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Essays on Economic Development, Energy Demand, and the Environment

by

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A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE

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ABSTRACT

Essays on Economic Development, Energy Demand, and the Environment

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The rapid expansion of industry at the outset of economic development and the subsequent growth of the transportation and residential and commercial sectors dictate both the rate at which energy demand increases and the composition of primary fuel sources used to meet secondary requirements. Each of these factors each has an impact on the pollution problems that nations may face. Growth in consumer wealth, however, appears to eventually lead to a shift in priorities. In particular, the importance of the environment begins to take precedent over the acquisition of goods. Accordingly, cleaner energy alternatives are sought out. The approach taken here is to determine the energy profile of an average nation, and apply those results to a model of economic growth. Dematerialization of production and saturation of consumer bundles results in declining rates of growth of energy demand in broadly defined end-use sectors. The effects of technological change in fossil fuel efficiency, fossil fuel recovery, and 'backstop' energy resources on economic growth and the emissions of carbon dioxide are then analyzed. A central planner is assumed to optimize the consumption of goods and services subject to capital and resource constraints. Slight perturbations in the parameters are used to determine their local elasticities with respect to different endogenous variables, and give an indication of the effects of changes in the various assumptions.

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CHAPTER 1

The Effect of Economic Development on Energy Demand and the Environment

An Overview

The economic development of nations results in increased demand for energy resources. Shifts in the structural composition of consumption and production change the energy intensity of GDP. Specifically, growth of industrial activity and the consumption of services and manufactured goods cause energy demand to increase. In 1997, the burning of fossil fuels accounted for 86% (24% coal, 39% oil and 22% natural gas) of the world's energy consumption (on a BTU basis).[1] Given the heavy reliance on fossil fuels to date, economic growth has consequences for the quality of the environment. In particular, the burning of fossil fuels emits carbon dioxide, a principle gaseous component of the global warming phenomenon. In determining policies regarding energy and the environment, therefore, the costs of environmental degradation must be weighed against the benefits of economic growth.

In order to proceed in a meaningful discussion of the effect of economic development on energy demand and the environment, it is important to understand the manner in which the structure of consumption and production change as an economy develops. Structural change is a key determinant of the intensity of energy use for the production and consumption of goods and services. Accordingly, the level of development, and hence economic structure, is an important factor in determining the

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[1] See EIA database (www.eia.doe.gov)

effect of future economic growth on energy demand. In fact, evidence will be presented that indicates energy requirement per dollar of output eventually declines as an economy develops. Many authors have given the issue of energy and development attention. Of note is *Energy Economics* by Richard Eden, Michael Posner, Richard Bending, Edmund Crouch and Joe Stanislaw (1981). Their work discusses the economics of energy by giving attention to a variety of topics including economic development, markets for primary fuel sources, prices, the environment, and the basic laws of thermodynamics.[2]

The relationship between economic development and the structure of production is one that is well documented by authors such as Kuznets (1971) and Chenery and Syrquin (1975). Aggregate economic output is the sum of the output contributions of the agricultural, industrial and service sectors of an economy. In the initial stages of economic growth, the share of agriculture in total output falls while the share of industry rises. As development continues, however, domestic demand for financial services, communications, and transportation begins to rise. Accordingly, the share of services in total output increases. In Table 1-1, real gross domestic product (GDP) and the structure of production are presented for a few select countries. There is a trend of declining agricultural share in GDP in every country. Furthermore, the share of industry increases for the less developed economies, a trend indicative of the accelerated growth of the industrial sector. In the industrialized nations, representative of the latter stages of development, the growth of services outpaces the growth of industry thereby obtaining an increasing share of total GDP.

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[2] The last of these aids in developing a basic understanding of converting primary fuels into usable energy. The heat content of various fuel sources is of the utmost important for conversion technologies.

Table 1-1: Structure of Production for Selected Countries

			GDP Share		
Country	Year	GDP/cap (1985 int $)	Agriculture (%)	Industry (%)	Services (%)
India	1965	751	44	22	34
	1980	837	38	26	36
	1995	1,514	29	29	42
China	1965	577	38	35	27
	1980	879	30	49	21
	1995	1,863	21	48	31
S. Korea	1965	1,058	38	25	37
	1980	3,321	15	40	45
	1995	8,465	7	43	50
Japan	1965	4,491	9	45	46
	1980	10,072	4	42	54
	1995	14,578	2	38	60
Italy	1965	5,691	10	42	48
	1980	10,323	6	39	55
	1995	13,192	3	31	66
Australia	1965	8,823	9	39	52
	1980	12,520	5	36	58
	1995	16,113	3	27	70
USA	1965	11,649	3	39	59
	1980	15,637	2	34	64
	1995	19,369	2	26	72

Sources: World Bank Development Report, various issues
Penn World Tables 5.6

The industrialization process is typified by enormous increases in energy consumption. For example, the production of cement and steel (heavy industry) for the development of infrastructure requires much more energy input per unit output than traditional methods of agriculture. As consumer wealth grows, however, the composition of the consumer bundle changes. A decreasing share of the consumer budget is devoted to food, and an increasing share is devoted to manufactured goods.[3] Hence, the industrial structure of a developing economy will begin to change, with a larger emphasis being

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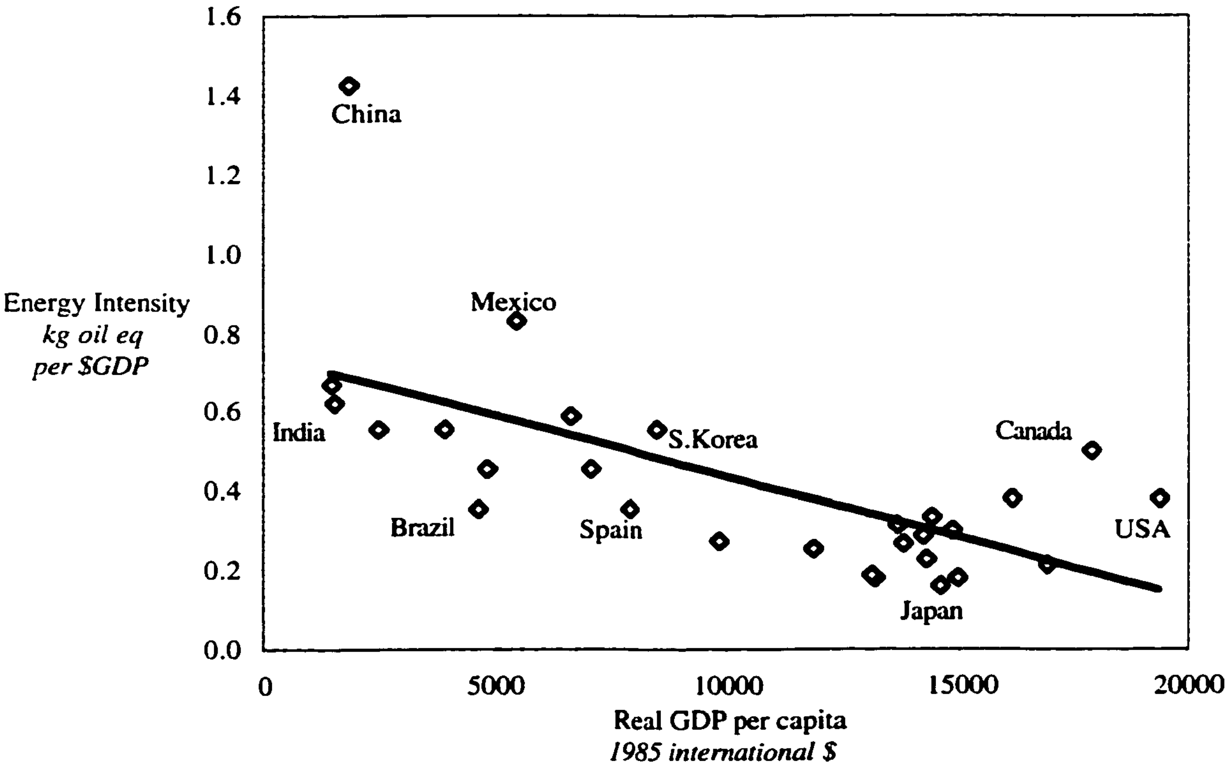
[3] This is the stipulation of Engle's Law.

placed on the production of consumer items (light industry).[4] The transition within the manufacturing sector to light industry, growth of the service sector, and innovations and improvements in technology will all tend to reduce the energy intensity of GDP. (Energy intensity is defined as energy unit input per unit output.) The cross-sectional evidence in Figure 1-1 serves to illustrate this point (a simple OLS trend line is included for illustrative purposes). This phenomenon is often attributed to *dematerialization*, the process by which material inputs into the production process decrease per dollar output with economic growth.

Figure 1-1: Energy Intensities of Selected Nations (1995)



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[4] There is not perfect correlation to the degree that nations engage in international trade.

Changes in the composition of production and consumption will affect end-use energy demand in various sectors differently. The growth of energy demand in the industrial sector is initially very high, as there is a build-up of heavy industry at the outset of economic development. This growth then slows as the transition from heavy to light industry takes place. As per capita incomes rise, however, energy requirements in the transportation and residential and commercial sectors begin to increase. Consumer durables such as air-conditioners, furnaces, refrigerators, and automobiles take up an increasing share of the consumer's budget (see Table 1-2). To the extent that services such as heating, refrigeration, and personal transport yield increasing utility to the consumer, utilization will increase with income thereby increasing energy demand for transportation and for residential and commercial uses.

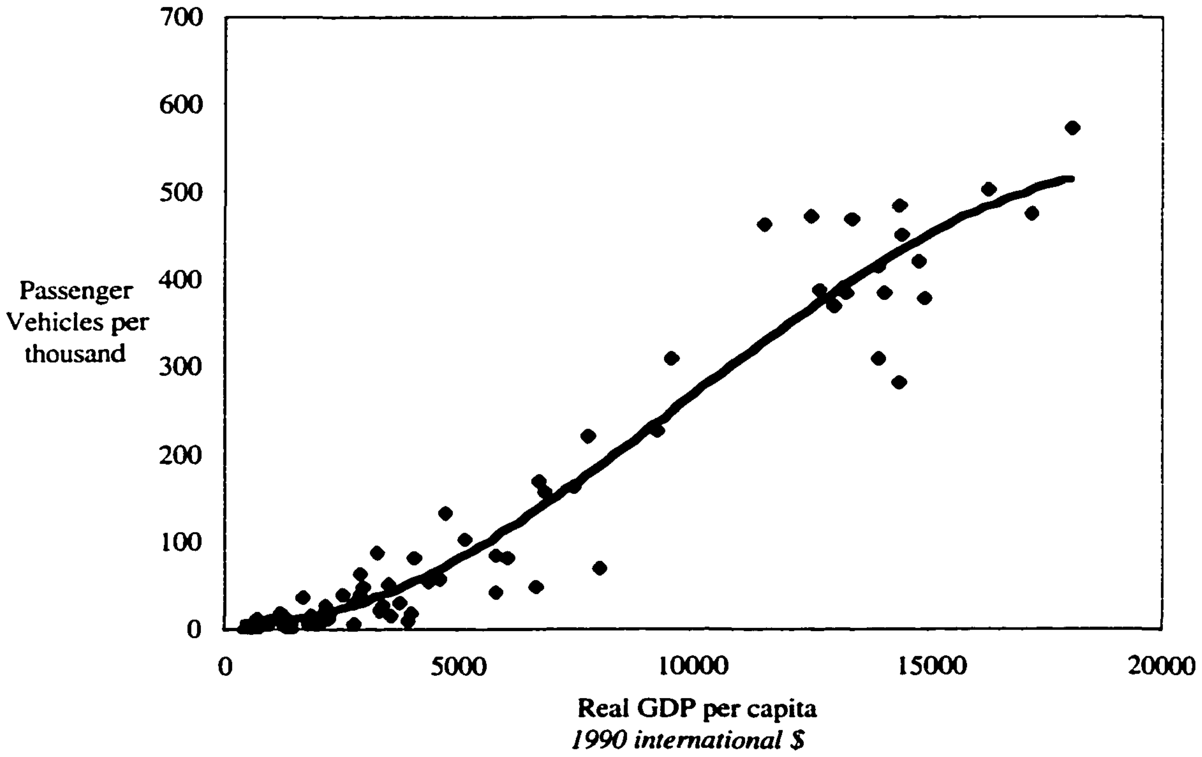
Table 1-2: World Structure of Consumption (1993)

GDP/cap (1993 PPP $)	Food and Clothing	Rent	Health Care	Education	Transport and Communications	Durables and Other
0-1,000	39	23	6	13	5	15
1,001-4,000	35	18	8	14	6	19
4,001-10,000	25	23	11	13	6	23
10,001-20,000	20	16	11	9	11	33
20,001-	16	18	14	9	11	31

Source: *World Bank Development Indicators, 1997*

Interest in the growth of energy demand in the transportation sector is largely the reason that growth of motor vehicle stocks has received considerable attention in the economic literature (see, for example, Dargay and Gately (1997), Hess (1977), Mogridge (1989), Tishler (1981,1983), etc.). There is evidence of an income threshold at which consumers make initial purchases of automobiles. As *per capita* income increases, the number of consumers at this threshold will initially rise, then fall as an increasing proportion of consumers own a motor vehicle. Hence, there will be periods of large increases in the aggregate vehicle stock followed by incrementally smaller increases as per capita income rises. In Figure 1-2, using data from 1990, we have plotted of the number of registered automobiles per capita against per capita GDP for most countries in the world.[5] The number of passenger vehicles increases from less than 25 per thousand persons at a per capita income of $4,000 to approximately 300 per thousand persons at a per capita income of $10,000.

Figure 1-2: Cross-section of World Motor Vehicle Ownership (1990)



Sources: World Bank Development Indicators, 1997
World Motor Vehicle Data, 1997

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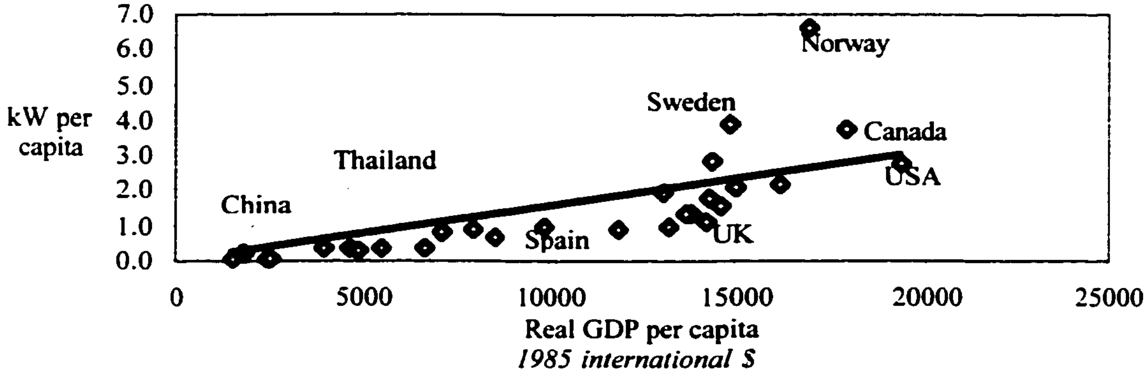
[5] A polynomial trend is included for illustrative purposes.

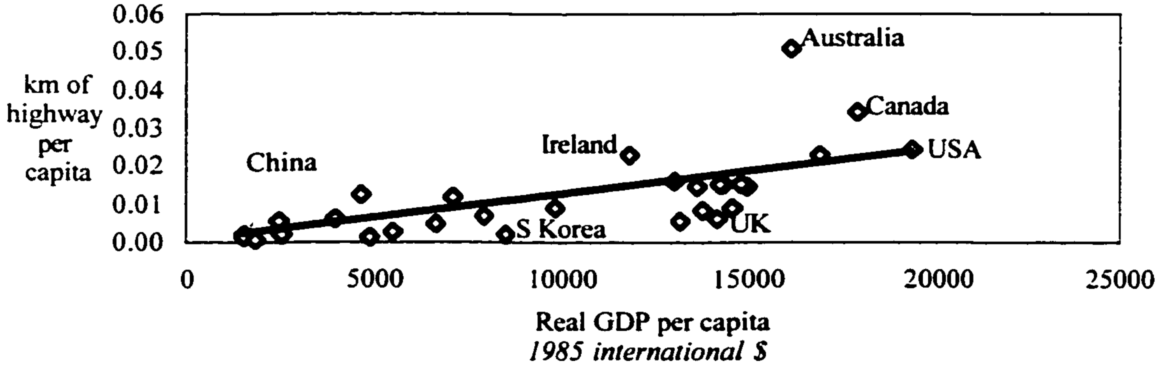
With the utilization of a growing vehicle stock comes an increase in the demand for motor fuel. An obvious prerequisite, however, for satisfying the increased demand for transport services, and non-transport (i.e.- electricity) uses for that matter, is the development of sufficient transport infrastructure. As is evidenced in Figure 1-3, there is an increasing trend of infrastructure development as per capita GDP increases.[6]

Figure 1-3: Infrastructure Trends for Selected Nations

Electricity Infrastructure (1995)



Transport Infrastructure (1995)



Source: CIA World Factbook, 1997

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[6] As in Figure 1-1, we have included a simple OLS trend line purely for illustrative purposes. The true relationship appears to be best described as exponentially increasing with income.

Infrastructure investment can be attributed, in part, to manufacturer's demands. Increasing levels of specialization and division of labor of the production process promotes an increase in the growth of demand for commercial transportation, which requires an increase in transport infrastructure. Similarly, the construction of power generating facilities and transmission networks is required to meet industrial needs for electricity. Governments, therefore, to the extent that they wish to promote economic development, have incentive to support investment in infrastructure development.

To the extent that output growth and energy demand growth are simultaneous[7], the consumption of energy is necessary to produce a flow of goods and services in an economy. As a result, lack of sufficient energy resource inflows will inevitably slow the industrialization process in developing countries,[8] and stifle growth in consumer demand for transportation and electricity in developed countries. In both cases, the result of rapid declines in energy use could be disastrous for economic growth.

Continued economic growth and the resultant growth of global energy consumption, however, could cause serious harm the environment. The majority of energy consumption is derived from the burning of fossil fuels (oil, coal, and natural gas), which creates a negative externality because it is associated with the release of various pollutants, such as carbon dioxide, into the air. The effects of structural and technological change, however, reduce the rate at which carbon dioxide and other pollutants flow into the atmosphere. Furthermore, at current rates of innovation, fuel cells, methanol or electricity may provide much of the energy needed in the transport

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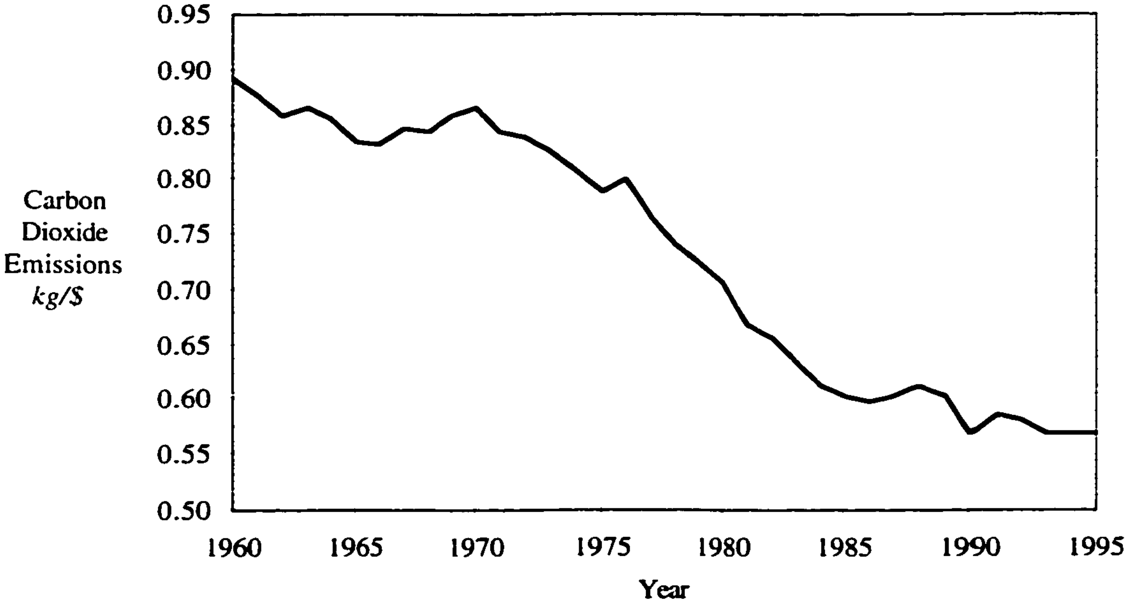
[7] This is an issue that we will address later in the text. The statistical evidence of simultaneity within the literature is not convincing, but the intuition behind the theory is. This leaves the question of appropriate treatment in modeling to resolve.

sector by the middle of the century. Similarly, advances in semi-conductor and transmission technology may allow a substantial fraction of electricity to be generated from solar power. These technologies can dramatically reduce the environmental costs of increased energy use without detriment to the development of the world's economies. In the US, increases in energy efficiency and structural change to a more service-oriented economy have resulted in a decline of carbon dioxide emission intensity of about 40% in only 35 years (see Figure 1-4).

Figure 1-4: US CO_2 Emission Intensity (1960–1995)



Source: United States Statistical Abstract

An important consideration in designing any strategy for reducing carbon dioxide flows is the impact on economic development.[9] If policies are potentially detrimental to a goal of economic advancement, then it is not clear that the benefits of reducing carbon

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[8] This is precisely the reason developing nations will not take part in any environmental treaties that call for reductions in emissions, which must be brought about by, for the most part, reducing energy consumption.

dioxide flows outweigh the costs. In particular, the costs of imposing controls on energy production or use are likely to be much higher in the short run than in the long run. The costs of adjusting to higher energy prices depend on how rapidly those price increases occur. In particular, large increases over a short time period can make substantial amounts of otherwise usable capital immediately obsolete. Thus, the benefits of reducing carbon dioxide emissions today must be large when compared to the benefits of doing so tomorrow.

In the long term, energy demand growth rates will fall as economic growth continues. As a result, the *rate* at which carbon dioxide is released into the atmosphere will fall as well. Nevertheless, global energy demand and carbon dioxide emissions are projected to increase well into the foreseeable future. This is attributable to the industrialization of less developed countries, where most of the world's population resides. Pressure to meet growing demand for energy resources and cleaner air will force governments find suitable compromises when determining energy policy. These pressures provide strong motivation for the questions asked herein.

We proceed in by first examining the effect of economic development on energy demand in Chapter 2. The main objective of this chapter is the identification of energy use patterns characteristic of particular economic sectors. Industrial energy demand increases most rapidly at the initial stages of development, but growth slows steadily throughout the industrialization process. Energy demand for transportation is initially low in comparison, but rises steadily, taking the majority share of total energy use at the latter stages of development. Energy demand originating from the residential and

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[9] This is important for any type of pollution. The focus in this thesis, however, is on carbon dioxide.

commercial sector also increases to surpass industrial demand, but growth is not as pronounced as it is in the transport sector. These results have implications for the primary energy demand of an economy as it develops, and, thus, ramifications for domestic energy security, global geopolitical relationships, and the environment. The results from this chapter are used to motivate the exercises in later chapters. In particular, the sector-by-sector approach of analyzing energy demand will provide an indication of the source of pollution as development progresses. This will prove to be an important result when addressing the issue of global warming.

Chapter 3 examines the effect of economic development on the demand for private transportation. Since the transport sector becomes the major source of energy demand as economies develop, it is important to understand the contributing factors. Utilizing the concept of the user cost of capital and the notion that the demand for automobiles can become saturated, a model of the relationship between economic development and per capita automobile ownership is constructed. Saturation levels are found to vary across countries (a finding consistent with differing levels of infrastructure development), and user costs are determined to be a significant factor in the evolution of vehicle stocks. Forecasts are then generated for each of the countries in the sample their implications for future energy related issues are discussed. The results are compared with those found elsewhere in the economic literature in order to highlight some key differences in our approach. The implications of the forecasts for the future of transport energy demand are discussed.

Chapter 4 focuses on the different national priorities of developing and industrialized nations. The global warming issue frames many of the issues that are addressed. A central focus is the reluctance of developing nations to adopt the guidelines set forth in the Kyoto Protocol. The costs of reducing energy use in order to comply with the protocol could include slower economic growth. It is not clear that controlling greenhouse gas emissions is as important to developing nations as addressing more immediate concerns, such as air and water pollution. Furthermore, technological advances in the development of fuel cells in the transport sector and solar generated electricity for industrial, residential and commercial uses may allow more energy to be consumed with fewer negative environmental consequences. In addressing these issues, the results of a forecasting exercise based upon the results of Chapter 2 are included in order to gauge the potential impact on global warming of four of the most populous developing countries, i.e.- China, India, Brazil, and Indonesia.

In Chapter 5, the ideas of the preceding chapters are used to motivate a model of economic development. This chapter centers on concerns that continued burning of fossil fuels will increase the concentration of carbon dioxide in the atmosphere and raise average global temperatures. A number of factors, some of which are at least partially offsetting, complicate matters. There is an inordinate amount of uncertainty in estimating the costs of an increase in carbon dioxide accumulation, as well as the costs of implementing regulations to reduce the emissions of carbon dioxide. In designing an appropriate policy there are fundamental economic phenomena, such as structural change and technological advancement, which must be given consideration, aside from the problems involved in setting guidelines for regulation and compliance. Moreover, given the nature of the global warming problem, flows of carbon dioxide are not the problem; rather, it is stocks. This makes control tomorrow a close substitute for control today.

When these things are accounted, the urgency of reducing the flow of carbon dioxide emissions into the atmosphere is called into question. In fact, it may very well be that continued economic growth is the fastest route to stabilizing carbon dioxide emissions. The counterweight being the damage from global warming that accumulates along the way.

CHAPTER 2

Economic Development and End-Use Energy Demand*

The importance of developing countries to the future of world energy markets is paramount. Increases in industrialization and consumer wealth will create new demands for energy resources. The aim of this chapter is to identify development patterns characteristic of particular economic sectors, and understand the relative rates of growth of energy demand in each of those sectors. This will give insight into how the fuel composition of total energy demand can be expected to change in developing countries. Moreover, the development of accurate expectations about the future growth and composition of energy demand in developing nations will allow a more meaningful examination of the future energy-related political and economic pressures to be faced. This, in turn, will provide greater opportunity to develop realistic and achievable energy security and environmental policy goals.

If one wishes to form some expectation about the growth of the demand for oil versus coal or natural gas, it will be important to have an adequate understanding of the growth of those economic sectors from which demand for each fuel type is derived. For example, consider the Chinese energy situation. Currently, coal is the primary choice of fuel for industrial activities, not to mention residential and commercial uses, and, in fact, has a dominant share of total energy consumption. However, if the energy used in

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* This chapter is taken from the paper entitled "The Effect of Economic Development on End-Use Energy Demand" co-authored with Ron Soligo, which was presented at the 21st Annual Conference of the International Association for Energy Economists in Rome, Italy in June 1999.

transportation is expected to increase at a faster rate than energy used in other sectors, we can expect that oil, to the extent that it is the dominant primary fuel choice for transportation, will take up an increasing proportion of total energy consumption. Because most of the oil in China would have to be imported, this would likely have consequences for the future political and economic policies of the Chinese government. Similar scenarios can be constructed for other countries, but the message is the same. The composition of fuel demand, as much as quantity, will more than likely change as economic development occurs given the relative rates of growth of the individual sectors of the economy, and this change will have ramifications for the geo-political picture of the world as a whole.

In order to examine end-use energy consumption by sector on a global scale we must assume that preferences are sufficiently alike across countries to make general statements about the growth of energy consumption in those sectors. (For the analysis herein we will use the broadly defined end-use sectors of transportation, residential and commercial, and industrial and other.) Why should we believe that the energy demand patterns of, say, China will ever look like those of the US? In short, shifts in the structure of production and consumption will affect the growth and composition of energy demand in all countries. Based on the reasonable assumption that common structural changes throughout the development process will beget common energy demand growth rates, we construct a ‘map’ for a general development path. We then use this global development pattern in order to ascertain the expected patterns of growth of energy demand in the various sectors.

Previous Research

The relationship between per capita energy demand and economic development has been explored on numerous occasions by many different authors.[1] The methods employed have been, for the most part, restricted to analyzing cross-section data for a large number of countries (see, for example, Zilberfarb and Adams(1981), or Ang (1987)) or applying time-series estimation techniques to data for individual nations (see, for example, Pourgerami and Hirschhausen (1991)). A principle advantage of the cross-section approach, especially in the case of developing nations, is that lengthy and reliable time-series data are often not available. It can be argued, therefore, that the long-run effect of income on energy demand, often called the energy coefficient, can be accurately revealed by the cross-section approach. However, the cross-section approach suffers from implicitly assuming that the same regularities apply to all nations. Countries can differ in their energy use because they use different technologies or different methods of production, face different energy prices (due to things such as different energy taxes), different factor endowments, and so forth. Ignoring these factors may bias the estimated energy coefficient.

The time-series approach enables the researcher to specifically account for any factors that may or may not be specific to an individual country thereby avoiding potential problems of omitted variables or country specific heterogeneity. However, the procedures have been, for the most part, applied only to industrialized nations. Time series analyses require sufficiently long data series, which are not available for most

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[1] Of note is *Energy Economics* by Richard Eden, Michael Posner, Richard Bending, Edmund Crouch and Joe Stanislaw (1981). Their work discusses the economics of energy by giving attention to a variety of topics including economic development, markets for primary fuel sources, prices, the environment, and the basic laws of thermodynamics.

developing nations. Besides resulting in a lack of research into the energy demand patterns for developing economies, this has also lead to, for the few existing studies, the omission of energy prices. The absence of price data can be justified by the argument that, because few substitutes exist for currently available energy resources, price effects should be negligible in the long run. However, the long run effect of higher prices may be reductions in energy requirements per unit of output (either through substitution to alternative inputs or less energy intensive production methods, or through increased efficiency).

In most energy studies, regardless of the type of data set chosen by the researcher, the specified demand equations are log-linear, which implies a constant elasticity of demand. However, an interesting statistical result within the literature is that the estimated income elasticity for energy demand is generally lower for countries with higher levels of GDP per capita. Previously, this has been attributed to a problem of omitted variables, such as changes in capital stock efficiency, rather than acknowledged as a fundamental characteristic of the structural relationship between energy demand and GDP (see, for example, Prosser (1985)). It is likely that structural changes in production and consumption are responsible for the instability of the linear models.

Brookes (1973) investigated the apparent instability of the energy coefficient, as estimated by log-linear specifications in cross-sectional studies. He noted that there was a significant difference in the estimated energy coefficients for a sample of countries over time. In fact, the energy coefficient tended to approach unity over the period of time studied. He did, however, point out,

> Societies moving into a post-industrial phase tend to increase their consumption of services (traditionally supplied by people rather than machines) and this could lead to increments of GDP per capita of lower than average energy content and hence to a useful energy coefficient lower than one. (p 85)

This suggests that there is some non-monotonic relationship between per capita energy consumption and per capita GDP. Hence, any linearly estimated relationship for a low-income nation is likely to change significantly as that nation grows economically, and, as a result, inferences based on linear analyses may be misleading.

Studies by Galli (1998) and Judson, Schmalansee and Stoker (1999) (henceforth JSS) are two examples of the more innovative recent work that have given reverence to the notion that the income elasticity of energy demand declines as income rises. Galli (1998) analyzes the energy-income relationship for a panel of ten Asian countries and claims that "a wide range in the level of development facilitates testing the relationship between energy intensity and the long-run development of economies" (p89). The principle result is that energy intensities tend to fall beyond some threshold level of income. However, Galli's study is limited to a sample of ten developing Asian countries. Therefore, despite the above claim, it is incomplete as far as delivering a picture of the economic development–energy demand relationship because there is no representation of developed nations within the data set. This would seem a necessary component of any attempt to model future energy demand in developing nations, and, in fact, opens the door to a more encompassing analysis - one that includes both developing and industrialized countries. Specifically, if all countries are thought to have similar patterns of energy demand growth, why not map the less developed nations into the developed world in order to form some expectation based upon existing information?

JSS disaggregate energy consumption by sector, and analyze energy demand patterns for a panel of 123 nations from all levels of development. Their findings indicate that household energy consumption falls with increasing income, energy consumed in transportation activities rises, and industrial energy consumption follows an inverted U-shape pattern. JSS do not account for price effects within their study, a factor attributed to a lack of data availability. The inclusion of prices would allow for a distinction between the impact of dematerialization (an income effect) and the impacts of world events (supply shocks) and domestic tax policy changes (both of which have price effects). Given the rather volatile behavior of world energy markets over the past two decades, it can be argued that the impact of energy prices on energy demand is something that should not be neglected. Doing so will inevitably disguise the true effect of income. For example, a decline in energy consumption following any major shock to energy prices might take a number of years to take full effect (assuming there exists some lag in adjustment to equilibrium). Compounded with increasing levels of development, this could incorrectly amplify the downward affect that increasing incomes have on energy demand growth rates. Thus, the impact of dematerialization would be overstated. While there are tremendous advantages to estimating relationships with an enormous number of observations, such as the data set used in JSS, the estimated parameters will invariably suffer from some omitted variables bias. It is up to the researcher to weigh the suspected size of that bias against the advantage of expansive data sets.

The Model

The research by Galli and JSS is distinguished from that of others because they allow for the fundamental relationship between energy and income to be non-monotonic. Given the preceding arguments (see Chapter 1), there is no reason to believe that per capita energy demand growth is a constant proportion of per capita GDP growth. As a result, it is important to derive an estimable relationship that is flexible enough to permit this. Building upon the work of our predecessors, we begin with the common assumption that the demand for energy per capita is some function of per capita income and the real price of delivered energy:

$$ec_t^* = f(y_t, p_t).$$

Furthermore, it is true, *ex post*, that total final energy consumption is the sum of final consumption in each end-use

$$ec_t^* = \sum_j ec_{t,j}^*$$

where j represents an end-use sector. For our purposes, j represents residential and commercial, transportation, or industrial and other. Accordingly, we can define

$$ec_{t,j}^* = f(y_t, p_{t,j})$$

where the j is dropped from the income variable as it is not sector specific.

