TRANSITION FROM FOSSIL FUELS TO RENEWABLE ENERGY: EVIDENCE FROM A DYNAMIC SIMULATION MODEL WITH ENDOGENOUS RESOURCE SUBSTITUTION

by

Ujjayant Chakravorty and Kin-Ping Tse*

ABSTRACT

This paper applies an economic model of climate change that is based on endogenous substitution of energy resources to determine the effect of advances in renewable technology on aggregate and sectoral fossil fuel use and energy prices. It uses a Nordhaus type partial equilibrium model of the energy sector with four demand sectors —electricity, transportation, residential and industrial energy and three of the commercially most important exhaustible resources —oil, coal and natural gas. The findings suggest that among the major commercial fuels, oil and natural gas use are not very sensitive to changes in the cost of solar energy, while coal use is expected to reduce drastically as solar becomes more economical. These results suggest that research and development in renewable energy may play only a limited role in the short run, while creating the basis for a transition to a sustainable energy economy over the longer time horizon.

NONTECHNICAL ABSTRACT

This paper focuses on the path of transition from fossil fuels to renewable energy resources. In particular, it examines how fast the world economy will move away from using commercial exhaustible fuels such as oil, coal and natural gas to renewable energy resources such as solar energy. The paper uses an empirical model of the world energy economy developed by the authors in earlier work. The point of departure of this model is that as the exhaustible resources become scarce over time, their price increases, and alternative fuels such as solar energy become economically feasible. Most economic models including those that predict various climate change scenarios, assume fixed extraction rates of the major fossil fuels and therefore cannot derive price-induced extraction paths for the various energy resources. The model is dynamic and has four demand sectors –electricity, transportation, residential and industrial energy. Extraction costs of each of the fossil fuel resources, their conversion efficiency in each demand sector and the cost of conversion(e.g., the cost of a passenger car that converts oil into transportation units) are explicitly accounted for in the model. Our results suggest that if solar energy costs remain unchanged, currently known oil and natural gas reserves will be exhausted in the near future and coal will be the main supplier of energy. However, if the historic evidence of solar energy cost reductions from research and development are extrapolated into the future, solar energy will substitute for coal in the second half of the 21st century. Aggregate coal use over time is found to be highly sensitive to the assumed rate of decrease in the cost of solar energy.

Major energy efficiency programs and domestic carbon reductions as proposed by the Kyoto Protocol will boost the use of cleaner fuels such as natural gas in the short run, but in the long run, there will be a need to find economic substitutes for coal, which is available in abundant

quantities. Development of clean coal technologies that reduce carbon emissions per unit of coal burning, could help in buying more time for the transition to a cleaner renewable resource. The paper suggests that current research and development into energy alternatives is miniscule compared to the revenue that could be generated from even moderate carbon taxes and one policy option may be to channel part of an energy tax into research and development.

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DYNAMIC SIMULATION MODEL WITH ENDOGENOUS RESOURCE SUBSTITUTION

I. Introduction

Most economic analyses of global warming tend to focus on the time path of carbon under

alternative assumptions of economic growth assuming a certain relationship between the level of

economic growth and particulate emissions (see for e.g., Nordhaus 1991; Peck and Teisberg

1992). Others have taken rising resource prices as exogenously given and have examined the

substitution of alternative energy resources such as oil, coal, natural gas, nuclear and hydro

electric energy and their impacts on greenhouse gas emissions (Manne and Richels 1991; Manne,

Mendelsohn, and Richels 1993). Although these studies have made a fundamental impact on our

understanding of the relationship between economic growth and global warming, another

literature has emerged that attempts to derive time paths of carbon emissions based on the

Hotelling theory of exhaustible resources (Hotelling 1931). This literature (Chakravorty and

Krulce 1994; Krulce, Chakravorty, and Roumasset 1996) uses the multi-sectoral energy sector

model proposed by Nordhaus (1973) to extend the standard Hotelling results from a single

demand, multiple grades framework (e.g., Herfindahl 1967; Kemp and Long 1980) to

independent multiple demands, e.g., transportation, residential/commercial use, industrial and

electricity sectors. This framework allows for endogenous substitution of resources in each sector

based on the total "cost" of a resource - the sum of its extraction cost, scarcity rent and

conversion cost to each demand.

Recently Chakravorty, Roumasset, and Tse (1997), hereafter called CRT, have developed

an empirical model using this extended Hotelling framework to address the issue of a decline in

backstop technology prices on global warming. In what follows, we adopt the CRT model to examine the effect of technological change on substitution among energy resources. That is, we ask the following questions: (i) how do advances in renewable energy technology affect aggregate and sectoral fossil fuel use (i.e., oil, coal and natural gas) in the next century and beyond ? (ii) how does sectoral energy demand vary with different rates of cost reduction in the backstop technology, and finally, (iii) how will sectoral energy prices change under alternative assumptions about technological progress ?

The findings suggest several policy conclusions that increase our understanding of the nature of resource substitution and the potential impact of the role of renewables, some of which is counter-intuitive if the traditional textbook Hotelling theory is applied. The results suggest that oil and natural gas use is not very sensitive to the cost of solar energy, while coal use is expected to decrease radically as solar becomes economical. Oil use increases while coal use decreases with higher rates of solar cost reduction. Even under rapid rates of cost reduction in renewables, our model suggests that energy prices will continue to rise significantly at least over the next 50 years. The benefits from major technological change in renewables may only be realized late in the next century. Policy measures such as carbon taxes will only shift the incidence of warming and other environmental impacts over time. Carbon taxes make oil and natural gas cheaper relative to coal and increase their rate of depletion. New clean coal technologies that are under development may kick in relatively early in the 21st century in which case there will be a significant reduction of carbon emissions.

These results have important implications for energy policies in the Annex I countries under the Kyoto Protocol who are expected to make major shifts in energy use patterns to meet their commitments under the Kyoto Protocol. Our results suggest several important policy

measures: (i) first, efforts need to be made to find long-run solutions to fossil fuel dependency, especially in searching for substitutes for coal which is available in cheap and abundant supply. The Clinton Energy Initiative announced recently that aims to increase R&D funding for renewables is a step in this direction. Other possible measures include tax and subsidy incentives for solar-powered electricity generation, installation of solar home heating, and wind energy installations; (ii) second, in the short run, which would mean the next 30-40 years, measures to improve the efficiency of energy consumption, which can effectively increase the available energy stock and will make a significant impact, should be promoted. Also, to meet the environmental and energy security objectives, the commercialization of clean-coal technologies and the expansion of natural gas use may be imminent. To some extent this is already happening as coal-fired power generation in the U.S. and other countries shifts to natural gas; (iii) third, in the more immediate future, other methods such as regional bubbles and emissions trading between developed and developing countries may work towards reducing the environmental cost of fossil fuel use.

The results also have a bearing on the recent energy market deregulation in the developed economies of North America and Europe and planned liberalization of major energy consuming nations such as China and India. Global integration of energy markets will increase the flow of modern energy technologies to the developing countries, which in turn will accelerate the process of their transition from a fossil fuel based economy to one that may be driven by a mixture of fules including fossil fuels, nuclear energy and renewables. In fact, if the Kyoto Protocol gets ratified, it is expected to open the doors for a massive technology transfer from developed to developing countries through arrangements such as the Clean Development Mechanism (CDM).

The process of switching to cleaner fuels, as reported in this paper is expected to accelerate with increased trade and globalization of energy and technology markets, with considerable social benefits in terms of a cheaper price of carbon.

The paper is organized as follows. Section II summarizes the theoretical framework that generalizes Hotelling's theory to multiple resources and demands. Section III reviews the empirical model developed by CRT. Section IV discusses energy demand projections from the modeling exercise. Section V concludes the paper.

II. The Model

The theoretical model is developed in Krulce, Chakravorty, and Roumasset (1996). It consists of a finite number of resources (e.g., oil, coal, natural gas and solar energy) available for use in the energy sector and a set of energy demand sectors (e.g., electricity, industrial heating, residential/commercial heating and transportation). Thus solar energy is assumed to be the only backstop technology, and the other resources are taken to be exhaustible. Each of the energy demand sectors faces a downward sloping demand function which is assumed to be positive at all prices. Each resource can be converted to an end-use or demand through a process of conversion that entails some frictional and other heat losses. The efficiency of conversion of a particular resource into an end-use is assumed to be a constant less than unity and it represents the proportion of delivered energy units relative to the total raw energy input contained in one unit of the resource. This concept of delivered energy demand is due to Nordhaus (1977) and takes into account the loss in converting resources into energy end-uses.

The initial stock of each exhaustible resource which includes proven and estimated but undiscovered reserves, is assumed to be given. Each resource is assumed to be extracted at a

constant marginal cost of extraction. In addition, each resource is assumed to have a conversion cost into each end-use, which is the annualized sum of capital and maintenance costs of the equipment used in converting the resource into usable energy service for a specific demand, e.g., a passenger car for conversion of gasoline to transportation energy. Thus the supply cost of each resource into a specific end-use is the sum of extraction cost and the conversion cost to that end-use. In the case of solar energy, extraction costs are assumed to be zero, and there are only conversion costs of solar into end-uses (e.g., the conversion cost of solar energy to transportation is the sum of two sets of conversion costs —solar to electricity through photovoltaic systems and electricity to transportation through an electric car). Given a fixed discount rate, the model maximizes discounted producer plus consumer surplus over an infinite planning horizon using a standard Hotelling-type formulation (Dasgupta and Heal 1974). Existence and sufficiency of the necessary conditions can be proved in the usual manner as has been done in earlier work (see Chakravorty and Krulce 1994).

The necessary conditions of the above Hotelling model suggest that the scarcity rent for each exhaustible resource will rise at the rate of interest. This in turn implies that the relative order of scarcity rents at any instant is completely determined by the ordering in the initial time period. The necessary conditions also suggest that the price of each exhaustible resource, which is defined as the efficiency-adjusted sum of the extraction and conversion costs and the scarcity rent, determines which resource will be used for a particular demand at any given instant of time. As resource prices rise over time because of increase in the scarcity rent component, substitution to other fuels may take place. Each demand has its own backstop price, given by the conversion cost of solar energy to that end-use (since extraction cost and scarcity rent for the backstop resource are identically zero), and the backstop technology kicks in for that specific end-use

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when the price of the backstop in that demand is less than or equal to the price of all the

exhaustible resources for that demand. Thus, in this generalized Hotelling framework, there are

as many terminal switch points as the number of demand sectors.

III. Empirical Specification and Data

In this section we summarize the empirical model, which is presented in detail in Chakravorty,

Roumasset, and Tse (1997). The model consists of four demand sectors: electricity, industry,

residential/commercial, and transportation. As in Nordhaus (1979), industrial demand is

composed of non-electric process and space heating, residential includes non-electric space and

other heating, while transportation includes all private and public transportation such as trucks,

buses, autos, and air, water and rail transport. To keep the model tractable, we only consider oil,

coal, and natural gas, which together account for 90 percent of the world's primary energy

consumption (International Energy Agency (IEA) 1995). Other resources such as nuclear,

hydropower, geothermal, and wind energy have much smaller shares of global energy

consumption and are neglected in this model. Similarly, although solar is chosen as the single

backstop technology, nuclear fusion is another candidate expected to become economical by the

middle of the next century (Furth 1995). However, solar is chosen over nuclear fusion because

major advances have been made in improving the former technology in the last two decades and

it is already commercially viable with annual U.S. sales of over $1 billion (Hoagland 1995).

