AN ANALYSIS OF THE COST-EFFECTIVENESS OF U.S. ENERGY POLICIES TO MITIGATE GLOBAL WARMING

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Abstract

The issue of global warming has sparked debate among scientists and policy makers over the last two years. Many studies have been undertaken in the U.S. and other nations to determine the potential severity of global climate change and appropriate policy responses.

The U.S. Department of Energy is now conducting one such study of energy technology and policy options to mitigate greenhouse gas emissions. The study is an attempt to assess the emissions reduction potential and costs of several policies, using the FOSSIL2 integrated energy model. This paper focuses on preliminary results of a subset of eight policy cases. It discusses the modeling methodology, the formulation of these policies, draft results and some policy insights gained.

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I. INTRODUCTION

The issue of global warming has sparked debate among scientists and policy makers. Increased world-wide emissions of certain gases (carbon dioxide, methane, ozone, nitrous oxide and CFC's) may be changing the atmosphere in ways that could alter the global climate through increases in surface temperatures. Although the magnitude and timing of such temperature changes is uncertain, potential impacts include sea level rise, decreased rainfall in agricultural regions, disruption of ecosystems and increased violence of tropical storms. In short, increased concentration of these "greenhouse" gases could adversely affect a wide range of human activities.

The U.S. and other nations are spending large sums of money in an effort to better understand the causal mechanisms of climate change. Major research is focused on improving general circulation models that model the biosphere as a system. However, it will likely be years before the uncertainty in the magnitude and timing of global warming forecasts is substantially reduced. In the meantime, prudent scientists and policy makers have suggested that, given the potential severity of global climate change, mitigation strategies be studied immediately.

This paper reports on one such study. Congress in late 1988 mandated the U.S. Department of Energy (DOE) to conduct a study of energy technology and policy options to mitigate greenhouse gas emissions (1989 Energy and Water Authorization Bill). The study mandate is quite broad, allowing DOE to evaluate a comprehensive set of policies aimed at reducing emissions by 20 percent (from 1989 levels) by the year 2000 and 50 percent by 2010.

The focus of the study is energy technologies and policy; the U.S. energy sector is a major producer of greenhouse gas emissions, accounting for about 57 percent of U.S. emissions in the 1980's (EPA, 1989). A number of recent studies have attempted to assess the potential reduction in emissions from specific policy actions (Manne and Richels, 1989). However, no study to date has attempted to comprehensively assess a full array of policies or measure their costs.

The current DOE study is an attempt to assess the emissions reduction potential and costs of a broad set of technology as well as several individual and combinations of policies. It is expected to be the most comprehensive and detailed analysis of this issue to date and have a major impact on both domestic global warming policies and international treaty negotiations. The focus of this paper is on CO_2 reduction policies. CO_2 represents 70 percent of energy-related greenhouse gas emissions. Of the other greenhouse gases, methane and CFC's are not directly related to energy consumption, and although methane is tied to natural gas production and distribution as well as underground coal mining, policies to reduce methane emissions are not discussed here. Nitrous Oxide (N_2O) is not considered in the DOE study because of the uncertainty of the emissions coefficients.

This paper is a summary of some preliminary results of this study. It discusses the analysis methodology, the policies assessed, some draft results and policy insights gained. Several dozen policies and policy combinations are considered in the full DOE study. This paper focuses on a subset of eight cases.