Typically, these demands are assumed to be of the form $ec_t^* = ap_t^{b_1} y_t^{b_2}$. A logarithmic transformation of this demand relationship, coupled with some dynamic adjustment mechanism of the form:

$$\ln ec_t - \ln ec_{t-1} = \gamma\left(\ln ec_t^* - \ln ec_{t-1}\right),$$

where γ is the adjustment factor with a value between 0 and 1, yield the familiar functional relationships that are often estimated within the economic literature. We propose a simple modification in order to allow for the possibility of a non-constant income elasticity of energy demand. Namely, we allow for the square of the log of income, presenting a non-monotonic relationship between energy consumption per capita and income per capita. The demand equation implied by this modification is $ec_t^* = ap_t^{b_1} y_t^{b_2 + b_3 \ln y_t}$. It is not our intention, however, that this is the true demand relationship. We merely posit this to be an approximation of the demand function for energy.

Adding the appropriate subscript, i, denoting each individual country, and incorporating the above lag adjustment mechanism, we have the following model for estimation:

$$\ln ec_{t,j,i} = \alpha_{j,i} + \beta_1 \ln p_{t,j,i} + \beta_2 \ln y_{t,i} + \beta_3 \left[\ln y_{t,i}\right]^2 + (1-\gamma)\ln ec_{t-1,j,i} + \varepsilon_t \qquad (2.1)$$

where the $\alpha_{j,i}$ is a sector-specific individual country effect that can be treated as fixed or random. Equation (2.1) yields a long-run income elasticity of

$$b_2 + 2b_3 \ln y_{t,j} \qquad (2.2)$$

where $b_2 = \frac{\beta_2}{\gamma}$ and $b_3 = \frac{\beta_3}{\gamma}$, and are the long-run coefficients of the demand equation

$$\ln ec_{t,j,i}^* = a_{j,i} + b_1 \ln p_{t,j,i} + b_2 \ln y_{t,j,i} + b_3 \left[\ln y_{t,j,i}\right]^2 \qquad (2.3)$$

The income elasticity given by (2.2) will decline as income increases provided $b_2 > 0$ and $b_3 < 0$. This is an important feature because it allows us to determine if indeed energy demand growth slows as income increases.

Data

The data set used in our analysis consists of 28 countries[2], and covers the period from 1978 to 1995. The data were collected from a variety of sources (including individual country statistical yearbooks, and international publications from the OECD, Asian Development Bank, the United Nations and the IEA), and were checked for both continuity and consistency. We use final energy consumption in each end-use sector (transportation, residential and commercial, and industrial and other) as our measure of energy demand. Accordingly, primary energy requirement is the sum of final demands in each sector plus transmission and conversion loss. The units of measurement are kilograms of oil equivalent per capita. Therefore, being a physical quantity, the data are comparable across countries.

Per capita GDP, a purchasing power parity measure obtained from the Penn World Tables 5.6 (PWT), is used as the measure of output, and is denominated in 1985 international dollars. This measure allows for comparisons across countries because it accounts for differences in the purchasing power of different currencies. Real per capita growth rates were applied to the final observation in the PWT data set in order to obtain values up to 1995, a process resulting in the calculation of 3 to 4 observations for each country. The GDP originating in each sector is not used. This is due to the fact that end-use energy demands will not be entirely reflective of output in each sector due to differences in definitions. For example, the output in transportation in national accounts measures the value added by public and private transportation enterprises, but does not include the benefit of driving for the consumer. Since per capita income is reflective of

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[2] A complete list is given in Appendix A.

the standard of living and is a motivator of consumption patterns, the aggregate variable, per capita GDP, is deemed to have better explanatory power of the end-use energy demand.

Price data was the most elusive of the variables to collect, with a good number coming from national sources. The energy price index used for the transportation sector is an index of the real price of gasoline, and was available for most countries from the IEA. While this is a less than perfect measure, due to things such as differing degrees of dieselization, the prices for petroleum products should generally move together, being reflective of the cost of crude oil.[3] The energy price index for the residential and commercial sector is the real price of fuel and light, and reflects the delivered cost of both electricity and heating oil. These data were obtained from both UN and national statistical sources. Both of the indexes used for the transportation and residential and commercial sectors are based upon consumer prices, and will therefore include any taxes on those particular fuels. The energy price index used for the industrial and other sector is the real producer, or wholesale, price of energy. This index was available for most countries from the IEA, but some data were obtained from national sources. Although these price indexes are less than perfect, they do capture information that both consumers and producers utilize in making maximizing decisions. Accordingly, we feel it is important to include this information, even at the cost of omitting some countries (for which price data is simply unavailable).

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[3] Unless there are changes in the relative rates at which each fuel is taxed.

Estimation Procedure and Results

A lot of theoretical work, notably that of Balestra and Nerlove (1966), Hsaio (1986), Arellano and Bond (1991) and Ahn and Schmidt (1995), has been done in the field of estimating dynamic panel data models. The more recent studies have been aimed at developing a 'better' estimator, on the grounds of increased efficiency, but applied work is at a minimum, so finite sample performances are not very well investigated. This is indeed surprising considering the inherently dynamic nature of many demand systems. One applied study of considerable interest is that of Baltagi and Griffin (1997). They evaluate the out-of-sample forecast performance of a number of estimators that have been proposed for a dynamic panel data model. Their method was applied to a very well researched field, gasoline demand, in order to provide comparisons to the numerous studies that have previously appeared in the literature.

Standard estimation procedures (such as ordinary least squares) applied to the model (2.1) may be inconsistent due to correlation between the lagged endogenous variable and the error term.[4] Therefore, a suitable alternative must be chosen. We use the two-stage least squares (2SLS) approach based upon the work of Balestra and Nerlove, using as instruments present and lagged values of the regressors and population. In choosing the set of instrumental variables, the treatment of the income and price variables as exogenous is crucial. If we assume that there exists an aggregate production function into which energy is an input, then the exogeneity assumption would certainly be incorrect. Nevertheless, we can look to previous economic literature for validation.

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[4] See Matyas and Sevestre(1992), among others, for a complete discussion of this issue.

The existence of a causal relationship between energy consumption and income has been investigated using a simple bivariate time-series model, but the results are mixed (see Kraft and Kraft (1978) and Yu and Hwang (1984) for opposing results). However, bivariate tests may suffer from a bias due to omitted variables because certain variable relationships that may be important will not receive consideration. Darrat, Gilley and Meyer (1996) use a vector autoregression to investigate the issue, thereby potentially avoiding the complication of omitted effects. They find evidence of unidirectional causality from GDP to energy consumption. This would suggest that the growth of energy demand and GDP is not simultaneous (there is no evidence of bidirectional causality). Regardless, some authors have employed more rigorous modeling exercises in an effort to account for simultaneity. For example, Moroney (1992) attempts to identify the energy-GDP relationship by constructing a system of simultaneous equations based upon an assumed functional form for production technology. He shows that per capita energy demand is significant in explaining real per capita output, but reports parameter estimates for the income effect on energy that do not differ significantly from those found in studies that are less ambitious.[5]

Given the evidence that exists in the literature, we choose to proceed with treating income as exogenous. Furthermore, the fact that we are using a sector-by-sector approach to modeling energy demand should alleviate any income-energy simultaneity. The reason being that it would seem hard to justify that energy consumed in transport, say, will have a significant effect on total per capita GDP. Transport fuels are by-and-

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[5] This brings into question his method. He employs two-stage least squares on two separate equations. While this is acceptable, there is no explanation as to why a system (full information) estimator is not employed. If it is done to avoid mispecification problems in one, or both, of the equations, then there is no reason to believe that those problems do not affect his results in either one of the equations.

large consumed to facilitate personal transport service, a measure of which is not included in standard national accounting practices.

The treatment of the price variable as exogenous is a rather standard approach. It is based upon the notion that price is determined in an international market, and energy consumers are price takers on that market. Deviations from the international price are the result of different tax and fuel choice policies. These are assumed to be independent of the level of output and current energy consumption.

In determining the appropriate econometric specification[6], we note that the hypothesis of poolability of the data is not rejected in the transport sector or the residential and commercial sector. However, it is rejected in the industrial and other sector. This result is not very surprising. To the extent that countries engage in trade, consumption demands can be met without dramatically altering the structure of manufacturing. In addition, certain countries have historically relied upon industrial activities as a means of employment. In some cases, government quotas and price controls have resulted in inefficient energy consumption practices. The degree to which those policies have changed, through liberalization measures, will impact the growth of industrial energy demand. Therefore, unlike in the residential and commercial sector and transport sector, industrial energy consumption patterns are not constrained to evolve according to consumer preferences. Rather, they will be reflective of things such as comparative advantage in production and government policy. In sum, the variability that is inherently present in the industrial sector not only affects the intercept term in (2.1),

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[6] This includes testing for heterogeneity in the intercept and slope, and testing for fixed vs. random effects. See Appendix B for a discussion of the econometric method. Results are in Appendix C.

but also affects the slope coefficients across countries. Interestingly, the use of a log-linear specification yields a rejection of the null of poolability for all three sectors.

We opt to pool the data for all three sectors, despite the evidence in the industrial sector, on the grounds that the information obtained by doing so will provide insight into the global *average* pattern of energy demand growth. In deciding to pool the data, we note the finding of Baltagi and Griffin (1997), "Using a root mean square error criterion, the efficiency gains from pooling appear to more than offset the biases due to inter-country heterogeneities" (p317). While the universality of this statement in its applicability to other data sets is certainly debatable, it does bring to light the possibility that pooled estimators in small samples contain more useful information than their single country counterparts, especially when making long term inferences.

In Table 2-1, we report the parameter estimates, with standard errors in parentheses, for each end-use sector.[7] In every case, we obtain plausible signs on the estimated coefficients. We have also reported the long run coefficients that are implied by the adjustment process. These are obtained by dividing the estimated coefficients for income and price by the adjustment coefficient (one minus the coefficient of the lagged endogenous variable). The parameter estimates on the income variables indicate, by equation (2.2), that the income elasticity of energy demand does indeed fall as income rises. Furthermore, since the estimated coefficients are different across sectors, the elasticity is also different across sectors for a given level of income. This is indicative of the different rates of growth of energy demand in each of the end-use sectors.

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[7] The parameter estimates for alternative methods of estimation are reported in Appendix C.

Table 2-1: Estimation Results

Estimated Relationship (equation (2.1)):

$$\ln ec_{t,j,i} = \alpha_{j,i} + \beta_1 \ln p_{t,j,i} + \beta_2 \ln y_{t,i} + \beta_3\left[\ln y_{t,i}\right]^2 + \left(1-\gamma\right)\ln ec_{t-1,j,i} + \varepsilon_t$$

Implied Long Run Relationship (equation (2.3)):

$$\ln ec^{*}_{t,j,i} = a_{j,i} + b_1 \ln p_{t,j,i} + b_2 \ln y_{t,j,i} + b_3\left[\ln y_{t,j,i}\right]^2$$

Estimated Coefficient	Residential and Commercial	Transportation	Industrial and Other
α_i	—	—	—
β_1	-0.0939	-0.0938	-0.0664
	(0.0216)	(0.0124)	(0.0157)
β_2	0.4632	0.4958	0.9531
	(0.2034)	(0.1371)	(0.2228)
β_3	-0.0222	-0.0188	-0.0493
	(0.0114)	(0.0078)	(0.0126)
$1-\gamma$	0.9292	0.8196	0.7541
	(0.0318)	(0.0337)	(0.0326)
R^2	0.9266	0.9584	0.8907
LR Coefficient			
b_1	-1.3263	-0.5200	-0.2700
b_2	6.5424	2.7483	3.8760
b_3	-0.3136	-0.1042	-0.2005

The level of GDP per capita at the point when the income elasticity becomes zero can be calculated from the parameter estimates in Table 2-1. Using the formula $y_{peak} = \exp\left(\frac{b_2}{-2b_3}\right)$, we find that the income elasticity becomes zero at per capita income levels of \$33,943, \$15,777 and \$532,943 for the residential and commercial, industrial and other, and transportation sector, respectively. Per capita GDP in the United States in 1995 was \$19,369. Thus, our results would indicate that the long-run income elasticity of energy demand has reached zero in the industrial sector in the US, but demand in the other sectors will continue to increase, albeit at different rates. Due to the lag adjustment and price changes, however, it is possible to see further increases in industrial energy demand.

The energy intensity in each sector is also recoverable from the parameters in Table 2-1. Using the relationship $y_{peak}^{\text{intensity}} = \exp\left(\frac{b_2 - 1}{-2b_3}\right)$, we find that the energy intensity in each sector peaks at per capita income levels of $6,890, $1,303 and $4,395 for the residential and commercial, industrial and other, and transportation sector, respectively. The level of GDP per capita at the peak energy intensity of total final energy consumption is approximately $2,500 1985 international. This value is obtained by simulating the sector-by-sector energy consumption for a hypothetical "average" country using the long run coefficients from Table 2-1 and the average of the country intercepts. Total per capita consumption at each level of GDP per capita is then calculated by summing up the sector values. This facilitates the calculation of total energy intensity and the approximate peak level of GDP per capita. The value of $2,500 is almost 40% lower than the reported value of $3,935 in Galli (1998), but our study encompasses a larger number of countries and focuses on the time period from 1978-1995 rather than 1973-1990. The inclusion of the time period 1973-74 may account for a significant portion of the difference. Those years are different from others because there were distinct structural shifts in the international energy market.

We have used the long run coefficients from Table 2-1 to generate the path of per capita energy demand for each sector, and in sum, for a hypothetical *average* country (see Figure 2-1). In doing this exercise we have assumed a fixed price, and an average intercept value.[8] The results illustrated in Figure 2-1 are meant to be illustrative of long-run tendencies for sector-by-sector energy demand. The data for any one country will

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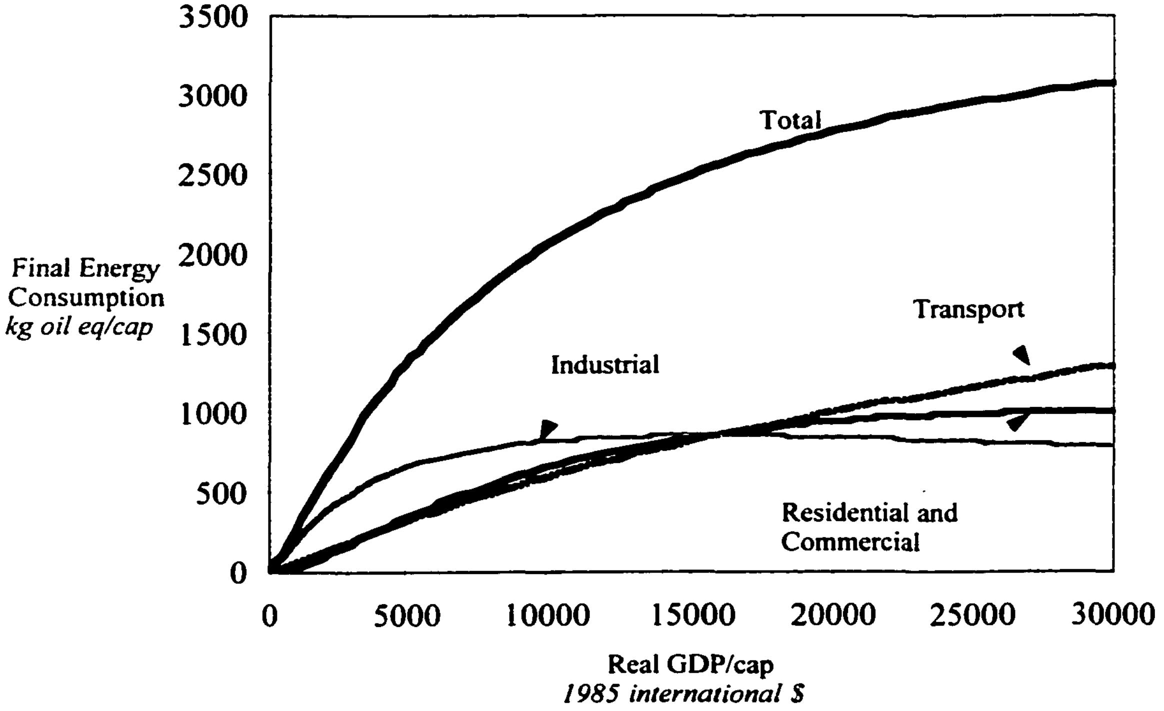
[8] The average effect is –1.4801 in the residential and commercial sector, -2.6433 in the industrial sector, and –1.3896 in the transport sector. Price is held fixed at an index value of 100.

certainly vary as there are country-specific effects. We can see that the industrial sector grows the most rapidly at the outset of economic growth. This is followed by increases in energy demand in the other sectors to the point where energy used in transportation surpasses the energy consumed in the industrial sector. We note the level of per capita GDP, approximately $16,000 1985 international, at which industrial energy consumption is surpassed by transport energy consumption. This resembles the situation in the US in the early 1990's.

Figure 2-1: Per Capita Energy Consumption by Sector for a Hypothetical Country



These results help us to form some expectations about the future composition of total final energy demand. Using the simulated data that generate the paths in Figure 2-1, we calculate and report the share of total energy in each sector for various levels of per capita income in Table 2-2. The trends implied by our results indicate that the energy consumed in the transportation sector will eventually exceed one-half of total final energy requirements. Although this will not occur until per capita incomes are well beyond what is currently observable, this is a staggering proportion, and, if it comes to bear, will have an enormous impact on world energy markets. Even if we allow for varying fuel mixes, the sample paths generated in Figure 2-1 would indicate that crude oil will take up an increasing share of total energy as development progresses. This is due to the fact that the majority of transport fuels are petroleum based, and, with the exception of converted coal, petroleum products are derived from crude oil. Therefore, any concerns about future oil supplies worldwide might be justified simply on the basis of expected increases in transportation demand from developing economies.

Table 2-2: Implied End-Use Sector Share of Total Energy Consumption

Real GDP/capita (1985 int $)	Residential and Commercial	Industrial and Other	Transportation
2000	15.3	67.4	21.0
6000	27.4	47.3	25.3
10000	31.6	39.6	28.7
14000	33.3	34.9	31.8
18000	33.8	31.6	34.6
22000	33.7	29.1	37.2
26000	33.3	27.0	39.7
30000	32.8	25.3	41.9

Sample Forecasts

The trends laid out above are generalizations that capture average global tendencies. Developing countries can be expected to exhibit growth patterns similar to those illustrated in Figure 2-1, but there most certainly will be significant variation about those trends for any one country. However, the concerns about meeting energy resource requirements are shared by all growing economies because, as our analysis shows, energy demand can certainly be expected to increase with the level of development. To illustrate this point, as an exercise, we provide forecasts of energy demand by sector, and in sum, in Table 2-3 for China, India, Indonesia and Brazil - the four largest developing nations in our sample - and the US as a point of reference. The forecasts were generated for the year 2010 under the assumption that prices are held constant at their 1995 levels, and are intercept corrected. We take the expected annual growth of per capita GDP in each country to be equal to the average annual growth rate from 1980 to 1995.[9]

Table 2-3: Forecast Estimates to 2010 for Selected Countries

	Year	Real GDP/cap *1985int$*	Residential and Commercial *	Industrial and Other *	Transport *	Total Final Demand *
China	1995	$1,863	113.8	443.9	37.0	594.6
	2010	$3,749	438.9	836.4	101.7	1387.0
India	1995	$1,514	21.0	92.1	41.7	154.7
	2010	$2,358	51.5	156.3	73.7	281.4
Indonesia	1995	$2,485	64.8	112.6	85.7	263.2
	2010	$4,937	170.5	209.2	180.7	560.3
Brazil	1995	$4,617	149.9	393.1	227.6	770.6
	2010	$5,330	219.6	430.8	282.9	933.3
US	1995	$19,369	1606.9	1671.7	2078.6	5357.2
	2010	$23,967	2294.4	1884.7	2658.9	6838.0

* - Note: All energy variables are in kilograms oil equivalent per capita

The share of energy consumed in industrial and other sector is predicted to fall in each of these countries - decreasing from 74.6% to 60.3% in China, 59.5% to 55.5% in India, 42.8% to 37.3% in Indonesia, 51.0% to 46.2% in Brazil, and 31.2% to 27.6% in the US. This implies that the sum share of energy consumed in the residential and

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[9] This may yield unreasonably high growth rates given the recent economic situation in Asia. The growth rates are 4.8% for China, 3.0% for India, 4.7% for Indonesia, 1.0% for Brazil, and 1.4% for the US.

commercial sector and the transportation sector will rise. Moreover, energy demand in the transportation sector is predicted to increase roughly by a factor of three in China, more than double in Indonesia, almost double in India, and increase by about 25% in Brazil and the US. Energy demand in the residential and commercial sector exhibits similar behavior in each of the countries. The increase in demand in the transportation sector would naturally translate into an increasing dependence on oil and petroleum products. The extent to which this effect is either mitigated or exacerbated by fuel substitution in other sectors will determine how prominent a role each of the developing giants adopts in future world oil markets. However, the degree of mitigation will most likely be minimal due to the fact that there is increased demand in those other sectors as well. In sum, the expectation that the developing giants are going to become increasingly important in world oil markets is most likely a well conceived one.

Influencing the accuracy of these forecasts (and the development map for that matter), among other things, will be the degree to which prices and technologies change, and the degree to which environmental concerns motivate substitutions to 'cleaner' energy. For example, if our expectations about increasing oil dependence from developing nations come to pass, it would be reasonable to expect higher future oil prices. This could be due to things such as supply constraints and the OPEC exerting monopoly power over international oil markets. The short run effect of such an occurrence might be a direct reduction in oil consumption, but the long run effect might be technological improvements that increase energy efficiency and reduce energy intensity. In addition, if the environment becomes of increasing concern, movements from dirty fuels to clean ones might occur. This may cause oil dependence to rise as producers move away from coal thereby instigating the aforementioned process of higher prices and technological improvements. In either case, the end result would be the same. On the other hand, if producers ignore environmental concerns and/or oil becomes increasingiy abundant through newly discovered recoverable reserves, then prices may remain relatively low and technological innovation at a minimum.[10]

Adequate supplies of exhaustible energy resources are crucial in determining a nation's patterns of development. Increasing scarcity leads to increasing prices. As the price of various fuels increase, substitution to cheaper resources will occur thereby altering the composition of energy demand. Likewise, environmental concerns are capable of reducing particular types of energy use through both public awareness and international carbon-tax policies. As implicit prices, such as those associated with pollution, increase or are internalized, substitution to cleaner fuels will be encouraged.[11] The extent to which explicit and implicit prices either offset or reinforce each other will be crucial in determining the composition of energy demand. There is considerable evidence that energy price increases reduce real GDP growth in the short run, but the long run effects are less clear. The adoption of conservation policies and the encouragement of technological innovation in response to higher explicit and implicit prices can both potentially have enormous impacts on the future energy consumption patterns of all nations.

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[10] In a recent issue of Hart's "Oil and Gas World", Peter Aronstam, director of technology for Baker Hughes, Inc. stated that the rate of technological progress in the oil and gas industry depends heavily upon the current economic environment, "In lean times... commercial introduction (of technologies) is delayed" (p.17).

[11] This can be encouraged through various tax policies.

Concluding Remarks

The ways in which consumer and producer demands change as per capita income increases, will have a direct effect on the composition and growth of energy demand. The initial stages of economic growth are characterized by the build-up of industries specific to the development of infrastructure as well as the changing structure of consumer demand. A continued rise in consumer income leads to higher demand for energy consuming goods and services thereby raising the energy intensity of the consumer bundle. As the composition of industrial output becomes increasingly dominated by the production of consumer goods, the energy intensity of the industrial sector falls. Furthermore, as the consumer bundle becomes saturated with energy consuming durable goods, per capita energy demand growth in the residential and commercial sector and in the transportation sector will slow as utilization of those durables approaches some time constraint.

One difficulty in forming accurate expectations about the future energy demand for developing nations is the difficulty in forming expectations about the future composition of production and consumption. We address this problem by using a panel of countries from all levels of development to trace a map of the development path. This gives us a basis upon which to form expectations about the future energy consumption of developing economies.

The results of our analysis show that, while energy demand can be expected to grow in all sectors of the economy, the largest increases will, eventually at least, come from the demand for transportation fuels. For countries at the lower levels of development, the bulk of energy demand can be expected to continue to come from the industrial sector. However, this trend will begin to change as the composition of production and consumption change. As consumer incomes increase, so will consumer demands for lifestyle services such as air conditioning. This will result in an increase in the demand for energy in the residential and commercial sector. In addition, increasing consumer wealth will cause passenger vehicle ownership to increase. The utilization of these vehicles will result in large increases in the demand for transportation energy, in particular, the demand for oil. This can have enormous effects on oil consumption in the near future, and, coupled with environmentally motivated substitutions away from the use of coal to alternative resources, will result in an increasing number of countries vying for the world's supply of oil.

With increasing domestic need for energy resources, as well as international pressure to abate pollution, steps toward cleaner energy, through either technology or substitution, should be expected. Accordingly, in most countries there will be increasing pressures to secure a stable flow of the 'cleaner' energy resources, such as oil and natural gas.[12] If the growth of aggregate output and aggregate energy demand is simultaneous, then a lack of sufficient energy resource inflows will inhibit substantial economic advancement. The need to meet growing demands will place pressures on governments to either develop domestic resource stocks or increase national dependence on international sources. An inability to do so will invariably interrupt the development process.

This brings us to the issue of energy security. It will depend heavily upon the ability to build and maintain good political relations with the oil supplying nations of

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[12] Coal (average US quality) emits approximately 26% more carbon per BTU than oil and 45% more than natural gas.

Middle East and OPEC and, perhaps more importantly, any neighboring countries through whose waters and lands resources must be transported. Moreover, any inability to overcome any existing inefficient market structures and mechanisms, which may have slowed domestic exploration and development endeavors, will have a significant impact on the security issue. Since, for a vast majority of the developing countries, a large portion of oil and natural gas demand must be satiated with imports, the geo-political environment of the world can be expected to change dramatically in the coming years. The issue of future energy security begs some difficult decisions. While the costs associated with pipelines versus tankers are essentially exercises in accounting, the potential costs associated with dependence upon long-time political rivals are unclear. Therefore, the expected costs and benefits of the different possible solutions must be weighed against one another.

CHAPTER 3

Automobile Ownership and Economic Development – Forecasts to the Year 2015*

The relationship between aggregate output and energy demand has been widely discussed in the economic literature. While it has been established that energy demand increases with the level of economic development, the factors responsible for this increase have not been given equal consideration. This is surprising because these factors are of considerable importance to policy-makers when addressing concerns about energy security and the environment. Recently, a number of studies in the economic literature have focused on the growth in demand for passenger vehicles, citing as motivation that increases in per capita vehicle stocks are highly correlated with increases in demand for transport fuel. In this chapter, we develop a framework for analyzing consumer demand for motor vehicles. This framework is then used to motivate an empirical analysis of the relationship between motor vehicle stocks and the level of economic development. Our results are used to generate forecasts of motor vehicle stocks in 28 different countries from all levels of development. We then discuss the implications of those forecasts for future energy and transport policies.

As outlined in the preceding chapters, in the initial stages of development, growth of the industrial sector is primarily responsible for increases in energy demand. As

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* This chapter is taken from the paper of the same title co-authored with Ron Soligo, a preliminary version of which was presented at the 19th Annual Conference of the International Association for Energy Economists in Quebec City, Canada, May 1998.

consumer incomes rise, however, end-use energy demand increasingly comes from households due to the changing composition of the representative consumer bundle.[1] The share of consumption expenditures devoted to transportation activities more than doubles between the per capita income levels of 4,000-10,000 US$.[2] The demand for these items is complicated by the fact that the services they provide (which is, in fact, the reason they are demanded in the first place) require some fuel input. Thus, as individual wealth increases, so will the demand for energy in residences and private transportation.

As discussed in Chapter 1, it is evident that there is some level of development at which the demand for passenger motor vehicles increases dramatically. In Figure 1-2, we saw that the number of passenger vehicles increases from less than 25 per thousand persons at a per capita income of $4,000 to approximately 500 per thousand persons at a per capita income of $10,000. With motor vehicle stocks reaching magnitudes on the order of one per two persons, it is apparent that the growth of the transport sector, and in particular private motor vehicle stocks, is a principle source of increasing per capita energy demand in post-industrialized societies. In fact, in Chapter 2, we showed that per capita energy demand in the transport sector steadily increases throughout the process of economic development, and eventually accounts for the largest share of total final energy consumption. This is precisely the reason that the growth of transportation sectors in developing countries is a topic that is receiving increasing attention, especially in light of the recent concerns about the energy security of industrialized nations and the world's environmental quality.

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[1] This follows from direct application of Engel's Law.

[2] See Table 1-2.

Previous Research

Modeling motor vehicle demand is a difficult task due to the distinct peculiarities that exist in the automotive market. Consumers make decisions about which car to buy based a number factors, including but not limited to fuel economy, size, comfort, status and safety. Typically, modeling exercises assume that the available stock at any one point in time is homogeneous. This allows for considerable simplification, and, in fact, makes any accompanying data analysis more tractable. Some authors have approached motor vehicle demand using a rather standard model of durable goods demand (see, for example, Diewert (1974), Hess (1977), and Deaton and Muellbauer (1981)). In these types of models, it is generally assumed that individuals maximize the present value of their lifetime utility. Utility is derived from flows of consumption goods and services provided by a stock of physical assets, assumed to be motor vehicles. Individuals purchase the physical asset subject to their budget constraint and some law of motion that describes the rate at which the asset is devalued, or depreciates. Therefore, individuals 'invest' in the physical asset each period in order to facilitate a flow of services generated by the asset stock. The general solution to this inter-temporal maximization problem reveals that the demand for vehicle stocks is a function of the consumer's wealth, and the 'user cost' of motor vehicles. User cost, in these models, refers to the opportunity cost of owning a vehicle, and if it increases, *ceteris paribus*, the consumer will shift his/her asset holdings so as to minimize total cost.

In principle, the user cost of capital should include the opportunity cost of foregoing other investments and the direct costs of ownership (these typically include depreciation and taxes). The models described above give attention to the former of these aspects, but not the latter. In discussing motor vehicle demand it is necessary to include fuel prices because these are representative of utilization costs (with actual costs dependent also on the number of miles driven).

Some authors have constructed models that specifically account for fuel prices as well as other characteristics affecting the demand for automobiles, such as engine size, and comfort (see, for example, Tishler (1981,1983)). While these studies are not as broad in their range of applicability to durable goods in general, they are attractive because they explicitly account for many of the factors that are unique to the automobile market. The fact that these models allow for variable costs of operation, such as fuel and maintenance, to affect the consumer's decision is a distinct advantage over models that do not account for them. Tishler (1981) builds a model based upon user cost principles, and shows that omission of utilization costs will result in biased estimates of motor vehicle demand. This would seem, *a priori*, to be a certainty. The rise in popularity of the compact car after the first oil shock is evidence that consumer demand for automobiles is indeed influenced by fuel prices.

Regardless of the modeling approach, the estimation of motor vehicle demand has been, for the most part, limited to fitting log-linear specifications with some type of adjustment mechanism implemented to incorporate the effect of past stocks on present stocks. Typically, these log-linear approximations of consumer demand include the variables from the general form of the solution of the modeling exercise. Although the log-linear specification may not be compatible with maximizing behavior, most authors proceed on the grounds that it will produce estimates that are comparable to those found elsewhere in the literature.[3]

While the linear models are attractive due to their simplicity, they are questionable as forecast mechanisms. Figure 3-1 depicts vehicle stocks per thousand people as a function of real GDP per capita for 28 different countries each at different levels of development. The data indicate that there is an eventual point of "saturation" in the growth of per capita motor vehicle stocks. Saturation implies that per capita motor vehicle stocks reach some steady state, where the stock grows at the same rate as the population. This, in turn, implies that the income elasticity of demand declines toward zero. Thus, any forecast generated from a model assuming a constant elasticity invariably overstates demand by increasing amounts as the forecast horizon is extended because it does not allow for slowing vehicle stock growth rates given a constant rate of GDP per capita growth. The only exception, of course, is for high-income countries that are approaching saturation levels.

