

Endogenous Substitution among Energy Resources and Global Warming

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The theory of resource extraction has focused primarily on extraction when there is a single, homogeneous demand for the resource. In reality, however, we observe the simultaneous extraction of different resources such as oil, coal, and natural gas and multiple demands such as transportation, residential and commercial heating, and electricity generation. This paper develops a model with multiple resources and grades and multiple demands. The model is simulated with extraction cost, estimated reserves, and energy demand data for the world economy. It is shown that if historical rates of cost reduction in the production of solar energy are maintained, more than 90 percent of the world's coal will never be used. The world will move from oil and natural gas use to solar energy. Global temperatures will rise by only about 1.5–2 degrees centigrade by the middle of the next century and then decline steadily to preindustrial levels, even without carbon taxes. These results are significantly lower than those predicted by the Intergovernmental Panel on Climate Change and suggest that the case for global warming may be seriously overstated.

I. Introduction

Popular predictions of the probable extent of global warming are based on models that do not completely account for price-induced energy conservation, including endogenous substitution between al-

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ternative energy sources, cost-saving improvements in extraction technology, and the rapidly declining cost of solar-powered electricity generation. To do so requires a disaggregated model that takes account of possibilities for energy consumers to convert to alternative fuel-using processes and simultaneously solves for efficiency prices of different energy sources and their respective scarcity rents. In what follows, we provide a multiple-resource, multiple-demand framework and develop a simulation model that yields the optimal extraction path for an arbitrary number of exhaustible resources and end uses.

The literature on resource extraction (e.g., Hotelling 1931; Dasgupta and Heal 1974) has focused mostly on developing a theory of resource extraction in which there is a single, homogeneous demand for the resource. A parallel effort has also been made (e.g., Solow and Wan 1976; Kemp and Long 1980) to examine the order of extraction of different grades of an exhaustible resource when there is a single demand function for the resource. Recently, Chakravorty and Krulce (1994) have extended this literature by examining the extraction profile of resources over time when there are multiple resources and multiple demands. In particular, they consider two exhaustible resources—oil and coal—and two demands—electricity and transportation—and obtain the time path of extraction in an infinite horizon planning model.

We modify an approach pioneered by Nordhaus (1973) in which he divided the energy sector into transportation, residential/commercial heating, industrial heating, and electricity sectors. We use this modified framework to simulate the effects of technological change in reductions in the cost of the backstop technology on resource extraction. Nordhaus's work was limited to examining the optimal path of resource extraction and its associated resource prices in the developed world and in the Middle East, an issue that was especially significant during the era of an OPEC-dominated world oil market. We also investigate the consequences for global warming of alternative extraction profiles, including those induced by different levels of technological change and carbon taxation.

Although there is a large and growing volume of literature on global warming (see, e.g., the *Journal of Economic Perspectives* [Fall 1993] Symposium on Global Climate Change), most of the existing studies model alternative scenarios of global warming by using a top-down growth-theoretic framework. These models assume a certain exogenous relationship between growth in gross domestic product (GDP) and the level of greenhouse gas emissions (as in Nordhaus [1991] and Peck and Teisberg [1992]) and determine the efficient level of emissions on the basis of alternative assumptions on the ben-

efits and costs of global warming. In contrast, Manne and Richels (1991) and Manne, Mendelsohn, and Richels (1993) use a model that explicitly accounts for the economywide impacts of rising energy costs. Their model considers alternative sources of energy supply such as hydroelectricity, nuclear energy, and oil, natural gas, and coal. In their models, production of an exhaustible resource is a fixed fraction of remaining reserves and resource prices are fixed exogenously.

The present paper models the consequences for global warming of energy use in a way that is consistent with Hotelling's theory of exhaustible resources. Current data on extraction costs and global reserves of the major exhaustible resources are used to develop marginal extraction cost functions for each resource. Costs of converting each resource into each end use and corresponding efficiency rates are obtained from engineering data. Thus the price and extraction paths of the exhaustible resources are determined endogenously. The focus of the paper is the analysis of fossil fuel extraction and global warming under alternative regimes of technological change and carbon taxes.

The results of the simulation under no technological change are comparable to those of earlier studies. What is new is the set of resource use and global warming projections developed under even conservative estimates of technological change. Under the assumption of current rates of cost reduction in the conversion of solar energy to electricity through photovoltaic technology, our results suggest that carbon emissions will continue to increase for the next three decades followed by a sharp drop as the electricity and transportation sectors shift from coal and oil, respectively, to solar generation. Global temperatures will correspondingly increase by about 1.5 degrees centigrade until 2055 and then decline steadily to zero.¹ A more conservative estimate on technological cost reductions in our model implies a maximum global temperature rise of about 2.3 degrees in 2095 followed by a steady decline as the world shifts from fossil fuels to solar energy. This "conservative" scenario combined with a carbon tax of \$100 per ton also generates a warming profile similar to the more optimistic case described above.

The results above suggest several major policy conclusions: (i) Global warming is a short-run problem of significance, at most, over the next hundred years or so; beyond this planning horizon, the problem declines over time under any reasonable scenario of technological change. (ii) The 1–2-degree centigrade temperature

¹ All figures for temperature change in this paper are relative to the historical year 1860.

rise predicted by our model is significantly lower than the 3–6-degree rise by the year 2100 projected by the Intergovernmental Panel on Climate Change (IPCC), an authoritative international panel of scientists (Schmalensee 1993).² (iii) The results also suggest that a reduction in damage from global warming can be achieved not only by taxing carbon emissions (which is well known) but by increasing research and development (R & D) in solar energy. A tax of \$5 per ton of carbon, which will increase the price of oil by \$0.65 per barrel, will generate \$10–\$15 billion in the United States alone. These revenues could be used to accelerate cost reductions for solar energy technologies.

For the sake of concreteness, this paper focuses on solar energy and, in particular, on reductions in the cost of photovoltaic technologies. A recent survey by Hoagland (1995) in *Scientific American* suggests that a mix of solar-based technologies including photovoltaic, electricity generation from biomass, wind turbines, solar-powered heat engines, and hydropower may predominate and contribute up to 60 percent of the electricity and 40 percent of the world's fuel requirements by the year 2025. These scientific predictions and the results from this paper for a specific solar technology suggest that it is important to explicitly include technological change in the economic analysis of global warming.

The paper is organized as follows. Section II outlines the basic model for multiple exhaustible resources and multiple demands. Section III develops the empirical model and describes the data used. Section IV analyzes the results, and Section V concludes the paper with a discussion on the policy implications and limitations of the model.

II. The Theoretical Model

The model proposed here abstracts from considering uncertainty and asymmetric information. Let there be I resources (e.g., oil, coal, natural gas, and solar energy) available for use in the energy sector, denoted by $i = 1, \dots, I$, and J energy demand sectors (e.g., electricity, industrial heating, residential/commercial heating, and transportation) denoted by $j = 1, \dots, J$. For simplicity, we assume that, except for solar energy, all the other I resources are exhaustible. We assume that the sun can, in effect, provide an unlimited amount of

² According to detailed cost estimates of Cline (1992) and Nordhaus (1992), a 3-degree warming would cause a cumulative damage of around 1–2 percent of world GDP. Given the considerable uncertainty regarding the global consequences of warming, even these authors admit that the numbers are rather speculative.

solar energy, which can then be converted into each end use by the application of certain technologies detailed below. Thus solar energy is regarded as a backstop technology, denoted by the subscript b when appropriate.

Each of the energy demand sectors faces a downward-sloping demand function given by $D_j(\cdot)$. We assume that demand is positive at all prices and that the area under each individual demand curve is finite. Since the process of conversion from a resource (such as oil) to an end use or demand involves frictional and other heat loss, let v_{ij} be the efficiency of conversion of a unit of resource i into demand j and $q_{ij}(t)$ be the extraction of resource i for use in demand j at any instant of time t . The efficiency factor $v_{ij} \in [0, 1]$ represents the proportion of delivered energy units relative to the total raw energy input contained in one unit of the resource. Generally $v_{ij} < 1$, so some part of the energy content of the resource input is lost in the process of energy conversion. Define $d_{ij}(t)$ as the net or delivered energy of resource i into demand j from $q_{ij}(t)$ units of the resource, so that

$$d_{ij}(t) = v_{ij} \cdot q_{ij}(t). \quad (1)$$

Thus demand in this model is measured in terms of energy services delivered, and not in terms of resources.³

The aggregate stock of resource i at time t is given by $Q_i(t)$. This includes proven reserves and estimated but yet undiscovered reserves of the resource. The cost of energy is the sum of extraction and conversion costs. Let c_i be the marginal cost of extraction of resource i . The conversion cost z_{ij} of resource i into end use j is equal to the amortized capital plus operation and maintenance costs of the equipment used in converting the resource into usable energy service for demand j , for example, a gasoline car for conversion of oil into transportation or a solar-powered water heater for conversion of the backstop solar energy into residential heating demand. Aggregation issues relating to these devices are discussed in more detail in Section IV. Thus both the efficiency factor v_{ij} and the conversion cost z_{ij} are resource and demand specific and each forms an $I \times J$ matrix. We assume that the extraction cost of the backstop technology is zero and that it has positive conversion costs to each end use given by z_{bj} , $j = 1, \dots, J$.