Global annual demand functions for each sector are assumed to be a Cobb-Douglas

function of price and income as follows:

$$D_j = A_j P_j^{\alpha_j} Y^{\beta_j} \qquad\qquad (1)$$

where α_j and β_j are respectively the price and income elasticities of demand in end-use j, A_j is the constant coefficient, P_j is the price of delivered energy service in sector j, and Y is the aggregate income or output level measured by the GDP of the world economy. The price and income elasticities are obtained from Nordhaus (1979) while the constant A_j is computed using equation (1) from world GDP, energy consumption, and price of energy resources in the base year, taken to be 1990.

Efficiencies of conversion from resources to end-uses are obtained from engineering data. Typically, there are a multitude of devices that convert a certain resource into an end-use; for example, buses, trains, ships, and autos all convert oil to transportation units. Even within each of these categories, fuel efficiencies vary dramatically. Instead of choosing the more appropriate but tedious procedure of computing weighted (by the proportion of resource consumed by that particular device) efficiencies, some of which are not well documented, we choose representative activities for each end-use sector such as light-duty passenger cars for transportation, stove heating for the residential/commercial sector, industrial process heating for the industrial sector, and electricity generation for the electricity sector. The conversion cost for these devices was computed from amortizing capital and maintenance costs over the lifetime of the device. In some cases, multi-step conversion processes were used. For example, since oil, coal, and solar energy are seldom used for stove heating, oil was first converted to Liquefied Petroleum Gas (LPG) and the cost of an LPG stove was used. Similarly, coal is gasified and then used for stove heating. Solar energy is converted to each demand by first converting solar energy to electricity and then electricity to that particular demand.

Extraction costs are estimated from data on worldwide proven and estimated reserves for oil, natural gas, and coal. Since extraction cost functions are expected to increase with cumulative extraction, non-linear exponential and S-specifications are estimated; these are in turn further approximated by step functions to reduce computational difficulties with continuous functional forms. This reduces the problem to one grade of natural gas, two grades of oil, and three grades of coal, each with a constant marginal cost of extraction.

Energy demand is expected to grow continually as the large low energy intensity countries in Asia such as China, India, and Indonesia continue to modernize their economies. Asian energy demand has been growing historically at rates significantly higher than the world average (International Energy Agency 1995), although analysts have been downgrading near-term projections of demand growth because of the recent currency crisis in several important Asian economies such as Japan, South Korea, Thailand, and Indonesia. However, various recovery scenarios constructed by the energy industry suggest that although short-run demand in these countries may decline by 10 percent or so, longer-run growth may not be significantly affected. Most global warming models assume a GDP growth rate of approximately 3 percent for the period 1990-2000 declining to 1.96 percent during 2050-75 (Manne and Richels 1991; Nordhaus 1992). Our model assumes an intermediate value of 3.0 percent world GDP growth in 1990 and decreasing at the rate of 10 percent every decade.

IV. Simulation Procedure and Results

The simulation algorithm is written in the programming language Pascal and guesses the scarcity rents of the six resources and grades (three grades for coal, two for oil and one for natural gas) in the initial time period. Since solar energy is available in unlimited supply, it is not an exhaustible

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resource, and so its scarcity rent is zero. The scarcity rents of the other six resources rises at the rate of interest and are completely determined by their initial guesses. Resources are allocated to each demand by comparing their prices, i.e., the sum of their extraction cost, conversion cost to the specific demand, and the scarcity rent. The six-dimensional vector that yields the maximum net benefits using an annual discount rate of 2 percent yields the optimal solution.

There is a large body of literature in electrical and power engineering that suggests that historically the costs of solar energy, more specifically the cost of converting solar energy to electrical energy through photovoltaic systems, has been going down in real terms by approximately 50 percent every ten years (Ahmad 1994). Surveys of the future potential for renewable energy resources have suggested that the costs of electricity generation are expected to decrease from the current 25¢/kwh (kilowatt-hour) to around 4-6¢/kwh. The precise estimates of a lower bound of course cannot be predicted accurately and hence vary across studies, but there is a clear consensus regarding its continuous decline in the next 3-4 decades, as a result of increased R&D as well as an expansion in the size of the market. For example, the new Clinton Energy Plan, announced before the 1997 Kyoto Summit on Global Warming, envisages a five-fold increase in renewable energy research that if implemented may have significant impacts on solar energy costs in the near term. Similarly, the Kyoto Protocol has called for "promoting research, development, and increased use of new and renewable forms of energy..." (Kyoto Protocol, 1997, p.2). Depending on how these proposals are implemented, the costs of production for renewable energy, in particular solar energy, are expected to decline at varying speeds. In this paper, we examine a range of cases, from the baseline case (no solar cost reduction) to the 50 percent per decade solar cost reduction projected by Ahmed (1994) and others, and set a lower bound for the cost of solar electricity at 2¢/kwh in all experiments. In the optimistic scenario of a 50 percent

per decade cost reduction, the cost of electricity from solar falls to 4¢/kwh in about 40 years, a trend supported by several studies (Ahmed 1994; Dracker and De Laquil 1996; National Renewable Energy Laboratory (NREL) 1992). The main results from the modeling exercise are discussed below:

Patterns of Resource Substitution Over Time

Resource substitution is the process by which at any given instant of time, the total costs of supplying different energy resources into end-uses are compared to each other, and the cheapest resource is selected. The total cost is made up of three components, the extraction cost, the conversion cost, and the scarcity rent. Table 1 shows the matrix of extraction plus conversion costs for the various grades of oil, coal and natural gas and for solar energy used in the simulations. Note the relative cost advantage of natural gas in the residential/commercial and oil (grade I) in the transportation sector compared to all other fuels. This suggests that it is likely that natural gas may be used in transportation and oil in electricity. This also suggests that since oil (grade II) is cheaper than coal and solar in industry, some oil may be used in that sector. Of course the precise allocation of resources is also governed by the relative size of the demand. For example, if transportation demand is very high compared to industrial demand, more oil (grade I and II) may be used in the former, and industry could be using the next costly fuel, grade I coal. In the case of electricity, although oil (grade I) and natural gas are cheaper than coal, it is plausible to expect the cheaper resources to be "saved" for the other sectors where their comparative advantage is larger in magnitude and expect coal to be used for electricity. These results are shown in Table 3 which gives the allocation of fuels over time in the baseline model assuming all parameters to be fixed and no technological change.

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Figure 1 shows the time paths of scarcity rents for selected grades (to avoid too much clutter) of fossil fuels in the baseline and 50% per decade solar cost reduction cases. There are two observations from Figure 1. First, scarcity rents for oil and natural gas are higher at the beginning since they are more "valuable" resources and rise rapidly relative to coal, and this has important implications for the switch to coal that will be highlighted below. Second, technological progress (i.e., solar cost reduction) lowers the scarcity rent of fossil fuels in general an observation that conforms to the standard Hotelling comparative dynamics result of the effect of lowering backstop technology prices in decreasing scarcity rents.

Figure 2 gives the total costs of different resources for the transportation sector in the baseline case. It shows that during the first 90 years, oil is used because it is the cheapest resource. In year 2085, the total cost curve for oil crosses the curve for coal from below and thus coal becomes the cheapest resource and is used for another 220 years. In year 2305, the transportation sector switches over to using solar energy. An analogous substitution process is followed in each demand sector as summarized in Tables 2 and 3.

In the baseline model, it is clear that there emerges a natural specialization of resource use, that is, coal is used primarily for electricity generation, oil in the transportation and industrial sectors, and natural gas for residential and commercial heating. The role of exogenous technological progress in advancing the use of solar energy can be seen by comparing Tables 2 and 3. In the baseline case, solar becomes economical first in the electricity sector followed by transportation, and it takes about 350 years from the base year 1990 for all sectors to shift over to solar energy; whereas in the case of a 50% per decade solar cost reduction, it takes only about 70 years for all sectors to use solar energy. Moreover, under no technological change, oil and natural gas run out and are replaced by coal until coal itself is replaced by solar energy. But when there is

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technological change, oil and natural gas are often replaced directly by solar energy (e.g., the transportation sector in the case of 30% per decade solar cost reduction) bypassing coal, and this results in a large reduction of coal consumption. Fourth, without technological change, carbon tax has a very small effect on the pattern of resource use. It extends the use of oil by 10 to 20 years in the transportation and industrial sectors and thus effectively postpones the use of coal in these sectors also (see Table 3).

Time Path of Fossil Fuel Resource Extraction under Alternative Technological Options

Let us now examine the effect of alternative rates of technological change on cumulative resource use. Figure 3 shows the percentage of aggregate estimated coal reserves consumed in the entire time period under different rates of solar cost reduction. It shows that even under low rates of cost reduction, aggregate coal use will decline significantly. In the baseline case with the cost of solar electricity generation constant at 1990 levels, all of the estimated coal reserves will be consumed, but at a low 10% per decade rate of reduction in the cost of photovoltaic technology, coal consumption declines by 33%. With a high rate of technological change in solar, i.e, a 50 percent per decade cost reduction, only 1.54% of the coal stock is used.

Figure 4 shows the time path of cumulative coal extraction under different rates of solar cost reduction. In the baseline case, coal is used for about 350 years (from base year 1990) until the year 2345. Prices of energy resources rise over time due to both an increase in extraction cost and scarcity rent. Scarcity rent plays a particularly important role since it rises at compound rates, and if the time period is long, the increase will be substantial. When the cost of solar energy goes down by 30% a decade, we use coal for about 110 years, and if it is 50%, coal will be used for only 40 years. Thus if technological progress in renewables can be maintained at a reasonable

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speed, for example 30% or higher in our context, the global economy is expected to shift to the

backstop solar energy some time in the next century. Of course, these results do not recognize the

major regional differences in the incidence of solar radiation and other important structural

differences across economies.

Figures 5 and 6 show the cumulative use of oil and natural gas reserves over time. Both

oil and natural gas stocks will be completely exhausted irrespective of the rate of technological

change in renewables. If the rate of solar cost reduction is greater than or equal to 20%, oil

reserves will be used up around the year 2055; whereas if the rate is below 20%, complete

exhaustion will be postponed by another 10-30 years. What is interesting is that oil use is not

particularly sensitive to solar energy cost reduction in the next 20 years or so, and oil extraction

rates begin to diverge significantly only beyond that period. Another pertinent observation about

oil extraction is that a faster rate of solar cost reduction does not necessary lead to a faster

consumption of oil. For example, around the year 2035, the cases with rates of solar cost

reduction at 20% and 30% per decade consume more oil than the cases with rates of 40% and

50% (see Figure 5). The explanation for this phenomenon is that in the latter cases with faster

rates, solar energy comes in early in the electricity and transportation sectors and thus displaces

some of the demand for oil.

Natural gas use over time is much less sensitive to cost reduction in solar energy than the

other two major fossil fuels, as shown in Figure 6. In most of the models examined, current

estimated gas reserves will be exhausted by the year 2055, and slightly earlier under 50 percent

solar cost reduction. In summary, the graphs (Figure 4 to 6) examined above suggest that

increased investment in renewable energy research will have only a relatively small effect on the

demand for natural gas (in all periods), for coal in the first 30 years and oil in the first 15-20

years of the next century.