Several authors have attempted to improve the forecast methodology by fitting the relationship between vehicles and income using various non-linear methods. For example, Dargay and Gately (1998) use a Gompertz function[4], Mogridge (1989) uses a logistics growth curve to estimate the relationship, and Button, Ngoe, and Hine (1993) use a quasi-logistic form. However, none of these studies is based upon an explicit modeling exercise. They appear to be attempts at data fitting with conventional wisdom dictating the set of included variables. While all of these models capture the idea of saturation, none of them incorporate price effects, and only one (Dargay and Gately)

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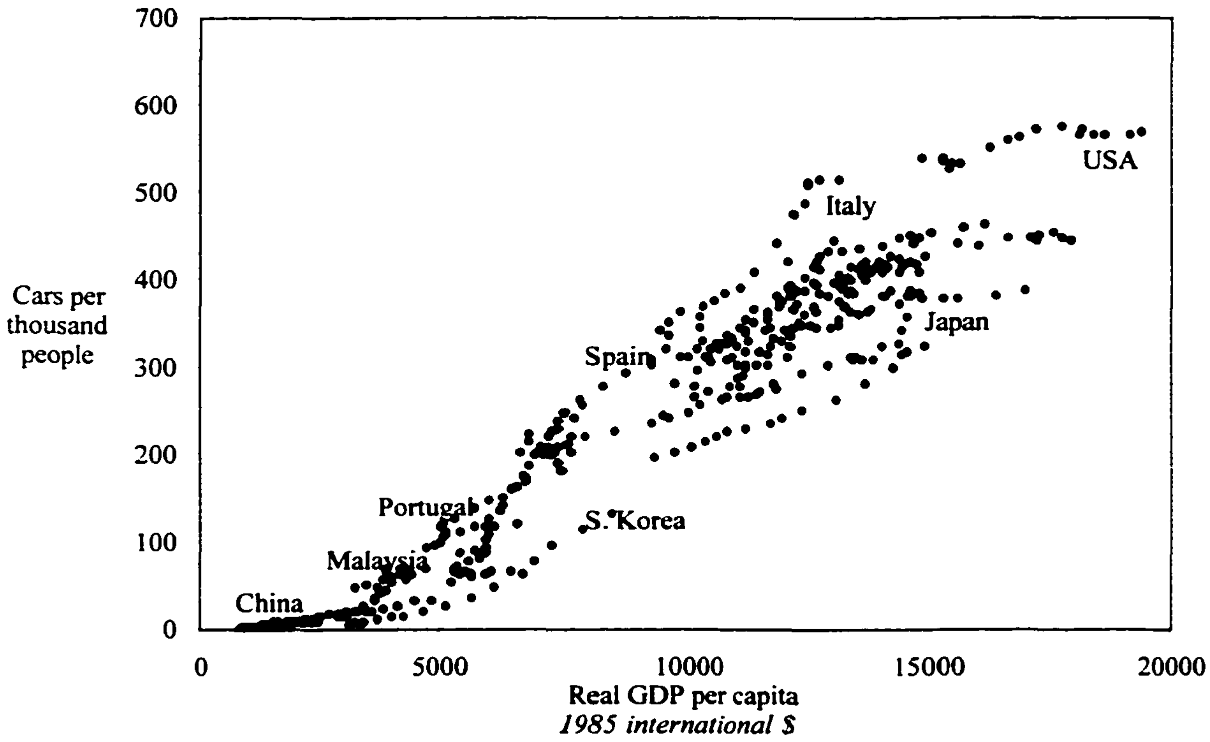
[3] Compatability, in this context, refers to the idea that the log-linear model is only an approximation. It may not accurately describe the true demand relationship implied by the modeling exercise, where truth is determined by the "correct" functional forms.

estimates a model using countries from all levels of development (the others are restricted to countries within a particular region or per capita income bracket). Furthermore, even though these models allow for saturation, due to the functional approach, the saturation level must be arbitrarily imposed. This has the potential of creating significant forecast error due to the fact that the curvature of each function being estimated depends heavily upon the assumed saturation level.

Figure 3-1: Passenger Motor Vehicle Stocks for 28 Countries (1978-1995)



Sources: World Motor Vehicle Data Book, various issues
Penn World Tables 5.6

To illustrate the importance of forming accurate expectations about future motor

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[4] The Gompertz function is of the form $v_t = \gamma e^{\alpha e^{\beta GDP_t}}$ yielding an elasticity that varies with GDP.

vehicle ownership, especially in developing nations, consider the following. The transportation sector currently accounts for only 7% of China's energy consumption with only one automobile for every 290 persons. This contrasts with one car for every 12 persons worldwide and one for every 2 persons in the US. Given a projected population of 1.5 billion by 2015, if only 10% of the population achieves incomes and automobile ownership comparable to the developed nations, the stock of automobiles could increase by some 40 to 60 million in China alone. The subsequent utilization of these vehicles will have a significant impact on energy demand. Per capita passenger vehicle stocks in China have risen by over 1000% in the last 20 years (growing from around 0.2 cars per thousand to just over 3 cars per thousand). This has been accompanied by an increase in transport energy demand per capita of approximately 300%. Because these are per capita quantities, they translate into enormous absolute quantities, and future growth of this magnitude will place increasing importance on the development of sustainable energy inflows. Given reasonable global supply constraints, this has the potential to place great strain on the energy security of other nations as well, highlighting the importance of this issue as one of global magnitude.

Theoretical Considerations

The approach taken here is an attempt to combine the more desirable properties of the modeling exercises that appear in the literature. We make use of the investment approach as it is general enough to allow for the analysis of durable goods other than motor vehicles. We also account for variable operating costs, as the cost of utilization of any durable good is certainly important in determining the service it renders to the consumer. We show that the user cost of motor vehicles (or any other energy-dependent durable good for that matter) can be extended to include the variable cost of operation as well as the opportunity cost of ownership.

Motor vehicles are a physical asset, which along with fuel, time and other goods, are inputs into a production function that produces a flow of transportation services[5]. The arguments in this production function are "derived" from the demand for transport services. The consumption of motor vehicle fuel is a proxy for utilization, which in turn is a proxy for the production of transportation services[6]. The relationship between fuel use and utilization is given by the identity

$$quantity_{fuel,t} = \frac{\left(\dfrac{dis\tan ce_t}{vehicle_t}\right)\cdot vehicle_t}{\left(\dfrac{dis\tan ce_t}{quantity_{fuel,t}}\right)} \qquad (3.1).$$

It can be readily seen from the above identity that any change in the number of vehicles, *ceteris paribus*, will cause the quantity of motor fuel demanded to change.

We assume utility to be a concave twice differentiable function of the consumption of transport services, as signaled by motor fuel consumption, g_t, taking efficiency to be constant, and all other goods, z_t. Therefore, consumers will

$$\max_{z,g,s} \sum_{t=0}^{T} \beta^t U(z_t, g_t) \qquad 0 < \beta < 1 \qquad (3.2).$$

It is through equation (3.1) that the stock of vehicles enters the consumer's utility function. In the conventional approach to modeling the demand for durable goods,

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[5] Automobiles may provide other services as well, such as convenience and status signaling, however, we will not explore this issue in our analysis.

[6] This does, of course, ignore the differences in fuel efficiency that would most certainly be a characteristic of a heterogeneous fleet of motor vehicles.

the stock variable enters directly into the consumer's utility function under the assumption that the flow of services provided is proportional to the stock. However, due to the nature of our problem, we can utilize the direct relationship between commodity consumption, namely fuel, and the durable stock, namely motor vehicles. Rewriting (3.1) into a more usable form, we have the constraint

$$g_t = \frac{d_t \cdot v_t}{e_t} \tag{3.3}$$

where each variable corresponds to its position in (3.1) with e_t, fuel efficiency, taken to be constant across the available vehicle stock.

Some studies of motor vehicle demand have emphasized the possibility of substituting between different types of a heterogeneous vehicle stock[7], where heterogeneity can be accounted for by classifying vehicles by engine size. This, in general, serves to provide a means of differentiating among the different average fuel efficiencies of the various classifications. The extension of our model to allow for heterogeneity is a straightforward one in that we can diversify the constraints to include multiple fuel efficiencies and allow the consumer's decision set to be expanded to account for this. In this environment, the representative agent could respond to fuel price changes by changing the composition of his/her stock rather than reduce vehicle utilization. Since these substitution effects are not the focal point of this study, we assume that the available vehicle stock is homogeneous in nature.

Consumers divide their income, y_t, plus returns from savings in each period among consumption and some financial asset, s_t, bearing the rate of return r. Consumption consists of purchases of vehicle fuel, g_t, net purchases of motor vehicles,

a_t[8], and all other goods, z_t. Specifically, we have that

$$p_{z,t}z_t + p_{g,t}g_t + p_{a,t}a_t + s_t \le y_t + (1+r)s_{t-1} \qquad (3.4).$$

Using the assumption that the physical asset depreciates at some rate, δ, proportional to the existing stock, we also have that

$$a_t = v_t - (1-\delta)v_{t-1} \qquad (3.5).$$

The rate of depreciation here is simply the devaluation that occurs as a vehicle ages.

This leads us to addressing the issue of motor vehicle purchases in each period. The treatment of motor vehicles as a continuous variable can be problematic given the fact they are purchased in integer quantities. Following Muth (1960), this problem is circumvented by arbitrarily selecting one motor vehicle as the standard unit and calculating the price ratios of all other vehicles relative to the standard. Since these price ratios will be continuous, a continuous number of units can be purchased. So, what exactly is a ‘unit’ of motor vehicle stock? Using the terminology of Deaton and Muellbauer (1981), we can think of individuals as purchasing 'efficiency units' when adding to their stock. The problem can be treated as if the individual buys a unit today, sells it at the end of the day, and buys another unit tomorrow. Increasing the stock can be thought of as increasing the quality of the stock, or buying a better unit tomorrow, which allows the consumer to expand the service rendered by his motor vehicle stock. Therefore, ‘efficiency units’ can be thought of as ‘utility units’ in that each purchase provides additional utils to the consumer.

Making the appropriate substitutions and taking the price of z_t to be the numeraire in order to express the other variables in real terms, we can formalize the

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[7] See, for example, Tishler (1983).

consumer's problem as

$$\max_{z,d,v,s} \sum_{t=0}^{T} \beta^{t} U\left(z_t, \frac{d_t \cdot v_t}{e_t} \right) \qquad 0 < \beta < 1 \tag{3.6}$$

subject to the constraints

$$z_t + p_{g,t}\left(\frac{d_t \cdot v_t}{e_t} \right) + p_{a,t}\left(v_t - (1-\delta)v_{t-1}\right) + s_t \le y_t + (1+r)s_{t-1} \tag{3.7}$$

$$z_t, d_t, v_t \ge 0 \qquad t = 1, \ldots, T \tag{3.8}$$

with all initial values given.

Maximizing (3.6) subject to the constraints via the Lagrangian

$$\Gamma = \sum_{t=0}^{T} \beta^{t} \left\{ U\left(z_t, \frac{d_t \cdot v_t}{e_t} \right) + \lambda_t \left(y_t + (1+r)s_{t-1} - s_t - p_{a,t}\left(v_t - (1-\delta)v_{t-1}\right) - z_t - p_{g,t}\left(\frac{d_t \cdot v_t}{e_t} \right) \right) \right\}$$

yields the constraint plus the following first order necessary conditions for a maximum:

$$\frac{\partial \Gamma}{\partial z} = U_z - \lambda_t = 0 \tag{3.9}$$

$$\frac{\partial \Gamma}{\partial d} = U_d - \lambda_t p_{g,t} = 0 \tag{3.10}$$

$$\frac{\partial \Gamma}{\partial v} = U_v \frac{d_t}{e_t} - \lambda_t \left(p_{g,t} \frac{d_t}{e_t} + p_{a,t} \right) + \lambda_{t+1} \beta \left(p_{a,t+1} (1-\delta) \right) = 0 \tag{3.11}$$

$$\frac{\partial \Gamma}{\partial s} = \lambda_t - \lambda_{t+1} \beta (1+r) = 0 \tag{3.12}.$$

We can use (3.12) to eliminate λ_{t+1} from (3.11), and use (3.9) to give

$$U_v \frac{d_t}{e_t} = U_z \left(p_{g,t} \frac{d_t}{e_t} + p_{a,t} - p_{a,t+1} \left(\frac{1-\delta}{1+r} \right) \right) \tag{3.13}.$$

Thus, the consumer will equate the marginal value of adding to his/her motor vehicle stock with the marginal value of increasing consumption of all other goods.

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[8] Individuals can buy and sell portions of their vehicle stock; thus, we use the term 'net additions'.

We define the "user cost" of vehicles as

$$\mu_{v,t} = p_{g,t}\frac{d_t^*}{e_t} + p_{a,t} - p_{a,t+1}\frac{(1-\delta)}{(1+r)} \qquad (3.14).$$

where the star denotes optimality. The term

$$p_{a,t} - p_{a,t+1}\frac{(1-\delta)}{(1+r)}$$

in equation (3.14) is essentially the opportunity cost purchasing vehicle stocks. However, as discussed above, it does not represent the full user cost of energy consuming durable goods such as motor vehicles because it ignores the cost of utilization. The true cost to the consumer of the purchase of a vehicle incorporates the cost of utilization as well as the net cost borne from the initial purchase and subsequent depreciation. It is precisely this attribute that is present in equation (3.14). Therefore, by making use of the identity in equation (3.3), we have incorporated the variable cost of operation associated with motor vehicles into the consumer's decision making process.

Notice that the consumer chooses his/her user cost to some degree in that distance is a choice variable. Letting $d_t = 0$ implies $g_t = 0$. Therefore, because vehicles yield no utility other than the facilitation of transport services, any vehicle stock holdings when $d_t = 0$ would be in violation of the marginal condition (3.13). Thus, it can be concluded that such a policy would most likely be accompanied by the sale of the individual's vehicle stock, reducing $v_t = 0$. The resulting income generated from the sale of the stock would then contribute to consumption of other goods, and the consumer's problem would reduce to that of the non-durable goods case.

The first order conditions (3.9) – (3.12) plus the constraint can be solved simultaneously to yield a set of $3(T+1)$ demand equations, one for each of the arguments in the utility function (z_t, v_t, d_t) at each of the $t+1$ time periods as well as a solution for the multiplier, λ. Each of these demand equations will be expressed as a function of the exogenous variables. In particular, the demand for motor vehicles will be given by

$$v_t^* = v(\mu_{v,t}, W) \qquad (3.15),$$

and the demand for distance traveled in each period will be expressed as

$$d_t^* = d(\mu_{v,t}, W) \qquad (3.16).$$

The demand for gasoline can be derived by multiplying both sides of equation (3.16) by the factor $\frac{v_t^*}{e_t}$. Notice that the left-hand side, by equation (3.3), is the demand for gasoline. Recognizing that we can now substitute on the right hand side for the vehicle stock variable using (3.15), it is possible to express the demand for gasoline as

$$g_t^* = g(\mu_{v,t}, e_t, W).$$

Accordingly, the demand for fuel is "derived" from the consumer's demand for distance.

A Statistical Model of Passenger Vehicle Stocks

Using the general solution to the consumer's problem above, we can express demand for the stock of motor vehicles as a function of consumer wealth and user cost, where the particular nature of these demands will depend upon the specification of the functional form for utility. Aggregation yields an optimal, or desired, stock of motor vehicles in the entire economy.[9] Using per capita income as a proxy for wealth (this is also, for our purposes, an indicator of the level of economic development), a log-quadratic approximation of the functional relationship in (3.15) for each country j is

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[9] We are ignoring here, of course, the problems associated with aggregation.

given by

$$v^*_{t,j} = \alpha_j + \rho_1 \mu_{v,t,j} + \rho_2 y_{t,j} + \rho_3 y^2_{t,j} \tag{3.17}$$

where the star denotes optimality, all variables are expressed as natural logarithms of their levels, are expressed as per capita, and are in real terms. The term α_j is a country specific intercept, and the slope parameters are assumed to be homogeneous.[10] Equation (3.17) is a very simple modification of the log-linear model that allows for a declining elasticity, provided the coefficient of the squared term is negative. The log-quadratic form is superior to the log-linear form because it allows for a declining elasticity as well as the prediction of the saturation level for motor vehicle stocks in each country. This latter point is a distinct advantage over the previous models that attempted to deal with saturation in that the data will determine the saturation level. By not arbitrarily restricting saturation, we avoid the associated potential bias.

The long run elasticity of demand for motor vehicles with respect to income (wealth) for each country j, as implied by equation (3.17), is

$$\frac{\partial v_{t,j}}{\partial y_{t,j}} = \rho_2 + 2\rho_3 y_{t,j} \tag{3.18}$$

where it is expected that $\rho_2 > 0$ and $\rho_3 < 0$. Setting the elasticity equal to zero and solving for y_t will give the level of per capita GDP at which saturation occurs,

$y^{sat} = e^{-\frac{\rho_2}{2\rho_3}}$. This can be inserted into (3.17) for a given price level to find the saturation stock of motor vehicles. Note that any level of income beyond this point will yield a negative long-run elasticity. Therefore, for every point beyond saturation it is assumed that stocks will no longer be influenced by income, only by user cost, thus the income elasticity is zero. Since saturation occurs at relatively high levels of income, however, this characterization of the functional form is of no practical relevance. As user cost approaches zero, the results from the modeling section indicate that vehicle stocks would increase until the marginal condition (3.13) is satisfied. One could expect stocks to grow to extremely high quantities in such a circumstance.

Because of factors such as habit persistence, uncertainty about the continuation current economic trends, or capacity constraints on the rate at which vehicles can be produced or imported, individuals do not adjust fully to changes in the factors affecting their desired demand for vehicles when they occur. In other words, in the aggregate, they may adjust to the optimal stock with a lag. In order to account for such a possibility, we incorporate a standard stock adjustment mechanism given by

$$v_{t,j} - v_{t-1,j} = \gamma\left(v^{*}_{t,j} - v_{t-1,j}\right) \tag{3.19}$$

where $\gamma \in [0,1]$ is the speed of adjustment. If $\gamma = 1$ the adjustment process is instantaneous, and the actual investment in new vehicles will be equal to the desired level, that is, $a^{*}_{t,j} = a_{t,j}$.

Substituting (3.19) into (3.17), we can eliminate $v^{*}_{t,j}$ to yield the equation to be estimated:

$$v_{t,j} = \phi_j + \beta_1\mu_{v,t,j} + \beta_2 y_{t,j} + \beta_3 y^2_{t,j} + (1-\gamma)v_{t-1,j} + \eta_t \qquad (3.20).$$

where $\beta_i = \gamma\rho_i$, and the term $\phi_j = \gamma\alpha_j$ is a country specific effect that can be treated as random or fixed. Equation (3.20) yields both long and short run impacts of each of the exogenous variables on vehicles stock. Specifically, the terms ρ_i give the long run impact of their respective variables, and the terms β_i are the short run impacts.

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[10] We will return to this point, as a statistical matter, in the next section.

Data

The estimation covers the period from 1978 to 1995 for the 28 different countries that are depicted in Figure 3-1 (see Table 3-4 below for a complete list). We use the price of motor fuel, as given by the IEA and various national statistical agencies, as a proxy for the user cost of motor vehicles. This index is less than perfect as a measure of user cost because it does not include maintenance costs or vehicle depreciation costs. However, as a measure of utilization price, it is sufficient if one makes the acceptable assumption that fuel costs are the largest single component of an individual's costs of operation. The data for per capita GDP are obtained from the Penn World Tables 5.6 with the data points beyond 1992 having been calculated using real growth rates. The data for passenger motor vehicle stocks is from various issues of the World Motor Vehicle Data Book as well as national statistical sources.

Estimation Procedure and Results

Equation (3.20) is estimated using the instrumental-variable (IV) estimation method suggested by Balestra and Nerlove (1966)[11]. The use of instrumental variables, which in this case are present and lagged values of the exogenous variables (per capita income and fuel prices) and population, are necessary due to the correlation that exists between the lagged endogenous variable and the error term. The technique is devised for estimation of dynamic panel data models with individual country effects. This method was chosen because we are interested in sample characteristics, which are reflective of a

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[11] A complete account of the econometric procedure is given in Appendix B.

common global development pattern, in order to make forecasts for each country. By imposing common slope parameters across countries, we are essentially mapping future paths of developing nations into the existing paths of industrialized nations. This is deemed the most appropriate approach under the maintained hypothesis that the per capita motor vehicle stocks of all countries will follow some similar long run path. The country effects are treated as fixed, not random, and account for the fact that not all countries have the same level of per capita passenger vehicle stocks at given levels of income. The heterogeneity is attributed to things such as differences in resource endowments as well as cultural and philosophical ideologies that dictate domestic policies.

Table 3-1: Estimation Results[12]

Estimated Relationship (equation (3.20)):

$$v_{t,j} = \phi_j + \beta_1 \mu_{v,t,j} + \beta_2 y_{t,j} + \beta_3 y_{t,j}^2 + (1-\gamma) v_{t-1,j} + \eta_t$$

Long Run Relationship (equation (3.17)):

$$v_{t,j}^{*} = \alpha_j + \rho_1 \mu_{v,t,j} + \rho_2 y_{t,j} + \rho_3 y_{t,j}^2$$

short run coefficients	**parameter estimates**	**long run coefficients**	**implied values**
ϕ_i	.....	α_i	.....
β_1	-0.1100 (0.0198)	ρ_1	-0.6753
β_2	1.6637 (0.3360)	ρ_2	10.2130
β_3	-0.0843 (0.0163)	ρ_3	-0.5175
$1-\gamma$	0.8371 (0.0445)		
R^2	0.9851		

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[12] The parameter estimates and standard errors for alternative estimation methods are given in the Appendix C.

The estimated coefficients and their standard errors (in parentheses) are given in Table 3-1. All of the coefficients are of the anticipated sign, and the model fits the data rather well with R^2 value of 0.9851. Also reported are the long run coefficients of equation (18) as implied by the estimated parameters. The estimated coefficient on the lagged endogenous variable suggests that adjustment to the long run, or optimal, stock occurs at about 16% per year ($1-\gamma = 0.8371$, therefore $\gamma = 0.1629$). This is a rather sluggish movement, and implies that price and income effects take some time to be fully realized.

Table 3-2: Income Elasticity of Passenger Vehicle Demand

Real GDP/cap *1985 int $*	**Short Run Elasticity**	**Long Run Elasticity**
$ 500	0.62	3.78
$ 2,500	0.34	2.12
$ 5,000	0.23	1.40
$ 7,500	0.16	0.98
$ 10,000	0.11	0.68
$ 12,500	0.07	0.45
$ 15,000	0.04	0.26
$ 17,500	0.02	0.10
$ 19,298	0.00	0.00

Using equation (3.18) we calculate the long-run income, or wealth, elasticity of vehicle demand that is implied by the estimated parameters. It falls from 3.78, at $500 per capita, to zero (the point of saturation), at $19,298 per capita (see Table 3-3). The short-run price elasticity is –0.11, and the long-run elasticity is –0.68.[13] Taken together, these indicate that a one-percent change in the price variable has a greater influence on per capita passenger vehicle stocks than a one-percent change in per capita income for all levels of income greater than $10,048. Therefore, in most of the countries in the OECD,

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[13] The possibility of a quadratic in the price variable was explored, but did not turn out to be significant.

the price elasticity is larger than the income elasticity. Moreover, tax policies aimed at reducing motor vehicle stocks will be increasingly effective as countries become more developed.

Increases in fuel efficiency could offset the effect of higher user prices in the demand for passenger vehicles. By equation (3.3), we know that motor fuel demand is derived from the demands for stocks and distance per vehicle, a reduction in per capita stocks will, *ceteris paribus*, reduce the consumption of motor fuel per capita. However, increases in fuel efficiency could leave agents' decisions about distance and motor vehicle stocks unaffected, despite higher user prices. From the definition of user cost in equation (3.14), $\mu_{v,t} = p_{g,t}\frac{d_t^*}{e_t} + p_{a,t} - p_{a,t+1}\frac{(1-\delta)}{(1+r)}$, increases in efficiency can offset increases in fuel prices. Consumers' total fuel bill would not increase, thus leaving user cost unchanged. A prerequisite condition for this is a change in the composition of the motor vehicle stock. In countries like the US, this would mean fewer heavy, recreational vehicles and more fuel-efficient, lightweight cars. Although we do not account for composition changes here, as this was not the focal point of our analysis, it is implicitly present through equation (3.3), and noteworthy nonetheless.

We generate Figure 3-2 using the coefficients reported in Table 3-1. Curve A is generated using the parameter estimates and an initial value for the stock of motor vehicles implied by the long run coefficients. Curve B is generated using the long run coefficients. Both of these curves are generated holding user cost constant and using the average intercept value. Notice the S-shape of Curve A that results from this exercise.[14]

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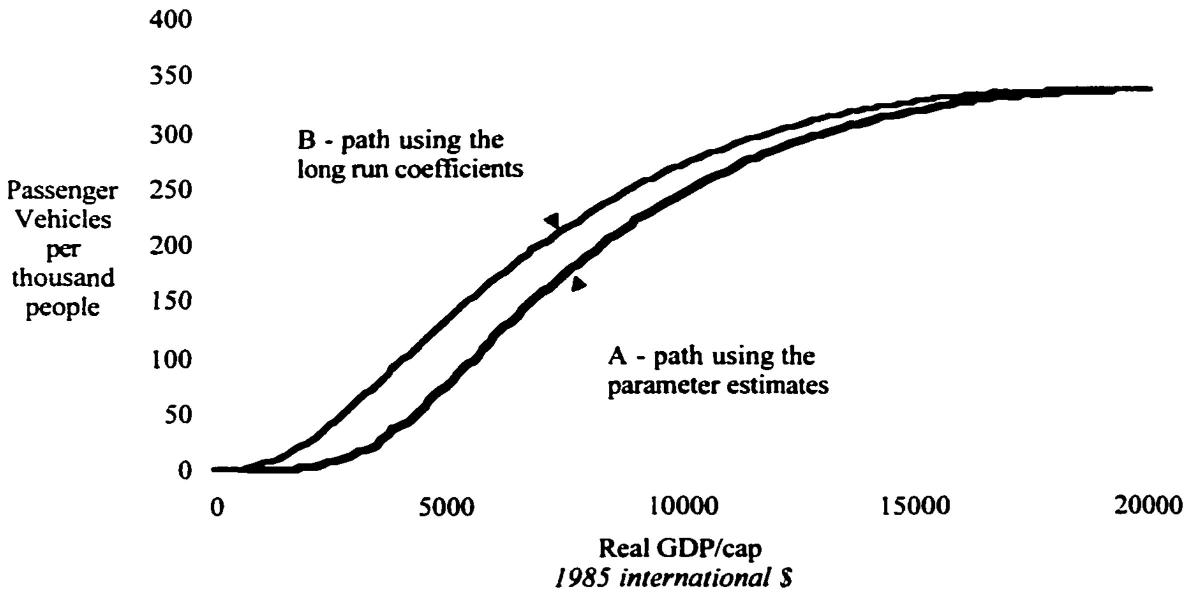
[14] Allowing price to change will alter the shape of the S-curve slightly, but it does not change the results significantly.

This brings up an important criticism of the non-linear models that have been used by previous authors. The usual claim is that the income elasticity first rises then falls as income increases. This is justified by the shape of Curve A in Figure 3-2, and is the reason that S-shaped functions are fit to the data. Contrary to this claim we find that the income elasticity falls continuously throughout the development process. The lower tail can be, at least in part, attributed to the adjustment process described by equation (3.19). Notice the lack of significant curvature in the lower portion of Curve B. Using the long run coefficients is akin to assuming instantaneous adjustment. If people adjust instantaneously to the optimal stock, then the long run adjustment process will disappear. However, we see that this is not the case, and, in fact, incomes initially rise faster than vehicle stocks because, in the aggregate, consumers are sluggish in their response.

Figure 3-2: Simulated Path of Passenger Vehicle Stocks for an Average Country



In Table 3-3 we have reported forecasts of motor vehicles stocks for the countries in our sample under the assumption that user costs remain at their 1995 levels, and that per capita income will grow at the same average annual rate it grew from 1978-1995. Due to the recent economic collapse in Asia, these growth rates are most likely overstated for the countries in that region. Furthermore, if convergence theory holds to be true, the growth rates will most likely be too high anyway. Nevertheless, the forecasts will give us some idea as to how per capita passenger vehicle stocks will evolve in the near future. Reported for each country are the projected vehicle stock, the corresponding level of per capita GDP, the income elasticity, and the implied saturation stock of motor vehicles. The last of these is found by using the long-run coefficients from Table 3-1, along with the saturation level of per capita GDP and the 1995 user price for each country. Under our growth assumptions, some countries will reach the saturation level of GDP by 2015 (elasticity equals zero), but their stocks will not yet have fully adjusted. This is due to the fact that those countries are only just beginning to reach those income levels.

The average saturation stock as reported by our model is 395, a number smaller than the saturation level of 620 assumed in Dargay and Gately (1998). However, there is significant variation for each country, the majority of which occurs across less-developed and developing nations. The average saturation stock in the developing Asian economies (Pakistan, India, China, Malaysia, South Korea, Thailand, Indonesia and Sri Lanka) is 239 cars per thousand, with the highest being Malaysia (401) and the lowest being China (114). The extremely low saturation stocks in the countries of developing Asia is reflective of the current state of transport infrastructure, a feature that would be captured by the country specific effect. This number is quite different for the rest of the sample, 457 cars per thousand, which is by-and-large the OECD. The highest is the US (683) and the lowest is Mexico (200).

Table 3-3: Forecasts to 2015[15]

	1995			Assumed	2015			
Country	GDP/cap *1985 int $*	Passenger Veh/thou	LR Income Elasticity	Growth %	GDP/cap *1985 int $*	Passenger Veh/thou	LR Income Elasticity	Peak Stock/thou
Pakistan	1498	7	2.49	2.42	2416	27	2.15	330
India	1514	4	2.48	3.21	2847	23	1.98	214
China	1863	3	2.29	5.06	5000	29	1.40	114
Sri Lanka	2454	17	2.04	3.14	4550	50	1.49	192
Indonesia	2485	10	2.03	4.97	6552	71	1.11	183
Turkey	3898	47	1.62	1.48	5228	92	1.35	248
Thailand	4805	34	1.43	5.34	13595	177	0.36	228
Mexico	5402	93	1.32	0.39	5845	94	1.23	200
Malaysia	6556	128	1.14	4.30	15205	348	0.24	401
Greece	7043	209	1.08	1.34	9191	290	0.76	408
Portugal	7859	253	0.98	3.24	14860	462	0.27	516
S Korea	8465	134	0.91	6.31	28785	*248*	0.00	248
Spain	9874	359	0.77	1.69	13804	499	0.34	551
Ireland	11877	275	0.60	3.66	24394	409	0.00	421
Austria	13081	448	0.51	1.99	19386	515	0.00	521
Italy	13192	517	0.51	2.27	20673	601	0.00	607
Belgium	13668	420	0.47	1.70	19162	473	0.01	478
Netherlands	13805	365	0.46	1.41	18256	415	0.05	421
U.K.	14187	419	0.44	2.12	21586	480	0.00	484
France	14262	430	0.43	1.51	19253	489	0.00	493
Finland	14402	374	0.43	2.66	24339	*421*	0.00	421
Japan	14578	357	0.41	2.90	25826	*464*	0.00	464
Sweden	14860	416	0.40	1.48	19935	421	0.00	422
Denmark	14960	326	0.39	1.87	21679	*392*	0.00	392
Australia	16113	496	0.32	1.85	23255	*523*	0.00	523
Norway	16932	389	0.28	2.61	28351	*388*	0.00	388
Canada	17900	450	0.23	1.80	25564	*504*	0.00	504
U.S.A.	19369	573	0.16	1.43	25744	*683*	0.00	683
Average	....	270	....	....	....	342	....	395

Note: Figures in italics indicate the saturation stock has been reached.

Different saturation stocks would imply different long-run growth patterns because each country is tending to a different end condition. In Figure 3-3, we have generated the growth path of passenger vehicles per thousand people for each of the countries in our sample. Each path was generated assuming a constant price, an index

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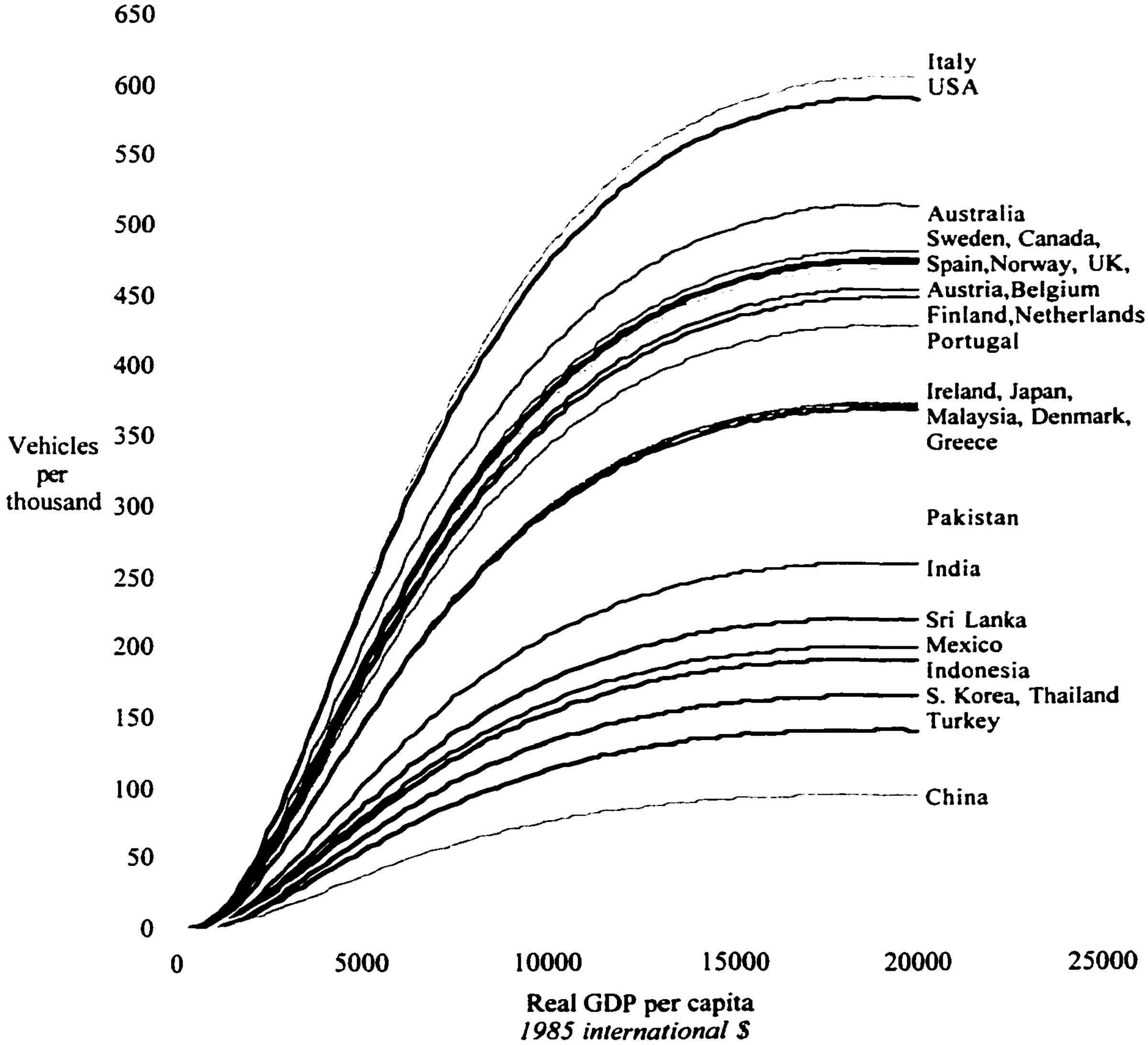
[15] Alternative forecasts under different growth scenarios are presented in Appendix D.

value of 100, which is the 1985 value. The actual paths will differ slightly for each country because different domestic tax policies and changes in prices will generate different user costs.