Let the discount rate be r , and define the sum of conversion and extraction costs as $w_{ij} \equiv c_i + z_{ij}$. With a continuous-time model, the

³ The concept of net or delivered demand was developed by Nordhaus (1977) in order to incorporate losses in energy conversion, e.g., energy lost as heat in the conversion of oil into mechanical energy.

objective is to maximize discounted producer plus consumer surplus over an infinite planning horizon as follows:

$$\max_{d_{ij}(t)} \int_0^{\infty} e^{-rt} \left[\sum_{j=1}^J \int_0^{\sum_{i=1}^I d_{ij}(t)} D_j^{-1}(\theta) d\theta - \sum_{j=1}^J \sum_{i=1}^I \frac{w_{ij}}{v_{ij}} d_{ij}(t) \right] dt \quad (2)$$

subject to

$$\dot{Q}_i(t) = - \sum_{j=1}^J \frac{d_{ij}(t)}{v_{ij}} \quad (3)$$

and z_{ij} given, $j = 1, \dots, J$. In (2), we assume that more than one resource may be used to supply any given demand, and the consumer surplus is summed over all demands, net of the costs of extraction and conversion. In both (2) and (3), we substitute $q_{ij}(t)$ using (1). Define $\lambda_i(t)$ to be the costate variable associated with the stock of resource i . Then the current value Hamiltonian for this problem is given by

$$\begin{aligned} H = & \sum_{j=1}^J \int_0^{\sum_{i=1}^I d_{ij}(t)} D_j^{-1}(\theta) d\theta - \sum_{j=1}^J \sum_{i=1}^I \frac{w_{ij}}{v_{ij}} d_{ij}(t) \\ & - \sum_{i=1}^I \lambda_i(t) \sum_{j=1}^J \frac{d_{ij}(t)}{v_{ij}}. \end{aligned} \quad (4)$$

For a proof of the existence of an optimal solution to a related problem, see the appendix of Chakravorty and Krulce (1994). Let the price of end use j be $P_j(t) \equiv D_j^{-1}[\sum_{i=1}^I d_{ij}(t)]$. Then the necessary conditions are straightforward and are given as follows:

$$\dot{Q}_i(t) = - \sum_{j=1}^J \frac{d_{ij}(t)}{v_{ij}}, \quad i = 1, \dots, I; \quad j = 1, \dots, J, \quad (5)$$

$$\dot{\lambda}_i(t) = r\lambda_i(t), \quad i = 1, \dots, I, \quad (6)$$

$$P_j(t) \leq \frac{w_{ij} + \lambda_i(t)}{v_{ij}}, \quad i = 1, \dots, I; \quad j = 1, \dots, J \quad (7)$$

(if $<$, then $d_{ij}(t) = 0$), and the transversality condition

$$P_j(T_j) = \frac{z_{bj}}{v_{bj}}, \quad j = 1, \dots, J, \quad (8)$$

where T_j are the switch points for transition to the backstop fuel for demand sector j . These conditions are straightforward extensions of Hotelling's rule to the case of multiple resources and multiple

demands. Condition (5) is the usual depletion equation stating that the stock of any resource will be depleted by the quantity extracted aggregated over all demands. Hotelling's rule, which states that the scarcity rent for an exhaustible resource will rise at the rate of interest, is shown to hold for each of the I resources in (6). Since scarcity rents grow exponentially over time, one implication of (6) is that the relative order of scarcity rents for the different resources is completely determined by their values at the initial time period.⁴ Equation (7) is the critical relationship that determines which resources are being used for which demand at any given instant of time. It says that if a particular resource is being used for a given demand, the price of the resource must be equal to the efficiency-adjusted sum of the extraction cost, the conversion cost of that resource for that demand, and the scarcity rent of the resource. In other words, the left-hand side of (7) is the marginal benefit and the right-hand side the marginal cost. Finally, (8) gives the usual condition for transition to the backstop technology in which the price in each demand sector j is exactly equated to the backstop price at the endogenously determined time T_j .

It is difficult to draw precise analytical conclusions on patterns of resource extraction in this very general model. In an earlier paper, Chakravorty and Krulce (1994) obtain a solution for the simple case of two resources and two demands under an assumed ordering of extraction plus conversion costs. In the present paper, we use the framework above for the development of an empirical model that addresses issues of global fossil fuel extraction and the generation of greenhouse gases.

III. Demand and Supply Parameters

In this section we provide the functional and parametric specifications for the empirical model. As in Nordhaus (1979), we assume that there are four demand sectors in the global economy: "specific" electricity, industry, residential/commercial, and transportation. Nonelectric industrial demand mainly consists of process and space heating. Residential nonelectric uses include space and other heating. Transportation comprises trucks, buses, autos, trains, ships, and airplanes. Demands in these sectors that are indirectly met by conversion of resources to electricity are grouped into the electricity sector. This classification separating resources directly used in each

⁴ In the simulation in Sec. IV, we use multiple grades of oil and coal. Grades of a resource are differentiated only by extraction cost. Condition (6) holds for each grade; i.e., the scarcity rent for each grade increases at the rate of interest.

demand from those used through conversion to electricity was developed by Nordhaus (1979), who defined the latter as "specific electricity." The important energy resources are oil, coal, and natural gas, which currently account for more than 90 percent of the earth's primary energy consumption (International Energy Agency 1995). Other resources such as nuclear, hydro, geothermal, and wind energy have much smaller shares of global energy use and are not explicitly included in this model as energy sources; instead they are netted out of the demand for petrochemical and solar energy sources.

The backstop technology is assumed to be solar energy with zero extraction costs but with nonzero costs of conversion into each demand. Although we have chosen solar energy as the backstop, another promising candidate is nuclear fusion, which is expected to be widely used by the middle of the next century (Furth 1995). In this paper, we use solar energy over nuclear fusion because the latter is still at an experimental stage whereas solar energy is already commercially viable, with annual U.S. sales of about \$1 billion (Hoagland 1995). There are various technologies that can be used to convert solar energy into usable forms of energy. They include biomass, wind turbines, solar-powered heat engines, and photovoltaic cells. We consider only photovoltaic technology, in which significant advances have been made in the last 20 years. Its high cost has long been a problem, but the application of modern manufacturing techniques is expected to bring down the cost to less than 10 cents per kilowatt-hour early in the next century (Hoagland 1995). Its commercialization is becoming a reality with Enron Corporation, the largest U.S. supplier of natural gas, and Amoco Corporation, currently building a 100-megawatt plant in Nevada to be commissioned in 1997.

Demand Equations

Sectoral annual demand functions are assumed to take the Cobb-Douglas form

$$D_j = A_j P_j^{\alpha_j} Y^{\beta_j}, \quad (9)$$

where α_j and β_j are, respectively, the price and income elasticities of demand, A_j is the constant coefficient, P_j is the price of delivered energy service j , and Y is the aggregate income or output level, measured by the GDP of the world economy.

For ease in programming, the empirical model is formulated as a discrete-time model. To reduce computational time, we take each time period to be L years, so that the annual growth rate of GDP,

TABLE 1
PRICE AND INCOME ELASTICITIES FOR ENERGY
DEMAND SECTORS

Final Demand Sector	Price Elasticity α_i	Income Elasticity β_i
Electricity	-.65	.92
Industry	-.52	.76
Residential/commercial	-.79	1.08
Transportation	-1.28	.81

SOURCE.—Nordhaus (1979).

g_t , is constant within each L -year time period t . This allows us to rewrite (9) as

$$D_{jt} = A_j P_{jt}^{\alpha_j} \left(\frac{Y_0}{1 + g_1} \right)^{\beta_j} \\ \times [(1 + g_t)^{\beta_j} + (1 + g_t)^{2\beta_j} + \dots + (1 + g_t)^{L\beta_j}] \quad (10) \\ \times [(1 + g_1)(1 + g_2) \dots (1 + g_{t-1})]^{L\beta_j},$$

where Y_0 is the GDP of the base year. Aggregation implies that P_j , the price of energy service j , is constant within each L -year time period and can be written as P_{jt} . Let γ_{jt} be defined as

$$\gamma_{jt} = A_j \left(\frac{Y_0}{1 + g_1} \right)^{\beta_j} \\ \times [(1 + g_t)^{\beta_j} + (1 + g_t)^{2\beta_j} + \dots + (1 + g_t)^{L\beta_j}] \quad (11) \\ \times [(1 + g_1)(1 + g_2) \dots (1 + g_{t-1})]^{L\beta_j},$$

which on substitution into (10) gives the inverse demand function

$$P_{jt} = \left(\frac{D_{jt}}{\gamma_{jt}} \right)^{1/\alpha_j} \quad (12)$$

This inverse demand function can be substituted into the maximization problem (2). The demand parameters remaining to be specified are the price and income elasticities for each sector and the constant A_j . For both the price and income elasticities, we follow Nordhaus (1979), and their values are shown in table 1. The constant A_j is computed from world GDP, energy consumption, and the prices of energy resources for a particular base year, using equation (9). The year 1990 is chosen as the base year, for which Y_0 , world

TABLE 2

PRICE AND WORLD GROSS CONSUMPTION OF ENERGY
RESOURCES IN 1990

Energy Resource	Price (\$/mmBtu)	World Consumption (Billion mmBtu)
Petroleum	3.73	108.04
Coal	2.08	41.67
Natural gas	2.35	42.56
Electricity	...	22.67

SOURCE.—The price figures for oil and natural gas are taken from British Petroleum (1992) and for coal from International Energy Agency (1992a). Data on world consumption of energy resources are obtained from International Energy Agency (1993).

