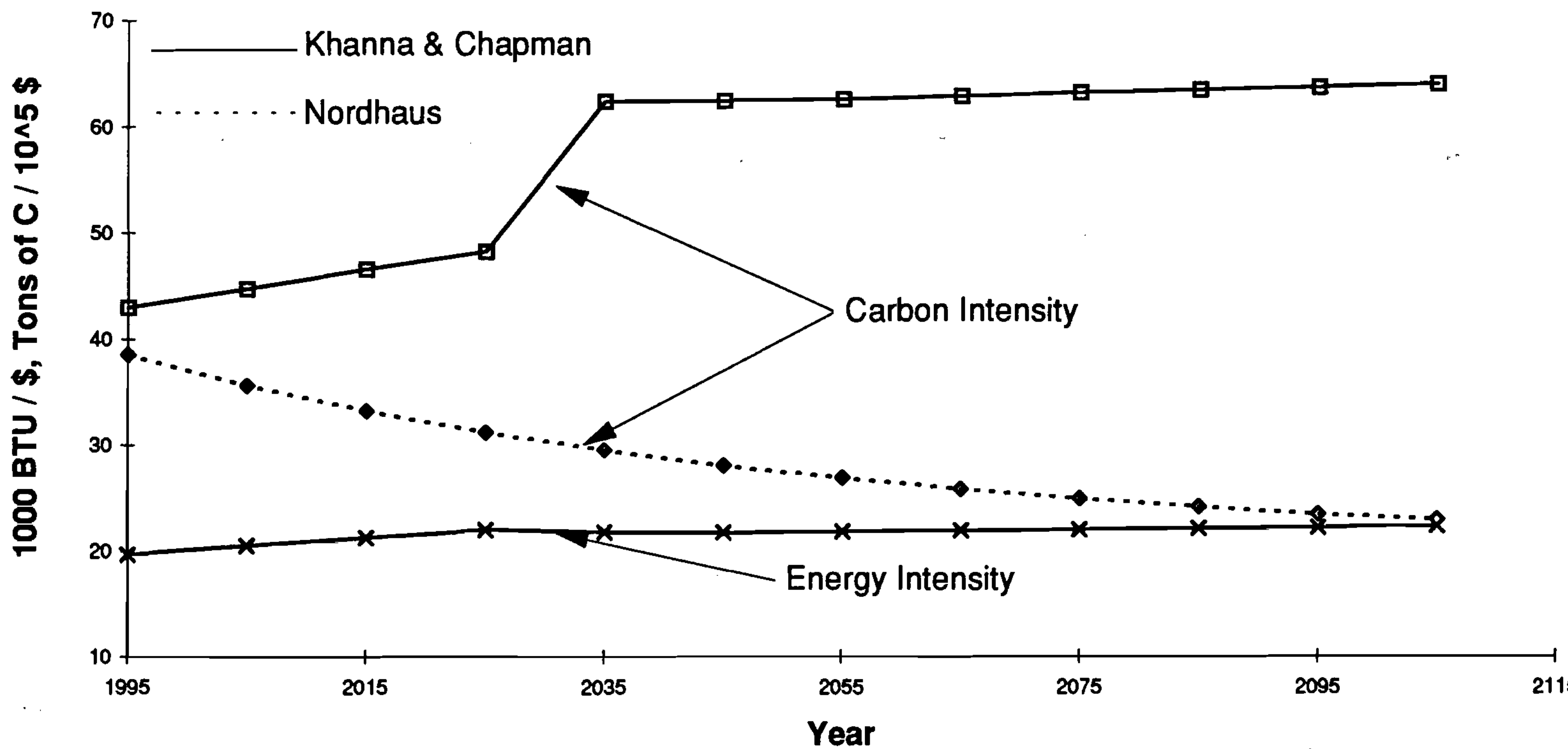


**Figure 2.4**
**Projected Energy and Carbon Intensity**
**(base case)**

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 various layers of the atmosphere and ocean, the difference in temperature becomes much greater after the mid-21st century.) As a consequence, the KCA optimal control rates for carbon emissions (figure 6) are also much higher than the Nordhaus projections.

Our conclusion is that a continuation of growth in oil use can lead to growth in synthetic liquid substitutes. This future has higher carbon emissions and global temperatures than is typically found in similar work.[13]

[13] See Peck and Teisberg (1992, 1995), Manne and Richels (1992), Manne *et al.* (1995), and Nordhaus and Yang (1996).