Sensitivity of Fossil Fuel Resource Use under Carbon Taxes

The worldwide concern over global warming from the burning of fossil fuels has caused many

economists to suggest imposing a carbon tax (e.g., Poterba 1993; OECD 1993). Tax rates of the

order of $20/ton of carbon to $100-200/ton have been proposed (Nordhaus 1993). A tax of

$100/ton of carbon would raise coal prices by about $70/ton or 300 percent and oil prices by

about $8/barrel. Questions of political feasibility and administrative complexity of a carbon tax

aside, in the next set of figures, we investigate the long-run impacts of these taxes on the use of

fossil fuels.

Figures 7 through 9 suggest that the long-run impacts of carbon taxes may be marginal.

For example, a tax of $100/ton will postpone exhaustion of coal stocks by about 20 years (Figure

7). For oil and natural gas, the effect of the carbon tax is even less pronounced (Figures 8 and 9).

Their reserves are exhausted at the same time as in the baseline model. One broad implication of

these results is that the global warming problem will not be solved by carbon taxes alone but

could only be delayed for a certain length of time, say by about 20 to 30 years. However, carbon

taxes may provide two important benefits: (i) by depressing fossil fuel consumption and

postponing the exhaustion date, it provides extra time for the "true solution" to emerge through

technological progress; and (ii) the substantial tax revenues could be used to finance research and

development efforts. On the other hand, carbon taxes raise the price of oil and coal relative to

natural gas which is a cleaner fuel, increasing the substitution of natural gas in energy projects in

the near term (Figure 9). This finding is consistent with current industry trends, especially the

increased substitution of natural gas for coal in new electric power generation projects

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(International Energy Agency 1995). It is possible that the rising use of natural gas today may not be due to a carbon tax but at least partly due to an anticipation of a tax in the near future. Such expectation will smooth the increase of natural gas consumption over time. Our model does not incorporate expectation as a factor, but the basic result should still be valid.

Sectoral Energy Use and Prices

In the case of fossil fuels, two opposing factors are at work in determining the path of energy consumption over time: first, the increase in resource prices, which in turn is caused by the rising scarcity rent and the increase in the cost of extraction, has the effect of depressing energy use; second, the exogenously determined growth of the world economy causes the demand for energy to rise. Depending on which of the two forces is stronger, energy consumption can increase or decrease over time. However, for renewables (solar) under technological progress, resource prices decrease over time and there is no increasing scarcity rent component of price, so the price effect on the growth of energy consumption is always positive. Figures 10 through 13 show the time paths of energy use for each sector in the baseline and technological change scenarios and illustrate the above discussion on consumption growth. In Figure 10, energy use in the electricity sector rises much faster under rapid than slow or insignificant technological change; in fact, it is easy to notice the sharp up-turns in the consumption of electricity under the 30 percent and 50 percent solar cost reduction cases. At these points, the cheaper backstop fuel (solar) replaces coal, resulting in a downward shift in the supply curve and increased consumption of electricity. Continued reductions in solar energy costs over time accelerate this trend.

A similar trend occurs in the transportation sector (see Figure 11). Energy consumption in the transportation sector shoots up around the years 2025, 2035 and 2075 respectively for solar

cost reduction rates of 50%, 30% and 10% respectively, and those years are precisely the time at which solar replaces oil in that sector. In the baseline case, the upturn is not obvious from the graph because the substitution to solar energy takes place after the year 2175 - the latest year shown. Although less conspicuous, we can observe a similar increase in energy consumption in the residential and industrial sectors when they switch to solar energy (Figures 12 and 13). Thus the upward rotation of the energy consumption curves during the post-fossil fuel extraction phase confirms what some energy analysts foresee happening in the near future - the move to an energy-abundant economy fueled by renewable energy (Flavin 1996).

Technological change brings a rapid increase in energy consumption, but without it, energy consumption can actually fall during some time in the future. In the baseline scenario, energy consumption in the residential and industrial sectors peaks around the year 2175 and then declines. The explanation for this is that even though GDP continues to grow in our model, albeit at a decreasing rate, rising resource prices "crowd out" the positive income effect.

Figures 14-17 show sectoral energy prices, normalized to the model base year (price of the baseline in 1990 = 1). To facilitate comparison across simulations, the initial sectoral energy prices of the baseline model are used as denominator to calculate the percentage change of the energy price. In the baseline model with no technological change, energy prices will increase several fold. Thus while it may be true that the world may have enough fossil fuel reserves to last another 300 years, energy prices may go up several notches ranging from three times in transportation to approximately 12 times for industrial energy. In the more immediate future before the middle of the next century, the model predicts sharp price increases in sectors that are heavily dependent on scarce oil and natural gas resources. For example, energy prices go up about 28 percent in the transportation sector (Figure 15), 38 percent in the industrial sector

(Figure 17), and more than 70 percent in the residential/commercial sector (Figure 16); whereas the relative abundance of cheap coal ensures an almost constant price of electricity generation for several decades (Figure 14).

Except in the residential sector where natural gas enjoys a major comparative advantage relative to other fuels including solar energy, any reasonable technological change scenario (30-50 percent reduction in photovoltaic costs per decade) will ensure that long run energy prices will stay roughly constant or decrease as in the electricity and transportation sectors (Figures 14 and 15). Use of solar in the residential sector when natural gas gets exhausted will mean a price rise of about 50 percent relative to 1990 levels (Figure 16). However, these figures make it clear that the effect of technological progress in depressing energy prices will not be fully felt until the second half of the next century.

Introduction of clean coal technologies

One of the most promising avenues for global emissions reduction from the burning of fossil fuels is the development of clean-coal technologies. For example, an important objective of the United States Department of Energy (DOE)'s Advanced Power Systems Program is to achieve the reduction of carbon dioxide emissions from coal by 47 percent around the year 2015 (Longwell, Rubin, and Wilson 1995). This approach is based on the premise that coal is the only truly abundant resource, and it may be worthwhile to focus R&D efforts in developing new technologies that reduce the pollutants emitted from burning coal. Several technologies are already at the prototype phase but are yet to be cost effective (Rose and Mor 1993).

For modeling purposes we assume that the new technology will remove 50 percent of the carbon dioxide emitted by the use of coal but will be available three decades from the base year — by the year 2020. Figure 18 shows global mean temperatures for moderate and high technological

change in solar energy, as well as for the baseline and clean coal technology (with solar costs remaining fixed) options. Emission and temperature relationships used here are all taken from Edmonds and Reilly (1985) and the DICE model (Nordhaus 1992). Temperature changes are relative to the historical year 1860. Baseline temperatures will rise by a maximum of 6 degrees Centigrade peaking around the year 2275 while with cheap solar energy, ambient temperatures will rise by only 1.5-2.2 degrees sometime in the second half of the next century. Clean coal technology causes peak temperatures of about 4 degrees, but more importantly in the short term, clean coal technology can produce a significant reduction in temperature control. Prior to the year 2045, the rise in temperature under clean coal is even less than the case with 50% rate of solar cost reduction. However over the long haul, as oil and natural gas run out and the global energy economy becomes totally dependent on clean coal, low temperatures cannot be sustained.

V. Conclusion: Implications for Energy Policy

Results from the model with endogenous resource substitution suggest the following main policy conclusions:

1. Energy prices will rise in the coming 40 to 60 years, and since the full effect of a backstop resource will only be realized in the second half of the next century, this problem cannot be totally avoided even with technological advances in alternative energy resources such as solar energy and nuclear fusion.

2. A rising concern over the environment will boost the use of natural gas and depress the use of oil and coal in the near future. The use of natural gas helps reduce the warming problem during this transitional period. These resource use changes can be a result of a carbon tax , a tightening of environmental regulation or expectations of new policy. For example, implementation of the Kyoto Protocol may boost use of natural gas in electric power generation —

a trend already in evidence because of electricity deregulation in the U.S. and other countries. Environmental protection measures can delay but cannot solve the global warming problem in the long term.

3. Clean coal technologies can play an important role in delaying the advance of global warming, although in the long run, heavy dependence on coal will still cause significant temperature rise.

4. A move to a new energy system powered by backstop resources such as solar energy seems to be a necessary step to solve both the energy security and global warming problem in the long run. This fact is consistent with the idea of Flavin (1996) and other energy futurists.

In view of the above observations, the energy strategy of the future may involve two main objectives. First, in the short run we may need to deal with the more immediate problem of energy availability and at the same time try to reduce the incidence of global warming. Second, in the long run, we need to ensure that there will be a smooth transition to a new energy system that is based on a supply of clean and abundant source of energy. The time line that divides the short and long run horizon is roughly around the middle of the next century.

Since the development of a backstop technology such as solar will not impact the short-run scenario significantly, we may need to look at alternative options. These options include the following: expanding the use of other non-fossil energy resources such as hydro-power, biomass, geothermal and wind power; developing clean coal technologies; and finally, increasing the efficiency of energy consumption. These efforts can help reduce the increase in energy prices that may result from growth-induced increases in energy demand and decreasing fossil fuel stocks. The purpose of the first two options is pretty obvious, that is, they will directly expand energy supply. The third option, the enhancement of energy efficiency, too, is virtually equivalent to an

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increase in the energy stock.

In the longer term, the objective of energy policy may be to maintain a rate of technological progress in any backstop technology and resources, such as solar or fusion energy, equivalent to or better than the 30% solar cost reduction rate. Governments can play a role in monitoring the development of energy technology and take appropriate measures to ensure the objective can be achieved in a time frame of roughly 50 years.

In order to accomplish the objective of environmental protection, energy options should be carefully chosen. Environmental regulation can be gradually tightened. Similarly, authorities can consider imposing a low carbon tax which can help internalize the cost of energy consumption to the environment, and also reduce the current cost differential between fossil fuels and environmentally clean technologies. According to some estimates, current annual subsidies for fossil fuels amounts to almost $200 billion. The purpose of these policy measures should not only be in controlling emissions *per se*, but to send the right signals to the private sector and the scientific community for encouraging the development of new technologies.

Some of these ideas are being already implemented, such as through government-industry partnerships like the Partnership for a New Generation of Vehicles (PNGV) in the U.S. In the long run, maintaining a competitive energy sector may be equally important. The tightening of environmental regulation and the development of backstop technology will gradually force the market to converge towards the desired objectives. The cost of backstop technology will always act as an upper bound for the cost of energy. For example if the price of solar energy falls, in order to be competitive in the market, other energy options will have to meet that cost standard.