GDP, was \$20,209.1 billion, and world consumption of electricity was 22.67 billion mmBtu (million British thermal units).⁵ World energy consumption and prices for 1990 are shown in table 2.

Detailed information on global resource use by sector is not readily available. We use shares computed for the OECD group of countries (shown in panel A of table 3) on the world consumption of each resource to obtain sectoral energy consumption in 1990, thereby making an assumption that OECD shares closely approximate world shares. For example, 19.17 percent of the oil consumed by the OECD countries (panel A) is used in industry, and the total world oil consumption is 108.04 billion mmBtu (table 2), which implies that world oil consumption by industry is 20.71 billion mmBtu (panel B). These figures are in turn multiplied by the corresponding efficiency factors (see below) to obtain 1990 consumption in delivered energy units (panel C).

Next we need to compute the price of delivered energy in each end use sector. Since these prices are not directly observable, they are computed from the prices of the fuels given in table 2 using the weights derived from panel B of table 3. These end use prices are shown in table 4. Substituting the values for world prices and consumption for each sector in (9) gives A_i and, hence, the complete system of annual demand equations:

$$\text{electricity: } D_1 = 0.015927 P_1^{-0.65} Y^{0.92};$$

$$\text{industry: } D_2 = 0.091866 P_2^{-0.52} Y^{0.76};$$

$$\text{residential/commercial: } D_3 = 0.006730 P_3^{-0.79} Y^{1.08};$$

⁵ World consumption figures for petroleum, coal, and natural gas are net of the resources used for electricity generation; electricity consumption figures include only electricity generated from petroleum, coal, and natural gas and exclude that from nuclear, hydro, and others. The figures are in delivered electricity units rather than raw energy resource units.

TABLE 3
ENERGY BALANCE FOR THE WORLD AND OECD COUNTRIES, 1990

	Residential/ Commercial*	Industry	Transportation	Electricity†
A. OECD Countries (mtoc)‡				
Oil	230.83 (16.67)	265.33 (19.17)	888.02 (64.16)	45.60
Coal	23.09 (12.35)	163.71 (87.59)	.10 (.06)	203.38
Natural gas	296.69 (53.04)	262.27 (46.89)	.36 (.07)	47.07
Total	550.61	691.31	888.48	296.05
B. World (Billion mmBtu)				
Oil	18.02	20.71	69.31	12.89
Coal	5.15	36.50	.022	46.22
Natural gas	22.58	19.96	.027	16.55
Total	45.75	77.17	69.359	75.66
C. World Delivered Energy (Billion mmBtu)				
Oil	14.41 (39.95)	14.50 (26.84)	20.79 (99.93)	4.07 (17.95)
Coal	3.60 (9.99)	25.55 (47.3)	.0056 (.03)	13.78 (60.79)
Natural gas	18.02 (50.06)	13.97 (25.86)	.0082 (.04)	4.82 (21.26)
Total (D_g)	36.03	54.02	20.8038	22.67

SOURCE.—Numbers for OECD countries are taken from International Energy Agency (1992c); world figures are taken from International Energy Agency (1992a).

NOTE.—Figures for world delivered energy are computed using information in panels A and B. Numbers in parentheses are row percentages (with electricity excluded) in panel A and column percentages in panel C.

* Includes all other residual sectors such as agriculture, public services, etc.

† Electricity consumed in the electricity sector is net of electricity generated from other sources such as nuclear, hydro, geothermal, etc.

‡ Figures in the electricity sector of OECD countries are in delivered energy units, not as gross resource input. mtoc stands for millions of metric tons of oil equivalent.

TABLE 4
WEIGHTED DELIVERED ENERGY PRICES FOR ENERGY DEMAND SECTORS IN 1990
(\$/Delivered mmBtu)

	Residential/ Commercial	Industry	Transportation	Electricity
Oil	\$7.26	\$2.14	\$74.86	\$3.44
Coal	\$2.27	\$5.71	\$0.03	\$10.87
Natural gas	\$5.12	\$1.42	\$0.03	\$3.18
Weighted price (P_g)	\$14.64	\$9.27	\$74.93	\$17.49

NOTE.—The figures above are computed using information in table 3, and efficiency factors and conversion costs.

TABLE 5

EFFICIENCY FACTORS

	Residential/ Commercial	Industry	Transportation	Electricity
Oil	.8	.7	.3	.3157
Coal	.7	.7	.25	.2983
Gas	.8	.7	.3	.2913
Solar	.1275	.1275	.1275	.15

SOURCE.—Efficiency figures are based on Office of Technology Assessment (1992a, 1992b, 1993), O'Callaghan (1993), and Ahmed (1994).

and

$$\text{transportation: } D_4 = 1.699235 P_4^{-1.28} Y^{0.81}.$$

Conversion Efficiency

A given resource may be converted to a particular end use through technological processes that have varying efficiencies; for example, conversion of oil to transportation is achieved through diesel, gasoline, and kerosene for autos, trucks, motorcycles, different types of airplanes, and so forth. The efficiency differences between them and even within any single category (e.g., gasoline cars with different fuel efficiencies) can be substantial. The same is the case in the residential sector, where space heating, space cooling, water heating, food storage, and lighting together account for 80 percent of sectoral energy consumption but efficiencies within each category (e.g., lighting or stove heating) may vary. Ideally, one would compute the average weighted efficiency of a resource in a given end use by listing the conversion efficiencies for each of the categories and subcategories mentioned above and weighting them by the proportion of the resource consumed in that activity. Except for electricity, use efficiencies for other resources are not well documented. Therefore, we simplify this process by choosing representative activities for each sector for which efficiency data are available. These are light-duty vehicles for transportation (more than half of the energy consumed in the U.S. transportation sector is used for light-duty vehicles [Department of Energy 1993]), stove heating for the residential/commercial sector, industrial process heating for the industrial sector, and electricity generation for "specific" electricity.

Efficiency values (see table 5) were computed using figures for different energy devices given in the Office of Technology Assessment (1992a, 1992b, 1993), O'Callaghan (1993), and Ahmed

(1994). Solar energy efficiencies are based on Ahmed (1994). Typical technologies in electricity generation are conventional steam engines powered by oil, coal, or natural gas. Although the efficiency figures for these devices are available, a better method for electricity was to use an input-output approach based on world data on electricity production by resources and consumption by sector available from the International Energy Agency (1992*b*) and the Office of Technology Assessment (1992*b*). As an illustration of the case of oil-based electricity generation, gross input of oil in energy units is 12.89 billion mmBtu and the output is 4.976 billion mmBtu of electricity. Netting out transmission and other losses yields a net output of 4.069 billion mmBtu, yielding an efficiency figure of 0.3157. Efficiency figures for solar energy in residential/commercial, industry, and transportation sectors are computed in two steps. First, sunlight is converted into electricity by photovoltaic systems with an efficiency of 0.15 (Ahmed 1994). Second, electrical energy is converted to each of the end uses with an efficiency of 0.85 (O'Callaghan 1993), yielding an aggregate efficiency of 0.1275.

Conversion Costs

The conversion cost of a resource into an end use per unit of delivered energy is given by the following relationship:

$$\text{conversion cost} \left(\frac{z_{ij}}{v_{ij}} \right) = \quad (13)$$

$$\frac{\text{annualized capital cost} + \text{operation and maintenance cost}}{\text{energy consumption} \cdot \text{efficiency factor} (v_{ij})},$$

where

$$\text{annualized capital cost} = K \frac{s(1+s)^m}{(1+s)^m - 1}, \quad (14)$$

K is the total capital cost of a conversion technology, s is the rate of interest, and m is the lifetime of the capital stock. Annualized capital costs, operation and maintenance costs, and energy consumption are all flow concepts. For simplicity, we ignore other costs such as the cost of transportation and refining.⁶

In the residential/commercial sector, stove heating is chosen as

⁶ Transportation costs can be incorporated by adding a constant; e.g., oil industry analysts add a constant \$0.50 per barrel to production costs. Including refining costs is more complicated and would require extension of the model to include joint products from refining crude oil such as gasoline, diesel, jet fuel, etc.