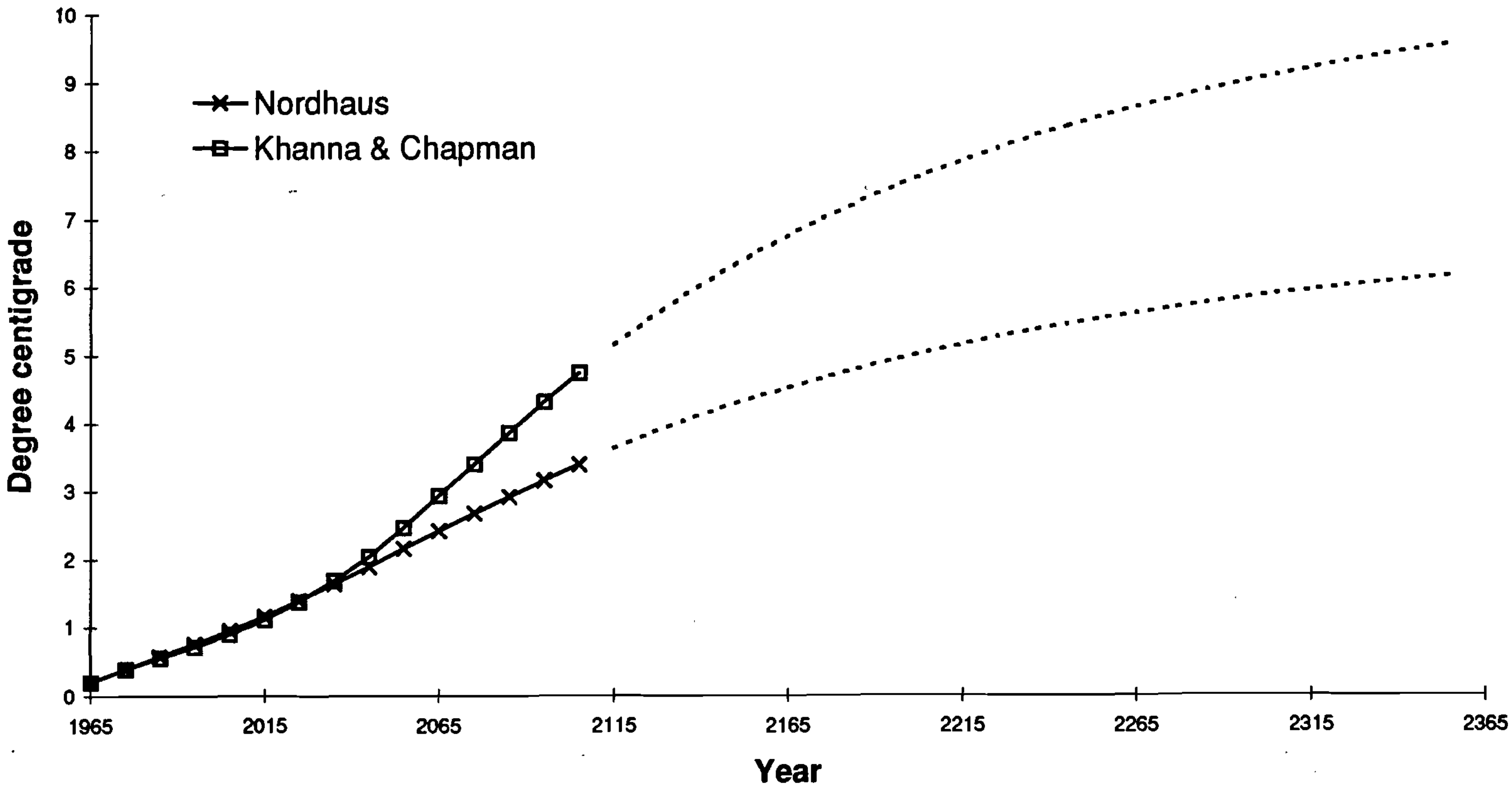


**Figure 2.5**
**Rise in Mean Surface Temperature**
**(base case)**

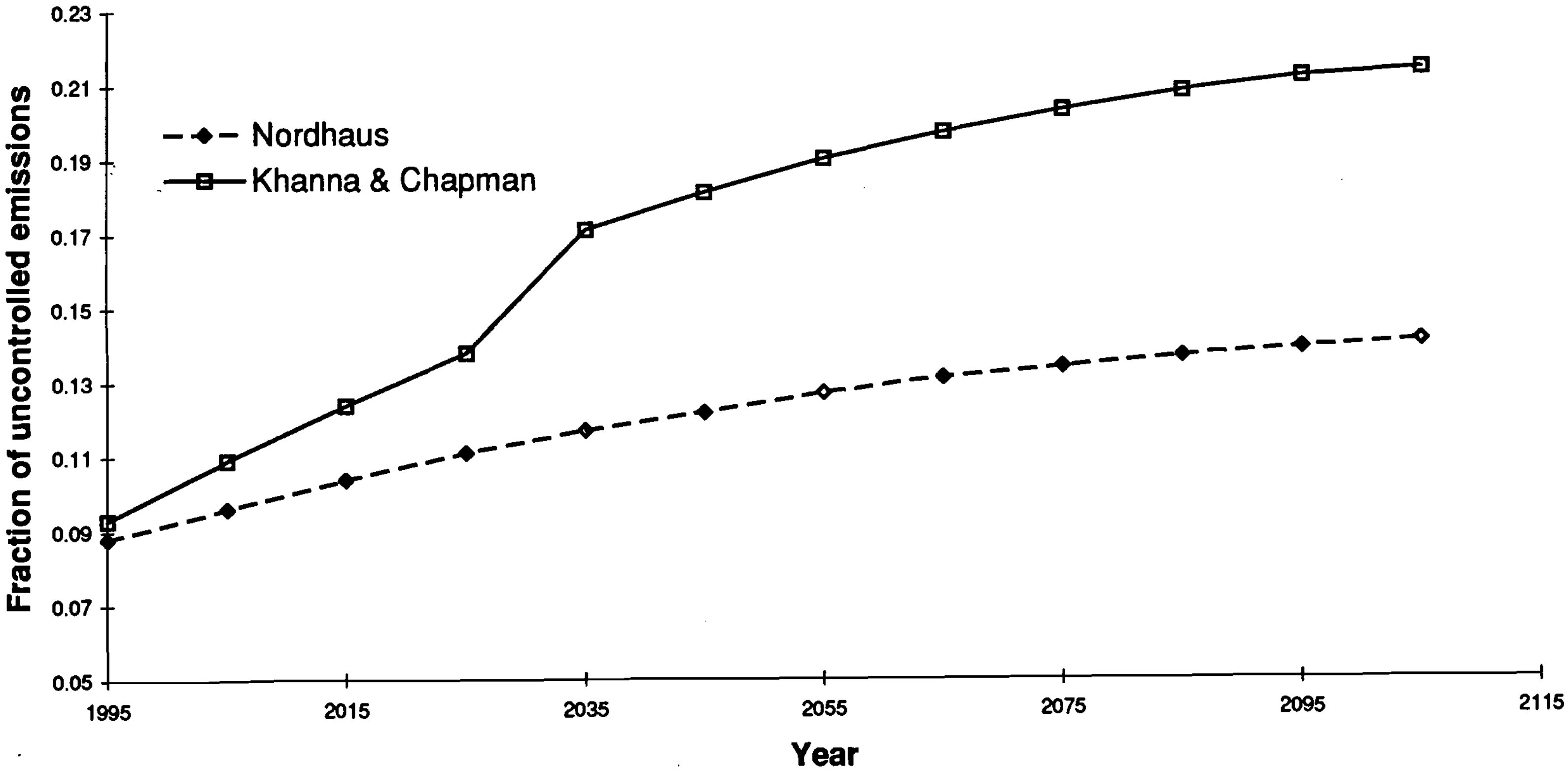


**Figure 2.6**
**Optimal Control Rate for Carbon Emissions**

## 4. Sensitivity Analysis

How assumption dependent are these KCA findings to the petroleum-linked parameter values? We investigate this question with sensitivity analysis.[14]

It is widely believed that the real marginal cost of extraction for oil resources is growing very slowly, if at all (Fagan 1997, Adelman 1992 and 1994). Therefore, in the first sensitivity case, A1, we allow the marginal cost of extraction to grow slowly, at 0.5% per year, as compared to 1.61% per year 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.

In the base case, we assume that oil resources are at the 95$^{th}$ 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 50$^{th}$ 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 97.5$^{th}$ 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 7 have obvious interpretation. However, note that scenario B1 (lesser remaining oil resources) results in visibly higher $CO_2$ emissions and optimal control rates.