Figure 3-3: Country–Specific Passenger Vehicle Stocks per Thousand



We see, in Figure 3-3, the inherent heterogeneity across countries that is indicative of different degrees of development of transport infrastructure and different long-standing attitudes and policies toward private transportation. For example, a proliferation of alternative modes of transport, such as bicycles, motorized scooters, and well-developed public transportation, will drive the saturation levels of passenger motor vehicle stocks down. This follows from the marginal condition in equation (3.14). If the demand for distance, d^*, can be satiated by alternative modes of transportation, then user costs can be kept extremely low, and income can be allocated to other consumption goods. By equation (3.3), the long term demand for transport fuel will be lower in countries where saturation stocks are lower. This is a rather intuitive result in that lower saturation stocks imply, among other things, a proliferation of alternative modes of transportation.

In Table 3-4, we have reported the forecasts of Dargay and Gately (1998) along with forecasts using our model under their assumptions about growth in order to provide some comparison. While some predicted stocks are higher, most are lower than Dargay and Gately. These differences in the forecast values are driven by the extreme difference in Dargay and Gately assumed saturation values and our estimated values. We suspect that in the very long term the saturation values of the less-developed economies will converge to those of the developed economies provided transport infrastructure is built up and maintained. However, even if there are significant developments in transport infrastructure, which would encourage vehicle ownership, it is unlikely that these occurrences would have a significant effect in the very near future. As a result, the use of a common saturation level is an over-restrictive constraint on the path of country specific per capita motor vehicle stocks.

Table 3-4: Forecast to 2015 with Comparison to Dargay and Gately (1998)

	Dargay and Gately forecasts			Forecasts with DG assumptions	
Country	Assumed Growth Rate (%)	Veh/thou*	Long-run Income Elasticity	Veh/thou**	Long-run Income Elasticity
Turkey	1.95	70	2.30	99	1.26
India	3.82	10	2.17	24	1.80
Pakistan	2.42	10	1.99	25	2.05
China	5.85	40	2.34	43	1.25
Mexico	1.43	170	1.89	113	1.06
Greece	1.68	350	1.07	304	0.78
Portugal	3.54	510	0.16	492	0.34
Korea	4.20	410	0.43	251	0.16
Spain	2.87	550	0.13	555	0.25
Ireland	3.75	520	0.14	453	0.00
Italy	2.20	590	0.05	638	0.11
Austria	2.04	560	0.15	543	0.15
Finland	2.66	550	0.16	448	0.00
Japan	2.78	550	0.10	451	0.00
Netherlands	1.94	540	0.25	441	0.11
U.K.	2.33	560	0.15	513	0.02
France	2.23	570	0.09	519	0.03
Australia	2.35	580	0.08	552	0.00
Denmark	2.36	520	0.27	413	0.00
Sweden	1.38	530	0.37	439	0.15
Norway	2.37	570	0.09	410	0.00
Canada	2.30	590	0.04	518	0.00
U.S.A.	1.67	610	0.02	695	0.00

* - The assumed saturation stock in DG is 620 per 1000. The average estimated saturation stock in MS is 425 per 1000 (see Table 3-3).

** - These forecasts assume a constant 1995 price.

Concluding Remarks

In developing a model of passenger motor vehicle demand, we have been able to accomplish a few key objectives. First, we have presented a modeling approach that incorporates some of the more desirable properties of previous studies. Many models are insufficient because they ignore variable costs of operation, such as fuel and maintenance. Attempts have been made to explicitly account for these costs, but they are usually at the expense of the more desirable properties of the durable goods framework, namely, the idea that consumers make an investment when they purchase a motor vehicle. Allowing for this facet of consumer behavior, as well as including the notion of variable costs, we have demonstrated that the cost confronting the consumer when purchasing a motor vehicle includes the cost of utilization, as well as the cost borne from foregoing an alternative investment. (It should be noted that the model presented herein is easily extendable to other fuel-consuming durable goods, such as household appliances.)

Second, we have given evidence that lags in adjustment are responsible for the lower tail of the S-shaped pattern motor vehicle stock growth. This is contrary to the widely held view posited in the literature that income elasticities rise then fall as countries become increasingly developed. We show that the income elasticity falls continuously, reaching zero at a level of per capita GDP equal to $19,298. Income per capita only grows faster than per capita vehicle stocks at low levels of income because consumers are sluggish to adjust to the optimal stock.

Third, we have demonstrated that user prices play an increasingly important role in determining vehicle demand. Using equation (3.3), we then showed how this could affect the demand for motor fuel. As user price increases, stocks may or may not change in level (depending upon the change in fleet efficiency), but fuel demand will definitely fall regardless. This is because it is negatively related to fuel efficiency, but positively related to distance and vehicle stocks (from equation (3)).

Fourth, we have highlighted a critical weakness in models that arbitrarily assume a saturation level. Given the current state of transport infrastructure and the various transport policies of different nations, it is hardly reasonable to expect all nations to reach some similar saturation stock. Rather, there should be fixed differences reflective of different economic and political environments. Any short-to-medium term forecasting exercise would benefit from such an allowance because it takes time to fully implement and adjust to changes in infrastructure and/or policy. While all nations may eventually approach a similar saturation stock, this would be a phenomenon unlikely to occur in the near future. It takes time and capital to develop transport infrastructure, and for a country like China to reach the road capacity of the USA it will take a lot of both. The current state of transport infrastructure in the USA took almost 100 years to develop. While current production technologies may speed the process in developing nations, it is unreasonable to assume that this can occur by 2015.

The results presented herein have interesting implications for energy demand in developing nations. In particular, if the trend observed here holds out into the future, then countries such as China and India portend to be major players in motor vehicle and motor fuel markets. For example, if China's development pattern fits the average, as it moves into higher stages of development, per capita demand for vehicles and fuel should increase dramatically. Specifically, if China grows at a rate of only 3% per annum, we could expect to see per capita vehicle demand increase by as much as 8% per year. This would, holding efficiency and the demand for distance per vehicle constant, lead to dramatic increases in motor fuel demand. With continuing development, the rate of increase would decline, but, for countries with a massive population, any growth in per capita variables equates to enormous increases in the absolute quantities demanded of vehicles and fuel.

CHAPTER 4

First Things First – Development and Global Warming[*]

This chapter focuses on the priorities of developing nations as they pertain to proposed controls over greenhouse gas emissions. Currently, such controls do not apply to developing countries, despite expectations they will become major producers of such gases. Considering the rapid growth in energy consumption that can be expected in developing nations and the slower growth of energy consumption in industrialized nations, it is likely that controls on the developed nations alone will do very little to reduce the accumulation of carbon dioxide in the atmosphere. Although industrialized nations account for the majority of past and current emissions, growth projections indicate that the emissions of developing nations will surpass those of industrialized nations in the next decade or so. As a result, it has been argued that developing nations need to take immediate action to curb what is presumed to be an escalating problem.

Developing nations counter, on the basis of the "polluter pays" and "common but differentiated responsibilities" principles, that the industrialized nations have placed the world in its current ecological state, and therefore these same nations ought to rectify it. Developing nations have also claimed that emissions regulations or taxes comparable to those placed on industrialized nations would be detrimental to their further growth. Such policies would compete with the goal of reducing poverty in the developing world. Finally, it is not clear that controlling greenhouse gas emissions is as important to

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[*] This chapter is taken from a paper of the same title, co-authored by Peter Hartley and Michael Warby.

developing nations as addressing more immediate environmental concerns, such as air and water pollution or deforestation.

In any rational ranking of national priorities in developing countries, many activities will take precedence over combating global warming. These include such things such as improving health and education, raising living standards and ameliorating other more urgent environmental problems. Accordingly, in order for the developing countries to take steps to combat global warming, they will have to be compensated until the net cost is acceptable. The cost of any sacrifice that is demanded of developing countries, therefore, is likely to fall on the taxpayers of developed countries. However, such massive transfers of resources will most likely be resisted by the electorate in the developed nations.

The Global Warming Issue

"Global warming" is a theoretical result from computer simulation models suggesting that an increase in the concentration of "greenhouse gases" will raise the surface temperatures of the earth. 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.[1]

High concentrations of greenhouse gases in the atmosphere create a 'heat-absorbing blanket' that raises the temperature at the surface of the earth above what it would otherwise be. CO_2 has received the most attention because it is currently responsible for the majority of *radiative forcing* - the phenomenon by which greenhouse gases raise the atmospheric temperature through increased absorption and re-emission of solar radiation. Despite increases in carbon concentrations in the atmosphere resulting from increased global industrialization and mobilization, CO_2 is not chiefly responsible for the predicted temperature increases. Rather, increases in CO_2 concentration (and other greenhouse gases for that matter), through radiative forcing, generates increases in water vapor. More water vapor increases the rate of absorption and re-emission of solar radiation by the atmosphere, which results in more water vapor. Hence, the absorption/re-emission cycle can build upon itself exponentially.

The detriments of warming could be enormous. For example, melting of Antarctic glaciers could cause a rapid rise in sea levels, thereby destroying many of the world's port cities. The phenomenon, however, may be quite non-linear. Initially, warming may cause a gradual melting of glaciers, but if the glaciers disengage themselves and move out to sea, they will melt more rapidly. The adjustment costs, and damages, are much larger in the latter case, but the amount of CO_2 that must accumulate before such an occurrence is uncertain. The timing and severity of damages, therefore, can be very difficult to predict.

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[1] Davis, R. W., Legates, D., (June 1998).

Apart from environmental damage, a change in water vapor and CO_2 concentrations could also generate increases in plant growth[2], and result in changes in weather cycles that create an increase in oceanic absorption. Factors such as these would tend to reduce CO_2 concentrations and, thus, the amount of radiative forcing that occurs. Moreover, if CO_2 concentrations do increase, the productivity of agriculture and forestry (and perhaps also fishing) could rise as well (and oceans). If these beneficial effects are large enough, it might be wise to simply cope with any adverse consequences of higher CO_2 concentrations. Competing factors, coupled with the fact that any increase in carbon in the atmosphere from human activity represents a marginal impact to a complex natural system, make the consequences of increased CO_2 concentrations difficult to predict.

Since 1958, the concentration of CO_2 in the atmosphere has risen about 14% (not a small increase in 40 years), and is now about 30% above pre-industrial levels.[3] The Intergovernmental Panel on Climate Change (IPCC) currently estimates that this will rise by another 48% during the next century to a level 90% above pre-industrial levels.[4] While this is a large increase in CO_2, there is substantial uncertainty as to the consequences for temperatures, sea levels or extreme weather events. The 1995 IPCC report's median projection is an increase in average temperatures of 2°C by 2100. This figure is 23% below the IPCC's 1992 median projection, 38% below their 1990 median projection[5], and it is only a quarter of the figure projected at the Toronto conference of 1988, the year the IPCC was created. The instability of the projections – a 75% fall in seven years and almost 40% in five – is an indication of the uncertainty.

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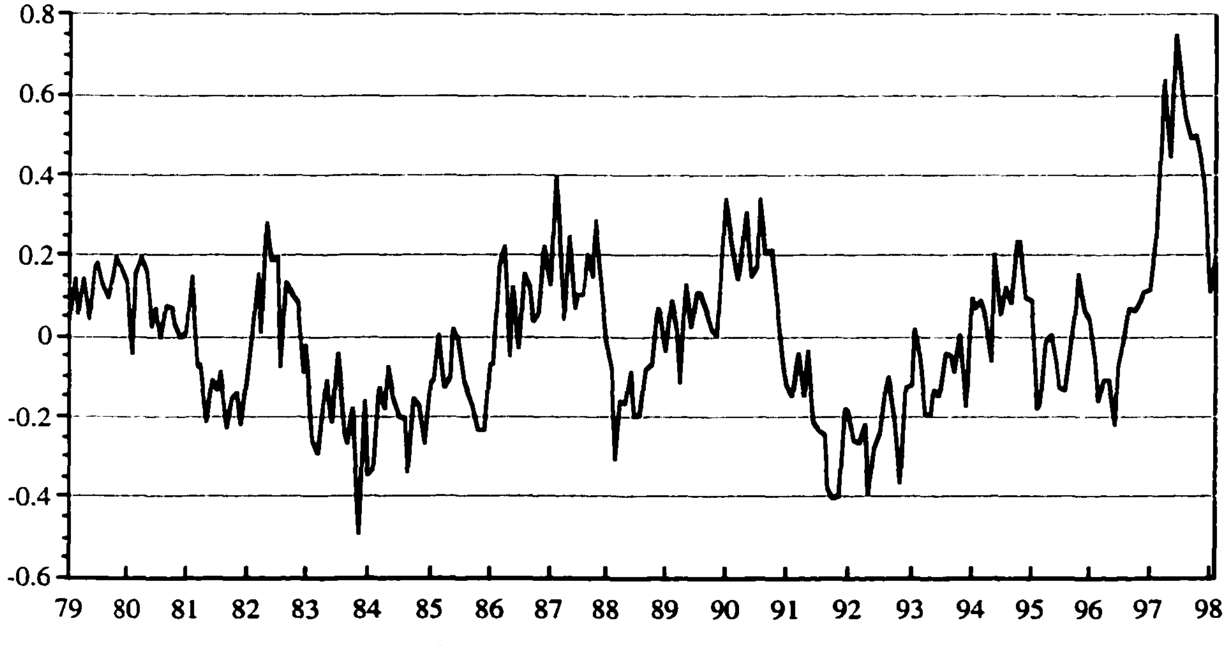
[2] Ellsaessar, H.W., (1997), P.11; Idso (1996), P.32. Michaels (1998) also notes evidence of increased take-up CO_2 from vegetation.

[3] World Resources Institute, (1997).

[4] Houghton, J. T. et al (eds) (1996) P.25.

Surface temperature records have revealed a slight warming trend since the late nineteenth century (approximately 0.8°C[6]). Over-sampling of urban and other highly populated areas, however, contaminates many of the land-based records due to what has been called the 'heat-island' effect. Urban areas raise temperatures relative to the surrounding countryside because extensive areas of pavement absorb heat during the day and radiate it back to the atmosphere at night. Furthermore, there is an inconsistency between the global surface temperature record and a record obtained from the Microwave Sounding Units (MSU) on the National Oceanic and Atmospheric Administration's (NOAA) TIROS-N series of polar-orbiting weather satellites.[7] The global record in the lower troposphere (the lowest 4 miles of the atmosphere) is illustrated in Figure 4-1.

Figure 4-1: Global Temperature Anomaly as Measured by Satellites



Source: NASA web-site *http://www.ClimateNews.com/*.

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[5] Houghton et al (1996); Houghton et al (eds) (1992); Houghton et al (eds) (1990).

[6] See the CDIAC web-site.

[7] In a press statement released February 4, 1999, the National Research Council stated "Deficiencies in the accuracy, quality and continuity of the records ... place serious limitations on the confidence that can be placed in the research results."

The satellite data show a warming trend of 0.059°C per decade, which is substantially below the warming trend in the surface record over the same period. There is also an indication that most of the warming that has occurred has been on winter nights in Alaska and Siberia, a pattern of warming that is consistent with the predictions of the computer simulation models. The satellite temperatures are consistent with two temperature series from weather balloons – one involving measurements made by thermometers and the other based on air pressure readings. The agreement between the three independently measured series, and the disagreement between those series and the surface record, suggests that the surface record is unrepresentative.[8]

Despite the fact that modest warming has occurred over the last century, there is uncertainty as to the source of that increase. The end of the nineteenth century was unusually cool relative to the previous 500 or so years (Figure 4-2) and the warming that may have occurred this century could be largely the result of other natural processes, such as fluctuations in solar energy output. Furthermore, the earth passed through ice ages in what is considered only the recent past on a geological time scale (Figure 4-2 and Figure 4-3 plot deviations in °C around the average global temperature for 1900). In fact, current IPCC projections of future temperatures are within the range of those previously encountered on a geological time scale. However, the rate of increase in temperatures since the middle 1800's is correlated with the rate of increase in CO_2 accumulation

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[8] Douglas Hoyt (http://www.erols.com/dhoyt1/index.html) observes "When the surface and MSU temperature trends are compared region by region, we note two things:
1. The MSU trends vary smoothly in passing from one region to another (i.e., smoothly geographically).
2. The surface network trends, in contrast, jump all over the place. For example, one region will appear to be sharply warming, but all the surrounding regions are markedly cooling. The MSU trends for the same region will show a smooth variation in cooling over the regions. It is physically implausible for a small region to warm with all surrounding regions, including the atmosphere above it, cooling." He also comments, "Many of the greatest discrepancies between surface and MSU observations occur in urban regions."

during the same period, which, coincidentally, was a period of rapid industrialization. Moreover, *rapid* temperature changes could devastate ecosystems that do not have time to adjust.

Figure 4-2: Average global temperatures in the last 1000 years

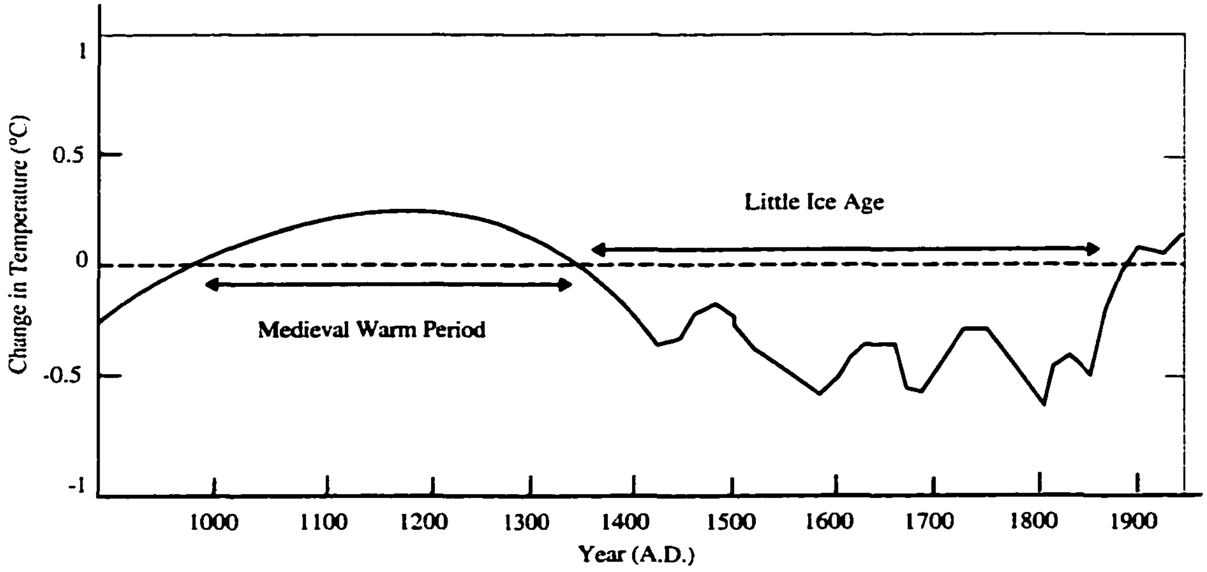
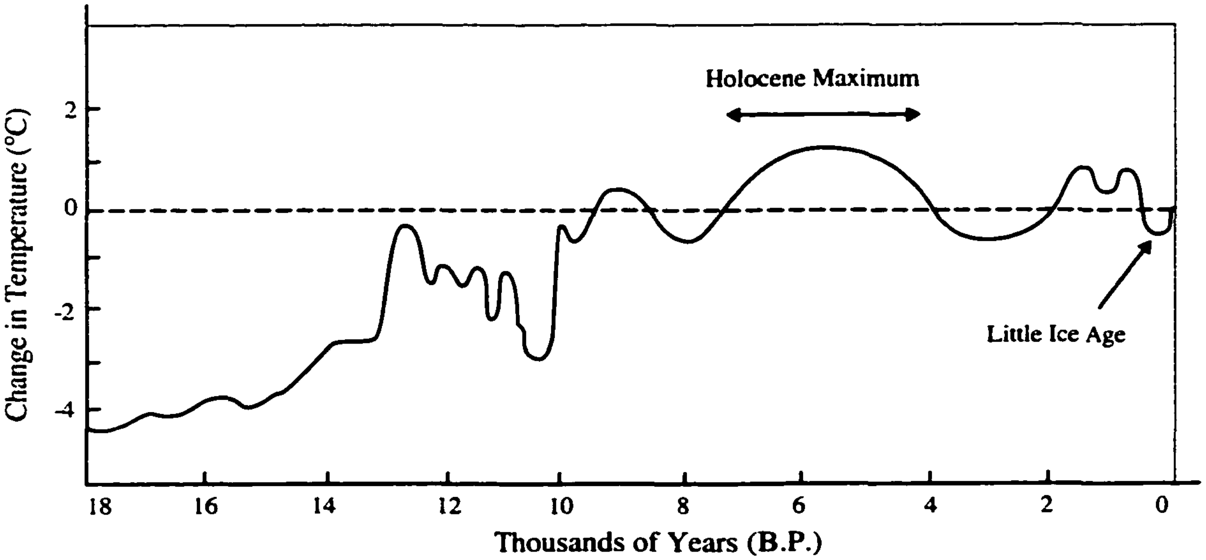


Figure 4-3: Air temperature near Antarctica for the last 150,000 years (inferred from hydrogen/deuterium ratios in an ice core)



Source: Thomas J. Crowley (1996). Compiled by R. S. Bradley and J. A. Eddy (1991) based on J. Jouzel et al., Nature vol. 329: 403-408, 1987.

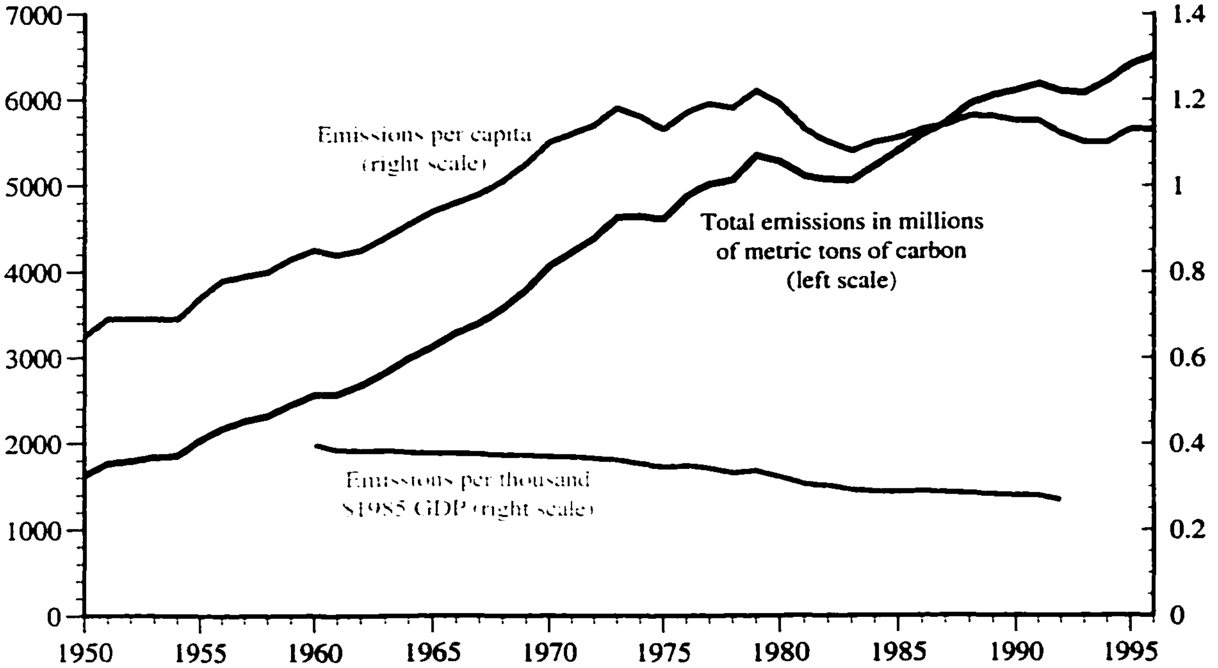
The accumulation of CO_2 in the atmosphere at projected levels of concentration is not in-and-of itself dangerous to human health or survival. This makes CO_2 emission a very different type of air pollution problem than, for example, sulfurous or nitrous oxides. The spillover costs associated with the latter pollutants arise from the *flow* of current emissions. In the case of CO_2, spillover costs arise from the gradual accumulation of emissions, or *stock*, in the atmosphere. If emissions had no effect on concentrations – because, for example, they were immediately absorbed in sinks such as increased vegetation – there would be no greenhouse gas issue. The real policy target, therefore, should be to stop the rise in CO_2 *concentrations* in the atmosphere. Therefore, unlike most other types of air pollution, control of CO_2 emissions in the future is a close substitute for control today (an issue we will explore more fully in Chapter 5).

Forecasting Emissions Growth

Aside from whether increased CO_2 stocks are harmful or beneficial on net, there is substantial uncertainty about the size of any increase in greenhouse gas emissions over the next century. Figure 4-4 shows that global per capita emissions of CO_2 have been relatively stable for 20 years while the emission intensity of overall economic production has been falling. Whether the stability in per capita emissions will persist is unclear.

The falling ratio of emissions to GDP reflects, in part, the increasing proportion of services, and decreasing proportion of manufacturing, in the production (and consumption) of developed economies (see Chapter 2). The falling ratio of emissions to GDP also reflects responses to higher prices for fossil fuels (particularly after tax). Higher energy prices directly discourage energy use in the short term, for example, by decreasing driving. There is considerable evidence that rapid changes in energy prices may also temporarily reduce energy demand by disrupting the economy at the macroeconomic level.[9]

Figure 4-4: Global CO_2 emissions from industrial processes



Sources: The Carbon Dioxide Information Analysis Center (*http://cdiac.esd.ornl.gov/*) and the Penn World Tables (*http://www.nber.org/*).

In the longer term, however, the effects of higher energy prices on economic growth are unclear because efficiency gains can offset price increases (see Chapter 3 for a discussion in the context of motor fuel demand). For example, following the oil price shocks of the 1970's, US average automobile fuel efficiency increased from 13 miles per gallon in 1977 to 21 miles per gallon in 1995. Furthermore, there is also a reasonable expectation that major advances in alternative energy technologies will occur in the relevant time frame. Already, newer technologies are showing promise to reduce

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[9] See, for example, Hamilton (1981) or Ferderer (1996).

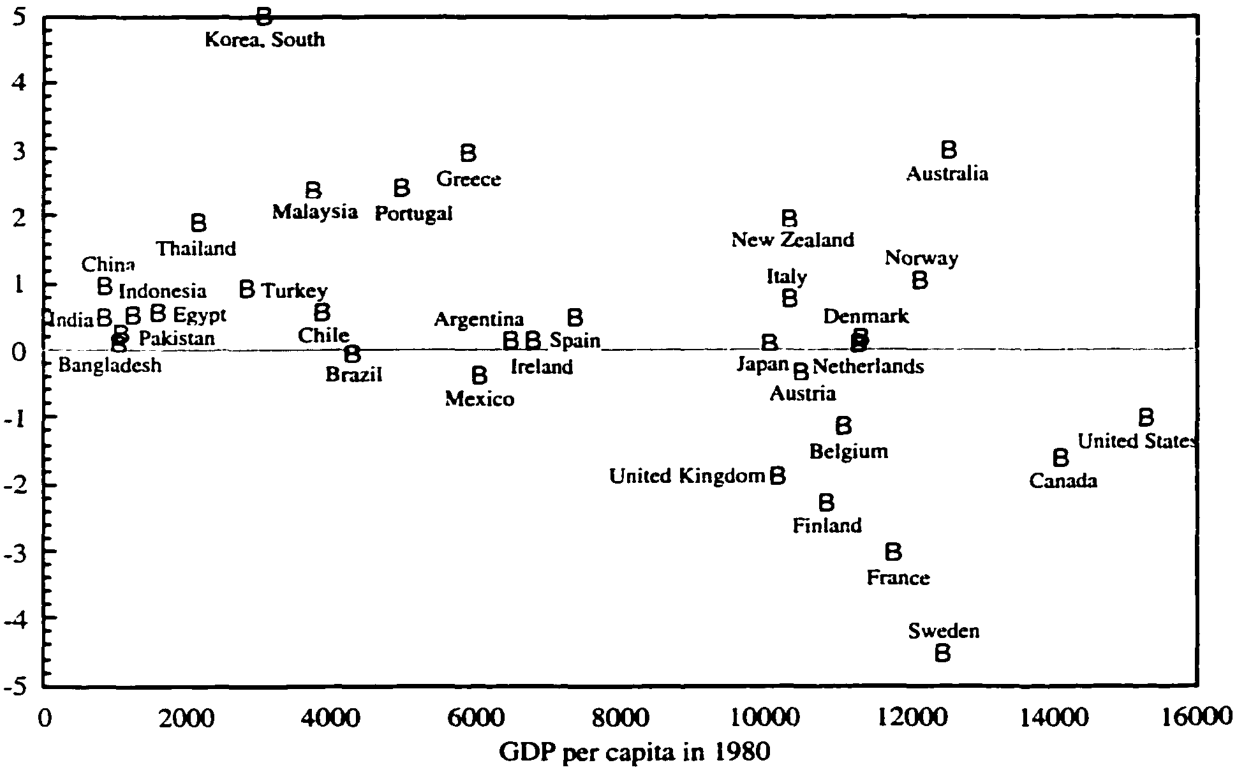
emission output. For example, gas-electric hybrid technologies can substantially reduce fossil fuel requirements for transportation, and fuel cell and solar technologies can virtually eliminate fossil fuel consumption in all sectors of the economy.

The conversion of the economies in the former Soviet Union and Eastern Europe from centrally-planned to market-oriented is also likely to provide a short-term reduction in the ratio of global emissions to global GDP. Managers in these countries previously were not concerned with energy efficiency, resulting in an extremely high energy intensity of production. In response to new market pressures, however, they are likely to improve management practices and adopt more energy-efficient technologies.

There are, however, extremely powerful forces that will tend to raise the ratio of CO_2 emissions to GDP for the world as a whole. Developing countries, such as India and China, are turning toward the export of low-cost manufactured goods as a basis for development, in some cases attracting industries away from the developed countries. On the one hand, since the technologies and mix of fuels currently used in the developing countries tend to produce more emissions per unit of output, a shift of manufacturing to these countries could increase world per capita emissions of CO_2. On the other hand, new manufacturing plants could incorporate advances in energy efficiency (which correlates strongly with emission-intensity), contributing to the trend of declining emissions per unit of world GDP (see Figure 4-4).

Improved standards of living within the developing economies are another major potential contributor to increased CO_2 emissions per capita. Higher incomes lead to increased demand for energy in all end-use sectors. Furthermore, new transportation infrastructure, made possible by economic development, facilitates increased commercial and personal use of transportation services.

Figure 4-5: Change in CO_2 emissions per capita 1980–1995 (metric tons of CO_2)



Sources: Calculations by the authors based on data from the US Energy Information Agency, World Bank Development Indicators and the Penn World Tables.

In summary, the roughly constant ratio of emissions to population from 1973-1997 (Figure 4-4) may be the result of a delicate balance of offsetting factors. Population growth has been higher in countries with a lower level of per capita emissions. This alone would tend to reduce the ratio of worldwide emissions to world population, especially in countries where growth rates have been negative or zero. In most developing countries, however, emissions per capita have increased. In addition, many developed nations have experienced significant reductions in emissions per capita (see Figure 4-5).

Table 4-1: CO_2 Emissions from Industrial Processes (1992)

	Total		Population		Per capita	
	million tons	*% world*	*millions*	*% world*	*tons*	*% world*
USA	4,881.35	21.9	255.2	4.7	19.13	466.6
China	2,667.98	11.9	1,175.3	21.6	2.27	55.4
India	769.44	3.4	874.4	16.0	0.88	21.5
Indonesia	184.59	0.8	194.3	3.6	0.95	23.2
Brazil	217.07	1.0	156.2	2.9	1.39	33.9
Sub-total	3,839.08	17.2	2,400.2	44.1	1.60	39.0
World	22,339.41	100.0	5,448.6	100.0	4.10	100.0

Source: World Resources Institute. Note that these figures are metric tons of *carbon dioxide* while Figure 4-6 focuses on metric tons of *carbon*. To convert from metric tons of carbon to metric tons of carbon dioxide multiply by 3.667 (the ratio of the molecular weight of CO_2 to the atomic weight of carbon).

Since some countries with large populations are beginning to experience faster economic growth, the constant ratio of CO_2 emissions to population may not persist. For example, by 1992, China was already emitting 55% of the US level of CO_2 emissions from industrial processes (Table 4-1). The Australian Bureau of Agricultural and Resource Economics (ABARE) projects that annual average growth of CO_2 emissions for the period 1990-2010 will exceed 5% for the developing world compared to under 1% for the developed world.[10]

Table 4-2: Population in selected countries

	1996		2010		Growth
	millions	*% world*	*millions*	*% world*	*% pa*
USA	265	4.6	294	4.3	0.7
China	1,215	21.1	1,349	19.9	0.7
India	945	16.4	1,129	16.6	1.3
Indonesia	197	3.4	236	3.5	1.3
Brazil	161	2.8	190	2.8	1.2
World	5,755	100.0	6,788	100.0	1.2

Source: World Development Indicators 1998, World Bank

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[10] Tulpule et al, (1998a). p 11 available at *http://www.abare.gov.au/pubcat/climchang.htm.*

The other major variable relevant to predicting energy consumption and, thus greenhouse gas emissions, is population. Table 4-2 provides 1996 populations, and UN projections for population growth, in these same countries. We have used the figures in the final column of Table 4-2 for our projected population growth rates.