TABLE 6

COST OF CONVERTING ENERGY RESOURCES INTO END USES (\$/Delivered mmBtu)

	Residential/ Commercial	Industry	Transportation	Electricity
Oil	\$13.50	\$2.64	\$62.48	\$7.35
Coal	\$19.71	\$9.10	\$107.74	\$10.90
Gas	\$7.29	\$2.13	\$72.32	\$6.87
Solar:				
Electricity generation	\$86.12	\$86.12	\$86.12	\$73.20
Other costs	\$10.43	\$1.59	\$126.95	\$0.00
Total	\$96.55	\$87.71	\$213.07	\$73.20

SOURCE.—The conversion costs are calculated from the following sources: residential/commercial sector: Office of Technology Assessment (1992b); industry sector: database from the Argonne National Laboratory (Daly and Kosobud 1992); conversion cost of private car: Office of Technology Assessment (1992b) (coal conversion includes the cost of a gasoline car [\$18.744] plus coal liquefaction [\$8.19]; see Grainger and Gibson [1981]); electricity sector: Office of Technology Assessment (1992b) and International Energy Agency (1992b) for oil, coal, and gas; Ahmed (1994) for electricity generated with solar energy.

the representative technology. However, oil, coal, and solar energy are seldom directly used for stove heating. So we use liquefied petroleum gas (LPG), a crude oil product, as fuel. Since LPG generally has a higher price and is assumed to be a perfect substitute for natural gas, we approximate the cost of converting oil to LPG by the price difference between natural gas and LPG. For coal in residential use, the cost of coal gasification is used to compute the conversion cost. The conversion costs for solar energy in all end use sectors are computed indirectly by first converting solar energy into electricity. That is, conversion costs consist of two parts: the cost of generating electricity from sunlight plus the cost of transforming electricity into a specific end use. The matrix of conversion costs is summarized in table 6. One can observe that industrial process heating is cheaper than other processes, mainly because of the economies of large-scale production and a relatively high efficiency of energy use.

Extraction Costs

Extraction cost functions for energy resources are estimated using original data on proven and estimated reserves in different parts of the world and their cost of extraction compiled by the East-West Center Energy Program. The relevant tables for oil, coal, and natural gas are given in the Appendix (tables A1–A4). First we estimate the continuous extraction cost equations, which are functions of cumulative extraction, using nonlinear regression with alternative functional specifications. Since we expect marginal extraction costs to increase with cumulative extraction, exponential and *S* specifications were fitted. The cost equations and the R^2 values are as follows:

TABLE 7
EXTRACTION COST (\$/mmBtu) AND RESOURCE STOCKS
(Billion mmBtu) BY GRADE

Resource	Grade I	Grade II	Grade III
Gas	\$0.92 (6,683.98)		
Oil	\$0.60 (11,242.67)	\$3.47 (4,916.13)	
Coal	\$0.65 (225,622.35)	\$2.37 (121,354.2)	\$5.08 (82,068.59)

NOTE.—Numbers in parentheses are resource stocks in energy units (billion mmBtu).

$$\text{oil: } c_{\text{oil}}(t) = 0.1774 e^{0.000217 Q_{\text{oil}}(t)}, \quad R^2 = .960; \quad (15)$$

$$\text{coal: } c_{\text{coal}}(t) = 0.2827 e^{0.00000743 Q_{\text{coal}}(t)}, \quad R^2 = .997; \quad (16)$$

and

$$\text{gas: } c_{\text{gas}}(t) = e^{0.8908 - [3,264.7/Q_{\text{gas}}(t)]}, \quad R^2 = .992. \quad (17)$$

To reduce computational complexity and be consistent with the theoretical model, extraction cost functions estimated above are further approximated by step functions.⁷ For simplicity, we assume that there is only one grade of natural gas, two grades of oil, and three grades of coal; their costs of extraction are shown in table 7.

Growth of GDP

It is reasonable to expect the demand for energy to increase over time because of the growth in income, especially in the newly developing regions such as Asia, Latin America, and the former Soviet

⁷ The method used to obtain step extraction cost functions is illustrated here for natural gas. In this case, there is only one step; i.e., the step function is a constant function that intersects with the continuous extraction cost function (17). This constant extraction cost is bounded by the smallest and largest extraction cost values given by (17). Suppose that the value of the step function is \bar{c} . Then the cumulative extraction Q_c , for which the step function intersects with (17), can be written as $Q_c = 3,264.7 / (.8908 - \ln \bar{c})$. When cumulative extraction is less than Q_c , \bar{c} is greater than the extraction cost obtained from (17) and vice versa. Thus the absolute difference (diff) between the step function and (17) is

$$\text{diff} = \int_0^{Q_c} \bar{c} - e^{0.8908 - (3,264.7/Q)} dQ + \int_{Q_c}^{6,683.98} e^{0.8908 - (3,264.7/Q)} - \bar{c} dQ.$$

The step function is now determined by choosing the \bar{c} that will minimize diff. A similar method is used for oil and coal, which have two and three steps, respectively. There two and three levels of constant extraction cost are chosen to minimize diff.

Union. For instance, energy demands in the booming economies of the Asia-Pacific region alone are growing at the rate of 5–6 percent per year, although the world average is closer to 2 percent (International Energy Agency 1995). Average global GDP growth rates for the periods 1965–80 and 1980–90 were 4.0 and 3.2 percent, respectively (World Bank 1992). Some other studies on global warming (Organization for Economic Co-operation and Development 1993) have assumed a future GDP growth rate of 3.01 percent for 1990–2000, falling to 1.96 percent during 2050–75. We assume an intermediate figure of world GDP growth in 1990 at 3.0 percent, decreasing at the rate of 10 percent every decade.⁸

IV. Simulation

An algorithm is written in the programming language Pascal that guesses the six scarcity rents (three grades for coal, two for oil, and one for natural gas) in the initial time period. Since solar energy is available in infinite supply, its scarcity rent is zero. Since scarcity rents rise at the rate of interest (by [6]), their paths are completely determined by the initial guesses. This is possible because we use step functions. Resources are allocated to each demand at any instant of time by comparing their prices (see [7]) and choosing the one with the least price. Finally, when we search over the six-dimensional space of initial scarcity rents, suitably bounded by cost and demand functions, and use an annual rate of discount of 2 percent over all periods, the point that maximizes (2) yields the optimal solution. The following scenarios are examined.

The Baseline Model (BASE)

In this scenario the model is run as described in Section III, that is, with all the parameters fixed over time.

Technological Change in Solar Energy Conversion to Electricity

Technological change in the energy sector could affect the base model in several ways. For example, new horizontal oil-drilling techniques have substantially enlarged the stock of resources that can be extracted at any given cost; combined cycle technology in natural

⁸ See the discussion on the long-term world GDP growth rate in Nordhaus (1992) and Manne and Richels (1991). The Nordhaus method is more complicated and starts from estimating total factor productivity changes. Manne and Richels appeal to “conventional wisdom,” and their numbers on GDP growth rates are slightly more optimistic than ours.

gas engines has now made natural gas use in power generation economically competitive relative to oil. In this paper we focus more specifically on R & D that may affect the backstop technology—a decrease in the cost of solar energy conversion to electricity. Perhaps the most important study on the subject is a comprehensive survey of the future cost of renewable energy technologies (Ahmed 1994). Ahmed reviews cost projections estimated by numerous engineering studies and concludes that the cost of electricity generation using solar energy is expected to go down from 25¢ per kWh (\$73.2 per mmBtu) to around 4¢ per kWh in about three decades. Ahmed further expects the cost to continue to decrease and stabilize at approximately 2¢ per kWh. Other studies arrive at similar conclusions. For example, the National Renewable Energy Laboratory (1992) estimates that in the long run, large-scale production of electricity from solar energy will enable the cost to drop from 25¢–50¢ per kWh in 1991 to 5¢–6¢ per kWh in the period 2010–30.

There are two important issues that determine future projected costs of energy technologies. One is the size or the rate of growth of the market, and the other is the extent of R & D support. On the basis of reasonable estimates of the growth of sales of photovoltaic technologies, Cody and Tiedje (1992) project a fall in the cost of photovoltaic electricity from 40¢ per kWh in 1988 to 7¢–12¢ per kWh in 2010. The significance of R & D is emphasized in a Department of Energy (1990) study that is based on two different assumptions for the rate of R & D: a business-as-usual scenario and intensified R & D. Both scenarios (shown in fig. 1) suggest a steady decline in photovoltaic cost, albeit at different rates. The cost of photovoltaics under intensified R & D falls below the cost of electricity generated from fossil fuels around 2026. Finally, in a recent work on the commercialization of solar energy, Dracker and De Laquil (1996) compare pure and hybrid (combination of solar and fossil fuels in electricity generation) solar systems and predict that the cost of electricity will fall to 3.5¢–10.6¢ per kWh by 2005–10.