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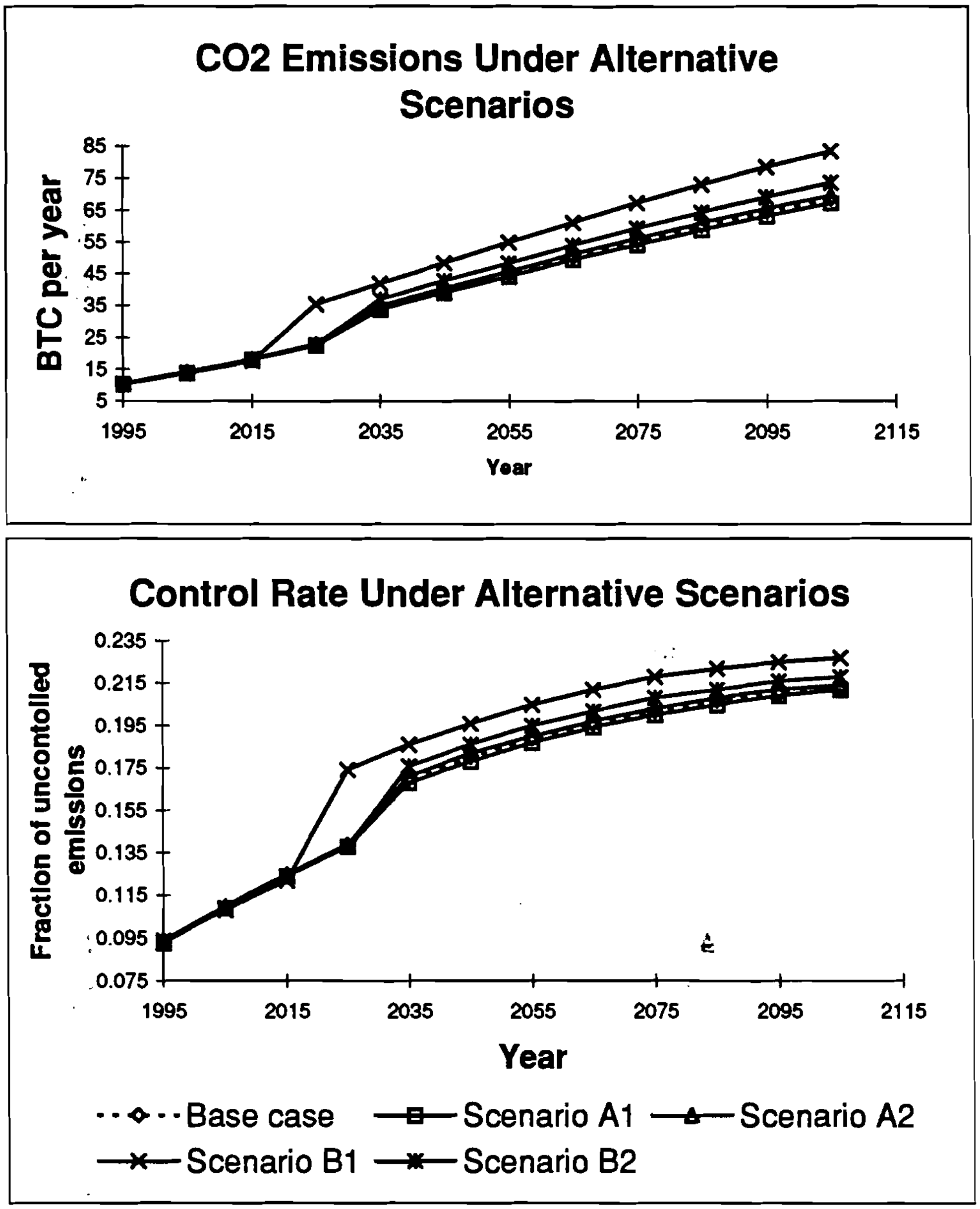
[14] Nordhaus (1994, pp. 101-190) and Nordhaus and Yang (1996, pp.758-761) examine the sensitivity of their results to several parameter values. Chapman *et al.* (1995) examine the sensitivity of DICE results with respect to the pure rate of time preference, $\mu$, and the emissions to output ratio, $\sigma(t)$.




| | |
|---|---|
| **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 the 50th percentile on frequency distribution for original resources. |
| **Scenario B2:** | Remaining oil resources estimated using the 97.5th percentile on frequency distribution for original resources. |

**Figure 7**

**Sensitivity Analysis**

## 5. A Tax Policy Simulation

By explicitly incorporating energy prices, the Khanna-Chapman framework facilitates the analysis of alternative energy tax scenarios. The impact of an energy tax on the emissions trajectory depends on the simultaneous interplay of the following 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. The exact paths depend on the interaction between the intertemporally increasing demand for oil, and the rising marginal cost of production. 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. This means that 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.