Using the results from the forecasting exercise in Chapter 2, along with UN and other projections of economic and population growth, we develop our own forecasts of the growth in emissions from the developing countries which are the four largest in terms of population – China, India, Indonesia and Brazil. In our projections, we have taken the likely GDP per capita growth rates to be the same as those used in generating the results in Table 2-3 – 4.8% in China, 3.0% in India, 4.7% in Indonesia, and 1.0% in Brazil.

Table 4-3: Projected emission levels to 2010 of four developing countries

		CO_2 emissions in millions of metric tons of carbon by sector					Per capita *metric tons of CO_2*
Country	Year	Residential/ Commercial	Transport	Industrial and Other	Total	Primary Requirement	
China	1995	131.80	38.61	477.19	647.60	675.06	2.06
	2010	550.81	115.0	974.29	1640.9	1709.1	4.70
India	1995	15.77	28.42	77.35	121.55	227.43	0.90
	2010	47.01	61.05	159.54	267.60	446.63	1.45
Indonesia	1995	9.52	12.86	15.95	38.32	61.18	1.16
	2010	30.67	33.20	36.28	100.15	159.79	2.48
Brazil	1995	4.27	25.71	27.25	57.23	64.93	1.50
	2010	7.48	38.18	35.69	81.35	95.88	1.85

The projections to 2010, using the model in Chapter 2, are presented in Table 4-3. An assumption underlying these calculations is that the fuel mix in each sector remains the same over the next decade or so. This enabled us to translate projected energy consumption figures into output of CO_2. There are major uncertainties in making projections such as those outlined in Table 4-3. The continuing economic progress of

China, for example, is not as inevitable as it is often made out to be. There are many tensions which could see the current Chinese state suffer a major political and economic crisis – the contradictions between market modernization and long-term authoritarian rule, the major disparities in economic progress between regions, the inherent difficulty of departing sufficiently from the patterns of Chinese history to sustain modernization. Projecting the future is an inherently difficult exercise. One needs only to consider how unpredictable the global economic and political patterns of 1998 were in 1968 to understand that the global situation in 2028 is similarly opaque.

As China, India, Indonesia and Brazil develop economically it is reasonable to expect, however, that their per capita emissions of CO_2 will rise. Table 4-1 shows that per capita emissions in China, India, Indonesia and Brazil in 1992 were on the order of 5–10% of the per capita emissions in the US and substantially below the world average. Using the projections in Table 4-3, growth in per capita emissions in these countries will have a dramatic effect on global greenhouse gas emissions due to massive populations. Each of these countries, therefore, is a necessary part of any effective regime for controlling emissions of greenhouse gases.

The Economics and Politics of Controlling CO_2 Concentrations

In order to understand the international relations dimensions of the greenhouse gas issue, it is important to recall that concentrations, not emissions, are the source of the externality. Current concentrations of greenhouse gases in the atmosphere are the result of past emissions. The developed countries, who currently emit about 60 to 70%[11] of

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[11] Heyhoe, E. et al (1998) available at *http://www.abare.gov.au/pubcat/climchang.htm.*

total annual anthropogenic CO_2 emissions, also are responsible for the majority of past anthropogenic emissions (about 80% of human contribution to current concentrations[12]).

The Framework Convention on Climate Change was opened for signing at the June 1992 'Earth Summit' held at Rio de Janiero. The Convention divides the world into so-called 'Annex I' countries, who have direct obligations under the Convention to mitigate their emission of greenhouse gases, and the developing world, who do not. This division of the world into Annex I countries and others, recognizes differing national priorities and capacity to pay. As noted above, however, CO_2 emissions are growing much faster in developing, than in developed, countries. Given current trends, emissions by the developing world will exceed those of the Annex I countries at some point during the first half of the 21st century. (Current UN projections are for that to take place by 2035[13] while ABARE projections assume equality of emissions by 2010.[14]) If the developed world takes any effective action to reduce emissions, this process will speed up.

The fact that anthropogenic emissions from developing countries come to equal, and then exceed, those from the developed countries does not undermine the argument that the developed world should bear the brunt of the cost of control. It simply increases the importance, for any effective regime, of gaining developing world participation.

If we want to stop the rise in greenhouse gas *concentrations*, then anthropogenic global *emissions* cannot exceed 40% of their 1996 levels (6.518 billion tons of carbon),[15]

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[12] *New Scientist* 'Editorial', 29 November 1997; *New Scientist*, 'Buenos Aires Daily Diary' 6 November 1998.

[13] United Nations (1999), *Setting the Record Straight: Global Climate Change.*

[14] Tulpulé et al (1998a) available at *http://www.abare.gov.au/pubcat/climchang.htm.*

[15] The Carbon Dioxide Information Analysis Center, http://cdiac.esd.ornl.gov/ftp/ndp030/global96.ems.

which amounts to 2.6 billion tons of carbon.[16] This implies an emissions reduction on the order of *ten times* the level of emission cuts agreed to at Kyoto. Suppose we assume continuation of the past trend toward declining carbon-intensity of production and relatively stable per-capita emissions in the face of continuing economic growth. Annual per capita emissions from industrial processes would remain at 4.1 tons of CO_2 (see Table 4-1 above). If the global population increases as indicated in Table 4-2, in 2010 it would be 6.788 billion, and annual emissions from industrial processes would be 27.83 billion tons of CO_2, which amounts to 7.6 billion tons of carbon. The annual emission reductions required in 2010 to stabilize the atmospheric concentration of CO_2 would then be about 5 billion tons of carbon.

Our own forecasts of emissions presented above can be used to derive an alternative estimate of annual emissions in 2010. The increased per capita emissions in China, India, Indonesia and Brazil as calculated in Table 4-3 imply that these four countries would produce 2.4 billion tons of carbon annually in 2010. Suppose we continue to assume that per capita emissions elsewhere in the world remain constant at their 1992 level of 6.07 tons of CO_2 (calculated from Table 4-1 above). Total emissions from the rest of the world in 2010 would then be 23.57 billion tons of CO_2, which amounts to 6.4 billion tons of carbon. The annual *world* total would then be 8.8 rather than 7.6 billion tons of carbon. The annual emission reductions required in 2010 to stabilize the atmospheric concentration of CO_2 would then be about 6.2 billion tons of carbon.

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[16] Tucker (1998), available at *http://www.arts.monash.edu.au/ausapec/imppaps.htm*. The implicit assumption is that some emissions are re-absorbed through natural processes – particularly by the oceans and in increased vegetation growth – so that emissions do not need to be cut 100% to prevent an increase in ambient concentration levels.

The cost per ton of reducing emissions has been estimated in many papers. A recent paper (October, 1998) by the Energy Information Administration (EIA, US Department of Energy) summarized the costs of meeting the Kyoto controls for the United States that have been calculated using a number of models. Specifically, the EIA examined results obtained from a number of general equilibrium models of the US economy. Each of the models was used to predict the effects of reductions in emissions to 7% below 1990 levels "without the benefit of sinks, offsets, international carbon permit trading, or the Clean Development Mechanism". The projected price in 2010, measured in $US1996 per metric ton of carbon, ranged from $221 on the low side to $265, $266, $280 and $295 in the middle, with the EIA's own estimate being the highest at $348. The agency researchers noted a number of features of the models that explained these differences. These essentially amounted to different judgements about the most likely values for various parameters that cannot be estimated accurately.

Similarly, a recent ABARE study (Tulpulé et. al. 1998b) examined the costs of meeting the Kyoto targets using a global trading and environment model. Their results for 2010 in $US1992 are presented in Table 4-4 (where 'Annex B' refers to the countries entering into emission control obligations if Kyoto is ratified).

The costs in Table 4-4 (or forecasts of permit prices if trading were to be allowed) should be interpreted as *marginal* costs. The *average* costs of control for emission cuts of the size agreed to at Kyoto are likely to be less than this since the least costly control methods would be used first. The lower costs in column two of Table 4-4 reflect the fact that trading emission quota among countries allows the largest reductions to be made in those countries where controls are least costly.

Table 4-4: Projected price of emissions/metric ton of carbon 2010 ($US1992)

	Independent abatement	Full trading in Annex B	Double bubble
United States	346	114	108
Canada	835	114	108
Japan	693	114	108
Australia	455	114	108
New Zealand	396	114	108
European Union	714	114	176
Former Soviet Union	0	114	108
Eastern Europe	40	114	176

Source: Tulpulé et. al. 1998b, Table 6, p15. The 'double bubble' involves emissions trading within Europe on the one hand and the rest of the developed world on the other hand.

The magnitude of emission reductions needed to stabilize the accumulation of CO_2 in the atmosphere would impose marginal and average costs far above the amounts in Table 4-4. The differences between the marginal cost figures in different columns of Table 4-4 reflect the higher costs of increasing the size of emission reductions in each country. The larger reductions that, for example, Canada would have to make to meet the Kyoto total without emissions trading are insignificant relative to the reductions that would be needed to stabilize the accumulation of CO_2 in the atmosphere.

In reality, there is substantial uncertainty about the cost of achieving the level of emission reduction required to significantly retard the accumulation of CO_2 in the atmosphere. The cost would depend greatly on many factors, each of which is very difficult to forecast. These factors include:

- the link between emissions and CO_2 accumulation;
- future population and economic growth;
- the nature of the control regime, including the possibilities for trading quota;
- incentives the regime generates for the development of new technologies;
- technological developments that are independent of the control regime;

- elasticities of substitution between energy and other inputs; and
- changes in the mix of industries and the location and age of industrial plants.

Suppose we take $US150 per metric ton of carbon (1996 prices) as an *extremely* conservative estimate of the average cost in 2010 of emission reductions needed to significantly retard the accumulation of CO_2 in the atmosphere. The annual cost of reductions needed in 2010 to stabilize greenhouse concentrations, therefore, would be at least $US750 billion under the assumption of constant world per capita emissions, and close to $US930 billion under the alternative estimates of emissions growth in Table 4-3. This is about 3.0% of current world GDP, and is of the same order of magnitude as the current GDP of China or Brazil, and more than the combined GDP of India and Indonesia. Calculations using the same models that predict global warming suggest that full implementation of the Kyoto Protocol will decrease average world temperatures by about 0.07°C[17] to 0.2°C[18] – a difference so small that it could not be reliably detected by ground-based thermometers.[19] The cost of reduction, therefore, is inordinately high for such a small decrease in temperatures. To contemplate costs of such magnitude, it must be that significant global warming is occurring and that it will be highly damaging.

As we noted above, unlike most other types of air pollution, the *flow* of emissions is not the problem. Rather, the potential problem arises only from the long-term accumulation of CO_2 in the atmosphere. Reduced emissions in the future are a substitute for reduced emissions today, and the earlier the implementation of controls, the higher the costs. 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

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[17] Wigley, (1998), quoted in Michaels (1998).
[18] Davis and Legates (June 1998).

resources will be available to compensate for the losses (given the continuing tendency of wealth to increase over time).[20]

There is no precedent for countries agreeing to incur costs of the order of magnitude required to stabilize CO_2 concentrations, let alone for actually following through with the implementation. To be sure, governments regularly impose costs on their societies in one form or another. Imposing costs to combat global warming, however, has no precedent for implementation.

National Priorities

What are the ongoing national priorities for the four most populous non-Annex I nations (China, India, Indonesia and Brazil)? Table 4-5 sets out some selected development indicators for those four nations, with the equivalent figures for the United States for comparison.

Table 4-5: Selected Development Indicators

	Life Expectancy at birth (1996)				Calories available (1988-90)	Child malnutrition (1995-96)	Child illiteracy rate, 15+ (1995)		Per capita GDP (1996 PPP)	
	Male		Female				Male	Female		
	years	*% US*	*years*	*% US*	*% need*	*% under 5*	*%*	*%*	*$US*	*% US*
USA	74	100	80	100	138				28,020	100
China	68	92	71	89	112	7	10	27	3,330	12
India	62	84	63	79	101	16	35	62	1,580	6
Indonesia	63	85	67	84	121	60	10	22	3,310	12
Brazil	63	85	71	89	114	40	17	17	6,340	23
World	65	88	69	86	n.a.	n.a.	21	38	6,200	22

Source: World Development Indicators, 1998, World Bank
World Resources 1996-97, World Resources Institute

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[19] Michaels (1998), Davis and Legates (June 1998).

[20] We address these issues in Chapter 5.

Current life expectancies in these developing nations range between 6-12 years lower for males and 9-17 years lower for females than the US. While, on average, an adequate number of calories are available, this was marginal for India at the beginning of the decade. Malnutrition remains a problem in all four countries, but particularly India. Talk of a possible mortality cost from global warming must be weighed against the mortality cost of lower economic growth. These costs most likely would be concentrated in the developing world, though action to reduce emissions could result in significant mortality costs even in developed societies.[21]

Illiteracy is still high in India and still a major issue, particularly for women, in all four countries. Even on a purchasing power parity basis, the level of resources available to tackle these basic problems is low. Brazil, the most prosperous of the four, has a per capita GDP less than a quarter of that of the US, China and Indonesia less than an eighth and India less than a seventeenth of the US.

Economic growth matters. The more resources that are available, the easier it is to achieve better outcomes. There is, for example, a vast difference between spending $US375 per person per year on health (US), compared to $US12 (China), $US9 (India), $US7 (Indonesia) and $US27 (Brazil).[22] Admittedly, countries with similar levels of GDP can have quite different life expectancies — Mozambique and Ethiopia have similar per capita GDP (the two lowest recorded by the World Bank), yet their average life

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[21] Cross (1998).
[22] Estimates made from data from WRI and World Bank 1998.

expectancies are very different (44 years for Mozambique, 67 for Ethiopia).[23] Nevertheless, life expectancy is positively correlated to per capita GDP.[24]

Development, in its broadest sense, has to be a priority for countries such as China, India, Indonesia and Brazil. Policies that impede economic growth generally can be expected to affect more than material standards of living. The benefits of such policies, therefore, need to be commensurate with the sacrifice made. While developing countries no doubt fear lost economic growth as the major cost of climate change policy, it is not the only potential cost. Within the realm of environmental policy, environmental problems that are blighting lives and killing people in the present loom much larger current flows of CO_2.

Resources devoted to reducing emissions of greenhouse gases could instead be applied to ameliorating other types of air or water pollution. In Figure 4-5, we have presented data for suspended particulates in a number of major cities in both the developed and developing countries. Major cities in the developing world typically suffer much worse air pollution than cities of comparable size in the developed world. This is not surprising when one considers the stage of development. Air pollution in US cities in the early 1900's was probably very similar to what is seen in major cities in the developing world today, as the industrialization process is highly energy (carbon) intensive (see Chapter 2). A recent report by Wood Mackenzie Global Consultants (1999) notes that 17% of deaths in China are from respiratory disease compared to 7% in the US.

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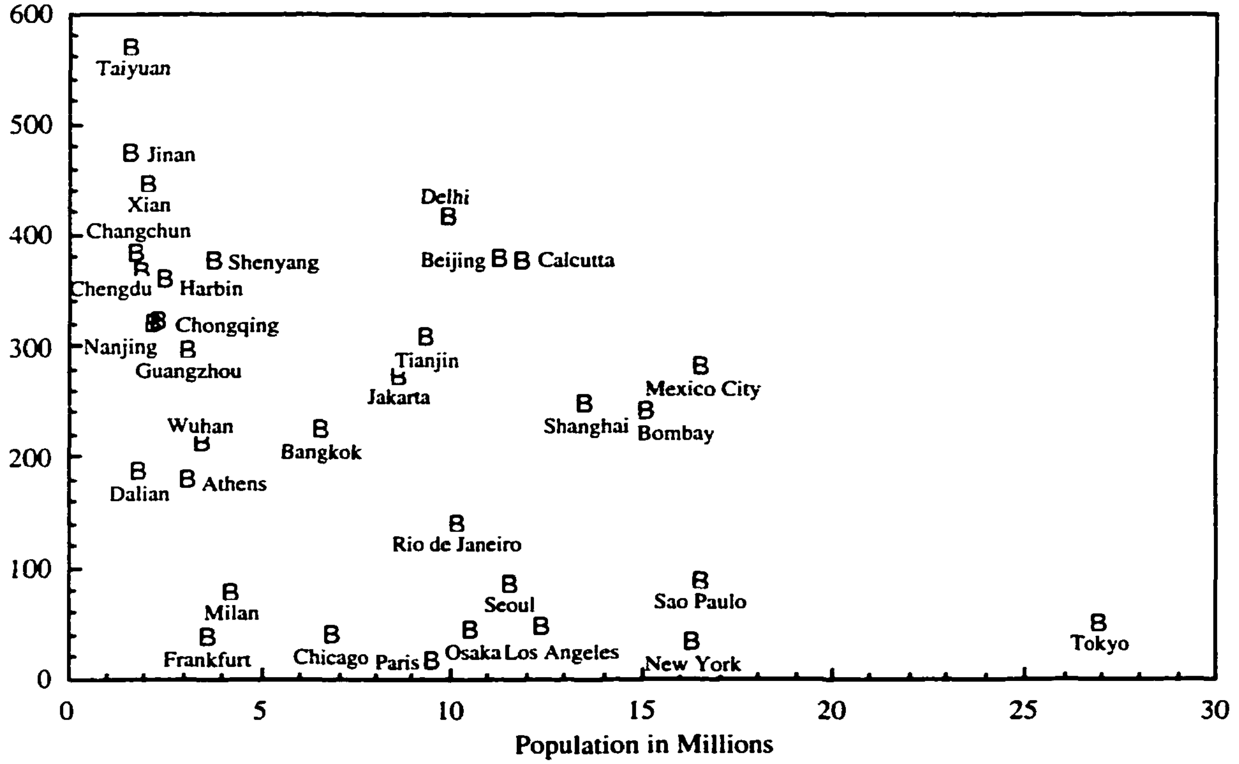
[23] World Bank 1998, (male life expectancy).

[24] The correlation between male life expectancy and per capita GDP (purchasing power parity basis) for 132 countries from the World Bank *World Development Report 1998* is 0.62.

Figure 4-6: Suspended particulates (micrograms/m^3) for selected metropolitan areas



Sources: For cities outside the US, data is for 1995 and from World Bank World Development Indicators 1998; for the US, data is for 1997 and from the Environmental Protection Agency (http://www.epa.gov/).

Many developing countries also suffer from substantial water pollution (see Table 4-6 below). The generally inadequate water supplies and sewage treatment facilities in the burgeoning cities of Asia and Latin America constitute a major health hazard. Less directly destructive, but nonetheless serious, are questions of deforestation and other ecological pressures. Scarcity of resources dictates giving priority to the most urgent environmental issues first.

While efforts are being made to deal with air and water pollution in the developing world, the results are far from satisfactory.[25] Environmental goals have to be weighed against other national goals, including the goal of higher economic growth. This is not merely a matter of 'consumer aspirations', powerful though these can be. Issues such as life expectancies, education, health care and quality of life for current and future generations are at stake.

Table 4-6: Emissions of Organic Water Pollutants (1993)

Country	Kilograms per day	Kilograms per day per worker
USA	2,477,830	0.15
China	5,339,072	0.15
India	1,441,293	0.20
Indonesia	537,142	0.19
Brazil	855,432	0.17

Source: World Bank World Development Indicators, 1998.

The radically different situation of developing countries is explicitly acknowledged in the FCCC, not merely in the division into Annex I and non-Annex I nations, but in wording such as the following extracts from the Preamble:

> **Noting** that ... per capita emissions in developing countries are still relatively low and that the share of global emissions originating in developing countries will grow as they experience economic growth to meet their social and development needs....
> **Recognizing** that States should enact effective environmental legislation, that environmental standards, management objectives and priorities should reflect the environmental and developmental context to which they apply, and that standards applied by some countries may be inappropriate and of unwarranted economic and social cost to other countries, in particular developing countries...
> **Recognizing** the special difficulties of those countries, particularly developing countries, whose economies are particularly dependent on fossil fuel production, use and exportation, as a consequence of action taken on limiting greenhouse gas emissions...
> **Recognizing** that all countries, especially developing countries, need access to resources required to achieve sustainable social and economic development and that, in order for developing countries to progress towards that goal, their energy consumption will need to grow...

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[25] For an informative discussion of the environmental problems confronting developing nations, see Brandon and Ramankutty (1993).

Western and, increasingly, East Asian experience has shown developing nations that higher living standards are attainable. The developed world's present is the developing world's future. Indeed, the World Bank rates three formerly less developed East Asian societies — Singapore, Hong Kong and Japan — amongst the top five richest on a per capita purchasing power parity GDP basis (see Table 4-7).

Table 4-7: Five Richest Countries by per capita GDP (1996)

	Per capita GDP *PPP*		Life expectancy at birth	
	$US	*Ratio to world avg.*	*Male*	*Female*
USA	28,020	4.5	74	80
Singapore	26,910	4.3	74	79
Switzerland	26,340	4.2	75	82
Hong Kong	24,260	3.9	76	81
Japan	23,420	3.8	77	83

Source: World Development Indicators 1998, World Bank

A key element in raising standards of living is increasing use of energy. Despite the decreasing energy intensity of production, high standards of living require high energy use (see Chapter 2). A reasonable doubt, however, is whether the world has sufficient energy resources to sustain future growth of past proportions. Current 'economically recoverable' reserves of coal, natural gas, and crude oil are enormous. Furthermore, there are extremely large reserves (including oil shale) available at higher recovery costs. The shear magnitudes of these figures, and the fact that huge oil fields continue to be discovered — most recently in Baku and in deep water in the Gulf of Mexico — indicate that fossil fuels can provide energy for economic development well into the future. Simply stated, these resources will be used until cheaper forms of energy abound.[26]

Technological progress in solar cell, fuel cell, nuclear and perhaps other, as yet unknown, technologies is likely to result in fossil fuels being replaced in most energy uses sometime in the next century. While the prospect over the next three decades may be for increased CO_2 emissions from the burning of fossil fuels, there is also a reasonable expectation that emissions could decline dramatically in the latter half of the next century. Until then, developing countries in Asia and elsewhere will not explicitly forgo the aspirations of development by limiting their use of, or increasing the domestic cost of, fossil fuel energy sources.

Indeed, developing countries have a positive incentive not to participate in any serious greenhouse gas control regime. They can seek to benefit from the relocation of carbon-intensive industries as developed countries raise the cost of such activities. The US Senate is certainly aware of the possibility of a transfer of industries, as the recent 'Byrd-Hagel' resolution passed 97-0 by the US Senate indicates (Appendix H).

'Carbon leakage' — the transfer of carbon-emissions by displacement of industries from countries undertaking serious abatement action to those not undertaking such action — is not a mere theoretical possibility. The first 'Oil Shock', which greatly increased the price of electricity in Japan, resulted in the transfer of aluminum smelting from Japan to Australia.[27] Even an industry such as aluminum smelting, which is reliant

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[26] Recent world prices for oil – in real terms considerably below those after the 1973 'Oil Shock' – suggest falling scarcity, relative to demand, of fossil fuels. At about $US12, or even $US20 a barrel, oil prices contrast markedly with projections – made during the previous energy hysteria of the 'Energy Crisis' of 1973-74 – that oil would reach prices of $US100 a barrel – more if we adjust for inflation – by the end of the century (Mills 1998).

[27] Presentation by Dr Vivek Tulpulé, Royal Society of Victoria Symposium, 21 October 1997.

on investment in immobile capital, has proved to be mobile in a relatively short time period given a sufficiently unfavorable shift in energy prices. Economic models have produced estimates of 'carbon leakage' ranging from 0 to 70% (ABARE estimates are in the range of 6 to 18% depending on whether emission trading occurs).[28]

Refusing to participate in a global greenhouse gas control regime, therefore, has a double benefit to developing countries. They do not bear the costs of cutting their own anthropogenic greenhouse gas emissions, and they can increase their own rate of economic development by the transfer of manufacturing from countries participating in the greenhouse gas control regime. (They may nevertheless oppose the policy since they would expect to suffer negative trade effects from reduced economic activity in the developed world.)

Any effective global greenhouse gas regime must confront the very powerful reasons developing countries have for not expending significant amounts of their own resources in such an effort. Mere preaching from the developed world — responsible, according to most estimates, for about 80% of the human contribution to current greenhouse gas concentrations — will not change this, as has been eloquently expressed in another context:

> Social forces have been set in motion that will not be contained ... Electricity, telephones, running water — once humans experience these things, they want more of them ... It is easy for outsiders to warn against the long-term costs of damming Africa's rivers, ruining its scenery, or destroying its woodlands, but it is akin to a glutton admonishing a beggar on the evils of carbohydrates — he lacks a certain moral authority.[29]

Leaders of developing countries can hardly be expected to be *more* willing than the US Senate to countenance significant costs for the people they govern. It is

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[28] Tulpulé, et al (1998b).

unreasonable to expect the citizens of developing countries to accept a policy that permanently relegates them to the status of 'second class global citizens' by denying them the chance to achieve developed world income levels.

Concluding Remarks

Any effective regime for reducing the stock of CO_2 in the atmosphere has to include developing countries. Those countries are likely to produce a rapidly growing share of world greenhouse gas emissions in coming decades. If developing countries are excluded from emission controls, many energy intensive industries will simply migrate from the developed to the developing world and possibly increase CO_2 emissions per unit of world GDP. Developing countries will not agree to control greenhouse gas emissions, however, unless the costs are low enough to be acceptable given the seriousness and urgency of the other problems such countries face.

The inescapable conclusion is that effective controls over emissions will only be implemented at enormous cost to the taxpayers of the developed countries.[30] There is a (partial) precedent for this. The 1987 Montreal Protocol on controlling emissions of CFCs has seen significant costs incurred by the US in particular. The US is the major jurisdiction effectively enforcing the ban on ozone-depleting substances. It is also the major country making compensatory contributions of assistance to developing countries to forgo use of CFCs and other chemicals to be phased out under the protocol.[31] But CFCs are far less central to economic processes than greenhouse gases, and the costs

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[29] Mark Hertsgaard, *Earth Odyssey* quoted in the *Australian Financial Review*, January 22 1999, Review 6.

[30] Note that the mechanism by which any such payments and transfers might be made is not part of the ambit of this paper. There may also be serious doubts about whether *any* type of compensation could lead developing nations to forgo the burning of more fossil fuel in the coming decades.

involved are far lower.[32] Compensating the developing world to accept substantially lower rates of economic growth will require an extraordinary level of resource transfer – greater than or equal to the current GDP of major developing nations.

There is a possibility for ulterior motives. The proposed policies of the Kyoto Protocol may serve a hidden agenda. Western European governments may be attempting to protect their heavy dependence on fossil fuels as a tax base. Without higher energy taxes elsewhere (particularly the US), competition from countries with lower energy costs might eventually force the Europeans to reduce their own taxes on energy use.

The attempt to control greenhouse gas emissions, though it may be sincere, will likely fail. It will be subverted by the aspirations of the developing world to turn the developed world's present into their own future. Such an outcome might represent a gain to the developing world at the expense of the developed world. There may also be a net loss overall, however, since economic growth in the developing world relies largely on access to the markets of the developed world. In any case, emissions reduction treaties such as the Kyoto Protocol are virtually useless because they address neither the potential for "carbon leakage" nor the propensity for an increasing proportion of emissions to come from the developing countries.

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[31] Lieberman (1998).

[32] CFCs are also, incidentally, manufactured at far fewer places and are far easier to detect than CO_2 and therefore are much easier to include in a formal treaty or protocol aimed at controlling emissions.

CHAPTER 5

The Urgency of Controlling Carbon Dioxide Emissions*

Some scientists have expressed concerns that increases in the concentration of carbon dioxide (CO_2) in the atmosphere over the next century will raise average global temperatures and substantially reduce human welfare. Compared to other air pollutants, CO_2 is unusual in so far as the potential externality is associated with the stock of CO_2 in the atmosphere rather than the flow of emissions. As a result, future control of emissions is a better substitute for current control than is the case for other air pollutants. In addition, technological change in the energy sector of the economy could significantly affect the path of CO_2 emissions over the next century. In this chapter, we develop a simple model to assess the influence of these and other critical factors on the urgency of controlling CO_2 emissions.

There is substantial uncertainty about the net costs of an accumulation of CO_2 in the atmosphere. For example, a potential benefit of emitting CO_2 into the atmosphere is that it could substantially enhance plant growth, increasing the productivity of agriculture and expanding the biosphere. The costs of reducing the emissions, or enhancing the absorption, of CO_2 are also difficult to calculate.

The benefits of controlling emissions today depend upon the likely future path of emissions, which are very difficult to forecast. Although industrialized nations account for the majority of past and current CO_2 emissions, growth projections indicate that the

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* This chapter is taken from the paper of the same title, co-authored by Peter Hartley.

emissions from developing nations will surpass those of industrialized nations in the next decade or so (see Chapter 4). Since energy intensity increases as economies begin to grow rapidly, assuming a constant ratio of emissions to GDP is likely to understate global emissions in the short term. In the long term, however, the energy intensity of production is likely to decline not only as a result of technical change but also as services become a larger part of total consumption (see Chapter 2). Using a panel of 141 countries covering a period of 40 years, Schmalensee, Stoker and Judson (1998), for example, find that CO_2 emissions exhibit an "inverted U-shape" over the course of development.

An issue that is closely related to the one we consider is whether "global warming" imposes limits on economic growth. Stokey (1998) analyzed the consequences for economic growth of instituting pollution regulations to internalize environmental costs. She found, under certain conditions, that technology can sustain perpetual economic growth even with emissions restrictions. Our premise is that technological advances ultimately will allow energy requirements to be met while emissions are kept to very low levels. For example, at current rates of innovation, fuel cells, methanol or electricity may provide much of the energy needed in the transport sector by the middle of the century. Similarly, advances in solar cell and transmission technology may allow a substantial fraction of electricity to be generated from solar power. These technologies can dramatically reduce the environmental costs of increased energy use.

Unlike pollutants such as sulfur or nitrous oxides the possible externalities associated with CO_2 depend on the stock of CO_2 in the atmosphere rather the current flow of emissions. So, future control of emissions substitutes for current control. The costs of imposing controls on energy production or use are, however, likely to be much higher in the short run than in the long run. Large price increases over a short time period would make substantial amounts of otherwise usable capital obsolete. Furthermore, time discounting reduces the present value of future controls, while higher future GDP reduces consequences for human welfare of a given sacrifice of resources.

The Global Warming Issue - Revisited[1]

The burning of fossil fuel, which is intimately linked to economic activity, is a major source of CO_2 emissions. Since 1958, the concentration of CO_2 in the atmosphere has risen about 14% to a level 30% above pre-industrial levels and the Intergovernmental Panel on Climate Change (IPCC) has estimated that this will rise another 48% by 2100. While this is a large increase in CO_2 accumulation, the likely consequences for temperatures, sea levels or extreme weather events is unclear. The uncertainty begins with the fact that CO_2 is not directly responsible for much of the predicted temperature increases. Rather, increases in CO_2 are projected to trigger increases in water vapor, which is far more effective at absorbing infrared radiation. Increased water vapor in the atmosphere has other effects, however, such as increasing cloud cover and precipitation.

Increased CO_2 concentrations, and the associated predicted changes in precipitation and temperatures, are also likely to increase plant growth, which would tend to increase the rate of re-absorption of CO_2 from the atmosphere. Moreover, predicted changes in weather cycles may increase the oceanic absorption of CO_2.[2] The

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[1] See Chapter 4 for a more in depth discussion of this issue.

[2] A prediction of some global climate models is that warming will produce more violent weather systems in the tropics and sub-tropics. An increase in oceanic weather activity exposes more cubic feet of ocean water to the atmosphere, resulting in increased rates of sequestration. Other scientists have argued, however, that since most models predict more warming at higher latitudes, less energy needs to be transferred from the tropics to the poles and this may produce fewer violent weather systems.

concentration of CO_2 in the atmosphere is thus not a simple function of emissions. Tracking the redistribution of carbon between the atmosphere, oceans and biosphere is, therefore, a complicated matter.

Any increase in carbon in the atmosphere resulting from human activity represents a marginal change to a complex natural system.[3] It is not surprising, therefore, that the consequences of increased greenhouse gas concentrations from human activity are very difficult to predict. The 1995 IPCC report's median projection is an increase in average temperatures of 2°C by 2100. This is a 75% fall from projections made in 1988 when concern about the issue first became widespread, and a 23% decline from projections made in 1992. A continual drop in the severity of predicted temperature increases is an indication of the uncertainty of the scientific theory.

The evidence linking temperature changes to changes in the concentration of CO_2 in the atmosphere is also inconclusive. While time series of surface temperatures show a warming trend, such series do not adequately reflect what is happening in the more remote parts of the globe and are difficult to adjust for factors such as urban heat island effects. Furthermore, a more representative series of temperatures in the lowest four miles of the atmosphere, which has been measured by satellites since 1979, has shown very little warming.

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[3] The earth's climate has fluctuated substantially in the absence of any human influences. Past ice ages have been related to changes in the structure of the earth's orbit, precession of the earth about its axis and changes in the incoming flux of solar radiation. Volcanic eruptions have also been shown to have a measurable effect on the earth's climate.