In recent years, the problem in energy policy has shifted from a concern with depleting reserves of oil to moving to cleaner fuels and reducing greenhouse gas emissions. The

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endogenous substitution approach taken in this paper provides insights into the underlying supply and demand factors that determine the outcome of government energy tax, subsidy and investment policies. Although many studies by energy "pessimists" (e.g., Korten 1990; Douthwaite 1992; and Trainer 1995a, b) essentially argue that there is no way out but to move to a "radical conserver society" which will need to learn to live efficiently on far lower levels of per capita energy consumption, there are other "optimists" who argue that the current coal and oil based energy economy will gradually shift to a new regime in which renewables, such as solar and wind energy, will play a major role. Flavin (1994, 1996), believes that the energy system of the future will become more decentralized with homes and buildings equipped with structures to collect energy from the sun. With the progress in energy storage technology, such as the technology to produce hydrogen fuel from solar electricity, energy collected from the sun can be transported around the world to satisfy the energy demand at locations where sun radiation is relatively low. Other expert opinion lies between these two polar extremes. Based on historical trends, many studies (see e.g., International Energy Agency 1995; Longwell, Rubin, and Wilson 1995) on future energy use project that fossil fuels will continue to dominate energy supply up to the middle of the next century, and renewables will only play a minor if growing role during this period. They believe that because of growing environmental concerns, the use of natural gas will rise in the near future, and the use of coal coupled with clean coal technologies will provide the bridge to the new energy future. Our paper provides another level of detail to this road map of the energy transition from fossil fuel to renewable energy.

TABLE 1

EXTRACTION PLUS CONVERSION COSTS ($/Delivered mmbtu)

	Electricity	Transportation	Residential/Commercial	Industry
Oil Grade I	8.49	64.48	14.25	3.50
Oil Grade II	17.58	74.04	17.84	7.60
Coal Grade I	11.75	110.36	20.65	10.03
Coal Grade II	17.52	117.23	23.10	12.49
Coal Grade III	26.58	128.05	26.97	16.35
Natural Gas	8.83	75.38	8.43	3.44
Solar	73.20	213.07	96.55	87.70

Source: The following are sources for the calculation of conversion costs: residential/commercial sector (stove heating), see Office of Technology Assessment (1992); for industry sector, see Argonne National Laboratory database, 1992 (Daly and Kosobud 1992); conversion cost of private car, see Office of Technology Assessment (1992); coal conversion includes the cost of gasoline car ($18.744) plus coal liquefaction ($8.19), see Grainger and Gibson (1981); the electricity sector, see Office of Technology Assessment (1992) and International Energy Agency (1992) for oil, coal and gas; for electricity generated with solar energy, see Ahmed (1994). Extraction costs are computed based on data available from the East-West Center Energy Program.

TABLE 2

SECTORAL RESOURCE USE PROFILE UNDER ALTERNATIVE RATES OF SOLAR ELECTRICITY COST REDUCTION

Period (Year)	10% Rate of Solar Electricity Cost Reduction				30% Rate of Solar Electricity Cost Reduction				50% Rate of Solar Electricity Cost Reduction			
	Elect	Tran	Resid	Indust	Elect	Tran	Resid	Indust	Elect	Tran	Resid	Indust
1990-99	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil
	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil
2010-19	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil
	Coal	Oil	Gas	**Oil**	Coal	Oil	Gas	Oil	**Coal**	**Oil**	Gas	Oil
2030-39	Coal	Oil	Gas	**Coal**	Coal	**Oil**	Gas	Oil	**Solar**	**Solar**	Gas	Oil
	Coal	Oil	Gas	Coal	Coal	**Solar**	Gas	**Oil**	Solar	Solar	**Gas**	Oil
2050-59	Coal	Oil	**Gas/Coal**	Coal	**Coal**	Solar	**Gas/Oil/Coal**	Coal	Solar	Solar	**Solar**	**Oil**
	Coal	**Oil**	Coal	Coal	**Solar**	Solar	Coal	Coal	Solar	Solar	Solar	**Solar**
2070-79	Coal	**Solar**	Coal	Coal	Solar	Solar	**Coal**	Coal	Solar	Solar	Solar	Solar
	Coal	Solar	Coal	Coal	Solar	Solar	**Solar**	Coal	Solar	Solar	Solar	Solar
2090-99	Coal	Solar	Coal	Coal	Solar	Solar	Solar	Coal	Solar	Solar	Solar	Solar
	Coal	Solar	Coal	Coal	Solar	Solar	Solar	**Coal**	Solar	Solar	Solar	Solar
2110-19	Coal	Solar	Coal	Coal	Solar	Solar	Solar	**Solar**	Solar	Solar	Solar	Solar
	Coal	Solar	Coal	Coal	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar
2130-39	Coal	:	Coal	Coal	:	:	:	:	:	:	:	:
	Coal	:	Coal	Coal	:	:	:	:	:	:	:	:
2150-59	Coal		Coal	Coal								
	Coal		Coal	Coal								
2170-79	**Coal**		Coal	Coal								
	Solar		Coal	Coal								
2190-99	Solar		Coal	Coal								
	:		Coal	Coal								
2210-19	:		**Solar**	Coal								
			Solar	Coal								
2230-39			:	Coal								
			:	Coal								
2250-59				Coal								
				Coal								
2270-79				**Coal**								
				Solar								
2290-99				Solar								
				:								
				:								

TABLE 3
SECTORAL RESOURCE USE PROFILE FOR BASELINE MODEL WITH CARBON TAX

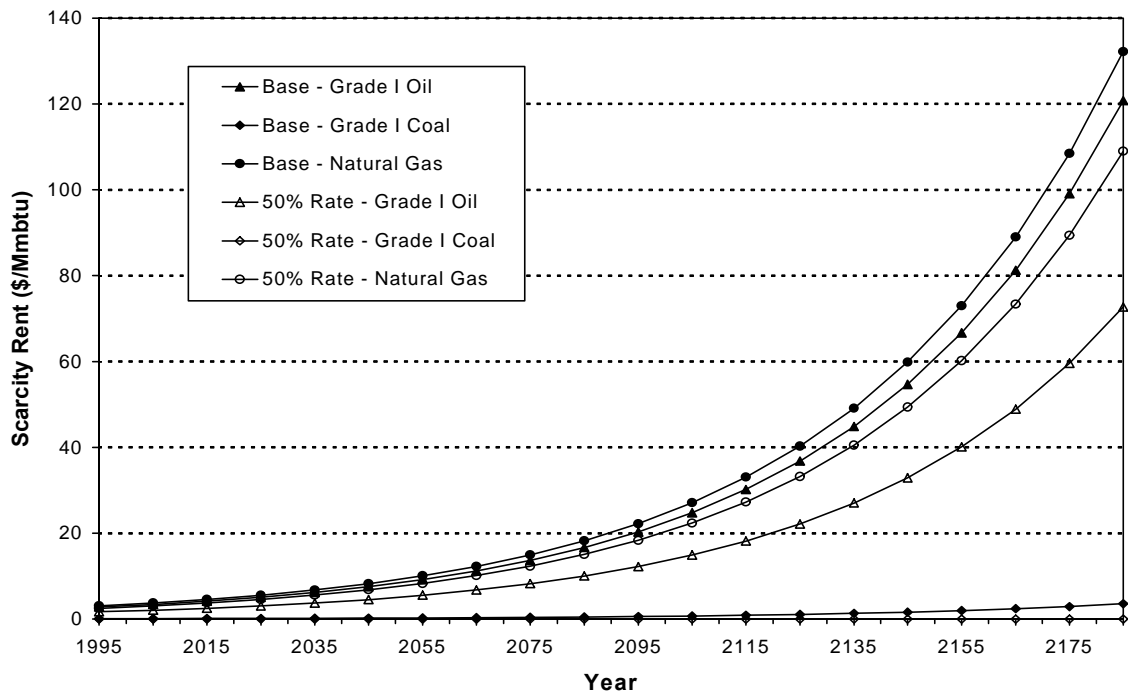| Period (Year)	Baseline				Baseline with $100 Carbon Tax				Baseline with $200 Carbon Tax			
	Elect	Tran	Resid	Indust	Elect	Tran	Resid	Indust	Elect	Tran	Resid	Indust
1990-99	Coal	Oil	Gas	Oil	Coal	Oil	Gas	**Gas**	Coal	Oil	Gas	**Gas**
	Coal	Oil	Gas	Oil	Coal	Oil	Gas	**Oil**	Coal	Oil	Gas	**Oil**
2010-19	Coal	Oil	Gas	**Oil**	Coal	Oil	Gas	Oil	Coal	Oil	Gas	Oil
	Coal	Oil	Gas	**Coal**	Coal	Oil	Gas	**Oil**	Coal	Oil	Gas	Oil
2030-39	Coal	Oil	Gas	Coal	Coal	Oil	Gas	**Coal**	Coal	Oil	Gas	**Oil**
	Coal	Oil	Gas	Coal	Coal	Oil	Gas	Coal	Coal	Oil	Gas	**Coal**
2050-59	Coal	Oil	**Gas/Coal**	Coal	Coal	Oil	**Gas/Coal**	Coal	Coal	Oil	**Gas/Coal**	Coal
	Coal	Oil	Coal	Coal	Coal	Oil	Coal	Coal	Coal	Oil	Coal	Coal
2070-79	Coal	Oil	Coal	Coal	Coal	Oil	Coal	Coal	Coal	Oil	Coal	Coal
	Coal	**Oil/Coal**	Coal	Coal	Coal	**Oil**	Coal	Coal	Coal	**Oil**	Coal	Coal
2090-99	Coal	Coal	Coal	Coal	Coal	**Coal**	Coal	Coal	Coal	**Coal**	Coal	Coal
	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal
2110-19	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal
2120-29	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2260-69	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal
2270-79	**Coal**	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal	Coal
	Solar	Coal	Coal	Coal	**Coal**	Coal	Coal	Coal	Coal	Coal	Coal	Coal
2290-99	Solar	**Coal**	Coal	Coal	**Solar**	Coal	Coal	Coal	Coal	Coal	Coal	Coal
	Solar	**Solar**	Coal	Coal	Solar	Coal	Coal	Coal	**Coal**	Coal	Coal	Coal
2310-19	Solar	Solar	Coal	Coal	Solar	**Coal**	Coal	Coal	**Solar**	Coal	Coal	Coal
	Solar	Solar	Coal	Coal	Solar	**Solar**	Coal	Coal	Solar	Coal	Coal	Coal
2330-39	Solar	Solar	**Coal**	Coal	Solar	Solar	Coal	Coal	Solar	**Coal**	Coal	Coal
	Solar	Solar	**Solar**	Coal	Solar	Solar	Coal	Coal	Solar	**Solar**	Coal	Coal
2350-59	Solar	Solar	Solar	**Solar**	Solar	Solar	Coal	Coal	Solar	Solar	Coal	Coal
	Solar	Solar	Solar	Solar	Solar	Solar	**Coal**	**Coal**	Solar	Solar	Coal	Coal
2370-79	Solar	Solar	Solar	Solar	Solar	Solar	**Solar**	**Solar**	Solar	Solar	Coal	Coal
	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	**Coal**	Coal
2390-99	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	Solar	**Solar**	**Coal/Solar**
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