For the purposes of this paper, we adopt Ahmed's projections and set a lower bound for the conversion cost of solar energy at 2¢ per kWh. However, we vary the time path of cost reduction according to a business-as-usual and an intensified R & D scenario as explained below.

Decreasing Cost of Solar Energy (DCSE50)

This is the intensified R & D case, and it uses the forecasts of solar electricity generation costs by Ahmed, which suggest that the costs of electricity from solar energy would decrease at an approximate

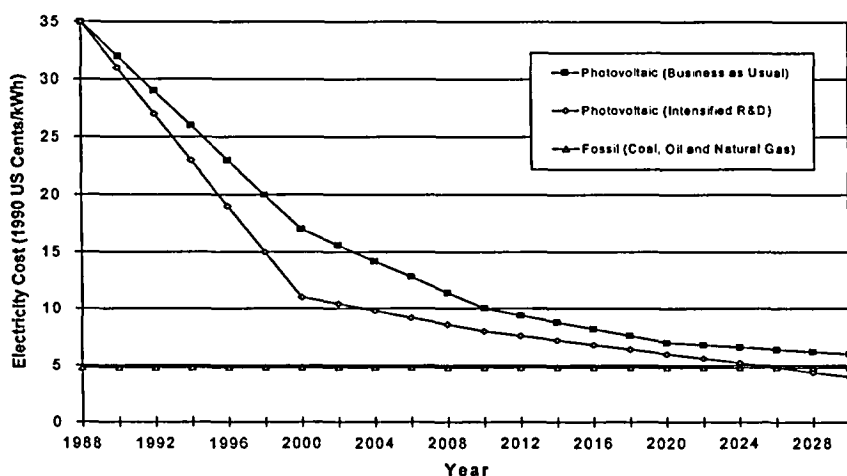


FIG. 1.—Projected cost of electricity. The cost of electricity from photovoltaic technologies is based on two different assumptions: business as usual and intensified R & D. All cost numbers are in 1990 constant prices. The cost of electricity from fossil fuels assumes base-load power. Source: Data on the cost of photovoltaic technologies are taken from Department of Energy (1990); data on fossil fuels are taken from Weinberg and Williams (1990) and the Office of Technology Assessment (1992b).

rate of 50 percent per decade. This would imply that the conversion cost would drop to reach 4¢ per kWh in about four decades.

Decreasing Cost of Solar Energy (DCSE30)

Here we adopt a more “pessimistic” business-as-usual scenario and assume only a 30 percent reduction in costs per decade, so that the costs of solar electricity generation would reach 4¢ per kWh in seven decades instead of four as above.

The use of solar energy is a two-part process. First sunlight is used to generate electricity. Then electricity is transformed into energy services in the various end use sectors. This implies that solar energy conversion costs are made up of two parts: the cost of converting solar energy to electricity and then the cost of converting from electricity to end uses. In both experiments, DCSE50 and DCSE30, the 50 and 30 percent reductions in conversion costs involve only the solar energy to electricity cost component. The second component, electricity to end use, has no reason to decrease at the same rates. Therefore, we keep it fixed for the residential/commercial and industry sectors. For the transportation sector (the electric car), there is reason to incorporate some cost reduction over time. Electric car technology is currently under intensive research for improvement, so we set a lower bound at 40 percent of the total conversion cost;

the remaining 60 percent is expected to decrease at the rate of 50 percent per decade. This assumption implies that service delivered from an electric car will cost roughly the same as the service from a gasoline car in about 30 years. This itself is a conservative estimate, given that currently the California Air Resources Board estimates the price difference between a gasoline car and an electric car to be about \$3,000–\$4,000 (Mestel 1994).⁹ The assumption above is realistic because electric cars are becoming a distinct reality, with one in 10 cars in California expected to be zero-emission (electric) by 2003 (2 percent by 1998), and 12 other states in the United States have either approved or are considering legislation requiring introduction of zero-emission vehicles by 1998.

An Across-the-Board Decrease in Conversion Costs (DCC)

Finally, we examine the impact of a decrease in conversion costs. In the absence of any compelling reasons why the conversion cost for a particular resource–end use combination should decrease at a different rate than others, we assume that they all decrease at an equal rate over time. Thus conversion costs for each resource are assumed to decrease to 40 percent of their present levels, at the rate of 50 percent per decade. The cost of solar energy is expected to decline as in DCSE50.

DCC with a Carbon Tax (DCCT100 and DCCT200)

Most carbon tax experiments choose tax rates that are designed to achieve a given carbon emission target at each time period. For instance, the targeted emission may be the 1990 level of CO₂ emissions or annual reductions of 1–2 percent from the 1990 base. Thus proposed tax rates usually vary by geographical region and increase over time. Tax rates varying between \$20 per ton of carbon in the initial years to \$2,000 per ton in future periods have been proposed (Organization for Economic Co-operation and Development 1993). Since our goal is to demonstrate the impact of carbon taxes in pushing forward the date of arrival of the backstop technology, we examine the effect of a flat tax of \$100 per ton and \$200 per ton of carbon on the DCC case. A flat tax of \$100 per ton of carbon would raise coal prices by about \$70 per ton or 300 percent and increase oil

⁹ Woodruff, Armstrong, and Carey (1994, p. 106) also reported that “Chrysler estimates that in volumes of 300,000, it could make electric vehicles, minus batteries, as cheaply as gasoline vehicles.” The problems of the electric car lie not only in the cost of production but in the reliability of the battery, the battery recharging time, and the drive range per charge. Our assumption that in 30 years the electric car will become a commercially feasible technology is not too optimistic.

prices by approximately \$8 per barrel. It would also raise roughly \$200 billion in revenues (Nordhaus 1993). Our purpose in performing these tax experiments is to demonstrate that taxes of this magnitude have a significant effect in reducing fossil fuel use and speeding the arrival of the cleaner backstop fuel.

*DCSE30 with a Carbon Tax of \$100 per Ton
(DCSE30T100)*

A carbon tax of \$100 per ton is imposed on DCSE30. This experiment will provide an insight into tax policies that could be implemented to control carbon emissions under "pessimistic" assumptions about solar energy cost reduction.

*BASE with Carbon Taxes of \$100 per Ton and \$200
per Ton (BASET100 and BASET200)*

Finally, the BASE model is run with uniform carbon taxes to examine the impact of taxation under a worst-case scenario of no technological change.

Simulation Results

The results can be summarized as follows.¹⁰

1. BASE model results are shown in table 8. Notice that each period is 10 years. With no technological change, it takes 370 years for the world to move completely to solar energy. In the electricity sec-

¹⁰ Since each time period in the model corresponds to 10 calendar years, annual carbon emission figures presented are model emissions divided by 10. This average is plotted in figs. 2, 4, and 6 against the midpoint of the 10-year interval. Carbon emissions in ton per mmbtu of resource input are obtained from Edmonds and Reilly (1985). They are 0.0203 for oil, 0.0251 for coal, and 0.0145 for natural gas. For the climate model used in temperature calculations, the historical base year is 1860, which is about the time of the industrial revolution. Model specifications are taken from Nordhaus's DICE model (see Nordhaus 1992). Let E_t denote global carbon emissions at time t . Then the various relationships are as follows: the accumulation of carbon concentration in the atmosphere, M_t :

$$M_t = 590 + 0.64E_t + 0.0167(M_{t-1} - 590);$$

the radiative forcing equation of CO_2 , F_t :

$$F_t = \frac{4.1 \ln(M_t/590)}{\ln(2)};$$

surface temperature in the atmosphere, T_t :

$$T_t = T_{t-1} + 0.226[F_t - 1.41 T_{t-1} - 0.44(T_{t-1} - T_{t-1}^*)];$$

and the temperature in the deep ocean, T_t^* :