Reducing Emissions or Mitigating Effects

Externalities often arise when some barrier prevents the formation of a relevant market. It may be difficult to assign property rights to a resource such as the atmosphere because of difficulties in controlling access. If infringements of property rights are impossible to detect, and, thus, charge for, then for all practical purposes the rights do not exist.[4]

In the case of CO_2, the possible damage to the earth's climate in any one year is related to the *stock* of CO_2 in the atmosphere, not the flow of emissions in that year. Therefore, unlike most other types of air pollution, control of CO_2 emissions in the future is a close substitute for control today. While reducing emissions of CO_2 will invariably be costly, the costs are likely to be higher the more rapidly controls are imposed. It would be very expensive to scrap existing capital that reflects current energy costs and replace it by new capital with higher energy efficiency. Nevertheless, concerns about the possibility of global warming have led to the negotiation of emissions reduction treaties such as the Kyoto Protocol in 1997.[5] This protocol specifies a greenhouse gas emissions target of between 5% and 8% below 1990 levels by 2008-2012 for a group of industrialized nations (the Annex I countries). The protocol envisages that countries may

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[4] A market for emissions of sulfur dioxides has been created in the United States. In this case, the Environmental Protection Authority monitors the major sources to ensure they remain in compliance with the permits they own. Carbon dioxide is much more difficult to detect than sulfur dioxide, however, and is emitted from many more sources. Furthermore, since CO_2 can be reduced through re-absorption, producers of ``carbon sinks" should be allowed to issue emission permits. Conflicts arise from the implicit wealth transfers resulting from the initial allocation of emission permits, and the method of financing a reduction in the number of permits. Although energy taxes may be more practical than permits, proposed taxes typically take no account of the possible desirability of subsidizing the production of `carbon sinks'. There is an extensive literature on the relative merits of using taxes or tradeable permits to control the level of CO_2 in the atmosphere (see, for example,).

[5] While parties to the negotiations signed the treaty, it is not clear that many countries will ratify it. For example, the United States Senate passed a resolution 97 votes to zero, that imposes conditions on ratification that are unlikely to be fulfilled.

meet their specified goals by other means than taxing energy use. For example, countries can alter land-use patterns to enhance the rate of carbon sequestration, obtain credits for reducing emissions in other countries (the clean-development mechanism) and develop institutions for trading emissions permits. Land-use changes, in particular, could be a feasible low cost alternative to reducing energy demand. The debate about the emissions credit that countries receive is, however, a centerpiece of climate change treaty negotiations. In fact, as currently stated, only `new-growth' sinks count for credit. `Old-growth' sinks yield no credit for emissions reduction. (See MacCracken et al (1999) for a complete discussion of these issues.)

Another alternative to reducing emissions of CO_2 involves mitigating the adverse effects. This strategy would retain any positive externalities associated with increased concentrations of CO_2 in the atmosphere.[6] The cost of mitigating the adverse effects will essentially be the opportunity cost of using resources for that purpose, rather than for increasing consumption or investment. As a result of economic growth, the marginal cost of mitigation in current value terms should, therefore, decline over time. Time discounting will, of course, also reduce the present value of future damages from CO_2 accumulation.

Since methods of control are not specifically defined in current international agreements, and because enforceability of compliance is an unresolved issue, the costs of responding to climate change may vary considerably. Fifteen different modeling exercises designed to estimate the costs of compliance are reported in a recent special issue of The Energy Journal (see Weyant (1999)). Under various scenarios, ranging from no permit trading to full global trading, the costs in the United States alone ranged from $5 billion to about $180 billion. It is not a stretch to say, therefore, that the exact cost of emissions abatement is something of a mystery.

The Ambiguous Role of Technological Change

During the last few decades, significant advances have occurred in fossil fuel (oil, coal, and natural gas) resource recovery technology, efficiency in the use of those resources, and the development of alternative energy sources (nuclear, hydro, solar and fuel cell). Even though the demand for energy has continued to increase, these technological developments have kept the real price of energy from increasing significantly by:

- expanding the life of resources through lowering mining costs and increasing the usable stock,
- reducing the amount of fossil fuel needed per unit of production, and
- providing alternatives to meet new demand.

These technological developments might seem to have undesirable consequences for emissions. By keeping energy prices low, technology has encouraged the burning of fossil fuels. Nevertheless, gains in energy efficiency and the development of alternative energy resources both directly decrease carbon emissions per unit of economic output.

If efficiency gains in the use of fossil fuels are large enough, the demand for fossil fuels and the associated emissions could decline despite continued economic growth.[7]

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[6] The latter include not only the positive effects of some climate change (for example, longer growing seasons in high latitudes, or increased global precipitation) but also the beneficial direct effects of atmospheric CO_2 on agricultural productivity and the productivity of land and oceanic ecosystems.

[7] Such a trend occurred in the US from 1978 to the late 1980s.

Even the concentration of CO_2 in the atmosphere could decline, if sequestration rates were high enough. Technical change in the mining industry is, however, another matter. By lowering the costs of producing fossil fuels, such developments maintain the competitiveness of the fossil fuel technologies while doing nothing to reduce the output of CO_2.

In so far as global warming is concerned, the critical issue may not be whether fossil fuel is replaced by alternative energy technologies, but, rather, how long it takes before emissions decline to sustainable levels. Technological changes that either improve energy efficiency or reduce the price of alternative energy resources both contribute to this end. Given the exponential nature of technology growth, expectations that past trends will continue into the future are probably understated. For example, the average fuel efficiency of a motor vehicle in the US has increased from 13.8 miles/gallon in 1978 to 20.6 miles/gallon in 1995, a 49% increase in 17 years. The actions of OPEC in the early 1970's, and subsequent government fuel efficiency standards, triggered much of this increase in fuel efficiency. Nevertheless, the gains stimulated the development of new technologies. One example of such a technology is the development of the gas-electric hybrid automobile. This innovation, as marketed today, has the potential to triple the fuel efficiency of the vehicle fleet. The actual change in fuel efficiency will depend upon the rate of diffusion into the economy.

The electricity industry is in a different situation. While hydroelectricity, wind and, to a lesser extent, nuclear power could already be considered as "backstop" technologies, the majority of electricity continues to be generated from coal, oil and natural gas. Furthermore, hydroelectricity and nuclear power create their own environmental problems. Solar power is perhaps the most likely "zero emissions" backstop technology. Currently, solar power is much too costly to replace fossil fuels. There is the possibility, however, that rapid improvement could be made in the cost of manufacturing solar cells, which, like computer chips, are based on silicon. Another problem with solar power is that an effective storage mechanism needs to be developed. One possibility is that solar power could be used to produce hydrogen, which is then burned in a gas turbine when needed. Improvements in transmission technology (including perhaps the development of superconductivity as a practical technology) could also allow power generated in sparsely populated desert regions to be shipped long distances.

Fuel cells are promising as a means of meeting almost all energy needs. Several automobile manufacturers are investigating fuel cells as a power source for vehicles and some experimental buses are already using them. Development of the gas-electric hybrid vehicle may, however, delay the widespread adoption of fuel cells for transport applications. Small fuel cells suitable for producing electricity for individual buildings (including single-family homes as well as offices) have already been deployed. A number of electric companies in the United States have investigated the technology as an alternative to supplying electricity through an interconnected grid.

The Model

The model developed herein focuses on the potential externalities associated with the burning of fossil fuels and the resulting accumulation of CO_2 in the atmosphere. Emissions resulting from the burning of fossil fuels are converted into a time path of the stock of atmospheric CO_2. The present value of the external effects is evaluated in two fashions. One, by assuming that the current value shadow price of those effects in each period (in terms of goods) is *proportional* to the stock of CO_2 in that period. And two, by assuming that the current value shadow price of those effects in each period (in terms of goods) is *increasing* in the stock of CO_2 in that period.

We consider an economy that contains a goods producing sector, which relies primarily upon electricity as an energy source, and a services sector, which uses energy primarily to provide transport services. Previous authors have investigated similar ideas, but have focused on optimal resource depletion, or optimal pollution flows, when the environmental cost is internalized, and have focused on only one type of production (see, for example, Krautkraemer (1985, 1986), and Stokey (1998)). Kolstad and Krautkraemer (1993) provide a good review of the literature. Unlike most of the literature, we do not assume the environmental costs are internalized. Rather, we examine the effects on the present value of costs of varying a number of key parameters.

We define $c_1(t)$ to be the consumption of goods and $c_2(t)$ to be the consumption of services, each as functions of time. We assume labor is inelasticly supplied, and, for simplicity, ignore labor as a factor of production.

We denote the fossil fuel resource that is used to produce energy by $R_1(t)+R_2(t)$ and assume a quantity $R_1(t)$ is used to produce goods (primarily through the production of electricity) while $R_2(t)$ is used to produce services (primarily transportation). Following Heal (1976) and Solow and Won (1976), we assume that the marginal resource costs of mining is increasing in the total quantity of resources mined to date, or the integral of $R_1(t)+R_2(t)$. This reflects an assumption that the most easily-mined, or the richest deposits or fields, tend to be exhausted first. Heal introduced the idea of an increasing marginal cost of extraction to show that the optimal price of an exhaustible resource begins above marginal cost, and falls toward it over time. This claim is rigorously proven in Oren and Powell (1985).

We modify the resource depletion model to allow for exogenous technical change in the mining industry. Specifically, we assume that the marginal cost of mining $g(S)$ depends on a state variable S. While S increases with $R_1(t)+R_2(t)$, as Heal assumed, S can also exogenously decline over time as "new reserves", N, are discovered. Thus, the variable N can partially offset the effect of mining on marginal mining costs $g(S)$.

We also assume there are two backstop technologies available for use in the two sectors of the economy. The backstop in the service sector, $B_2(t)$, is a perfect substitute for $R_2(t)$. Specifically, the production function for services is assumed to be

$$c_2(t) = c_2(E_2(t))$$

$$E_2(t) = \varepsilon_2(t)R_2(t) + B_2(t)$$

where $\varepsilon_2(t)$ is the exogenous efficiency of fossil fuel use in the service sector.[8] The output of goods can be written as a function of the stock of physical capital $k(t)$ and the use of energy in the goods sector:

$$y(t) = \tilde{f}(k(t), E_1(t))$$

$$E_1(t) = \varepsilon_1(t)R_1(t) + B_1(t)$$

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[8] We ignore the effect of capital on the demand for energy in service production primarily for convenience. In fact, we can write, $E_2 = \varpi k_2 / \varepsilon_2$, where ϖ is a utilization rate, k_2 is capital in the service sector, and ε_2 is capital stock efficiency, giving a direct relationship between energy use and capital. However, ignoring the evolution of capital in the service sector reduces dimensionality.

where $\varepsilon_1(t)$ is the exogenous efficiency of fossil fuel use in goods production. The backstop in the goods sector, $B_1(t)$, is a perfect substitute for fossil fuel burning in the production of goods. For simplicity, we shall assume that there is a fixed ratio, α, between minimum energy input requirements and capital. We can then define a new production function

$$y(t) = f(k(t))$$

while imposing the constraint

$$\varepsilon_1(t)R_1(t) + B_1(t) \geq \alpha k(t) \tag{5.1}$$

We shall assume the pace of exogenous technological progress in developing alternative energy technologies ensures that fossil fuel is replaced by the backstop technologies before the available reserves are exhausted. We define $p_1(t)$ and $p_2(t)$ to be the exogenous marginal cost (measured in terms of goods) of the backstop technologies in each sector of the economy.

Formally, we have the following maximization problem (dropping the time variable for convenience):

$$\max \int_0^\infty e^{-\beta\tau} U\left(c_1, c_2\left(\varepsilon_2 R_2 + B_2\right)\right) d\tau$$

subject to the constraints:

$$\dot{k} = f(k) - c_1 - g(S)(R_1 + R_2) - p_1(B_1) - p_2(B_2) - \delta k$$

$$\varepsilon_1 R_1 + B_1 \geq \alpha k$$

$$\dot{S} = R_1 + R_2 - N$$

$$B_1, B_2, R_1, R_2 \geq 0$$

$$k(0) = k_0 > 0,\ S(0) = S_0 > 0$$

We, then, define the Hamiltonian

$$H = e^{-\beta t}\Big\{U\big(c_1, c_2(\varepsilon_2 R_2 + B_2)\big) + \lambda_S\big(R_1 + R_2 - N\big) \\ + \lambda_k\big(f(k) - c_1 - g(S)(R_1 + R_2) - p_1 B_1 - p_2 B_2 - \delta k\big)\Big\}$$

for the unconstrained problem. Incorporating the constraints , we define the Lagrangian:

$$L = H + e^{-\beta t}\Big\{\mu_{B1}B_1 + \mu_{B2}B_2 + \mu_{R1}R_1 + \mu_{R2}R_2 + \mu_E\big(\varepsilon_1 R_1 + B_1 - \alpha k\big)\Big\}$$

The current control variables are c_1, R_1, R_2, B_1, and B_2, while the state variables are k and S. The multipliers, λ_k and λ_S, on the state transition equations are in current value terms, as are the multipliers, μ_i, on the constraints.

The first order conditions for a maximum of L are:

$$\frac{\partial U}{\partial c_1} = \lambda_k \qquad (5.2)$$

$$\lambda_k g(S) = \lambda_S + \mu_{R1} + \varepsilon_1 \mu_E \qquad (5.3)$$

$$c_2' \varepsilon_2 \frac{\partial U}{\partial c_2} = \lambda_k g(S) - \lambda_S - \mu_{R2} \qquad (5.4)$$

$$\lambda_k p_1 = \mu_{B1} + \mu_E \qquad (5.5)$$

$$c_2' \frac{\partial U}{\partial c_2} = \lambda_k p_2 - \mu_{B2} \qquad (5.6)$$

$$\dot{\lambda}_k = \lambda_k\big(\beta + \delta - f'(k)\big) + \alpha \mu_E \qquad (5.7)$$

$$\dot{\lambda}_S = \lambda_S \beta + \lambda_k\big(R_1 + R_2\big)g'(S) \qquad (5.8)$$

$$\dot{k} = f(k) - c_1 - g(S)(R_1 + R_2) - p_1(B_1) - p_2(B_2) - \delta k \qquad (5.9)$$

$$\dot{S} = R_1 + R_2 - N \qquad (5.10)$$

and, if energy is not a free good, the constraint (5.1) will hold as an equality with $\mu_E > 0$.

There are many potential solutions to this problem. To be concrete, we shall suppose that fossil fuel initially is burned to provide energy in both sectors of the economy, but that the switch to alternative energy technologies occurs earlier in the goods producing than in the services sector. The primary reason is the more rapid progress in improving efficiency in using fossil fuels in the transport sector. While improvements in the efficiency of fossil fuel use delay the switch to backstop technologies, they nevertheless reduce CO_2 emissions per unit of output. By contrast, technical progress in the mining industry delays the switch to backstop technologies in both sectors without reducing emissions.

Switching to the Backstop Technology

If fossil fuel is used in both sectors, then $R_1, R_2 > 0$ and $\mu_{R1}, \mu_{R2} = 0$. Equation (5.3), then, implies that

$$\varepsilon_1 \mu_E - \lambda_k g(S) = -\lambda_S \tag{5.11}$$

The first term on the left of (5.11) is the marginal benefit of energy in producing goods. The second term represents the marginal costs of extraction measured in terms of goods, ignoring opportunity costs. The term, $-\lambda_S$, on the right of (5.11), therefore, can be interpreted as a mark-up to reflect the future effects of current resource depletion. This is similar to the description of resource pricing found in Heal(1976). Solow and Won (1976) refer to $-\lambda_S$ as a "degradation charge". Since resource extraction raises the marginal cost of mining, the shadow price of S, λ_S, has to be negative as long as $R_2 > 0$. This can be seen from (5.4). Energy resources will only be used in the service sector if the marginal benefit of doing so exceeds the marginal resource cost of mining, so the left side of (5.4) must be positive. For $R_2 > 0$, however, the multiplier μ_{R2} equals 0. Hence, $\lambda_S < 0$.

Observe that, since $\mu_{B1} \geq 0$, from (5.5) and (5.11):

$$\mu_{B1} = \lambda_k p_1 - \frac{\lambda_k g(S) - \lambda_S}{\varepsilon_1} \geq 0. \tag{5.12}$$

The first term in (5.12) is the marginal cost of the backstop technology. The term $\frac{\lambda_k g(S) - \lambda_S}{\varepsilon_1}$ represents the *full* marginal cost of fossil fuel use measured in terms of goods. The numerator is the effect of extraction, and the denominator is the effect of efficiency gains. Thus, increases in efficiency effectively prolong the life of the fossil fuel by driving down the full marginal cost in terms of goods.

From (5.5) the switch to the backstop technology occurs if the marginal cost of the backstop in terms of goods falls to equal the marginal benefit of energy in producing goods so that $\mu_{B1} = 0$. From (5.12), this implies

$$\varepsilon_1 \lambda_k p_1 = \lambda_k g(S) - \lambda_S. \tag{5.13}$$

Thus, the goods producing sector will switch to the backstop technology only if the marginal cost of the backstop technology falls faster than the marginal cost of using fossil fuel for a sufficiently long period of time.[9] That is, taking the time derivative of (5.13),

$$\dot{\varepsilon}_1 \lambda_k p_1 + \varepsilon_1 \dot{\lambda}_k p_1 + \varepsilon_1 \lambda_k \dot{p}_1 < \dot{\lambda}_k g(S) + \lambda_k g'(S)\dot{S} - \dot{\lambda}_S. \tag{5.14}$$

Making use of (5.8) and (5.10), we can express (5.14), after some manipulation, as

$$\frac{\dot{\varepsilon}_1}{\varepsilon_1} + \frac{\dot{p}_1}{p_1} + \frac{g'(S)N}{\varepsilon_1 p_1} < \frac{\dot{\lambda}_k \left(g(S) - \varepsilon_1 p_1\right) - \lambda_S \beta}{\varepsilon_1 p_1 \lambda_k}. \tag{5.15}$$

The right side of (5.15) will be positive since $\dot{\lambda}_k, \lambda_S < 0$, and, by (5.12), $g(S) - \varepsilon_1 p_1 > 0$. In order to switch out of the region where fossil fuel is used to produce goods, therefore, the rate of improvement in energy efficiency, $\frac{\dot{\varepsilon}_1}{\varepsilon_1} > 0$, plus the rate of discovery of new deposits, N, cannot remain too large relative to progress in reducing the cost of the backstop technology, $\frac{\dot{p}_1}{p_1} < 0$.

The Initial Fossil Fuel Economy

Returning to our analysis of the solution when fossil fuel is used in both sectors, (5.1) as an equality (with $B_1 = 0$) implies

$$\varepsilon_1 R_1 = \alpha k. \tag{5.16}$$

Also, (5.11) and (5.4) together imply:

$$c_2' \varepsilon_2 \frac{\partial U}{\partial c_2} = \varepsilon_1 \mu_E. \tag{5.17}$$

which can be interpreted as requiring that the marginal benefit of energy use be the same in either sector.

Equation (5.11) also can be substituted into (5.8) and (5.10) to produce a differential equation for λ_S:

$$\dot{\lambda}_S = \lambda_S \beta + \frac{g'(S)}{g(S)} \left(\dot{S} + N\right)\left(\lambda_S + \varepsilon_1 \mu_1\right). \tag{5.18}$$

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[9] It is possible for the economy to switch to the backstop technology even if the marginal cost of using fossil fuel falls faster for some interval of time, but ultimately the cost of the backstop technology needs to fall at a faster rate.

Equation (5.18) implies that the rate of change of λ_S depends on the time discount factor, β, as in a standard resource extraction model (i.e.- Hotelling's Rule). In addition, λ_S depends on the rate of change of mining costs, so the faster resources are mined, the faster will λ_S increase toward zero. If new reserve additions are large enough, however, $\dot{\lambda}_S$ could become more negative.

In this region, the differential equation (5.9) becomes

$$\dot{k} = f(k) - c_1 - g(S)(R_1 + R_2) - \delta k. \tag{5.19}$$

The solution of the model can be described as follows. Given current values for the shadow prices, λ_k and λ_S, an exogenous path for N, and current values for the state variables k and S, (5.2), (5.11), (5.16) and (5.17) can be solved for c_1, R_1, R_2 and μ_E. Then, (5.7), (5.10), (5.18) and (5.19) control the evolution of λ_k, S, λ_S, and k.

The Final Backstop Technology Economy

Once the economy switches to an energy technology that is itself produced (and effectively relies upon the sun for its energy source), we can have perpetual economic growth. While the model appears to conflict with biological models of the limits to growth, the economic growth in our model takes the form of a growth in the utility obtained from economic activity. Although the value of goods consumption remains bounded, the value of service consumption can grow without bound. Similarly, education and scientific progress permit continual enhancement of the productive services available from a finite resource of physical capital and numbers of people. The economic growth that occurs in our model, therefore, is quite different from biological notions of growth of the population, or "resource footprint", of a species.

Mathematically, the critical assumptions required to achieve perpetual growth are constant returns to scale production functions, and the ability to produce all the factors of production.

When both sectors are using backstop technologies, $B_1, B_2 > 0$ and $\mu_{B1}, \mu_{B2} = 0$. From (5.5), we find $\mu_E = \lambda_k p_1 > 0$. The constraint (5.1) requires

$$B_1 = \alpha k \tag{5.20}$$

while (5.2) and (5.6) together yield

$$c_2' \frac{\partial U}{\partial c_2} = \lambda_k p_2 = \frac{\partial U}{\partial c_1} p_2 \tag{5.21}$$

which has the same interpretation as (5.17). For current values of λ_k and k, equations (5.2), (5.20) and (5.21) can be solved for c_1, B_1, and B_2. The differential equation for k is then given by:

$$\dot{k} = f(k) - c_1 - p_1(B_1) - p_2(B_2) - \delta k \tag{5.22}$$

while (5.5), (5.7) and $\mu_{B1} = 0$ imply λ_k satisfies:

$$\dot{\lambda}_k = \lambda_k \left(\beta + \delta + \alpha p_1 - f'(k) \right). \tag{5.23}$$

For the simple functional forms that we use, equations (5.22) and (5.23) have an analytical solution. We show, in Appendix A, that, for a range of parameter values, the economy can enter a state of perpetual economic growth.

The Intermediate Economy

If only the goods producing sector is using a backstop technology, we again have $B_1 > 0$ and $\mu_{B1} = 0$. In addition, $R_2 > 0$ so $\mu_{R2} = 0$, but in general $\mu_{R1} > 0$. Since $\mu_{B1} = 0$, (5.1), (5.5) and (5.7) again imply (5.20) and (5.23). Since $\mu_{R2} = 0$, (5.4) implies

$$c_2'\varepsilon_2\frac{\partial U}{\partial c_2}-\lambda_k g(S)=-\lambda_S. \tag{5.24}$$

In this case, given current values for λ_k, λ_S, S and k, equations (5.2), (5.20) and (5.24) can be solved for c_1, B_1, and R_2. The differential equations governing the evolution of the shadow prices and state variables are again (5.23), (5.8) and (5.10) (with $R_1=0$), while (5.9) becomes, in this case:

$$\dot{k}=f(k)-c_1-g(S)(R_2)-p_1(B_1)-\delta k. \tag{5.25}$$

The necessary condition for switching to the backstop technology in the service sector is analogous to the condition (5.15) derived above for the goods sector:

$$\frac{\dot{\varepsilon}_2}{\varepsilon_2}+\frac{\dot{p}_2}{p_2}+\frac{g'(S)N}{\varepsilon_2 p_2}<\frac{\dot{\lambda}_k\left(g(S)-\varepsilon_2 p_2\right)-\lambda_S\beta}{\varepsilon_2 p_2\lambda_k} \tag{5.26}$$

for a sufficiently long period of time.

The boundary between the second and third regions occurs where we are just indifferent between using fossil fuel or the backstop technology in the services sector of the economy, that is, $\mu_{B2}=0$. From (5.6) and (5.2), the price of the backstop at the boundary, therefore, satisfies (5.21). At the time of the switch between the use of fossil fuel and backstop technology B_2, we also have $\mu_{R2}=0$, so that (5.24) holds.

Oren and Powell (1985) prove that $\lambda_S=0$ at the time of the switch out of fossil fuels. Intuitively, with fossil fuels no longer being burned, the shadow price of S ought to be zero. Thus, when fossil fuels are finally abandoned, (5.24) becomes:

$$\varepsilon_2 p_2=g(S). \tag{5.27}$$

Since the economy has already switched to a backstop technology in the goods sector at that time, $\mu_{B1}=0$ and $\mu_{R1}>0$. This requires, from (5.3), (5.5) and $\lambda_S=0$, $g(S)>\varepsilon_1 p_1$.

Thus, from (5.27), a necessary condition for the switch to the backstop to occur first in the goods sector is that $\varepsilon_2 p_2 > \varepsilon_1 p_1$ at the time of the switch in the service sector. The primary reasons for assuming the switch to a backstop technology occurs later in the services sector is that we expect ε_2 to increase more rapidly, and for a longer period of time, than ε_1, and p_2 to decrease more slowly than p_1.

Since the values of λ_S and λ_k in the first two regimes depend on the timing of the second switch point, the timing of the first switch point also depends on the timing of the second switch point. The switch points depend on the rate of decline in the costs of the backstop technologies, the rate of efficiency improvement and the marginal costs of using fossil fuel. For the first switch point, the latter, in turn, depends not only on the physical resource costs of mining, $\lambda_k g(S)$, but also on the future effects of mining fossil fuel as reflected in the shadow price λ_S.

The Externality Associated with CO_2

The possible externality associated with CO_2 arises from the *stock* of CO_2 in the atmosphere. We let θ denote the ratio of CO_2 emissions to the amount of fossil fuel burned, η the re-absorption rate and $\bar{P}$ "the equilibrium" [10] level of CO_2 in the atmosphere. The stock of atmospheric CO_2 will satisfy the differential equation:

$$\dot{P} = \theta(R_1 + R_2) - \eta(P - \bar{P}). \tag{5.28}$$

Given time paths for R_1 and R_2, the differential equation (5.28) will yield a time path for P. A positive flow of emissions from the burning of fossil fuels does not

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[10] Since the evidence appears to show substantial fluctuations in the concentration of CO_2 in the atmosphere, it is doubtful that there is a single natural level.

guarantee a positive accumulation. The rate of sequestration will also be a critical determinant of the accumulation of P. For example, fuel efficiency gains could be so great that the rate at which fossil fuel is burned is below the rate of sequestration. Once the burning of fossil fuels ceases, at time T, the stock of CO_2 will gradually decline back towards $\overline{P}$.

We shall calculate the present value of the externality (measured in utility terms and discounted to the initial period, $t = 0$) using two different functions:

$$D_1 = \int_t^{\infty} e^{-\beta\tau} \lambda_k \Phi_1 \left(P - \overline{P}\right) d\tau \tag{5.29}$$

and

$$D_2 = \int_t^{\infty} e^{-\beta\tau} \lambda_k \Phi_2 \left(P - \overline{P}\right)^2 d\tau. \tag{5.30}$$

The social cost functions (5.29) and (5.30) reflect a number of assumptions. Both of the damages functions assume that the "natural" level of CO_2, $\overline{P}$, is optimal from a welfare perspective. Despite the tendency of some to claim that "whatever is natural is best" this is by no means an obvious proposition. For example, if the earth were to return to an ice age, artificially increasing the amount of CO_2 in the atmosphere by rapid burning of fossil fuel may be the only way to avoid a natural disaster of truly catastrophic proportions for human welfare. For D_1, we assume that the externalities are proportional to the stock of "excess" CO_2 in the atmosphere, with a constant of proportionality Φ_1. By contrast, D_2 assumes that costs increase quadratically as P increases above $\overline{P}$ with a possibly different constant of proportionality Φ_2. In the second case, the marginal cost of global climate change is assumed to increase as the total amount of CO_2 in the atmosphere increases. In both (5.29) and (5.30), we also assume that the present value of the material sacrifice that may be needed to offset the externalities depends on the shadow price of goods in present value terms, $e^{-\beta t}\lambda_k$. This cost declines over time, not only as a result of time discounting, but also because economic growth reduces the marginal utility of goods consumption. A consequence of both (5.29) and (5.30) is that future control will be cheaper than current control.

From (5.29) or (5.30), D_1 or D_2 satisfy the differential equations:

$$\dot{D}_1 = -e^{-\beta t}\lambda_k \Phi_1\left(P - \bar{P}\right) \tag{5.31}$$

and

$$\dot{D}_2 = -e^{-\beta t}\lambda_k \Phi_2\left(P - \bar{P}\right)^2, \tag{5.32}$$

respectively. As discussed in Appendix J, we obtain D_1, D_2, and P by appending (5.28) and either (5.31) or (5.32) to the original system of differential equations.

A Particular Parameterization

In the next section of the paper, we shall use a number of sources of data to assess likely values for various model parameters. We then examine the sensitivity of the present value of the external effects (5.28) to variations in a number of key parameters including:

- the determinants of the current value of the external effects in any given period;
- rates of technical progress in producing substitutes for fossil fuels as an energy source (the changes in p_1 and p_2);

- rates of progress in retarding the increase in mining costs (N) and raising the energy efficiency of fossil fuel combustion (the changes in ε_1 and ε_2);
- the composition of consumption, and, thus, indirectly the energy intensity of production, as the economy grows;
- the time discount rate, β; and
- the rate of re-absorption of CO_2 out of the atmosphere and into the oceans and the biosphere, η, and the conversion of fossil fuel into CO_2, θ.[11]

The functional forms we focus on reflect the effects of these critical parameters in the simplest possible way. We shall present these functional forms in this section of the paper and discuss their implications for the behavior of the model. The numerical analysis will be presented after we discuss the parameterization in the next section of the paper.

The key idea we want to capture in the utility function is that consumers favor goods over services at low levels of total consumption, but as expenditure increases they favor services. A simple utility function with these properties is:

$$U(c_1,c_2) = c_1(\bar{c}_1 - c_1) + \chi_0 \ln(\chi_1 + c_2). \tag{5.33}$$

For the utility function (5.33),

$$\frac{\partial U}{\partial c_1} \to 0 \text{ as } c_1 \to \frac{\bar{c}_1}{2}$$

so the consumer becomes satiated in goods as the consumption level approaches $\frac{\bar{c}_1}{2}$. In addition,

$$\left.\frac{\partial U/\partial c_1}{\partial U/\partial c_2}\right|_{c_1=0,c_2=0} = \frac{\chi_1 \bar{c}_1}{\chi_0}$$

so that if χ_0 is small enough relative to $\bar{c}_1$ the initial preference for goods over services can be arbitrarily strong even though the possibility of becoming satiated in goods implies that consumption ultimately shifts toward services.

We assume the production functions are constant returns to scale in energy, or energy and capital. Since labor is also implicitly a factor of production, we would normally expect decreasing returns to scale in the remaining factors. If labor services can be continually incremented through investment in human capital, however, then we can avoid the decreasing returns to scale in the remaining factors. Following the endogenous growth literature[12] we use the simple linear functions

$$c_2 = \zeta E_2 \tag{5.34}$$

for services production and

$$f(k) = Ak \tag{3.35}$$

for goods production.

We also assume that the marginal cost of mining, $g(S)$, is linear in S:

$$g(S) = \gamma_0 + \gamma_1 S \tag{3.36}$$

with the level of "new reserves", N, declining at a constant rate over time:

$$N = n_0 e^{-n_1 t}. \tag{3.37}$$

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[11] The value of θ will depend on the mix of fuels used. Chakravorty, Roumasset and Tse (1997) focus on the effect of fuel substitution on the flow of CO_2 into the atmosphere. They model substitution between coal, oil and natural gas.

[12] See for example, Stokey (1998) for a discussion of endogenous growth and sustainability.

Finally, we need to specify functional forms for the exogenous technological changes in producing output from fossil fuel energy inputs, and the marginal costs of the backstop technologies. For simplicity, we assume the following forms for technical progress:

$$p_1 = a_1 + b_1 e^{-\pi_1 t} \text{ with } a_1, b_1 > 0 \tag{3.38}$$

$$p_2 = a_2 + b_2 e^{-\pi_2 t} \text{ with } a_2, b_2 > 0 \tag{3.39}$$

$$\varepsilon_1 = l_1 - m_1 e^{-\varphi_1 t} \text{ with } l_1 > m_1 > 0 \tag{3.40}$$

$$\varepsilon_2 = l_2 - m_2 e^{-\varphi_2 t} \text{ with } l_2 > m_2 > 0 \tag{3.41}$$

We assume that $\varphi_2 > \varphi_1$, so that technical progress in improving energy efficiency is much greater in the services sector (which includes transport) than in the goods producing sector (which includes electricity).

In Appendix G, we discuss the equations that describe the behavior of the economy under these particular assumptions on functional forms. This enables us, in particular, to provide an analytical expression for the transversality condition on the shadow price of capital, λ_k, and discuss the conditions under which sustainable growth can occur.

Numerical Analysis

The behavior of the system in the first two regimes is governed by a system of four differential equations. The equations for $\dot{k}$ and $\dot{S}$ are accompanied by initial conditions at $t = 0$. For the two shadow prices, λ_k and λ_S, we effectively have terminal conditions for the time T when fossil fuel burning ceases. All four differential equations have to be solved simultaneously moving backwards through time. The iterative algorithm we use is described in Appendix H.

The parameter values we used in the "base case" are summarized in Table 5-1. These were obtained from a range of sources, which are described in Appendix I. Appendix I also outlines the statistical techniques we used to obtain estimates for some of the parameters of the model. The parameter values were chosen assuming one period of time represents one year. Units were chosen so that $k_0, S_0, \overline{P} = 1$.

Table 5-1: Parameter Values

Parameter	Base Value	Parameter	Base Value	Parameter	Base Value
α	0.04	γ_0	0.99	a_1	0.09
ζ	100.0	γ_1	0.006	b_1	1.1
δ	0.07	n_0	0.06	π_1	0.06
A	0.19	n_1	0.07	a_2	0.3
β	0.05	l_1	1.1	b_2	2.7
χ_0	0.004	m_1	0.1	π_2	0.06
χ_1	1.0	φ_1	0.02	θ	0.44
$\bar{c}_1$	0.25	l_2	3.0	η	0.028
k_0	1.0	m_2	2.0	$\overline{P}$	1.0
S_0	1.0	φ_2	0.04	P_0	1.3

The data and estimations provided a starting point for obtaining the parameter values. We subsequently adjusted some of the parameters to ensure the model produced a "realistic" growth rate for the world economy, both c_1 and c_2 remain positive at all times, and the initial share of expenditure falling on c_1 and c_2 matches the data for the world economy.[13] In line with our earlier discussion, we also chose parameter values that resulted in the backstop technology being used in the goods before the services sector.