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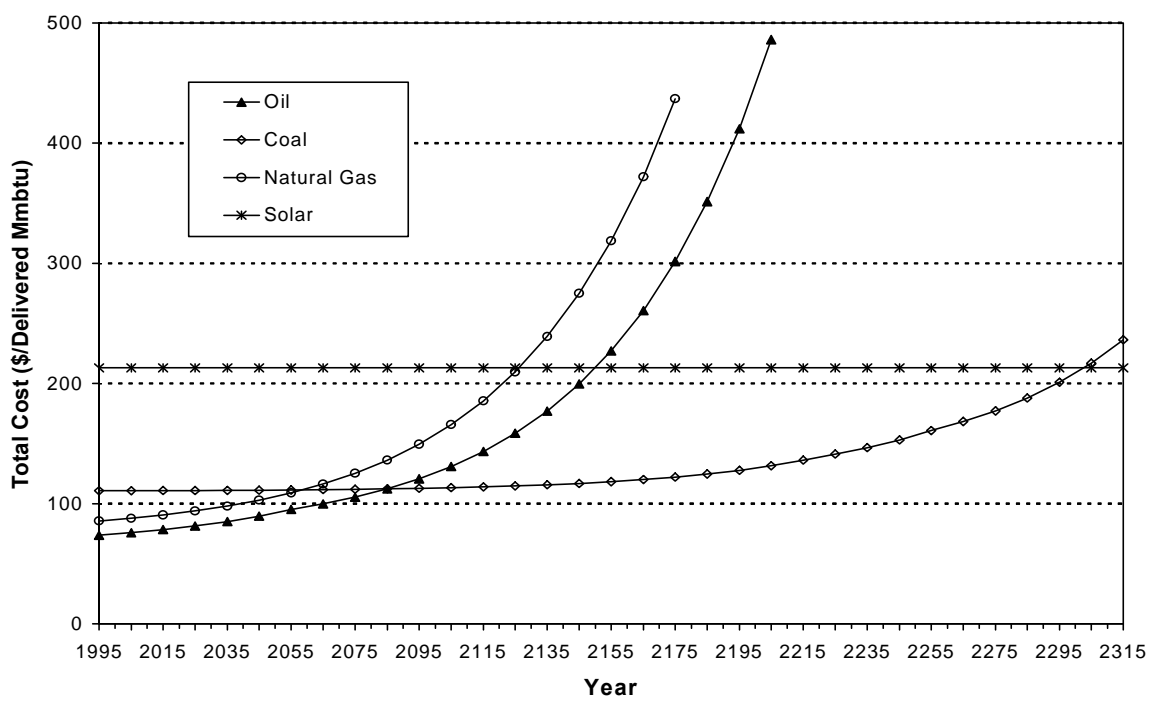Figure 1. Time Paths of Scarcity Rents for Oil, Coal and Natural Gas

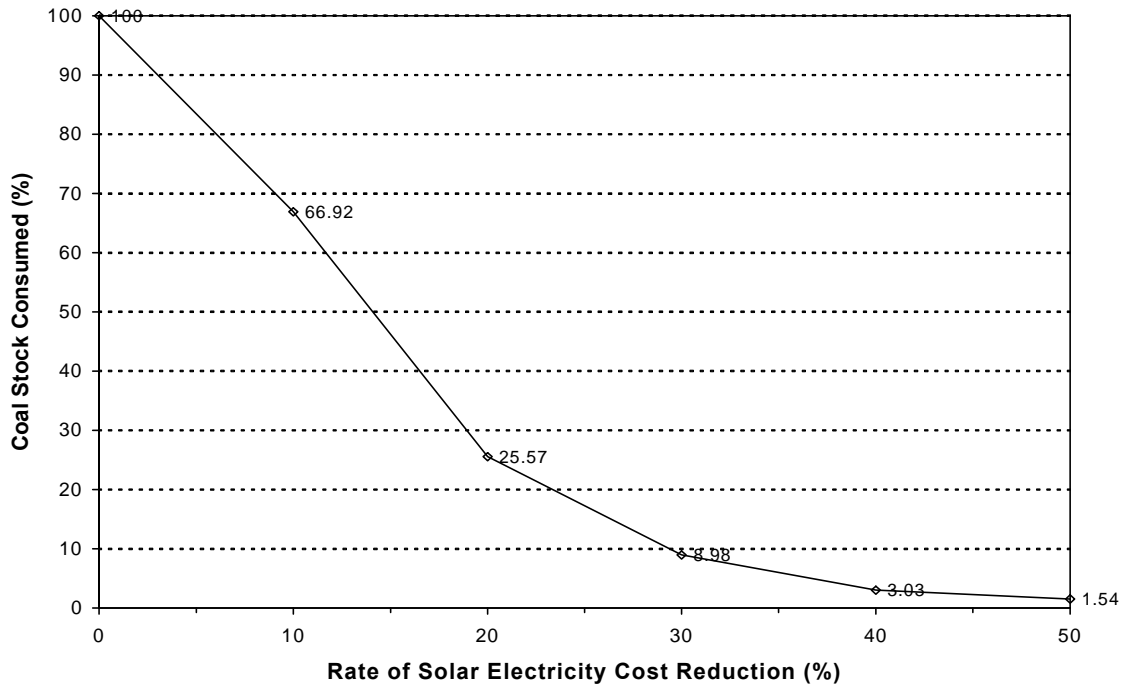Figure 2. Total Costs of Using Oil, Coal and Natural Gas in Transportation: Baseline Model

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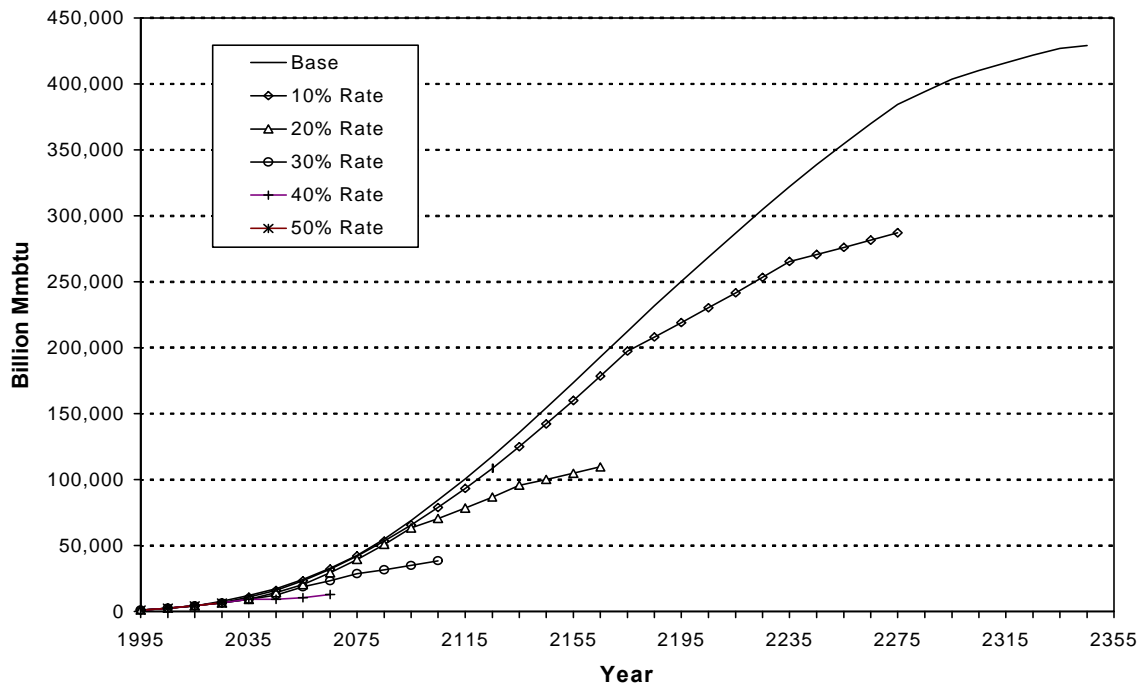Figure 3. Effect of Solar Electricity Cost Reduction on Aggregate Coal Use

Figure 4. Time Paths of Cumulative Coal Use under Alternative Rates of
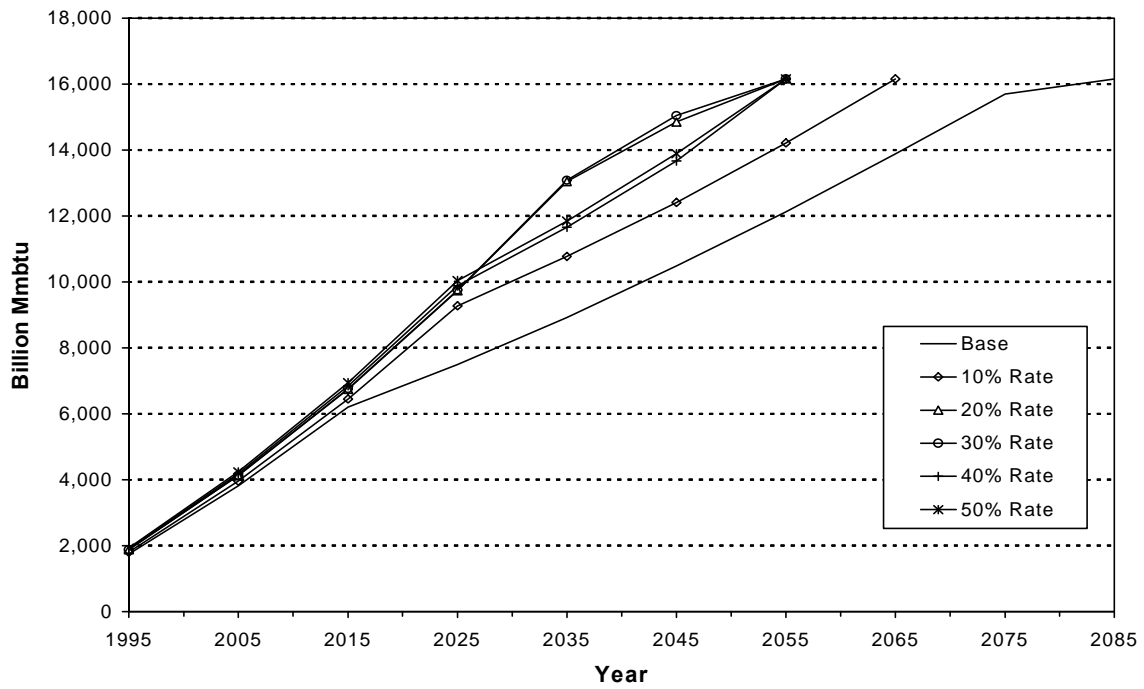Solar Electricity Cost Reduction