$$T_t^* = T_{t-1}^* + 0.02(T_{t-1} - T_{t-1}^*).$$

TABLE 8

ENERGY RESOURCE USE SEQUENCE AND CARBON EMISSIONS

										CARBON EMISSIONS (Billion Tons)	
BASE					DCSE50						
Period	Electricity	Transportation	Residential	Industrial	Period	Electricity	Transportation	Residential	Industrial	Year	BASE
1	Coal	Oil	Gas	Oil	1	Coal	Oil	Gas	Oil	1995	7.1691
2	Coal	Oil	Gas	Oil	2	Coal	Oil	Gas	Oil	2005	8.8716
3	Coal	Oil	Gas	Oil	3	Coal	Oil	Gas	Oil	2015	10.6948
4	Coal	Oil	Gas	Coal	4	Coal	Oil	Gas	Oil	2025	13.3516
5	Coal	Oil	Gas	Coal	5	Solar	Solar	Gas	Oil	2035	15.6003
6	Coal	Oil	Gas	Coal	6	Solar	Solar	Gas	Oil	2045	17.8627
7	Coal	Oil	Gas/Coal	Coal	7	Solar	Solar	Solar	Oil	2055	21.7682
8	Coal	Oil	Coal	Coal	8	Solar	Solar	Solar	Solar	2065	25.2134
9	Coal	Oil	Coal	Coal	9	Solar	Solar	Solar	Solar	2075	27.9959
10	Coal	Oil/Coal	Coal	Coal	:	:	:	:	:	2085	32.0235
11	Coal	Coal	Coal	Coal	:	:	:	:	:	2095	35.458
12	Coal	Coal	Coal	Coal	19	Solar	Solar	Solar	Solar	2105	38.2686
:	:	:	:	:	20	Solar	Solar	Solar	Solar	2115	40.8508
28	Coal	Coal	Coal	Coal	:	Coal	Coal	Coal	Coal	2125	43.1531
29	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2135	45.129
30	Solar	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2145	46.7385
31	Solar	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2155	47.9489
32	Solar	Solar	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2165	48.7361
33	Solar	Solar	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2175	49.0859
34	Solar	Solar	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2185	48.0842
35	Solar	Solar	Coal	Coal	Coal	Coal	Coal	Coal	Coal	2195	46.6957
36	Solar	Solar	Solar	Coal	Coal	Coal	Coal	Solar	Coal	2205	46.4315
37	Solar	Solar	Solar	Solar	Coal	Solar	Solar	Solar	Coal	2215	45.7866
:	:	:	:	:	Solar	:	:	:	Solar	2225	44.7728
:	:	:	:	:	:	:	:	:	:	2235	43.4116
53	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	2245	41.7336
54	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	2255	39.7551
55	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	2265	38.1977
										2275	36.4222

NOTE.—Each period represents 10 years: the first period is 1990–99. Carbon emissions are shown only for the corresponding years.

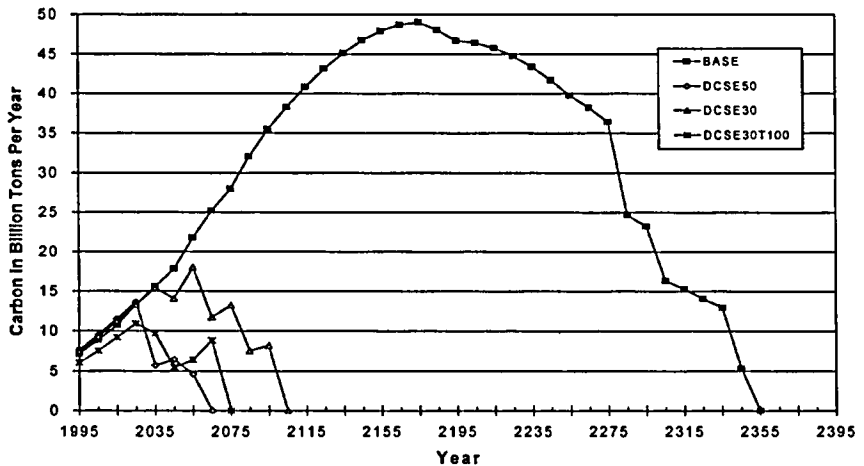


FIG. 2.—Worldwide carbon emissions. The four cases shown are the baseline (BASE), the cost of solar energy decreasing at the rate of 50 percent per decade (DCSE50), at the rate of 30 percent per decade (DCSE30), and at the rate of 30 percent per decade together with a carbon tax of \$100 per ton (DCSE30T100).

tor, coal is used exclusively until the transition to the backstop. The transportation sector relies primarily on oil until it is exhausted and then moves to coal. Oil is also used in industry for a relatively short period, followed by coal. Natural gas is exclusively used in residential/commercial heating and is replaced by coal on exhaustion. These results indicate the comparative advantages of oil in transportation, gas in heating, and coal in electricity generation and industry and conform reasonably well with real-world observation. In reality, of course, many other factors such as fuel availability, geographical location of resources, scale of project, security, and trade considerations must be incorporated into the choice of the appropriate energy source. Global carbon emissions around the year 2100 are approximately 37 billion tons, which is within the 22–40 billion tons range of six major global models surveyed by the Organization for Economic Co-operation and Development (1993) and reviewed by Dean and Hoeller (1993). BASE emissions are on the higher side relative to models that assume annual increases in energy efficiency of 0.5–1 percent over time.

2. BASE emissions peak in the year 2175 (49 billion tons) and then decline as each of the fossil fuels gets successively exhausted and is replaced by solar energy (fig. 2). Because of the slow atmospheric absorption of greenhouse gases, global temperatures continue to rise by a maximum of 6 degrees (relative to the historical base year 1860) until the year 2275 (see fig. 3). As long as cumulative emissions are above a certain threshold level, they continue to exert

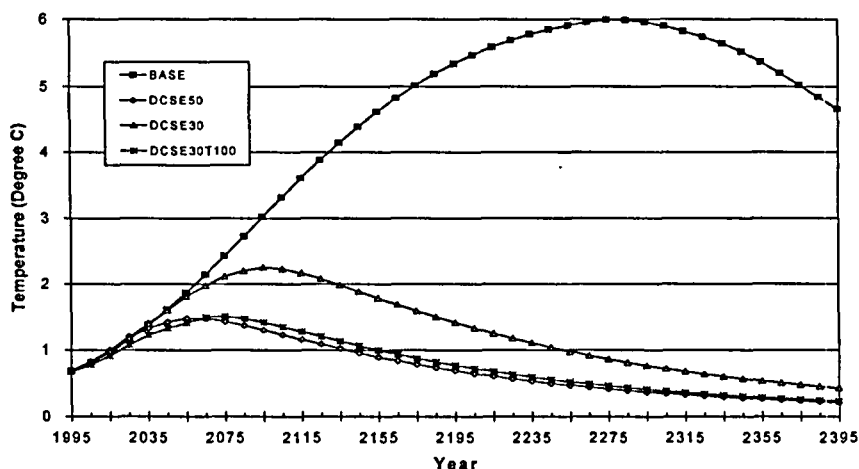


FIG. 3.—Change in global mean temperature. The four cases shown are the base-line (BASE), the cost of solar energy decreasing at the rate of 50 percent per decade (DCSE50), at the rate of 30 percent per decade (DCSE30), and at the rate of 30 percent per decade together with a carbon tax of \$100 per ton (DCSE30T100).

a positive effect on ambient temperatures. The model also generates 1995 emissions of 7.2 billion tons, which compares favorably with actual emissions of approximately 7 billion tons (Flavin and Tunali 1996).

3. Under rapid technological change in solar energy (DCSE50), there is an interesting specialization of resources: coal in electricity generation, oil in transportation and industrial use, and natural gas in the residential sector. In contrast to the BASE model, in which abundant coal reserves emerge as a backstop when oil is exhausted, under technological change, there is a direct transition from oil to solar energy in transportation and industry. Carbon emissions peak around 2025 at 13 billion tons, and temperature rises by 1.5 degrees and declines after 2055 (see figs. 2 and 3). In fact, it is comforting to know that under these rates of reductions in solar energy costs, the global mean temperature increases early in the next century but bounces back to the 1995 level in the year 2195.

4. With more "conservative" estimates of technological change (DCSE30), carbon emissions peak in 2055, that is, 20 years later than in DCSE50 (see fig. 2). Solar energy takes over in all sectors by 2105, 40 years late compared to the optimistic case. Temperature peaks in 2095, and it takes 320 years to return to the 1995 level, compared to only 100 years in DCSE50. The maximum level of aggregate emissions is about 18 billion tons reached in the year 2055.

5. However, even under conservative estimates of technological change (DCSE30), figure 2 shows that a uniform carbon tax of \$100

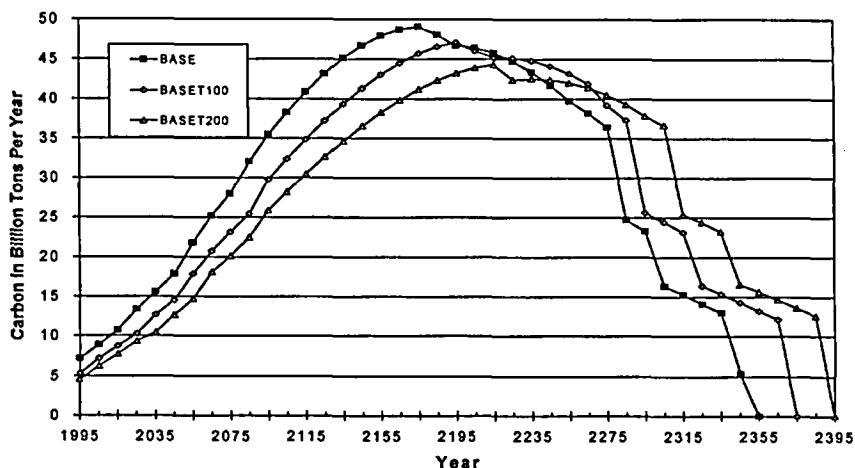


FIG. 4.—Worldwide carbon emissions. The three cases shown are the baseline (BASE), the baseline with a carbon tax of \$100 per ton (BASET100), and the baseline with a carbon tax of \$200 per ton (BASET200).

per ton (DCSE30T100) will simulate a resource use pattern very similar to the case of rapid technological change (DCSE50). This implies that a moderate level of carbon taxes plus slow improvements in solar technology could be used to simulate the effect of rapid technological change. Or, if there are no future cost reductions in solar technology, these carbon taxes could be used to subsidize the cost of solar energy, and the effect on global warming would be even less than under DCSE50. Of course the growth and distributional implications of such a tax, which implies that coal and oil prices would go up by \$70 per ton and \$8 per barrel, respectively, may be serious. An equally serious issue is who will collect and control these tax revenues: a carbon tax of \$100 per ton in the United States alone is expected to raise nearly \$200 billion (Poterba 1993).