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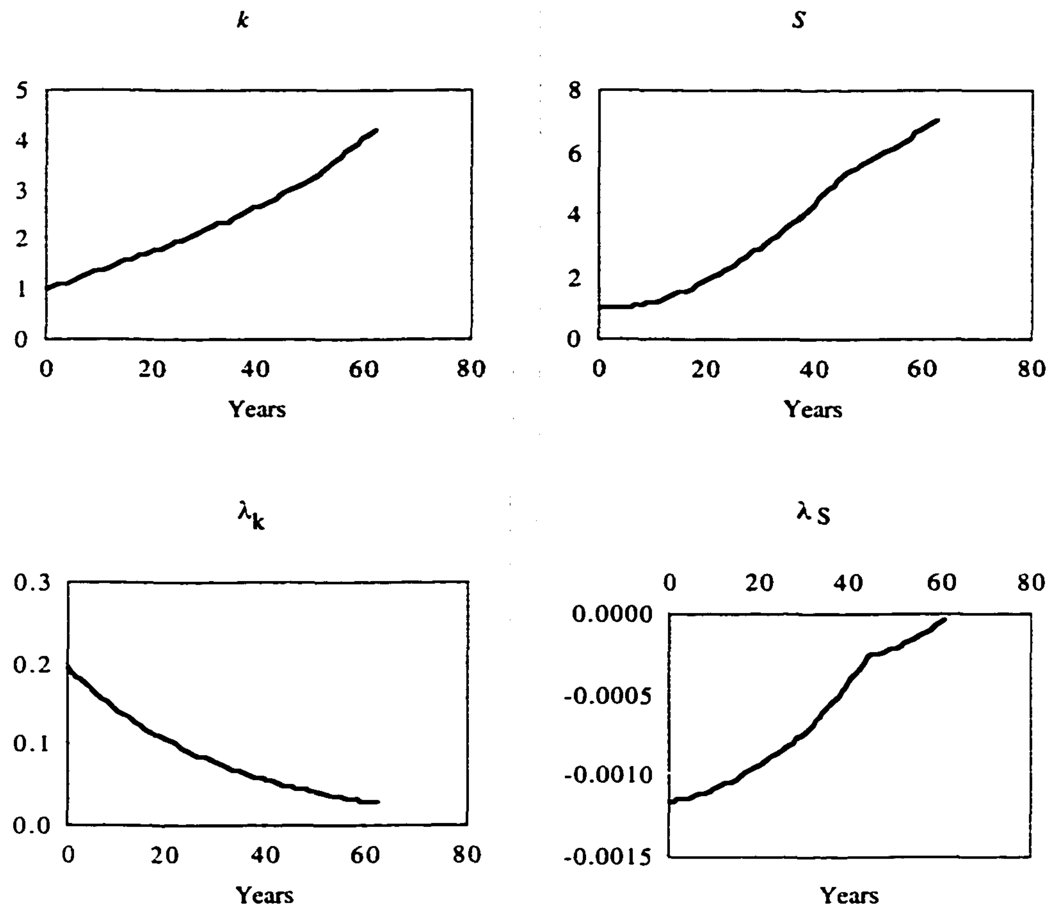
[13] The linear production functions and the specific form of the utility function limited our ability to replicate some features of the data. These simple functional forms were used to facilitate calculation of the analytical solution in the regime where only backstop technologies are used. The variables measured in the

Figure 5-1: Model Solution for Base Case Parameter Values



For the base case parameter values in Table 5-1, the solution paths for the state variables, k, S, λ_k and λ_S, are graphed in Figure 5-1. The switch to the first backstop technology occurs after 46 years while the final switch out of fossil fuels occurs after 62 years. The first switch point is barely evident in the graphs of k and λ_k. The growth in

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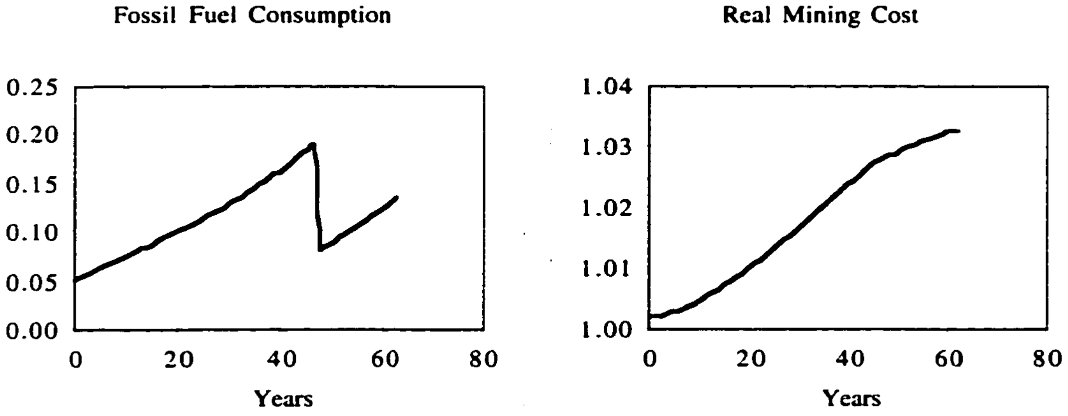
data also often do not correspond to the theoretical variables of interest. For example, k in the model really corresponds to physical and human capital combined, whereas the data used for calibration relates to physical capital only. The data on oil mining and reserves also does not correspond to the total "fossil fuel" quantities represented in the model. In particular, data on coal mining costs, production and reserves ought to be included along with oil and natural gas. The reserves data also ought to be corrected for changes in the *quality* of deposits, although this may be reflected in concepts such as "economically recoverable". We have attempted to limit the consequences of these data problems by focusing on the *elasticities* of the key

k does accelerate slightly after about 40 years as a backstop technology with declining marginal cost replaces fossil fuel in the goods sector (more goods can be allocated to capital stocks, as well as consumption). The average annual growth rate of (human and physical) capital in the first 80 years is about 2.3%. The long run asymptotic growth rate of capital in the final backstop regime is 3.4%. As we remarked above, parameter values were chosen in part to yield "realistic" values for these growth rates.

Figure 5-2: Fossil Fuel Extraction and Mining Costs



The graphs of S and λ_S in Figure 5-1 are more interesting. Interpretation of these is assisted by examining the graphs in Figure 5-2 of fossil fuel use and the real costs of mining, $\frac{\lambda_k g(S) - \lambda_s}{\lambda_k}$. The first graph in Figure 5-2 shows that, for our base case parameter values, despite the assumed gains in energy efficiency the continued growth in output raises fossil fuel use. The variable S reflects, in addition to fossil fuel consumption, the effect of new discoveries N. For our base case parameter values, these

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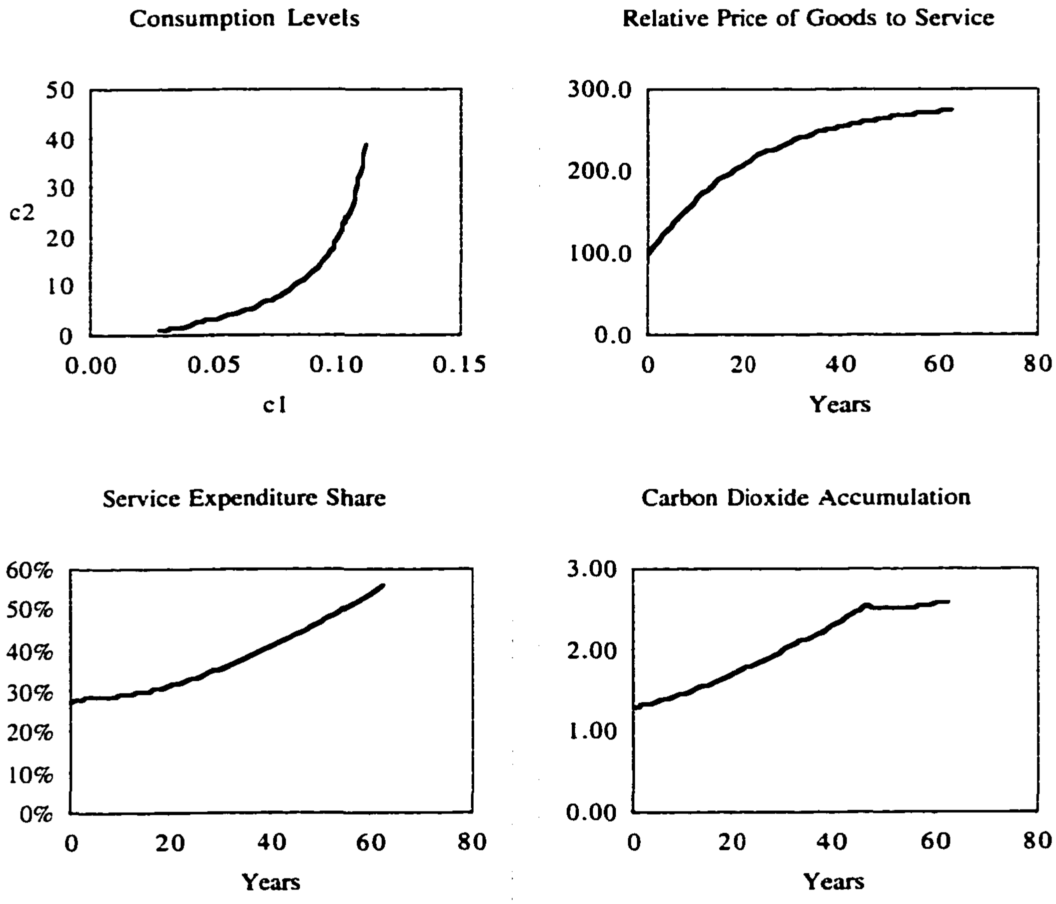
variables in response to changes in parameter values, not the *levels* of those variables in the base case. Thus, changes in the scale of variables, for example, will have no effect on the resulting elasticities.

slow the growth in S, but are not sufficient to prevent S, and, thus $g(S)$, from eventually rising. The second graph in Figure 5-2 shows that the real costs of mining rise smoothly over time despite the kinks in the paths of S and λ_S, and the discontinuities in $R_1 + R_2$. The shadow price λ_S adjusts to smooth out any incipient sharp movements in the real price of fossil fuel.

Figure 5-3: Consumption and CO_2 Accumulation in the Base Case



Consumption Levels

Relative Price of Goods to Service

Service Expenditure Share

Carbon Dioxide Accumulation

The first three panels of Figure 5-3 provide further insight into the behavior of the model. These graph the relative consumption of goods and services, the relative price of goods to services $\left(\dfrac{\lambda_k \zeta \varepsilon_2}{\lambda_k g(S) - \lambda_S}\right)$, and expenditure shares. The consumption expansion path reflects the assumption that preferences are biased toward goods relative to services at low levels of overall consumption.

The second graph in Figure 5-3 shows that the relative price of goods rises throughout the first 60 years. The greater opportunities for efficiency gains in the production of services from fossil fuel, nevertheless, mean that the price of services *in terms of the cost of fossil fuel input*[14] declines relative to the cost of goods. As noted above, we chose the $\bar{c}_1$ and χ parameters in the utility function, in part, to produce an expenditure share that grows from slightly below 30% in period zero to about 60% after the first 60 years.[15] The final panel in Figure 5-3 reveals that CO_2 accumulation flattens out after the goods sector switches to the backstop technology.

We examined the sensitivity of the system to each parameter by re-calculating the solution after increasing each parameter value by 1% above the values specified in Table 5-1. The resulting elasticities of a number of endogenous variables are presented in Table 5-2, grouped according to type of variable.

The influences of the parameters on the linear measure of damages, (5.29), can be summarized by regressing the first column of Table 5-2 against the remaining columns. The resulting regression equation is (with standard errors in parentheses):

$$e_{D_1} = \underset{(0.060)}{-0.115} + \underset{(0.327)}{0.512} e_{\hat{p}} - \underset{(0.195)}{0.267} e_{T_1} + \underset{(0.151)}{0.730} e_T + \underset{(0.273)}{1.149} e_{k(T)} + \underset{(0.191)}{1.211} e_{\lambda_k(T)}$$

$$R^2 = 0.88$$

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[14] This relative price is the values graphed in the middle panel of Figure 5-3 divided by $\zeta\varepsilon_2$, which is just the inverse of the real mining cost graphed in Figure 5-2.

[15] The figure of 60% for the world in 60 years is about where the US is currently.

The regression coefficients are merely a way of summarizing how the different elasticities in Table 5-2 are related to each other. Thus, a parameter change that increases the maximum level of CO_2 accumulation also tends to raise damages, D_1; a change that extends the horizon before the switch to a backstop technology in goods production tends to reduce D_1; a change that increases the time horizon for the final switch out of fossil fuel tends to increase D_1; a change that increases capital accumulation tends to raise D_1; and a change that increases the shadow value λ_k of goods at time $t = T$ tends to raise D_1.

Table 5-2: Elasticities

	D_1	D_2	$\hat{P}/P_0$	T_1	T	$k(T)/k_0$	$\lambda_k(T)$
β	-0.89	-1.49	-0.77	0.18	0.08	-2.30	2.34
$\bar{c}_1$	0.95	0.55	-0.40	0.10	0.04	-0.42	1.11
χ_0	0.52	0.85	0.26	-0.07	-0.03	0.40	0.39
χ_1	-0.09	-0.11	0.01	0.00	0.00	0.04	-0.06
A	-2.51	-1.31	3.80	-0.77	-0.37	7.80	-10.73
δ	0.94	0.49	-1.33	0.28	0.13	-2.67	4.30
α	0.92	1.18	-0.59	0.07	0.05	-1.55	2.43
ζ	0.09	0.11	-0.01	0.00	0.00	-0.04	0.06
γ_0	-0.15	-1.89	-3.68	-4.07	-1.36	-3.08	4.55
γ_1	-0.02	-0.07	-0.14	-0.16	-0.06	-0.11	0.16
n_0	0.00	0.01	0.02	0.02	0.01	0.01	-0.02
n_1	0.00	-0.01	-0.02	-0.02	-0.01	-0.01	0.02
l_1, m_1	-0.56	0.39	3.30	4.89	-0.30	0.87	-1.21
φ_1	-0.01	0.03	0.10	0.16	-0.01	0.02	-0.03
l_2, m_2	0.14	0.23	0.63	-0.11	1.82	2.63	-3.61
φ_2	0.02	0.05	0.09	-0.02	0.26	0.36	-0.51
a_1	0.33	1.48	2.53	4.65	-0.24	-0.64	1.11
b_1	0.02	0.11	0.18	0.34	-0.02	-0.04	0.07
π_1	-0.07	-0.31	-0.47	-0.93	0.05	0.13	-0.23
a_2	0.04	0.10	0.52	-0.09	1.51	2.21	-3.05
b_2	0.01	0.02	0.11	-0.02	0.31	0.45	-0.64
π_2	-0.03	-0.08	-0.36	0.07	-1.17	-1.66	2.42
η	-0.26	-0.65	-0.38	...	...	...	...
θ	0.59	1.44	0.59	...	...	...	...
Φ	1.00	1.00	...	...	...	...	...

The related regression for the alternative quadratic measure of damages, (5.30), is:

$$e_{D_1} = \underset{(0.084)}{-0.182} + \underset{(0.485)}{1.890} e_{\hat{P}} - \underset{(0.274)}{0.832} e_{T_1} + \underset{(0.212)}{1.118} e_T + \underset{(0.382)}{1.142} e_{k(T)} + \underset{(0.267)}{1.594} e_{\lambda_k(T)}$$

$$R^2 = 0.82$$

Not surprisingly, the measure of damages D_2 is affected more by parameter changes that also increase the maximum level of pollution, $\hat{P}$. Since the quadratic measure is also more sensitive to what happens when P is larger, it is also more affected than is D_1 by parameter changes that also affect the switch dates. Finally, although the regression coefficient on λ_k at time $t = T$ is no longer the largest, it is still larger in the D_2 regression than it is in the D_1 regression.

The regression coefficients only reflect "general tendencies" because the model is, in reality, quite non-linear. Furthermore, the solution takes the form of paths of variables over time while the regression equations focus on the way parameter changes affect the values of variables at one point in time. Nevertheless, the effects summarized by the regression equations are quite intuitive.

A parameter change that increases the maximum value attained by P is positively associated with a parameter change that raises either D_1 or D_2. A parameter change that raises economic growth will also tend to raise both $k(T)$ and $P(T)$. The regressions indicate that such a change will be associated with a higher present value of damages.

Higher economic growth has other consequences. By raising the demand for fossil fuel, higher growth increases S and mining costs. This causes the backstop technologies to become competitive with fossil fuels at an earlier date.

Higher economic growth also lowers the marginal utility of consumption, λ_k. In fact, the change in $\lambda_k(T)$ is most closely related to the change in damages D_1 and is the second most closely related variable to changes in D_2. An increase in $\lambda_k(T)$ also raises the values of λ_k for $0 \leq t \leq T$. Both measures of damages assume that global warming affects the available supply of goods (for example, total agricultural production) or has consequences that can be largely offset by expenditures that could otherwise be consumed or invested. For example, the opportunity costs of building dikes, shifting agricultural production to new locations or moving people from low-lying coastal areas are likely to be related to the value of goods consumption.[16] Thus, economic growth indirectly reduces the cost of responding to global warming in the future since a given sacrifice of resources has a smaller impact when people are better off.

The first set of elasticities in Table 5-2 relates to parameters that affect the utility function. A 1% increase in the time discount rate, β, reduces the final capital stock at T by almost 2.3%. A higher rate of time discounting results in higher current consumption and, thus, lower rates of economic growth. As a result, the output of CO_2 also declines as indicated in column 3 of Table 5-2. On the other hand, lower economic growth reduces the demand for fossil fuel and, thus, the rate of increase in fuel prices. The time until the economy switches to the backstop technologies is, therefore, delayed as indicated in columns 3 and 4 of Table 5-2. The final column of Table 4 shows that lower economic growth raises the marginal utility of consumption at T and would, on this account, raise the present value of damages D_1 or D_2. Finally, a higher rate of time discounting directly

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[16] In so far as the consequences of global warming are related to the value of services rather than goods consumption, our measure would *understate* the costs. As the second panel of Figure 5-3 shows, the relative price of goods to services rises throughout the period of fossil fuel use.

reduces the ***present value*** of the damages. This effect reinforces the reduced rate of accumulation of P. The consequence is that D_1 falls by about 0.9% and D_2 by almost 1.5%, for each 1% rise in β. The ***appropriate*** rate of time discounting depends on the risks associated with global warming. One could view measures aimed at avoiding climate change as a risky investment, due to the large amount of uncertainty, to be compared with other investments in physical or human capital. In general, the more uncertainty that there is about the possible costs or benefits of controlling CO_2 concentrations in the atmosphere, the higher should be the discount rate.

The effects of the remaining utility function parameters appear to be dominated by their consequences for the shadow price of goods λ_k, although the effect of the parameter change on $\hat{P}$ is also important in the case of D_2. An increase in the satiation level of goods consumption, $\bar{c}_1$, raises consumption and tends to reduce economic growth. The consequences for $\hat{P}$, $k(T)$, T_1 and T are similar, although smaller in magnitude, than the effects of increasing β. On the other hand, an increase in $\bar{c}_1$ directly increases the marginal utility of goods consumption, and this effect dominates to produce a net increase in D_1 and D_2.

An increase in χ_0 raises the marginal utility of service consumption, and has an opposite set of effects, on most variables, to an increase in $\bar{c}_1$. Like $\bar{c}_1$, however, an increase in χ_0 raises λ_k. This reinforces the effects of higher economic growth on P and damages rise. It is interesting to note that a change in $\bar{c}_1$ has a larger effect on D_1 whereas a change in χ_0 is more important for D_2. This can be explained by the fact that these parameter changes have different implications for $\hat{P}$, and D_2 is more sensitive than D_1 to high values of P.

Increasing χ_1 lowers the marginal utility of consuming services. Resources shift into goods production, which increases the capital stock and the accumulation of CO_2. Damages, nevertheless, decline again primarily because λ_k falls.

The variable with the greatest effect on D_1 is the marginal product of capital, A. A 1% increase in A raises the capital stock at T by almost 8%, and the maximum accumulation of CO_2 is almost 4% greater. On the other hand, higher economic growth reduces the marginal utility of consumption and makes the cost of damages (or control measures) easier to bear. The shadow value $\lambda_k(T)$ of goods falls by over 10%, and, as a result, the present value of damages D_1 declines by more than 2.5%. Higher economic growth also results in the economy switching away from fossil fuels more quickly because the marginal cost of mining rises faster. Higher economic growth has less of a negative effect on D_2 than it does on D_1 because the quadratic measure is more sensitive to the increased growth in P.

The effects of increasing δ are similar to reducing A. In fact, in this linear production model, the net output $A-\delta$ is all that matters. The magnitude of the effects of A exceed those of δ because a given percentage change in A has a larger percentage effect on $A-\delta$.

A higher value of α implies that more energy is required to produce goods, whereas a higher value of ζ implies that less energy is needed to produce services. An increase in either variable reduces capital growth, and the maximum accumulation of P, while delaying the switch time to the backstop technologies. An increase in either variable also raises λ_k, however, and this effect dominates the movement in damages.[17]

The next set parameters in Table 5-2 determine mining costs. Only the level of mining costs γ_0 has a non-negligible impact when the damages are linear, D_1. In particular, the parameters n_0 and n_1, which govern the rate of new resource discoveries, have minor effects on D_1. Although n_0 and n_1 have a larger effect on D_2, the magnitudes of the elasticities are still quite small. Changes in the level of mining costs γ_0, however, become quite important when damages depend on the square of the increase in the stock of CO_2. Indeed, the elasticity of D_2 is larger with respect to a change in the level of mining costs, γ_0, than it is with respect to any other parameter. Higher mining costs advance the time when fossil fuels are replaced by the backstop technologies, and also reduce economic growth and the accumulation of P. In this case, the indirect effects on the marginal utility of consumption, λ_k, are dominated by the remaining effects, and higher mining costs reduce the present value of damages.

The effects of changing any of the technological progress growth rates tend to be relatively small. The largest are π_1 and π_2, the rates decline in the marginal costs of the backstop technologies. An increase in either of these growth rates reduces damages (either measure) primarily by advancing the dates when the economy switches to the backstop technologies. This, in turn, reduces the accumulation of CO_2. Increasing π_1 means that the first switch point is reached sooner. The average growth of capital also is

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[17] There are two major qualitative differences between the effects of α and ζ on the economy. Since α affects the production of goods, some of which are used as capital, α directly affects the growth of k through a feedback mechanism. Thus, α appears on the coefficient of k in the capital evolution equations (5.45), (5.61) and (5.68) in Appendix G whereas ζ affects the exogenous variables in those equations.

higher because more resources can be devoted to capital stock investment due to lower energy costs. The second switch occurs later because mining costs do not rise as fast. Increasing π_2 means that the second switch point occurs sooner (as can be seen in equation (5.27)). The first switch occurs later because the marginal value of extraction reflects the earlier second switch date. Although an increase in π_2 raises the shadow price of capital, the earlier value of T would itself tend to raise $\lambda_k(T)$, so the effect on the whole path of values of λ_k is less marked than the change in $\lambda_k(T)$ alone would appear to imply.

An increase in both l_1 and m_1 raises the long-run energy efficiency gains in the use of fossil fuel to produce goods without affecting energy efficiency at $t = 0$. Higher economic growth again results in increased accumulation of P. When damages are linear in P, the decline in λ_k dominates and D_1. If contemporaneous damages are quadratic in P, however, the increase in P dominates the reduction in λ_t, and the present value of damages, D_2, rises. Although both l_1 and m_1 directly affect only the goods sector, the second switch point occurs sooner because higher growth causes a greater amount of fossil fuel to be consumed.

An increase in both l_2 and m_2 also raises economic growth. In this case, the first switch point occurs earlier and the second switch point later. Again the induced increase in economic growth drives up energy consumption and increases mining costs. After the first switch, however, the growth of capital no longer affects fossil fuel extraction. Since energy efficiency in services is now higher, mining costs grow more slowly, and fossil

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Second, only ζ continues to affect S, and thus mining costs, after the switch to the backstop technology in the goods sector.

fuel is used longer. Even though $\lambda_k(T)$ declines substantially, the fact that T is further into the future means that a given decline in $\lambda_k(T)$ is associated with a smaller decline in λ_k for $0 \le t \le T$. In this case, damages rise despite falls in both $\hat{P}$ and $\lambda_k(T)$.

An increase in a_1 or b_1 implies that the backstop price of energy for goods production does not decline to as low a value or begins at a higher value. While the first switch date occurs later, the second switch date occurs sooner. The greater use of fossil fuel for goods production raises $g(S)$ and makes fossil fuel less competitive for producing services. A higher cost of the backstop for producing goods also reduces economic growth and increases λ_k. The accumulation of CO_2 is higher because the extension of the time horizon more than offsets the effect of lower capital stocks. This, coupled with a higher shadow price of goods, results in higher damages. The long run level a_1 of the backstop price is one of the most important determinants of D_2.

If the backstop price of energy for services does not decline to as low a value (a_2 increases) or begins at a higher value (b_2 increases), then the second switch point occurs later. It takes longer for equation (5.27) to be satisfied. The first switch point, however, occurs sooner. This is the result of higher mining costs (more fuel is being consumed), and reflects the idea expressed in the last paragraph of the above section entitled "The Intermediate Economy". Both the accumulations of CO_2 and damages are higher.

A 1% increase in the emissions rate θ associated with a given level of fossil fuel combustion increases the present value of damages in the linear case by almost 0.6% and in the quadratic case by more than 1.4%. Conversely, a 1% increase in η, the natural re-absorption rate for CO_2 by the biosphere and the oceans, reduces damages by less than 0.4% in the linear case and a little over 0.65% in the quadratic case. A higher value of η

implies not only a lesser accumulation of CO_2 in the fossil fuel period, but also a more rapid decline of CO_2 once the burning of fossil fuel ceases. The higher costs associated with an increase in θ compared with an equal percentage decrease in η are to reflect changes in the time profile of the accumulation of P in the two cases.

Finally, the elasticity of the relationship Φ_1 or Φ_2 between the stock of CO_2 in the atmosphere and the presumed contemporaneous cost of the externalities is 1.0, by assumption. Since the damages are proportional to the Φ coefficients, a change in either Φ has no effect on any variables other than the corresponding damages measure. The possible consequences of increased CO_2 that are the focus of the scientific debate surrounding global warming are a primary determinant of the appropriate functional form for damages and also the value of the corresponding Φ coefficient. The contemporaneous costs depend not only on the physical effects, however, but also on the economic costs of mitigating or countering the effects, minus any potential benefits.

Concluding Remarks

Some of the detailed conclusions from our analysis are no doubt specific to the parametric model we have examined. A number of lessons are, however, likely to apply more generally.

To begin with, we showed how perpetual economic growth is not necessarily inconsistent with biological notions of the limits to the growth of the population or resource demands of a particular species. The key distinction is that economic growth consists of growth in the *value* of output consumed and this could grow without bound even though the resource inputs remain bounded. Essentially, we require that the growth of scientific knowledge and other types of human capital allow us to extract greater benefits in utility terms from the same input of physical resources.

In so far as energy use is concerned, perpetual growth will eventually require that we shift toward a virtually inexhaustible source of energy, such as solar power. That does not imply, however, that we should in the meantime limit economic growth based on the use of fossil fuels. On the contrary, a high rate of economic growth and the associated technological and scientific progress might be the only way of eventually achieving a "sustainable growth" economy.

Our model also illustrates how the demand for fossil fuels is associated with a stabilizing feedback mechanism. Higher economic growth will tend to raise the real price of fossil fuel as deposits are depleted more rapidly. Economic growth may therefore advance the date when backstop technologies become competitive with fossil fuels as a source of energy.

Economic growth has other conflicting effects on the likely damages associated with global warming. Higher economic growth will, in the short term, increase the production of CO_2. A high rate of economic growth may, however, also be associated with a more rapid transition to a "post-industrial" economy where services become much more important to human welfare than does agricultural or manufacturing output. Most importantly, economic growth affects the marginal costs to society of delaying the response to a given set of consequences of global warming. In our model, this effect tends to dominate. While it may not dominate in all cases, it is likely to remain an important consideration. The economic consequences of global warming depend on more than the physical effects. The costs of those effects, or the costs of mitigating them, both depend on how wealthy we become as a society.

A related issue is that the potential externality associated with global warming depends on the stock of CO_2 in the atmosphere, not the flow of CO_2 produced. This makes future control a close substitute for current control, something that does not apply for other types of air pollution. The possibility of substituting future for current control has another consequence. As with the modern theory of investment, delaying action has an option value. As a result, the best policy may be to devote resources to eliminating uncertainty, rather than controlling the output of CO_2.

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Appendix A

The countries, by geographic region, included in the study for Chapter 2 are:

Asia/Pacific -

Pakistan, India, China, Indonesia, Thailand, Malaysia, South Korea, Japan, Australia

Europe -

Turkey, Greece, Portugal, Spain, Ireland, Austria, Italy, Belgium, Netherlands, United Kingdom, France, Finland, Sweden, Denmark, Norway

North/South America -

Canada, United States, Mexico, Brazil

Appendix B

We first estimate the pooled model with constant intercept and slope (2SLS). This is then compared to the specification in which there are different intercepts with common slopes (2SLS-Within). This is the fixed-effect estimator based upon the work of Balestra and Nerlove (1966). The principle advantage of this estimator over its pooled 2SLS counterpart is that it allows for individual country effects. Hence, country specific heterogeneities can be explicitly taken into account. An F-test reveals that the null of no individual country effects is rejected. The test is distributed as F(27,443) under the null of homogeneity. In Chapter 2, it yields a value of 3.46 in the industrial and other sector, 7.11 in the transport sector and 2.19 in the residential and commercial sector. All of these are significant at the 5% level. In Chapter 3, the test yields a value of 5.58, which also significant at the 5% level.

Having established that there are different intercepts does not preclude the possibility that the slope parameters are also different. Pesaran and Smith (1995) claim that imposing homogeneity among the slope parameters across different cross-sectional units is overly restrictive and could result in biased estimates. To avoid this, they argue in favor of averaging the parameter estimates of the individual units, a method that produces consistent estimates as long as N (# of cross-sectional units) and T (# of time periods) approach infinity. While their criticism has its merit, it is often ignored in many panel studies. Fortunately, the issue is testable. Following Baltagi and Griffin (1997), we use the test based on the work of Wooldridge (1990) to ascertain whether the data can indeed be pooled. This test is distributed as F(108,336) under the null of homogeneity. In Chapter 2, this yields a value of 2.47 for the Industrial and Other sector, 0.63 for Residential and Commercial, and 1.40 for the Transportation sector. In Chapter 3, the test yields a value of 0.62. The 5% critical value is 1.43. The numerator is based upon the second stage residual sum of squares of 2SLS allowing for varying intercepts and slopes in its unrestricted version and varying intercepts and common slopes under its restricted version. The denominator is based on the unrestricted 2SLS residual sums of squares.

This leaves us to determine the nature of the individual effect, i.e.- is it fixed or random? The distinction between fixed and random effects is whether or not the effect is correlated with the regressor set. If the effects are correlated with the other regressors, then a fixed effect specification is warranted, and the random specification will "suffer from the inconsistency due to omitted variables" (Greene p633). This type of statistical definition makes the issue of specification a testable one. The fixed effect, or within, estimator, is consistent always. The gain from choosing the random specification where indicated is one of efficiency. A Hausman-type specification test indicates that the fixed effect approach is the suitable one for each sector. The test is based upon the difference of the variance of the within and random effect estimators, and is distributed as $\chi^2(4)$. The results in Chapter 2 are as follow: Industrial and other: 150.23, Residential and Commercial: 14.08, and Transportation: 32.45. In Chapter 3, we have 242.9. All are significant at the 5% level (Critical value = 9.48).

Appendix C

The results from the alternative methods of estimation, in Chapter 2, for each sector are as follow:

Residential and Commercial –

OLS

	parameter	std error
constant	-0.1395	0.2501
y	0.1079	0.0603
y^2	-0.0054	0.0036
p	-0.0506	0.0138
ecL	0.9758	0.0043
Peak GDP/cap	$21,823	

2SLS

	parameter	std error
constant	-0.1415	0.2502
y	0.1095	0.0605
y^2	-0.0056	0.0037
p	-0.0513	0.0139
ecL	0.9770	0.0052
Peak GDP/cap	$17,620	

Within

	parameter	std error
y	0.4991	0.1784
y^2	-0.0240	0.0103
p	-0.0965	0.0204
ecL	0.9204	0.0208
Peak GDP/cap	$32,791	

W-2SLS

	parameter	std error
y	0.4633	0.2031
y^2	-0.0223	0.0114
p	-0.0939	0.0215
ecL	0.9292	0.0317
Peak GDP/cap	$32,464	

Random-2SLS

	parameter	std error
constant	0.5394	0.0286
y	0.0091	0.0070
y^2	0.0066	0.0004
p	-0.1200	0.0011
ecL	0.9022	0.0006
Peak GDP/cap	.....	

Average

	parameter
constant	57.4225
y	-11.4783
y^2	0.6423
p	-0.1527
ecL	0.1971
Peak GDP/cap	.....