Figure 5. Time Paths of Cumulative Oil Use under Alternative Rates of
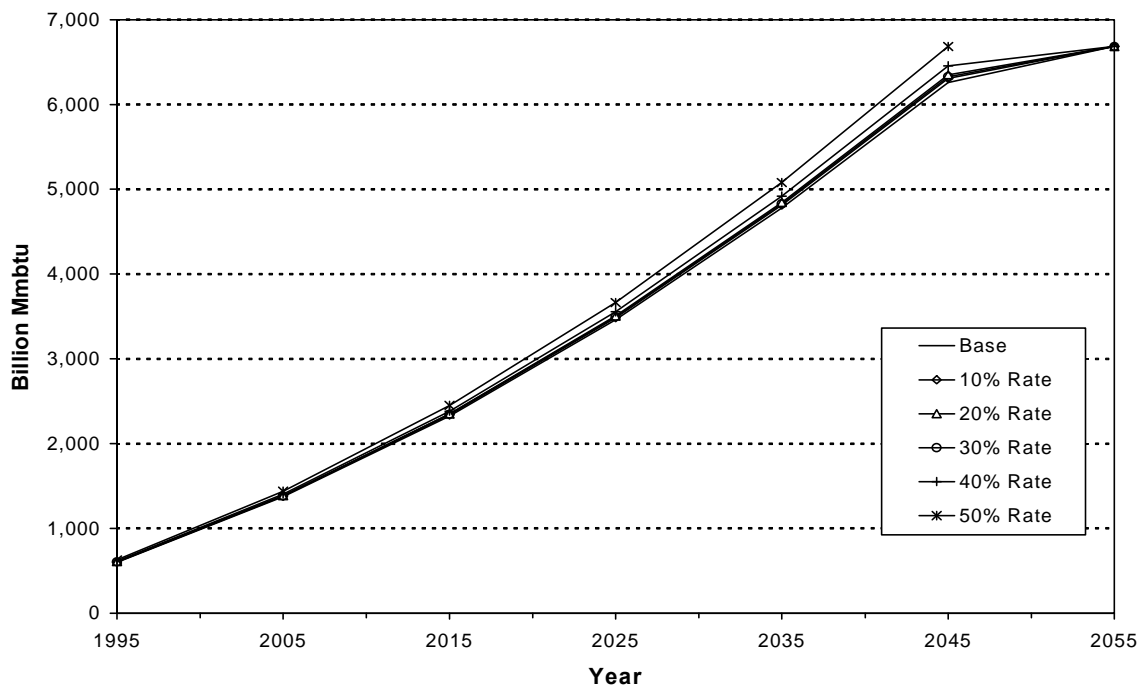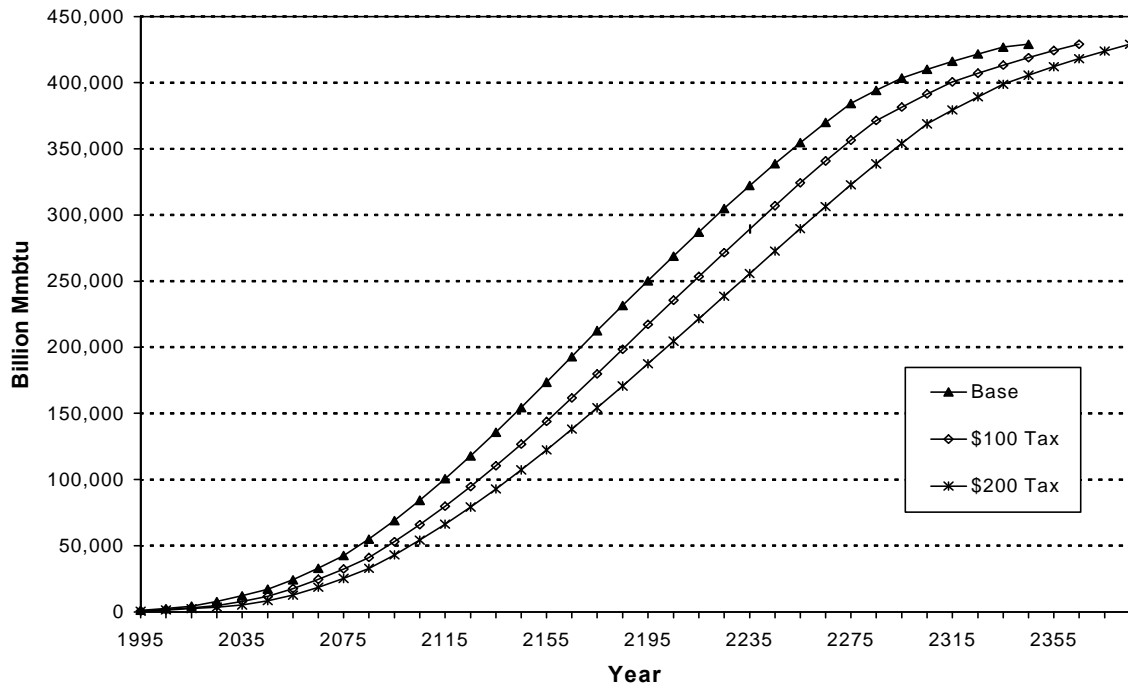Solar Electricity Cost Reduction

Figure 6. Time Paths of Cumulative Natural Gas Use under Alternative Rates of
Solar Electricity Cost Reduction

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Figure 7. Cumulative Coal Use in Baseline Model and with Carbon Tax
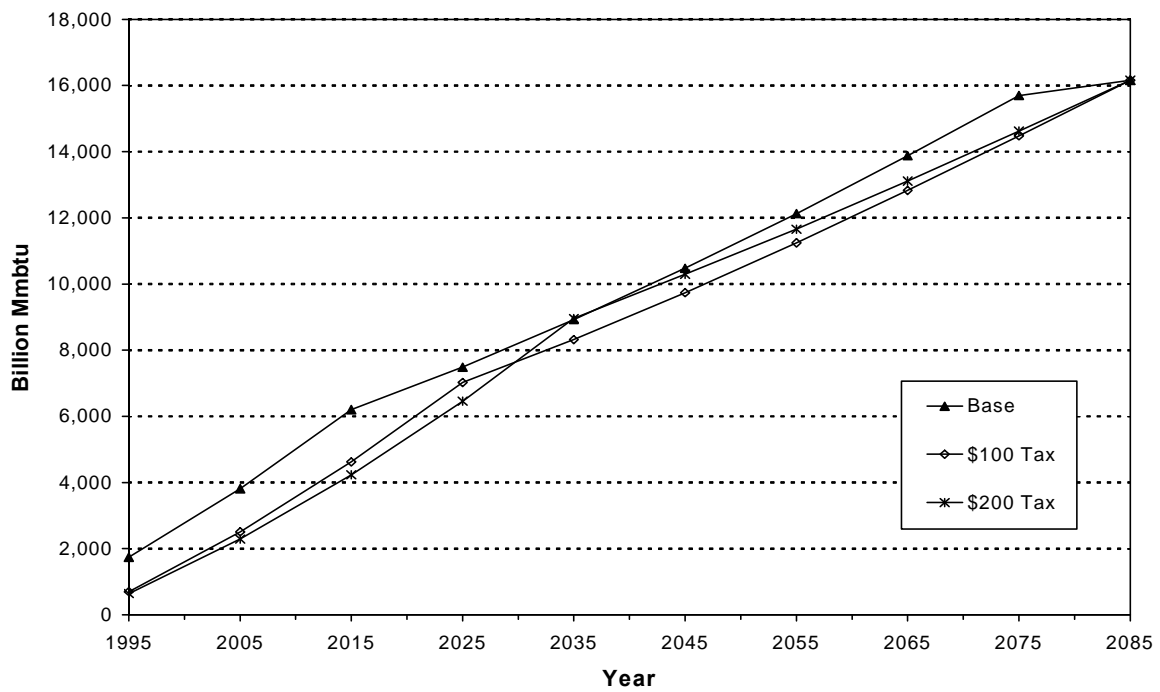
Figure 8. Cumulative Oil Use in Baseline Model and with Carbon Tax

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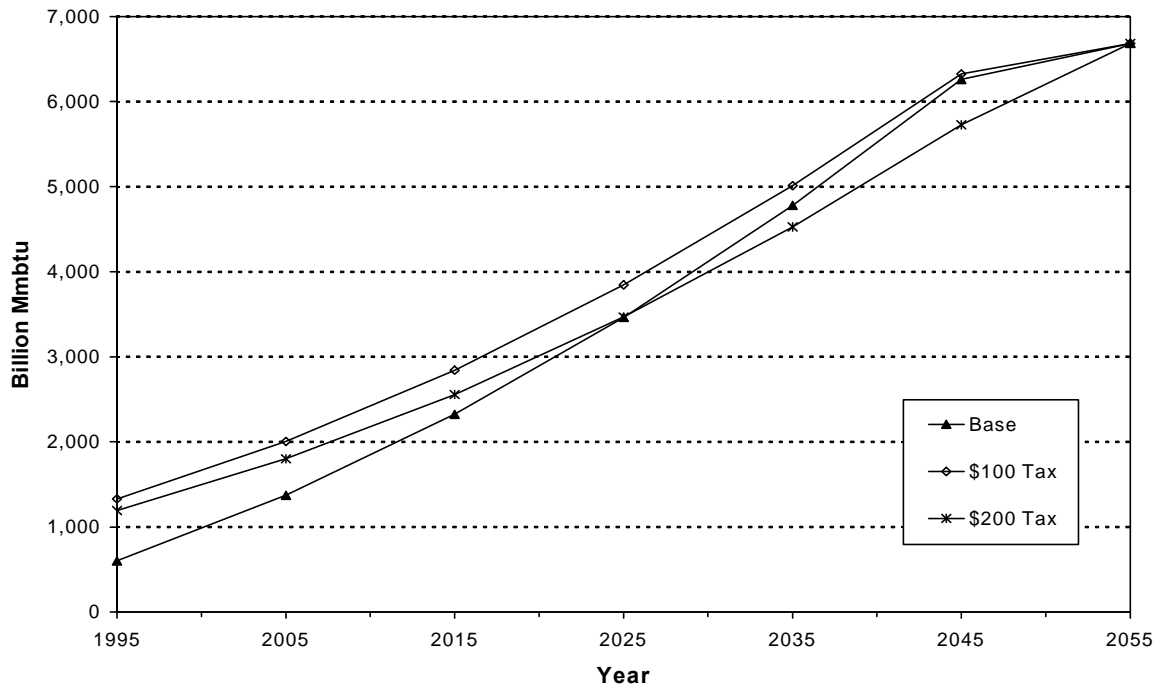
Figure 9. Cumulative Natural Gas Use in Baseline Model and with Carbon Tax
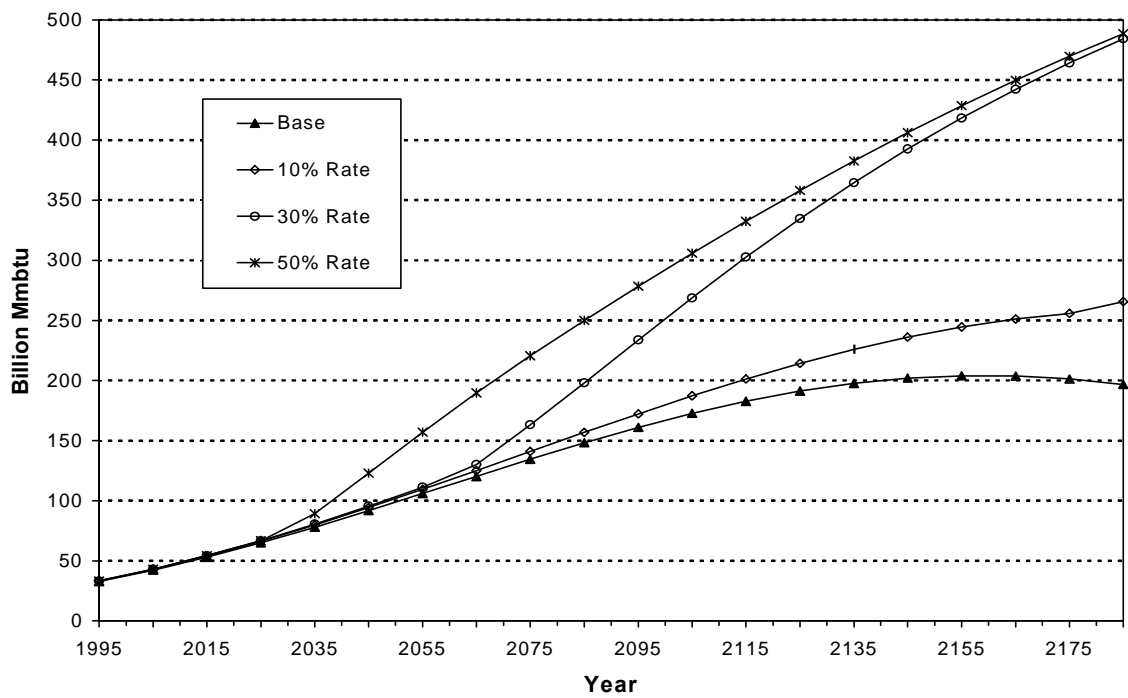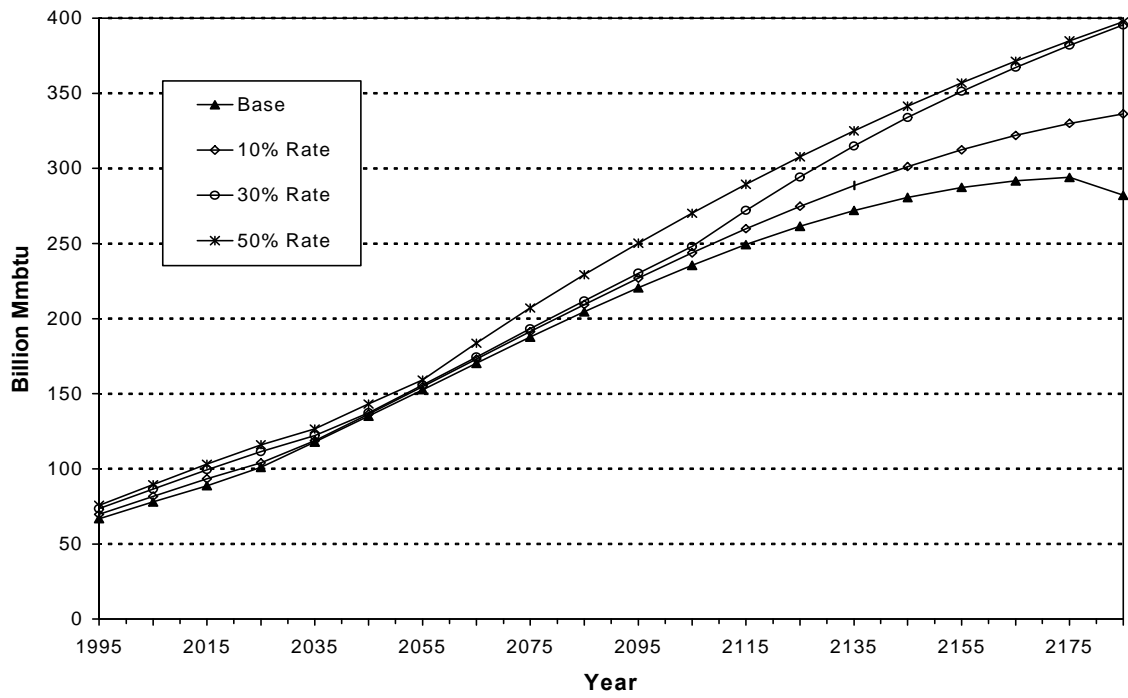