6. Figure 4 shows that the effect of a carbon tax on the BASE model is to shift the emission curve down and to the right. That is, a \$100 tax shifts the emissions trajectory by about 20 years and reduces maximum emissions by about 2–3 billion tons. This experiment suggests an important conclusion: flat carbon taxes will only postpone global warming and reduce it somewhat (fig. 5). To achieve permanent and major reductions, a more complex tax structure differentiated across end use sectors may need to be created.

7. It is useful to examine the different scenarios with respect to the aggregate use of the fossil fuel stock. Under BASE, all resources are consumed. Under DCSE30, only 8 percent of the world's estimated coal reserves are exhausted. The rest is never used. Under

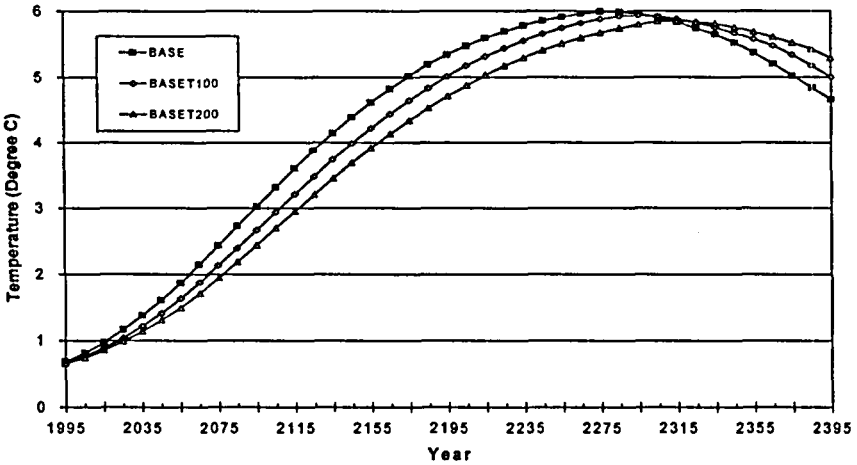


FIG. 5.—Change in global mean temperature. The three cases shown are the baseline (BASE), the baseline with a carbon tax of \$100 per ton (BASET100), and the baseline with a carbon tax of \$200 per ton (BASET200).

DCSE50, only 1.5 percent of the coal is used. Thus under any reasonable scenario for technological change, most of the earth's coal resources will never be used. Oil and natural gas, however, are both completely exhausted in all three situations.

8. We calculate the loss in world GDP from a rise in temperature using a relationship given by Nordhaus (1992).¹¹ It suggests that the maximum percentages of world GDP loss within the first 100 years are 0.32 percent, 0.74 percent, and 1.3 percent, respectively, for the three models DCSE50, DCSE30, and BASE. Beyond this 100-year horizon, the annual GDP loss will continue to rise only for the BASE model and will peak at 5.2 percent in the year 2285. Thus, under plausible assumptions on technological change, the losses are much less significant compared to BASE. However, models with a carbon tax will affect GDP levels to a greater extent.

9. The impact of an across-the-board reduction in all conversion costs is very different from the scenario above of a decrease only in solar energy conversion costs to electricity (figs. 6 and 7). Carbon emissions in this scenario will be higher than in BASE over the next 150 years. The maximum level of aggregate emissions reached is also higher: approximately 58 billion tons. A reduction in all conversion costs reduces the price of energy, thereby increasing energy con-

¹¹ According to Nordhaus, the percentage loss in GDP is $.00144 T_i^2$, where T_i is the global mean temperature.

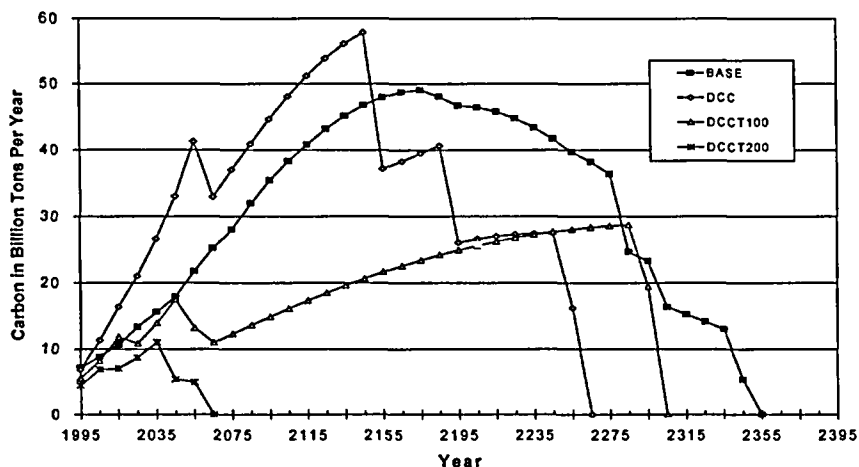


FIG. 6.—Worldwide carbon emissions. The four cases shown are the baseline (BASE), an across-the-board decrease in conversion costs (DCC), an across-the-board decrease in conversion costs together with a carbon tax of \$100 per ton (DCCT100), and an across-the-board decrease in conversion costs together with a carbon tax of \$200 per ton (DCCT200).

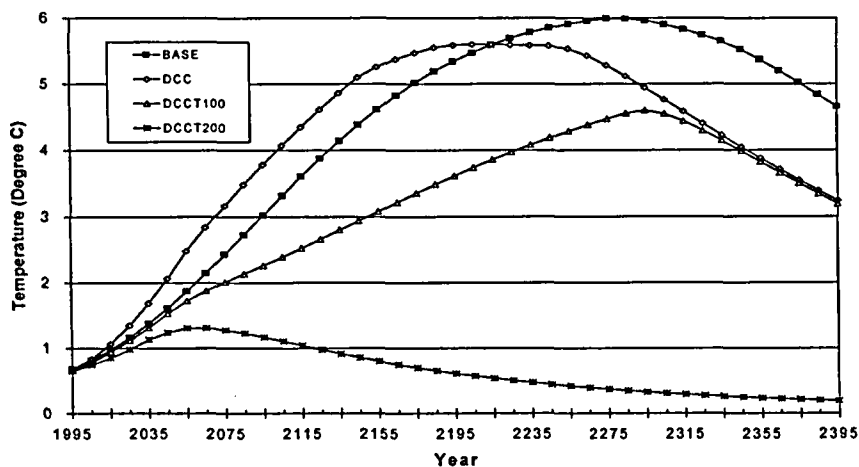


FIG. 7.—Change in global mean temperature. The four cases shown are the baseline (BASE), an across-the-board decrease in conversion costs (DCC), an across-the-board decrease in conversion costs together with a carbon tax of \$100 per ton (DCCT100), and an across-the-board decrease in conversion costs together with a carbon tax of \$200 per ton (DCCT200).

sumption (and carbon emissions) in the immediate future. Since solar energy costs also decrease as in DCSE50, emissions drop abruptly as fossil fuels are exhausted and each sector moves to solar energy. Carbon taxes of \$100 and \$200 per ton reduce emissions substantially. In fact, the latter tax will produce emissions comparable to DCSE50. These runs suggest that what seems to be important in affecting emissions is not technological change in the energy sector as a whole, but the magnitude of cost reductions in the backstop technology relative to that of fossil fuels.

V. Policy Implications and Further Research

Unlike most other economic analyses of global warming, this paper adopts a modified Hotelling framework and obtains the time path of exhaustible resource use and carbon emissions under plausible industry-based assumptions on technological change. It shows that moderate rates of technological change will lead to a global temperature increase of about 2.3 degrees, which will decline beyond the next century. However, faster rates of technological change such as those observed in the recent past will increase temperatures only by 1.5 degrees, which will decline after the year 2055.