In this section we simulate the effectiveness of three tax scenarios in lowering the emissions trajectory towards the optimal level.[15] Under the first two scenarios, we impose taxes at differential 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

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[15] 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.

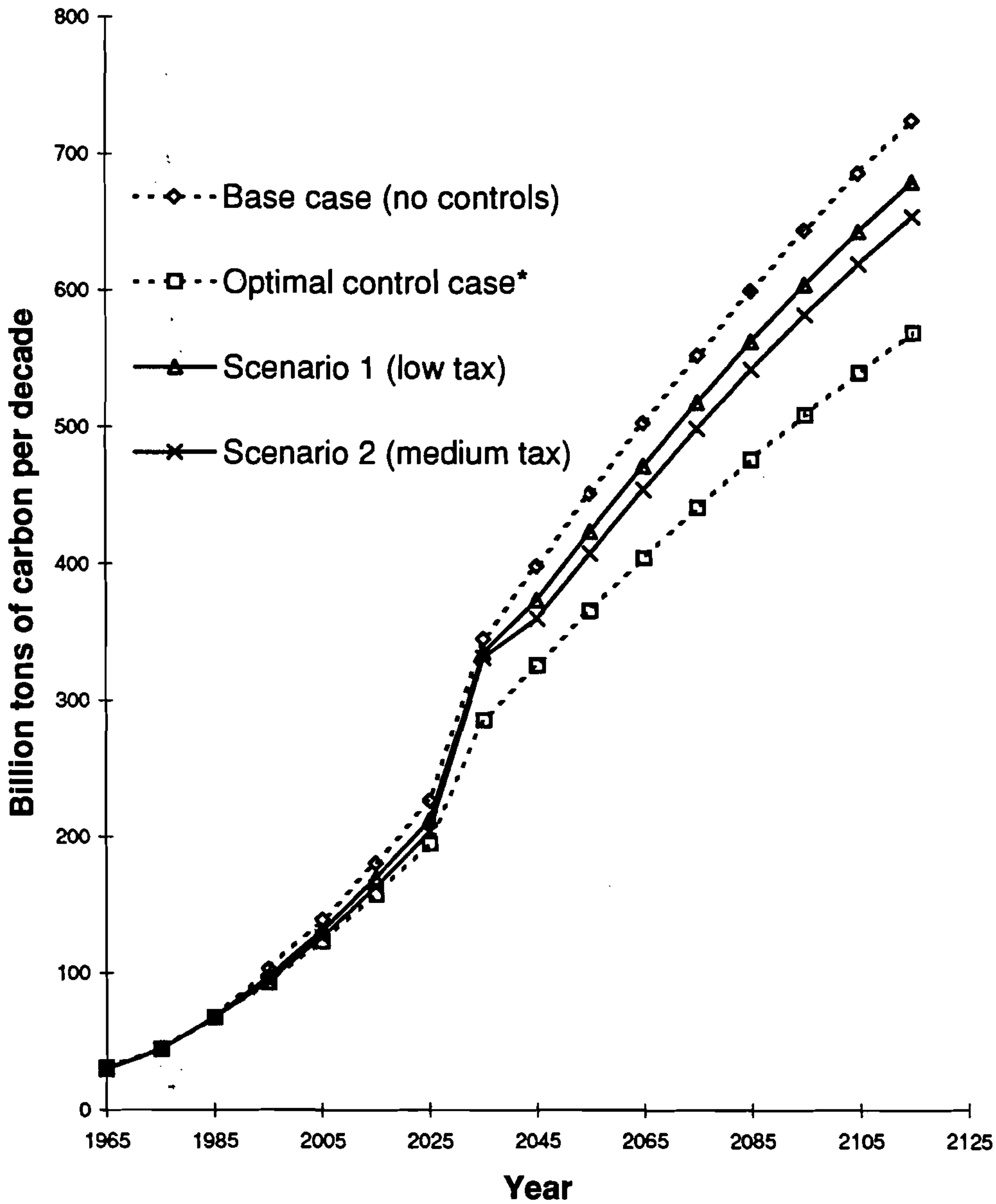
trajectory approximately tracks the optimal emissions trajectory obtained earlier. The exact tax rates used for the analysis are shown in table 2. Note that the tax on oil is levied on the marginal cost of extraction.