Figure 10. Energy Use in Electricity Sector (in Delivered Energy Units) under Alternative
Rates of Solar Electricity Cost Reduction

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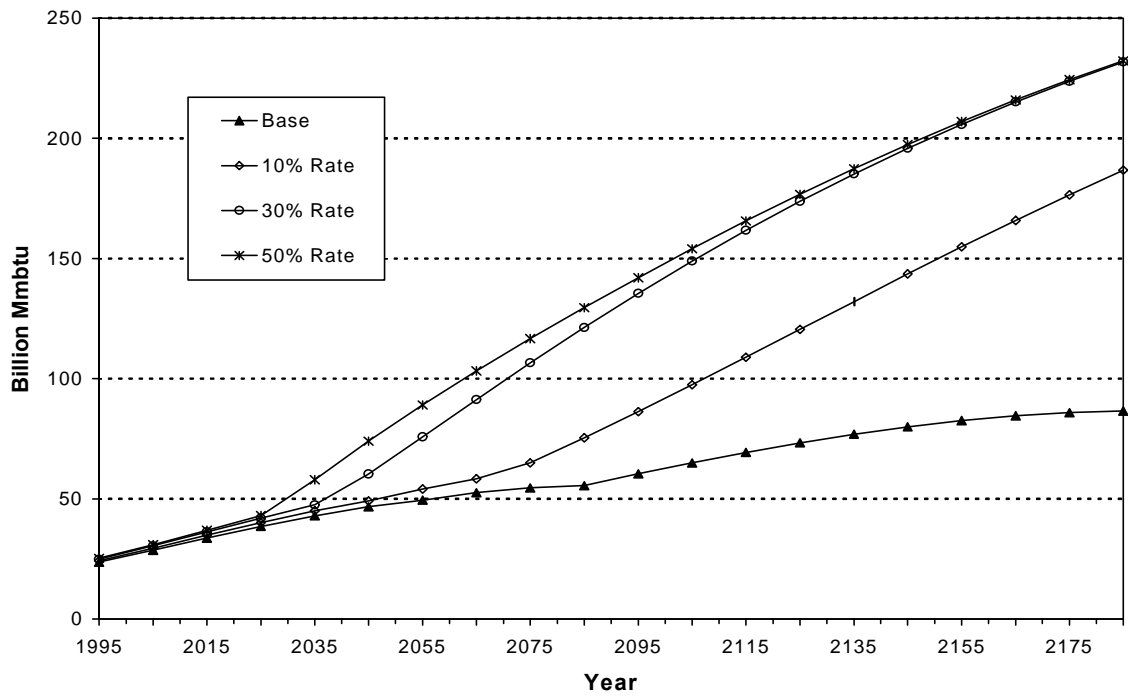
Figure 11. Energy Use in Transportation Sector (in Delivered Energy Units) under Alternative
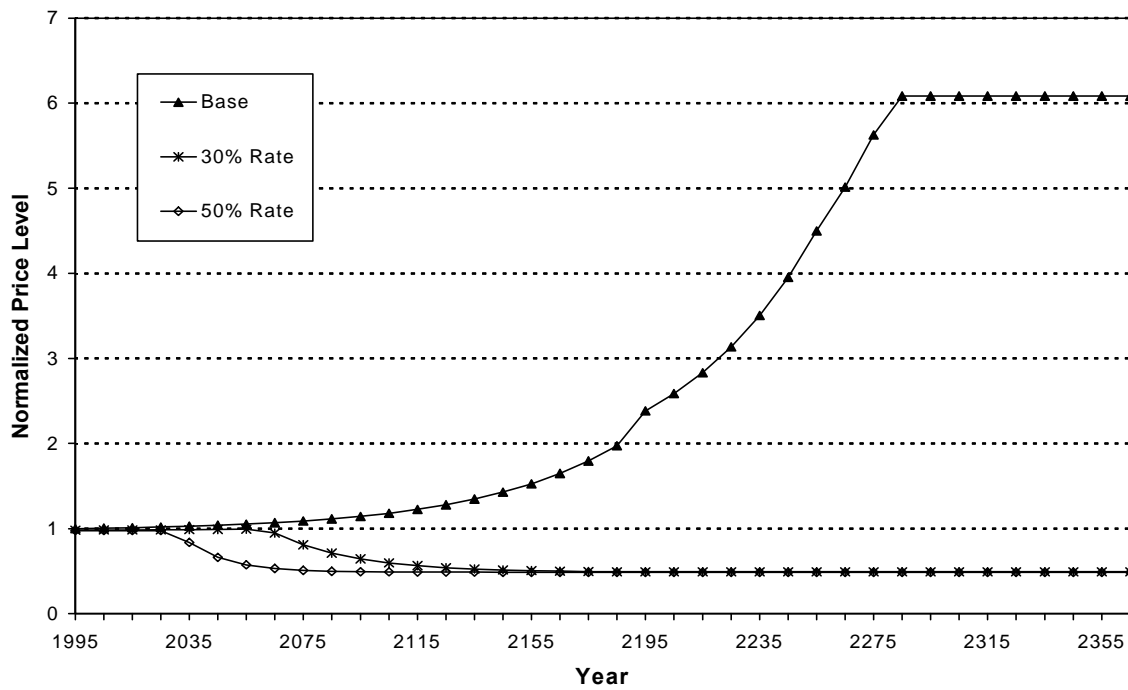Rates of Solar Electricity Cost Reduction
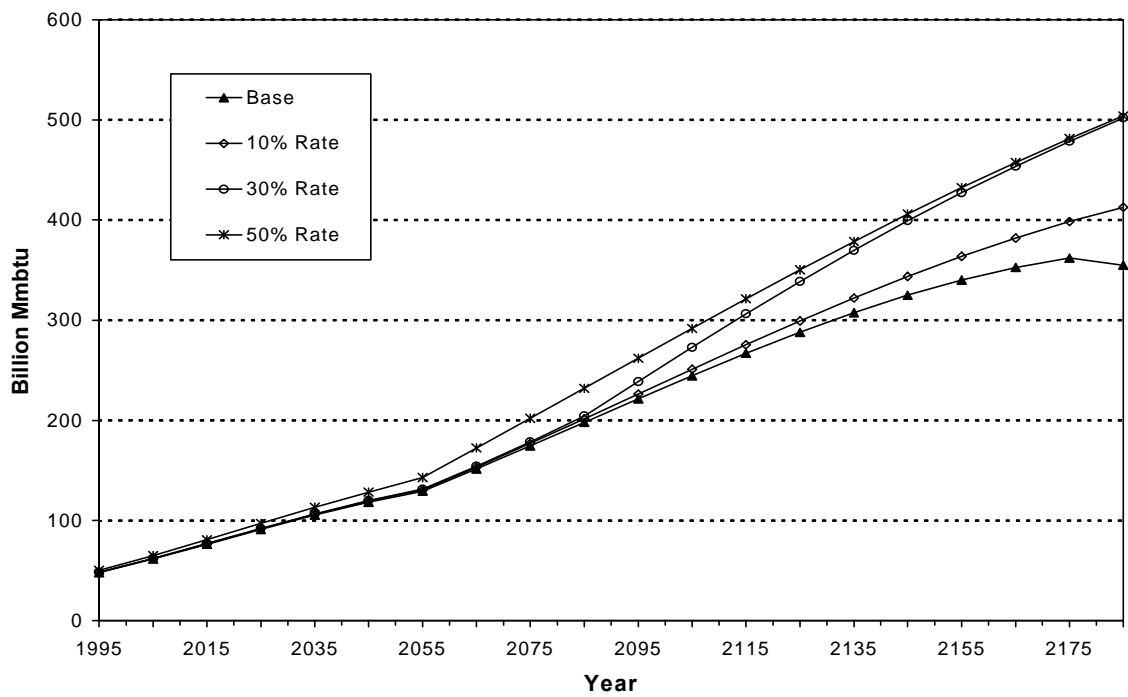
Figure 12. Energy Use in Residential Commercial Sector (in Delivered Energy Units) under Alternative
Rates of Solar Electricity Cost Reduction