These results are substantially different from projections made by the authoritative Intergovernmental Panel on Climate Change (1990) and other economic studies in two respects: First, their projections show a monotonically increasing global emissions curve until the year 2100. Our analysis shows a drastic decline in emissions around the middle of the next century under any reasonable estimate of technological development. Second, our predictions of a 1–2 degree centigrade temperature rise conform to the “low” range of most economic studies and are much lower than the IPCC “business-as-usual” scenario of a 3–6-degree rise. Indeed, the IPCC projections are reminiscent of the Club of Rome predictions of the 1970s, by whose account most of the earth’s minerals would have been exhausted by today. If current rates of R & D and interfuel substitution possibilities are recognized, a 1–2-degree temperature rise may need no or little policy intervention, given the considerable skepticism regarding the magnitude and distribution of the impacts of the warming process.

These results also suggest the need to adopt policies that ensure continued R & D in solar energy research and in other promising backstop technologies. In fact, given the dramatic rise in environmental consciousness all over the world, carbon taxes could be used to finance R & D as well as mitigate negative impacts, especially in the case of the poorer developing countries. For example, the U.S.

nuclear fusion program has been cut from a level of \$357 million in 1995 to \$244 million in 1996 (see Department of Energy 1996). Annual federal expenditures in solar energy research are even lower. These research programs can be sustained at much higher levels by using a minuscule portion of any carbon tax receipts.

Our analysis indicates that a transition to the backstop technology may be the only viable solution to the threat of global warming. As such, government policies, while recognizing that fossil fuels are going to be the most economical energy option until about the middle of the twenty-first century, also need to promote the use of solar-based technologies in the longer run. This realization may already be happening. For example, Detroit-based auto companies have active programs to develop cars running on electricity. The California legislature has recommended that by 1998, at least 2 percent of all the vehicles in the state must be run on electricity. The U.S. Department of Energy has granted tax exemptions to the Enron-Amoco solar power plant in Nevada, making its power cheaper than that generated by oil, coal, or gas. The immediate benefits of such regulation can be debated, but promotion of these ideas may be appropriate in the long run.

There are several limitations of this study that could be overcome by further research. One follows from the assumption that energy users have perfect foresight about future prices and can time their investments in alternative fuel-using technologies accordingly. To the extent that this is not so, transitions to new energy sources will be more costly, especially in the retrofitting of existing plant and equipment, and will also require adjustment on the part of consumers. As a result, transition from one fuel to another will be much slower than predicted by the programming model used in this study. Perfect information is also assumed with respect to the cost and demand parameters. The discount rate is assumed fixed. Changes in any of these parameters would affect the results. While the estimates of petrochemical resources on which we have relied include anticipated discoveries, to the best of our knowledge such forecasts do not include the extent to which rising energy prices will induce accelerated exploration. For example, even a decade ago, few analysts would have predicted the large discoveries of oil in the non-OPEC world (e.g., Venezuela) and the emergence of non-OPEC countries as dominant producers of oil.

Each sector could be further disaggregated. For example, the industrial sector could be further divided into different types of industries, for example, petrochemicals, agriculture, mining, and so forth. Resource stocks could be subdivided by quality (e.g., coal of varying sulphur content, sweet and sour crudes), and refining and transport-

tation could be explicitly included in the model. More important, the world could be divided into subregions, each with its own demand and supply characteristics and the option to trade.

Although we have focused on solar energy as the most likely backstop resource, other technologies such as geothermal and hydro may also be important, even if water shortages around the world may make the latter only a limited option. Some energy experts believe that nuclear fusion may be an equally viable backstop technology (see Conn et al. 1992; Furth 1995; Hoagland 1995). In the United States, nuclear fusion is expected to be commercially viable by the year 2040. It is then possible to have two backstop technologies arriving at about the same time, creating opportunities for specialization.

Appendix

This Appendix contains supplementary data tables. Tables A1–A4 provide the basic information for the determination of extraction cost functions. Table A5 illustrates the calculation of the conversion cost for natural gas.

TABLE A1
COST DISTRIBUTION OF OIL RESERVES

	Billion Barrels	5th Percentile: Low Cost (\$/Barrel)	95th Percentile: High Cost (\$/Barrel)
Cumulative production	681	\$0.50	\$4.50
Proven reserves	924	\$1.99	\$6.35
Asia-Pacific	41	\$3.50	\$16.00
Western Europe	14	\$5.50	\$15.00
USSR/Eastern Europe	62	\$2.50	\$8.00
Middle East	585	\$1.50	\$4.00
Africa	60	\$1.50	\$8.00
Latin America	119	\$2.00	\$7.00
North America	42	\$6.00	\$20.00
Undiscovered	469	\$4.52	\$17.04
Asia-Pacific	75	\$5.50	\$25.00
Western Europe	34	\$5.50	\$20.00
USSR/Eastern Europe	111	\$2.50	\$10.00
Middle East	103	\$2.00	\$7.00
Africa	39	\$3.00	\$10.00
Latin America	23	\$3.50	\$12.00
North America	84	\$10.00	\$35.00
Enhanced recovery	97	\$12.00	\$30.00
Superheavy Orinoco	267	\$14.00	\$22.10
Bitumen processing	308	\$18.50	\$30.80
Total	2,746		

SOURCE.—East-West Center Energy Program.

TABLE A2
ESTIMATED LONG-TERM WORLD CRUDE
SUPPLY SCHEDULE

Production Cost (\$/Barrel)	Cumulative Production (Billions of Barrels)
.00	.00
.50	34.55
1.50	188.78
2.00	312.09
2.50	484.79
3.00	657.48
3.50	830.18
4.00	1,002.88
4.50	1,199.03
5.00	1,346.05
5.50	1,459.02
6.35	1,651.07
10.00	1,824.17
12.00	1,898.56
14.00	1,991.15
17.00	2,200.11
18.50	2,292.79
22.00	2,496.02
30.00	2,733.57
31.00	2,761.60
40.00	2,786.00

SOURCE.—Based on table A1.

TABLE A3
ESTIMATED LONG-TERM WORLD COAL SUPPLY SCHEDULE

PRODUCTION COST (\$/Ton)	PRODUCTION COST (\$/Barrels of Oil Equivalent)	CUMULATIVE PRODUCTION	
		Billion Tons	Billion Barrels of Oil Equivalent
.00	.00	.0	.0
5.00	1.71	100.0	486.7
6.00	2.05	1,100.0	5,353.3
8.00	2.74	2,200.0	10,706.7
10.00	3.42	3,500.0	17,033.3
15.00	5.14	5,500.0	26,766.7
20.00	6.85	7,000.0	34,066.7
25.00	8.56	8,500.0	41,366.7
30.00	10.27	9,000.0	43,800.0
35.00	11.99	9,700.0	47,206.7
40.00	13.70	10,000.0	48,666.7
45.00	15.41	10,500.0	51,100.0
50.00	17.12	10,800.0	52,560.0
60.00	20.55	11,700.0	56,940.0
80.00	27.40	13,500.0	65,700.0
100.00	34.25	14,200.0	69,106.7
110.00	37.67	15,200.0	73,973.3

SOURCE.—East-West Center Energy Program.

TABLE A4
ESTIMATED LONG-TERM WORLD NATURAL GAS SUPPLY SCHEDULE

PRODUCTION COST (\$/Thousand Cubic Feet)*	PRODUCTION COST (\$/Barrel of Oil Equivalent)	CUMULATIVE PRODUCTION	
		Trillion Cubic Feet	Billion Barrels of Oil Equivalent
.00	.00	.00	.00
.20	1.07	1,179.73	220.60
1.00	5.37	2,809.00	525.25
1.50	8.05	6,162.96	1,152.41

SOURCE.—East-West Center Energy Program.

* Roughly equal to 1 mmBtu.

TABLE A5

CONVERSION COST FOR THE RESIDENTIAL/COMMERCIAL SECTOR

	Gas Stove	Electric Stove	LPG Stove	Coal	Solar
Total capital cost (<i>K</i>) (\$)	600	500			
Annualized capital cost (\$/year)	48.12	40.1			
Lifetime (<i>m</i>) (years)	20	20			
Annual energy consumption per household (mmBtu/year)	23.7	23.7			
Annual operation and maintenance cost (\$/year)	90	170			
Interest rate (<i>s</i>) (%)	5	5			
Conversion cost (\$/mmBtu)	5.83	8.87	10.8	13.8	12.31
Conversion cost (\$/delivered mmBtu)*	7.29	...	13.5	19.71	96.55

SOURCE.—Office of Technology Assessment (1992a).

NOTE.—The conversion cost for LPG stove is obtained by adding the price difference between LPG and natural gas to the cost of the gas stove. For coal, the cost of coal liquefaction is added to the cost of the gas stove (see Grainger and Gibson 1981). The conversion cost of solar is obtained by adding the cost of electricity generation to that of the electric stove.

* Conversion cost for delivered mmBtu is obtained by dividing the conversion cost per mmBtu by the corresponding efficiency factor from table 5.

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