**Table 2**
**Tax Rates and Levels Under Alternative Tax Scenarios**

| | Scenario 1 (Low tax) | | | Scenario 2 (Medium tax) | | | Scenario 3 (Optimal control) | | |
|---|---|---|---|---|---|---|---|---|---|
| | % | Level of tax | | % | Level of tax | | % | Level of tax | |
| | | 1995 | 2105 | | 1995 | 2105 | | 1995 | 2105 |
| **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 |

a: The tax is levied on extraction.
b: The tax is levied once synfuel production begins in the decade of 2035.

As evident from figure 8, the first two scenarios have limited success in reducing the emission levels to the optimal trajectory. For this to be achieved, we require extremely high tax rates, an example of which is shown in scenario three, which raise energy prices by as much as four times.




* Same emissions trajectory as scenario 3 in table 2.

**Figure 8**

**CO2 Emissions Under Alternative Tax Scenarios**

## 6. Conclusion

This paper extends the seminal work by William Nordhaus on climate change. An explicit treatment of energy-economy interactions which takes account of resource depletion is incorporated. The result is a framework that allows the analysis of the effects of specific energy technology developments, such as changes in the cost and nature of the backstop technology, and also impacts of energy taxation on carbon emissions. As a consequence, the 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 implication for greater, quicker and, consequently, more expensive abatement efforts.

Furthermore, we find that high levels of energy taxation would be required to reduce the carbon emissions to their optimal level. 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.

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 carbon free electrolysis, or solar and nuclear power, will take its place. See, for instance, Manne and Richels (1992) and Peck and Teisberg (1995).[16] This presumption is particularly important in the global warming context because, in a sense, it describes the "don't worry, be happy" approach: if you wait long

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[16] A contrasting view is expressed 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. A sustained R&D program is required to make a renewable energy future feasible.

enough, the problem will solve itself because the very source of the problem will begin to disappear. In this analysis, we consider the problem from a different 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 a continuation of rising energy intensity in developing countries such that the oft posited decline in global energy and carbon intensity from current levels is not realized. In this case, our analysis shows that the greenhouse problem is exacerbated.

A broader question follows: will the integration of annual, fully detailed climate modeling with macro-economic energy modeling result in higher trajectories for $CO_2$ and temperature? We do not have the answer, but raise the question because of its significance.

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## Appendix 1

## A Brief Overview of the Nordhaus Model[17]

The DICE model developed by William Nordhaus comprises a representative agent, optimal growth model with an intertemporal objective function which maximizes the present value of utility. A unique feature of the model is the linkage of these economic relationships with several significant geophysical relationships that are a stylized presentation of a global circulation model. The decision variables are the rate of investment and the fraction by which GHG emissions are reduced. These variables are analogous to investment in tangible capital in the Ramsey (1928) model: present consumption must be curbed to decrease GHG emissions which would ameliorate climate change which, in turn, would allow higher levels of future consumption.

The world economy produces a composite economic product using a constant returns to scale, Cobb-Douglas production function in capital and labour with Hicks neutral technical change. Production is associated with the emissions of GHGs. The model assumes that only $CO_2$ and chloroflorocarbons (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

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[17] This section is based on Nordhaus (1994, pp. 7-21). The GAMS program for the model is presented in pp. 191-197. The regional RICE model is defined in the appendix to Nordhaus and Yang (1996). The appendix here is presented to provide access to the logic and structure of the model.

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 parameters - the atmospheric retention ratio and the rate of transfer to the deep ocean. These parameters are assumed to be time invariant.

With the accumulation of GHGs comes the rise in 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 $CO_2$ emissions increases radiative forcing by 4.1 watts per meter square.

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.

Finally, the model is designed to maximize the discounted value of the utility of per capita consumption, using a pure rate of time preference of 3% per year. The model has a horizon of 400 years starting from 1965, and operates in time steps of one decade.

# Appendix 2

## Parameter values

| Parameter | Value | Data sources |
|---|---|---|
| Energy demand elasticities | | |
| own-price | - 0.5 | Drennen (1993) |
| cross-price | 0.25 | |
| income | 1 | Drennen (1993) |
| 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), and EIA (1996). |
| Growth rate (% per year) | 0.1 | |
| 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 ($/bl) | 60 | |
| Growth rate (% per year) | 0.1 | |
| Cost of extraction | | Based on Chapman (1993). |
| 1965 value ($/bl) | 6.71 | |
| Growth rate (% per year) | 1.61 | |
| 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 consuming sectors.

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