Figure 13. Energy Use in Industrial Sector (in Delivered Energy Units) under Alternative
Rates of Solar Electricity Cost Reduction

Figure 14. Electricity Sector Prices under Alternative Rates of Solar Electricity Cost Reduction
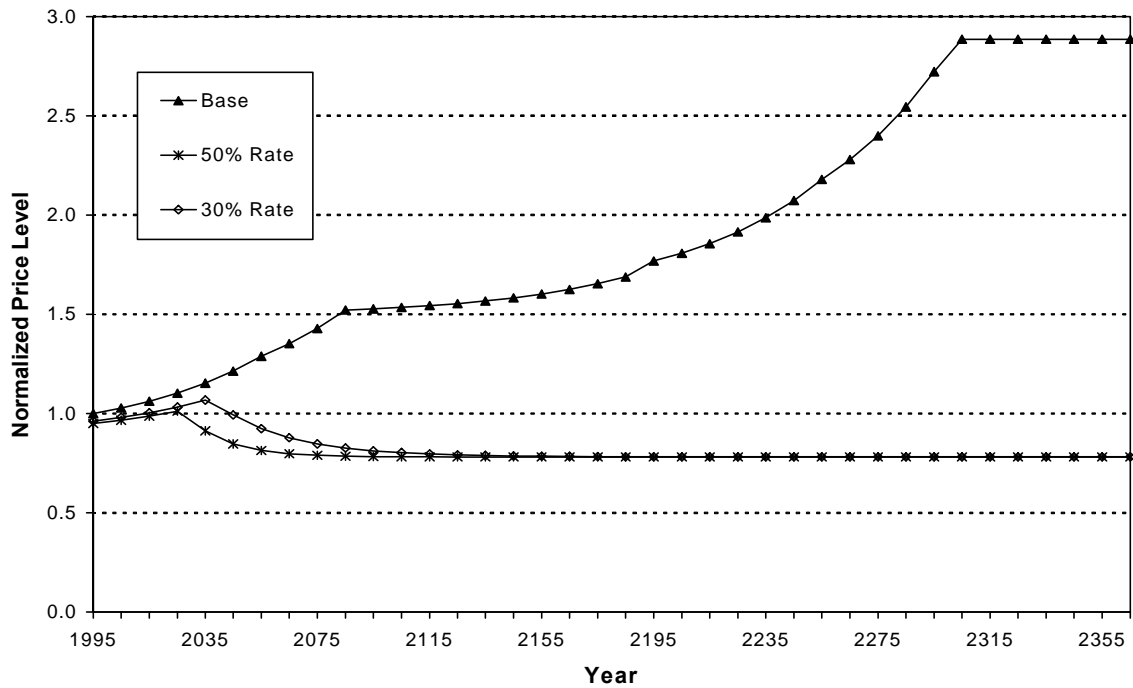(Normalized to the Base Year Price of the Baseline Model)

Figure 15. Transportation Sector Prices under Alternative Rates of Solar Electricity Cost Reduction (Normalized to the Base Year Price of the Baseline Model)
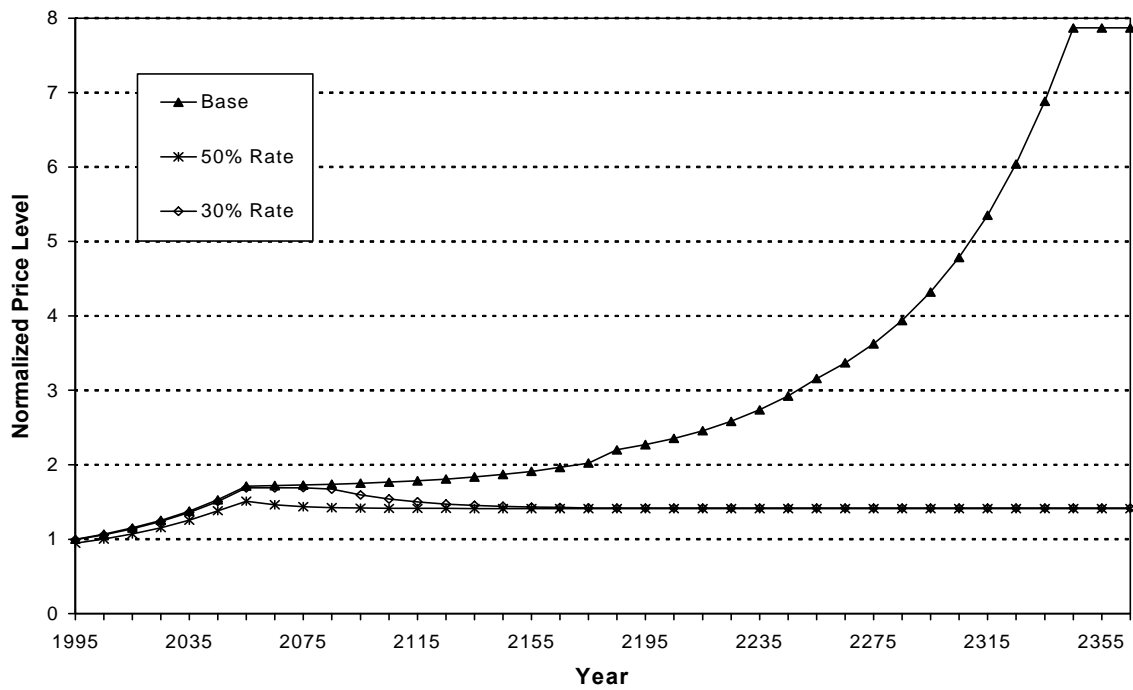

Figure 16. Residential Commercial Sector Prices under Alternative Rates of Solar Electricity Cost Reduction (Normalized to the Base Year Price of the Baseline Model)
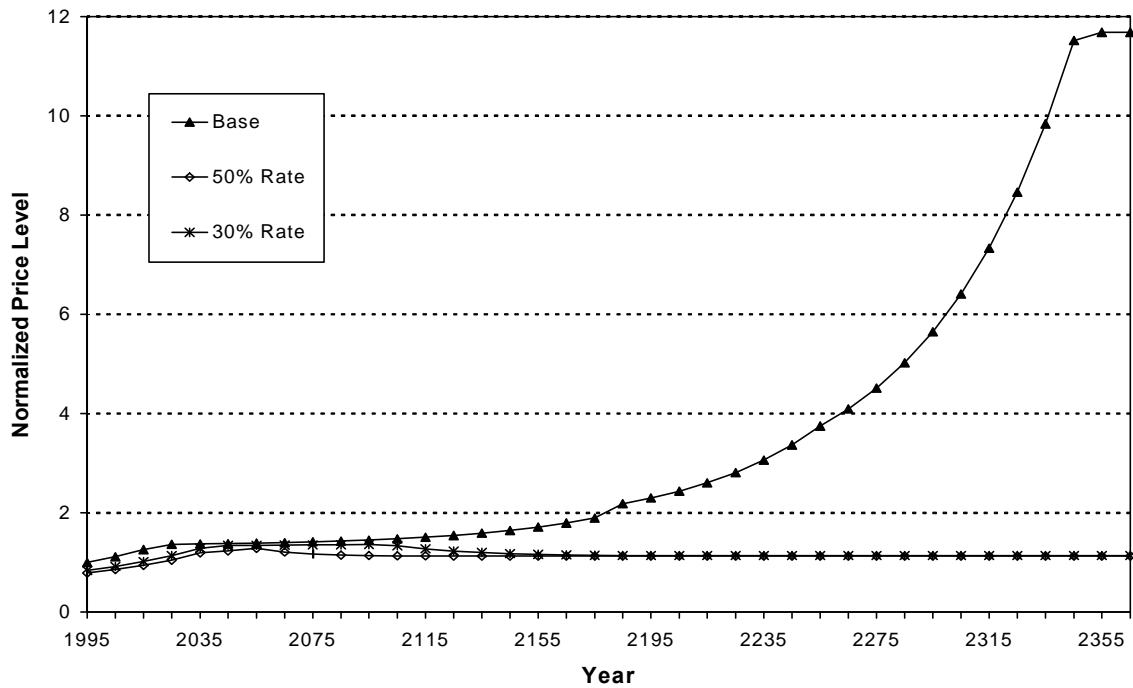
Figure 17. Industrial Sector Prices under Alternative Rates of Solar Electricity Cost Reduction
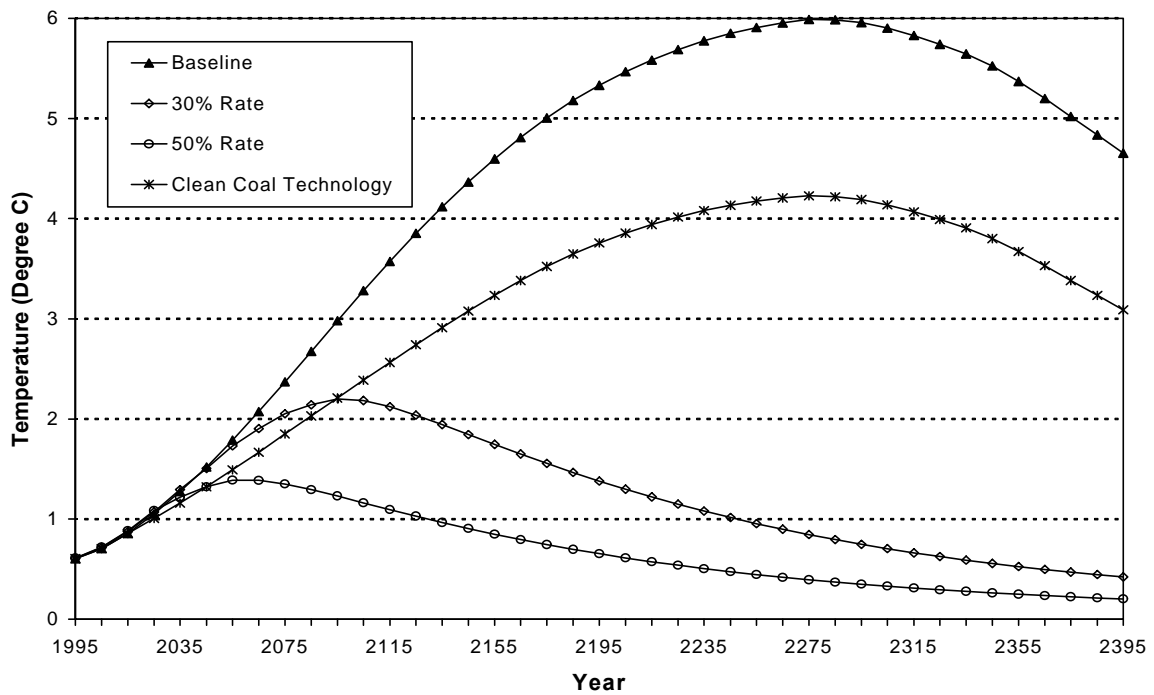(Normalized to the Base Year Price of the Baseline Model)

Figure 18. Change in Global Mean Temperature

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