Industrial and Other –

OLS

	parameter	std error
constant	-0.1178	0.2805
y	0.1124	0.0666
y^2	-0.0078	0.0040
p	-0.0494	0.0116
ecL	0.9958	0.0065

Peak GDP/cap $1,346

2SLS

	parameter	std error
constant	-0.1408	0.2812
y	0.1188	0.0668
y^2	-0.0085	0.0041
p	-0.0510	0.0117
ecL	0.9999	0.0072

Peak GDP/cap $1,084

Within

	parameter	std error
y	0.7082	0.2002
y^2	-0.0367	0.0115
p	-0.0626	0.0156
ecL	0.8070	0.0251

Peak GDP/cap $15,499

W-2SLS

	parameter	std error
y	0.9623	0.2230
y^2	-0.0497	0.0126
p	-0.0663	0.0157
ecL	0.7521	0.0326

Peak GDP/cap $16,012

Random-2SLS

	parameter	std error
constant	-0.6513	0.0202
y	0.2532	0.0048
y^2	-0.0155	0.0003
p	-0.0612	0.0007
ecL	0.9875	0.0005

Peak GDP/cap $3,525

Average

	parameter
constant	101.7700
y	-20.7266
y^2	1.0906
p	-0.1522
ecL	0.5676

Peak GDP/cap .....

Transportation –

OLS

	parameter	std error
constant	-0.5488	0.2608
y	y	0.0602
y2	y^2	0.0033
pgas	p	0.0091
carL	ecL	0.0091

Peak GDP/cap $52,974

2SLS

	parameter	std error
constant	-1.2956	0.3418
y	0.3895	0.0796
y^2	-0.0150	0.0038
p	-0.0638	0.0096
ecL	0.8888	0.0202

Peak GDP/cap $435,101

Within

	parameter	std error
y	0.5192	0.1332
y^2	-0.0191	0.0078
p	-0.0955	0.0121
ecL	0.8020	0.0240

Peak GDP/cap $799,405

W-2SLS

	parameter	std error
y	0.4959	0.1369
y^2	-0.0188	0.0078
p	-0.0938	0.0124
ecL	0.8195	0.0337

Peak GDP/cap $534,363

Random-2SLS

	parameter	std error
constant	-5.0235	0.1314
y	1.4371	0.0314
y^2	-0.0260	0.0017
p	-0.1101	0.0025
ecL	0.1363	0.0070

Peak GDP/cap $1 trillion

Average

	parameter
constant	23.9931
y	-4.8136
y^2	0.3367
p	-0.2399
ecL	0.0700

Peak GDP/cap .....

The results from the alternative methods of estimation, in Chapter 3, for each sector are as follow:

OLS

	parameter	std error
constant	-2.8715	0.2848
y	0.7113	0.0629
y^2	-0.0359	0.0035
p	-0.0545	0.0087
carL	0.9348	0.0046

Peak GDP/cap $20,064

2SLS

	parameter	std error
constant	-4.7558	0.5341
y	1.0912	0.1115
y^2	-0.0520	0.0053
p	-0.0469	0.0099
carL	0.8837	0.0127

Peak GDP/cap $36,037

Within

	parameter	std error
y	0.8551	0.1477
y^2	-0.0470	0.0083
p	-0.0703	0.0124
carL	0.9534	0.0124

Peak GDP/cap $8,927

W-2SLS

	parameter	std error
y	1.6637	0.3360
y^2	-0.0843	0.0163
p	-0.1100	0.0198
carL	0.8371	0.0445

Peak GDP/cap $19,298

Random-2SLS

	parameter	std error
constant	-24.2016	0.3126
y	5.8737	0.0692
y^2	-0.2907	0.0037
p	-0.3822	0.0055
carL	0.3365	0.0085

Peak GDP/cap $24,408

Average

	parameter
constant	-119.4105
y	26.3042
y^2	-1.3832
p	-0.1397
carL	0.1033

Peak GDP/cap $13,473

Appendix D

Forecasts - Alternative Growth Scenario (50% of Reference Growth Rate)

Country	1995			Assumed Avg Annual Growth %	2015			Peak Vehicle Stock/thou
	GDP/cap *1985 int $*	Passenger Veh/thou	LR Income Elasticity		GDP/cap *1985 int $*	Passenger Veh/thou	LR Income Elasticity	
Pakistan	1498	7	2.49	1.21	1905	18	2.39	330
India	1514	4	2.48	1.60	2081	13	2.30	214
China	1863	3	2.29	2.53	3071	15	1.90	114
Sri Lanka	2454	17	2.04	1.57	3349	43	1.62	192
Indonesia	2485	10	2.03	2.48	4059	41	1.61	183
Turkey	3898	47	1.62	0.74	4517	78	1.50	248
Thailand	4805	34	1.43	2.67	8137	132	0.89	228
Mexico	5402	93	1.32	0.20	5619	90	1.27	200
Malaysia	6556	128	1.14	2.15	10028	292	0.67	401
Greece	7043	209	1.08	0.67	8049	266	0.90	408
Portugal	7859	253	0.98	1.62	10834	409	0.59	516
S Korea	8465	134	0.91	3.16	15757	227	0.21	248
Spain	9874	359	0.77	0.84	11683	470	0.52	551
Ireland	11877	275	0.60	1.83	17076	406	0.12	421
Austria	13081	448	0.51	0.99	15940	504	0.20	521
Italy	13192	517	0.51	1.14	16535	591	0.16	607
Belgium	13668	420	0.47	0.85	16195	465	0.18	478
Netherlands	13805	365	0.46	0.70	15883	408	0.20	421
U.K.	14187	419	0.44	1.06	17519	476	0.10	484
France	14262	430	0.43	0.76	16580	483	0.15	493
Finland	14402	374	0.43	1.33	18755	417	0.03	421
Japan	14578	357	0.41	1.45	19443	459	0.00	464
Sweden	14860	416	0.40	0.74	17221	417	0.11	422
Denmark	14960	326	0.39	0.94	18024	387	0.07	392
Australia	16113	496	0.32	0.93	19374	522	0.00	523
Norway	16932	389	0.28	1.31	21946	388	0.00	388
Canada	17900	450	0.23	0.90	21408	504	0.00	504
U.S.A.	19369	573	0.16	0.72	22341	683	0.00	683
Average	....	270	....	....	....	329	....	395

Appendix E

The Byrd-Hagel Resolution - U.S. Senate, June 12th 1997

105th CONGRESS 1st Session - S. RES. 98

Expressing the sense of the Senate regarding the conditions for the United States becoming a signatory to any international agreement on greenhouse gas emissions under the United Nations Framework Convention on Climate Change.

IN THE SENATE OF THE UNITED STATES - June 12, 1997

Mr. BYRD (for himself, Mr. HAGEL, Mr. HOLLINGS, Mr. CRAIG, Mr. INOUYE, Mr. WARNER, Mr. FORD, Mr. THOMAS, Mr. DORGAN, Mr. HELMS, Mr. LEVIN, Mr. ROBERTS, Mr. ABRAHAM, Mr. MCCONNELL, Mr. ASHCROFT, Mr. BROWNBACK, Mr. KEMPTHORNE, Mr. THURMOND, Mr. BURNS, Mr. CONRAD, Mr. GLENN, Mr. ENZI, Mr. INHOFE, Mr. BOND, Mr. COVERDELL, Mr. DEWINE, Mrs. HUTCHISON, Mr. GORTON, Mr. HATCH, Mr. BREAUX, Mr. CLELAND, Mr. DURBIN, Mr. HUTCHINSON, Mr. JOHNSON, Ms. LANDRIEU, Ms. MIKULSKI, Mr. NICKLES, Mr. SANTORUM, Mr. SHELBY, Mr. SMITH of Oregon, Mr. BENNETT, Mr. FAIRCLOTH, Mr. FRIST, Mr. GRASSLEY, Mr. ALLARD, Mr. MURKOWSKI, Mr. AKAKA, Mr. COATS, Mr. COCHRAN, Mr. DOMENICI, Mr. GRAMM, Mr. GRAMS, Mr. LOTT, Ms. MOSELEY-BRAUN, Mr. ROBB, Mr. ROCKEFELLER, Mr. SESSIONS, Mr. SMITH of New Hampshire, Mr. SPECTER, and Mr. STEVENS) submitted the following resolution; which was referred to the Committee on Foreign Relations.

A RESOLUTION

Expressing the sense of the Senate regarding the conditions for the United States becoming a signatory to any international agreement on greenhouse gas emissions under the United Nations Framework Convention on Climate Change.

Whereas the United Nations Framework Convention on Climate Change (in this resolution referred to as the 'Convention'), adopted in May 1992, entered into force in 1994 and is not yet fully implemented;

Whereas the Convention, intended to address climate change on a global basis, identifies the former Soviet Union and the countries of Eastern Europe and the Organization For Economic Co-operation and Development (OECD), including the United States, as 'Annex I Parties', and the remaining 129 countries, including China, Mexico, India, Brazil, and South Korea, as 'Developing Country Parties';

Whereas in April 1995, the Convention's 'Conference of the Parties' adopted the so-called 'Berlin Mandate';

Whereas the 'Berlin Mandate' calls for the adoption, as soon as December 1997, in Kyoto, Japan, of a protocol or another legal instrument that strengthens commitments to limit greenhouse gas emissions by Annex I Parties for the post-2000 period and establishes a negotiation process called the 'Ad Hoc Group on the Berlin Mandate';

Whereas the 'Berlin Mandate' specifically exempts all Developing Country Parties from any new commitments in such negotiation process for the post-2000 period;

Whereas although the Convention, approved by the United States Senate, called on all signatory parties to adopt policies and programs aimed at limiting their greenhouse gas (GHG) emissions, in July 1996 the Undersecretary of State for Global Affairs called for the first time for 'legally binding' emission limitation targets and timetables for Annex I Parties, a position reiterated by the Secretary of State in testimony before the Committee on Foreign Relations of the Senate on January 8, 1997;

Whereas greenhouse gas emissions of Developing Country Parties are rapidly increasing and are expected to surpass emissions of the United States and other OECD countries as early as 2015;

Whereas the Department of State has declared that it is critical for the Parties to the Convention to include Developing Country Parties in the next steps for global action and, therefore, has proposed that consideration of additional steps to include limitations on Developing Country Parties' greenhouse gas emissions would not begin until after a protocol or other legal instrument is adopted in Kyoto, Japan in December 1997;

Whereas the exemption for Developing Country Parties is inconsistent with the need for global action on climate change and is environmentally flawed;

Whereas the Senate strongly believes that the proposals under negotiation, because of the disparity of treatment between Annex I Parties and Developing Countries and the level of required emission reductions, could result in serious harm to the United States economy, including significant job loss, trade disadvantages, increased energy and consumer costs, or any combination thereof; and

Whereas it is desirable that a bipartisan group of Senators be appointed by the Majority and Minority Leaders of the Senate for the purpose of monitoring the status of negotiations on Global Climate Change and reporting periodically to the Senate on those negotiations: Now, therefore, be it

Resolved, That it is the sense of the Senate that —

(1) the United States should not be a signatory to any protocol to, or other agreement regarding, the United Nations Framework Convention on Climate Change of 1992, at negotiations in Kyoto in December 1997, or thereafter, which would —

  (A) mandate new commitments to limit or reduce greenhouse gas emissions for the Annex I Parties, unless the protocol or other agreement also mandates new specific scheduled commitments to limit or reduce greenhouse gas emissions for Developing Country Parties within the same compliance period, or

  (B) would result in serious harm to the economy of the United States; and

  (C) any such protocol or other agreement which would require the advice and consent of the Senate to ratification should be accompanied by a detailed explanation of any legislation or regulatory actions that may be required to implement the protocol or other agreement and should also be accompanied by an analysis of the detailed financial costs and other impacts on the economy of the United States which would be incurred by the implementation of the protocol or other agreement.

SEC. 2. The Secretary of the Senate shall transmit a copy of this resolution to the President.

This resolution was passed without dissent.

Appendix F

Units and Conversions

Standard metric prefixes

kilo (k) = 10^3 (thousand) mega (M)= 10^6 (million)
giga (G) = 10^9 (billion) tera (T) = 10^{12} (trillion)
peta (P) = 10^{15} (quadrillion) exa (E) = 10^{18}

Standard conversions

(barrel to litres)
1 barrel = 158.987 L
(kilowatt hours to kilojoules)
1 kWh = 3600 kJ
(BTU to kilojoules)
1 BTU = 1.055056 kJ

Energy content of fuels

(gigajoules per metric ton)

Black coal:	13.5 to 30. [27][*]
Brown coal:	9.8
Coke:	27.0
Wood (dry):	16.2
Crude oil:	44.9

(megajoules per cubic metre)

Natural gas:	38.5 to 40.8 [39][*]

(petajoules per metric ton)

Uranium:	0.56

Source: *Energy Demand and Supply Projections Australia 1992-93 to 2004-05*, Australian Bureau of Agricultural and Research Economics (ABARE), Research Report 93.2, Canberra, 1993.

Average carbon dioxide emissions from burning fuels

(millions of metric tons of carbon per quadrillion BTU of energy)

Coal (average US quality): 26.13; Oil: 19.47; Natural gas: 14.47

Source: *Emissions of Greenhouse Gases in the United States 1997*, Energy Information Administration, Washington D.C., Document DOE/EIA-0573(97), October 1998.

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[*] Figures used for conversions in text.

Appendix G

Equations for the Parametric Example

This appendix presents the equations that describe the behavior of the economy when the functions take the special parametric forms specified in Chapter 5. We continue with the numbering in Chapter 5 for continuity.

The long-run sustainable growth economy

For given values of λ_k and k we need to solve (5.2), (5.20) and (5.21) for c_1, B_1, and B_2:

$$c_1 = \frac{\bar{c}_1 - \lambda_k}{2} \tag{5.42}$$

$$B_1 = \alpha k \tag{5.43}$$

$$B_2 = \frac{\chi_0}{\lambda_k\left(a_2 + b_2 e^{-\pi_2 t}\right)} - \frac{\chi_1}{\zeta} \tag{5.44}$$

where we have also used the assumed functional forms (5.33) and (5.35). We then can write the differential equations (5.22) and (5.23) as:

$$\dot{k} = k\left[A - \delta - \left(a_1 + b_1 e^{-\pi_1 t}\right)\alpha\right] - \frac{\bar{c}_1 - \lambda_k}{2} - \frac{\chi_0}{\lambda_k} - \frac{\chi_1\left(a_2 + b_2 e^{-\pi_2 t}\right)}{\zeta} \tag{5.45}$$

$$\dot{\lambda}_k = \lambda_k\left[\beta + \delta - A + \left(a_1 + b_1 e^{-\pi_1 t}\right)\alpha\right] \tag{5.46}$$

Equation (5.46) can be solved to yield:

$$\lambda_k(t) = K_0 \exp\left[\left(\beta + \delta + a_1\alpha - A\right)t - \frac{b_1\alpha}{\pi_1}e^{-\pi_1 t}\right] \tag{5.47}$$

for some constant K_0.

To obtain perpetual growth, we need, in particular, to have c_1 growing forever, and, thus, $\lambda_k \to 0$. Asymptotically, the per capita consumption of goods, c_1, approaches the satiation level $\frac{\bar{c}_1}{2}$ and almost all consumer expenditure falls on services. For this to happen, we see from (5.47) that the productivity of capital in producing output needs to be high enough relative to the time discount factor, the depreciation rate of capital and the asymptotic cost of producing the required energy input to production:

$$A > \beta + \delta + a_1\alpha\,. \tag{5.48}$$

To solve (5.45), we note that the integrating factor is given by:

$$\exp\left[\left(\delta + a_1\alpha - A\right)t - \frac{b_1\alpha}{\pi_1}e^{-\pi_1 t}\right] = \frac{\lambda_k(t)}{K_0}e^{-\beta t}.$$

One can show that k, therefore, must be given by:

$$k(t) = \frac{K_1 K_0 e^{\beta t}}{\lambda_k(t)} + \frac{\chi_0}{\beta\lambda_k(t)} + \frac{K_0}{\lambda_k(t)}e^{\beta t}\int \frac{\lambda_k(\tau)}{K_0}e^{-\beta\tau}\left(\lambda_k(\tau) - \frac{\bar{c}_1}{2} - \frac{\chi_1 p_2}{\zeta}\right)d\tau \tag{5.49}$$

where K_1 is another constant of integration. The transversality condition requires $e^{-\beta t}\lambda_k k \to 0$ as $t \to \infty$. From (5.49) and (5.48), guaranteeing that $\lambda_k \to 0$ as $t \to \infty$, the transversality condition will hold as long as the constant of integration, K_1, in the first term in (5.49) is equal to zero. The term in the integral in (5.49) satisfies the transversality condition. To see this, define

$$\lambda_k(t) = K_0 \exp\left[(\beta+\delta+a_1\alpha-A)t - \frac{b_1\alpha}{\pi_1}e^{-\pi_1 t}\right] < K_0 \exp\left[(\beta+\delta+a_1\alpha-A)t\right] = \hat{\lambda}_k(t).$$

It is true, therefore, that $0 < \lambda_k(t) \le \hat{\lambda}_k(t)$. Using the variable $\hat{\lambda}_k(t)$ to solve the integral term in (5.49), the integral term can be expressed as

$$-\frac{K_0\bar{c}_1 e^{(\beta+\delta+a_1\alpha-A)t}}{2\lambda_k(t)(\delta+a_1\alpha-A)} + \frac{K_0^2 e^{2(\beta+\delta+a_1\alpha-A)t}}{2\lambda_k(t)(\beta+2\delta+2a_1\alpha-2A)}$$
$$+\frac{K_0\chi_1 a_2 e^{(\beta+\delta+a_1\alpha-A)t}}{\zeta\lambda_k(t)(\delta+a_1\alpha-A)} + \frac{K_0\chi_1 b_2 e^{(\beta+\delta+a_1\alpha-A-\pi_1)t}}{\zeta\lambda_k(t)(\delta+a_1\alpha-A-\pi_1)}$$

All of these terms, when multiplied by $e^{-\beta t}\lambda_k$, approach zero as $t \to \infty$ provided $A > \beta+\delta+a_1\alpha$. Therefore, so must the integral solution with $\lambda_k(t)$ approach zero as $t \to \infty$ because it is bounded above by $\hat{\lambda}_k(t)$.

The remaining constant, K_0, in (5.47) and (5.49) will be determined ultimately by the initial condition $k(0) = k_0$. If the price of the backstop technologies began at their asymptotic values and fossil fuels were never used, we would have the expression

$$k(t) = \frac{\chi_0 e^{-(\beta+\delta+a_1\alpha-A)t}}{\beta K_0} + \frac{\bar{c}_1}{2(\delta+a_1\alpha-A)} + \frac{K_0 e^{(\beta+\delta+a_1\alpha-A)t}}{2(\beta+2\delta+2a_1\alpha-2A)} - \frac{\chi_1 a_2}{\zeta(\delta+a_1\alpha-A)} \quad (5.50)$$

to solve for K_0. In the current model, however, the actual value of K_0 will differ because the initial periods of resource extraction will alter the accumulation of capital before the economy enters the final "sustainable" regime.

If we let P_T denote the stock of CO_2 in the atmosphere at time T, when the burning of fossil fuel ceases, the differential equation (5.28) describing the evolution of P implies

$$P(t) = \bar{P} + e^{-\eta(t-T)}\left[P_T - \bar{P}\right] \quad \text{for } t \ge T$$

The present value of the externality for period T and beyond, discounted to $t = 0$, will be one of:

$$D_{1T} = \Phi_1\left(P_T - \bar{P}\right)e^{\eta T}\int_T^\infty e^{-(\eta+\beta)\tau}\lambda_k(\tau)d\tau$$

or

$$D_{2T} = \Phi_2\left(P_T - \bar{P}\right)^2 e^{2\eta T}\int_T^\infty e^{-(2\eta+\beta)\tau}\lambda_k(\tau)d\tau$$

depending on the measure of damages.

The fossil fuel and intermediate economy

The fossil fuel economy has four state variables instead of two, and at least some of the differential equations describing the evolution of the state variables are non-linear. Consider first the regime where fossil fuel supplies energy in both sectors of the economy. For current values of the state variables, k, S, λ_k, and λ_S, we solve for the current optimal values of the controls using (5.1), (5.2), (5.11) and (5.17):

$$c_1 = \frac{\bar{c}_1 - \lambda_k}{2} \tag{5.51}$$

$$\mu_E = \frac{\lambda_k g(S) - \lambda_S}{\varepsilon_1} \tag{5.52}$$

$$R_1 = \frac{\alpha k}{\varepsilon_1} \tag{5.53}$$

$$R_2 = \frac{\chi_0}{\lambda_k g(S) - \lambda_S} - \frac{\chi_1}{\zeta \varepsilon_2} \tag{5.54}$$

After substituting (5.51), (5.52), (5.53) and (5.54) into (5.7), (5.8), (5.10) and (5.19) (and using the functional forms specified in (5.33) – (5.41)) we obtain the following differential equations for the evolution of the state variables:

$$\dot{S} = \frac{\alpha k}{\varepsilon_1} + \frac{\chi_0}{\lambda_k g(S) - \lambda_S} - \frac{\chi_1}{\zeta \varepsilon_2} - n_0 e^{-n_1 t} \tag{5.55}$$

$$\dot{\lambda}_S = \beta \lambda_S + \lambda_k \gamma_1 \left[\frac{\alpha k}{\varepsilon_1} + \frac{\chi_0}{\lambda_k g(S) - \lambda_S} - \frac{\chi_1}{\zeta \varepsilon_2} \right] \tag{5.56}$$

$$\dot{k} = k(A - \delta) - \frac{\bar{c}_1 - \lambda_k}{2} - g(S) \left[\frac{\alpha k}{\varepsilon_1} + \frac{\chi_0}{\lambda_k g(S) - \lambda_S} - \frac{\chi_1}{\zeta \varepsilon_2} \right] \tag{5.57}$$

$$\dot{\lambda}_k = \lambda_k(\beta + \delta - A) + \alpha \left(\frac{\lambda_k g(S) - \lambda_S}{\varepsilon_1} \right) \tag{5.58}$$

Equations (5.55) – (5.58) can be simplified using a change of variables. Defining the marginal cost of energy to be $z \equiv \lambda_k g(S) - \lambda_S$, we observe that

$$\dot{z} = \dot{\lambda}_k g(S) + \lambda_k \gamma_1 \dot{S} - \dot{\lambda}_S .$$

Using (5.55), (5.57) and (5.58), one finds:

$$\dot{z} = z\left(\beta + \frac{\alpha g(S)}{\varepsilon_1} \right) + g(S)(\delta - A)\lambda_k - \lambda_k \gamma_1 n_0 e^{-n_1 t} \tag{5.59}$$

The remaining differential equations (5.55), (5.56). (5.58), can also be written in terms of z as:

$$\dot{S} = \frac{\alpha k}{\varepsilon_1} + \frac{\chi_0}{z} - \frac{\chi_1}{\zeta \varepsilon_2} - n_0 e^{-n_1 t} \tag{5.60}$$

$$\dot{k} = k\left(A - \delta - \frac{\alpha g(S)}{\varepsilon_1} \right) - \frac{\bar{c}_1 - \lambda_k}{2} - g(S)\left[\frac{\chi_0}{z} - \frac{\chi_1}{\zeta \varepsilon_2} \right] \tag{5.61}$$

$$\dot{\lambda}_k = \lambda_k(\beta + \delta - A) + \frac{\alpha}{\varepsilon_1} z \tag{5.62}$$

While (5.62) is linear in the variables, the remaining three differential equations are not. We solve this system of equations numerically. The boundary of the region will is defined by (5.13), where $\varepsilon_1 p_1 \lambda_k = z$.

When fossil fuel is used to produce services but not goods, the system of differential equations is a hybrid of the two systems already examined. Now, the optimal values of the controls will be given by:

$$c_1 = \frac{\bar{c}_1 - \lambda_k}{2} \tag{5.63}$$

$$B_1 = \alpha k \tag{5.64}$$

$$R_2 = \frac{\chi_0}{\lambda_k g(S) - \lambda_S} - \frac{\chi_1}{\zeta \varepsilon_2} \tag{5.65}$$

After substituting (5.63), (5.64), and (5.65) into the differential equations, we find that we can again simplify by defining the marginal cost of energy, z,as above. Following some algebraic manipulation, we can write the resulting differential equations as:

$$\dot{z} = \beta z + g(S)(\delta + \alpha p_1 - A)\lambda_k - \lambda_k \gamma_1 n_0 e^{-n_1 t} \tag{5.66}$$

$$\dot{S} = \frac{\chi_0}{z} - \frac{\chi_1}{\zeta \varepsilon_2} - n_0 e^{-n_1 t} \tag{5.67}$$

$$\dot{k} = k(A - \delta - \alpha p_1) - \frac{\bar{c}_1 - \lambda_k}{2} - g(S)\left[\frac{\chi_0}{z} - \frac{\chi_1}{\zeta \varepsilon_2}\right] \tag{5.68}$$

$$\dot{\lambda}_k = \lambda_k(\beta + \delta + \alpha p_1 - A) \tag{5.69}$$

As in the sustainable growth economy, (5.69) can be solved to yield (5.47). Substituting for λ_k in (5.66) makes the differential equation for $\dot{z}$ linear in z and S. The equation for $\dot{S}$ is, however, linear in z^{-1}, while the equation for $\dot{k}$ retains a term in z^{-1}. We also solve this system of equations numerically after specifying values for the parameters. The boundary of this region is defined by (5.27).

Appendix H

Iterative algorithm

We can describe the algorithm in the following steps:

1. Guess values for K_0 and the terminal date T when fossil fuel burning ceases. Numerically integrate the integral term in (5.49), approximating an upper bound by increasing the time horizon until the value of the integral does not change by more than "epsilon" small amount. This provides $k(T+j)$ (with $K_t = 0$) where j is number of time periods to the upper bound. We then find $k(T)$.

2. Using K_0 and T, solve (5.47) for $\lambda_k(T)$, and the boundary conditions $\lambda_S(T) = 0$ and $\varepsilon_2(T)p_2(T) = g(S)$ for $S(T)$ and $z(T) = \lambda_k(T)g(S)$.

3. Solve the differential equations describing regime 2, where fossil fuel is used only in the service sector, backward in time until the boundary $\varepsilon_1 p_1 \lambda_k = z$ is encountered.[1] The state variables at that time become the initial conditions for the first regime, where fossil fuel is used in both sectors.

4. Solve the differential equations describing regime 1 backward in time until either $t = 0$ or $k = k_0$, whichever comes first.

5. Compare the value of S at the stopping point with the assumed initial condition S_0. If $t = 0$ is encountered before $k = k_0$, the value of k at $t = 0$ is compared with the assumed initial condition k_0. Conversely, if $k = k_0$ is encountered first, $t = 0$ becomes the relevant "`initial condition". If the calculated values are sufficiently close to the required values proceed to step 8 below.

6. The mapping from the values for K_0 and T (used in step 2) to the target initial conditions ($S = S_0$ and *either* $k = k_0$ *or* $t = 0$) can be viewed as a pair of simultaneous equations. Obtain numerical partial derivatives of these mappings by slightly perturbing K_0 and T and solving the systems of equations two more times.

7. Use the Newton-Raphson algorithm to obtain new values for K_0 and T and return to step 2.

8. Once solutions have been obtained for $k(t)$, $S(t)$, $\lambda_k(t)$, $z(t)$, and the two "transition times", $T_1$and T, between regimes, the differential equations are solved forward to calculate an implied stock, P_T, of CO_2 at T. The previously calculated initial conditions for $\lambda_k(0)$ and $z(0)$, together with k_0, S_0, and P_0,form the initial conditions for a system of five equations (the four original equations plus (5.28)).

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[1] We used the MatLab implementation of the Runge-Kutta algorithm to solve the differential equations.

9. Use the terminal value P_T and numerical integration to calculate the cost, D_{1T} or D_{2T}, of the externality after the burning of fossil fuel ceases. The values P_T and D_{1T} or D_{2T}, together with the four state variables at T, provide six initial conditions for a six equation system (with (5.28) and (5.31) added to the four original equations).

10. The six equation system is solved backwards in time and the calculated value of P_0 compared with the known P_0. If the calculated value is too large, P_T is reduced (and conversely), D_{1T} or D_{2T} is recalculated and the system solved backwards again. The process is repeated until the initial value P_0 is obtained. The present value of the cost of the externality at $t = 0$ is then given by the calculated value $D_1(0)$ or $D_2(0)$.

Appendix I

Data sources and parameter values

The set of parameter values was constructed using data from a variety of sources. The time discount rate of approximately 5% annually may be considered a little high if we view it as a riskless rate of return. As a required real return on risky capital investments, however, 5% annually may be considered too low.

When suitable empirical proxies for the theoretical variables of interest were available, the various functional forms presented in Chapter 5 were estimated using simple regressions. For example, the parameter A was estimated using time series data on US per capita capital stocks from the Penn World Tables 5.6 and per capita output of goods from the US Statistical Abstract. Both series are denominated in real 1985 dollars. The output of goods was calculated by subtracting the consumption of services from total output. Implicit in this construction is the idea that services are consumed as they are produced.

The series for fossil fuel consumption was calculated using data from the CDIAC web-site[2] on flows of emissions by source since 1751. Standard conversions were used to relate CO_2 emissions to corresponding levels of aggregate oil consumption $R_1 + R_2$.[3] The state variable for mining costs, S, depends on cumulated production $R_1 + R_2$, but also additions to reserves, N. The latter was retrieved from the *International Energy Statistics Sourcebook*. Adding the change in total reserves to production for a given year provides us with an estimate of N. The series for S is then constructed by subtracting N from $R_1 + R_2$. Marginal mining costs were then obtained by assuming oil extraction costs are quadratic. Total cost was calculated using average cost and total production. The resulting marginal cost for production was estimated to lie in the range of $4.25 to $4.31 per barrel, which knowledgeable people in the oil industry in Houston informed us was a "reasonable" value. The parameters in the $g(S)$ function (5.36) were then obtained using OLS. The S variable used throughout is 25% of that calculated from the data. This is due to the fact that we are parameterizing all other variables using US data, and the US, historically, has accounted for approximately 25% of world oil consumption.

The parameters for the function N, equation (5.37), and the initial guess for the parameter $\bar{c}_1$ were obtained by fitting exponentials in time to the paths of N and of goods consumption derived as described above. For N, this provides direct estimates of n_0 and n_1. For $\bar{c}_1$, the exponential function provides us with an estimated value of the asymptote of c_1. By the form assumed for utility, we know this is one-half of $\bar{c}_1$. The initial guess values for χ_0 and χ_1 were calculated from the income expansion path implied by the utility function (5.33).

Values for α and ζ were obtained as follows. We set 1990 to be the initial observation, and re-scaled the data for consumption of goods and services and the burning of fossil fuels by setting k_0 and S_0 equal to one. Re-scaling in this way amounts to defining units of "goods", "services" and "energy". We also assume that the initial

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[2] The internet site is http://cdiac.esd.ornl.gov/home.html.

[3] In practice, of course, coal and gas were also burned for energy, but we have scaled all the calculations as if only oil is burned. This was done, in turn, because we have better data on oil costs and reserves.

efficiency in each sector, ε_1 and ε_2, equals one. Subsequent values for ε_1 and ε_2 should then be interpreted as efficiency gains relative to the starting levels. Direct substitution into equations (5.16) and (5.34) then yields α and ζ.

In order to arrive at reasonable values for the potential efficiency gains, we used data on the rate of change in efficiency in goods production (industry) to set a value for π_1 and assumed that ε_1 will asymptote to a level about 10% higher than it currently is. For the service sector, however, it is assumed that efficiency will increase by about 300%. This would, for example, be the impact of replacing the full stock of vehicles in the US with gas-electric hybrid vehicles. The rate of change is calculated by assuming that full diffusion of hybrid technologies will occur in 28 years, approximately four life cycles of US automobiles.

The values of the parameters for the backstop prices were chosen somewhat differently. The initial value of the backstop in goods production, p_1, was chosen so that it is about 2 times the size of $g(S_0)$. This is approximately the case for solar versus coal fired electricity, where average costs for the latter are around $0.09 per kilowatt-hour compared to over $0.20 per kilowatt-hour for solar energy. The rate of change assumed in the price of the backstop, as well as the lower bound, is subjective.[4]

The initial value of the backstop in services production, p_2, is chosen so that it is about 3 times larger than $g(S_0)$. This is more costly than solar power, which is reasonable considering the fact that solar generation is already economical in certain areas, but fuel cell technologies for transport applications are still in development stages. Again, the rate of change assumed in the price of the backstop, as well as the lower bound, is subjective.

The parameter values that were estimated using real data only serve to provide us with reasonable starting points. In order to arrive at the final values, iterations were performed on the various parameter values until the initial period reasonably matched the "real" world, and the paths of various endogenous variables were also reasonable. In particular, we attempted to replicate world data on long run economic growth rates, the share of services in total consumption expenditure and the share of total energy consumption in transport by manipulating the parameter values for the utility and production functions.

The parameter values for the accumulation of CO_2 are obtained in the following way. First, data for CO_2 flows from fossil fuel combustion were obtained from the CDIAC internet site referenced above. The same source also provides data on measured atmospheric concentrations of CO_2 in parts per million by volume. We obtained a conversion factor between tons of carbon and parts per million by volume from another internet site.[5] Rescaling the data so that $\bar{P} = 1$, we found $P_0 = 1.3$. Rescaling total energy consumption by dividing by S_0, and rescaling the flow of emissions from fossil fuels by

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[4] Chakravorty, Roumasset and Tse (1997) allow the rate of technological improvement (or price reduction) in the single backstop solar technology to vary from 50% to 30% per decade. Conversion costs, which are directly related to efficiency, are assumed either constant or to decline to 40% of their current levels at a rate equivalent to 50% per decade. They represent the marginal cost of fossil fuel with an exponential increasing function, but their estimated parameters for this function make it close to linear over the relevant range.

[5] http://www.radix.net/~bobg/faqs/scq.CO2rise.html

dividing by $\overline{P}$, we calculate θ as the ratio of the latter to the former. The rescaled data was also substituted into equation (5.28) to obtain η.