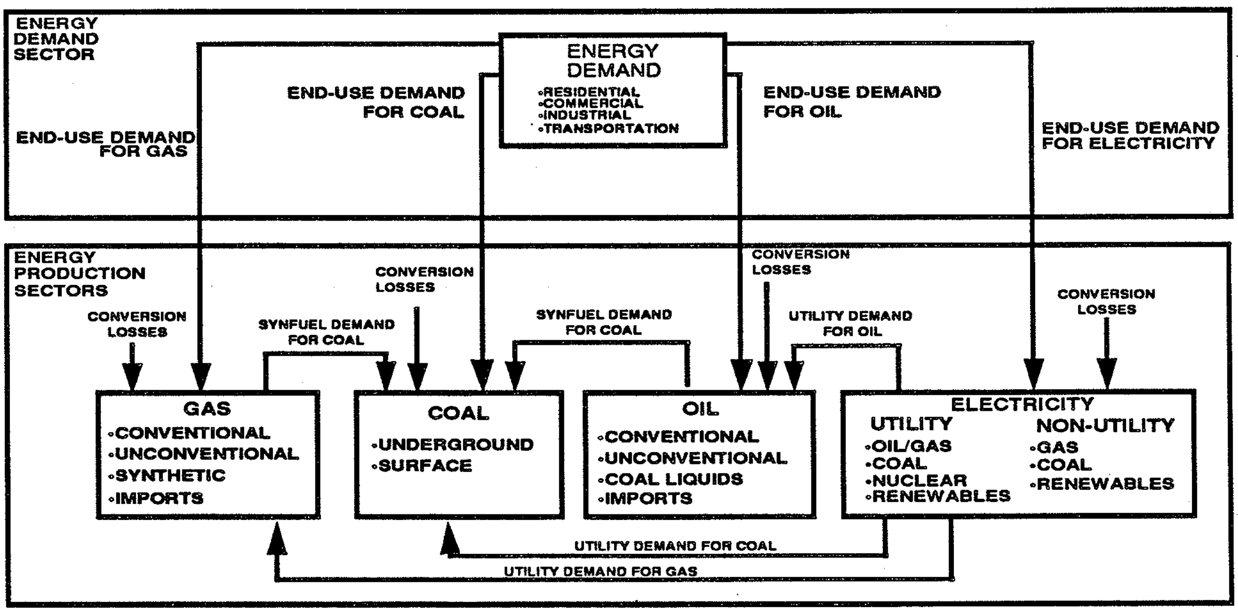
II. THE FOSSIL2 MODEL

The principal analysis tool for this study is a large-scale system dynamics model of the U.S. energy system called FOSSIL2. FOSSIL2 is a technology simulation model that projects energy production, imports, consumption and prices over a 40-year time period. It is used by the Department of Energy to analyze long-term energy policies and alternative energy futures.

The model can be characterized as an energy market equilibrium model, as energy markets clear over time through feedback among prices, demand and production capacity. The model is used in this study as an integrated analysis framework to incorporate a large set of assumptions generated by both the Department of Energy and the DOE national laboratories. The model is uniquely suited for long-term energy policy analysis because of its technology based structure, the integrated feedback of all sectors and fuels, and the inclusion of the long-term effects of resource depletion on fuel costs.

Figure 1 shows the basic interactions between energy producers and consumers included in the FOSSIL2 model. In the demand sector, energy consumers make decisions to utilize oil, gas, coal, or electricity based on both fuel prices and availability of fuels. Energy producers, in turn, choose

FIGURE 1
BASIC STRUCTURE OF THE FOSSIL2 ENERGY MODEL



to invest in the production technology that maximizes the industry's rate of return (or minimizes the average cost of production), subject to environmental constraints (for example, SO_2 restrictions or water availability).

Investment decisions by both end-users and energy producers accumulate through time as capital equipment is purchased. The existing stock of energy-consuming and energy-producing equipment largely determines the demand and production capacity for each fuel. If an imbalance develops between demand and capacity, then energy prices adjust to restore the balance, simulating the effect of market-forces.

Energy Demand

The FOSSIL2 model uses a "Least-Cost" analytical approach to model U.S. energy demand. Following this approach, the model first projects the demand for energy services (heat, light, steam, shaft power) and then calculates the share of specific end-use markets captured by energy-using technologies and fuels—including, for example, conservation, cogeneration, or conventional energy-using technologies.

The concept of measuring energy services—not just fuel use—considers energy as a means of providing services to final consumers (for example, mobility, comfort, or industrial processes such as steam or machine drive). Fuel is only one necessary component in providing energy services—end-use equipment such as a furnace or air conditioner is also needed. Consumers do not simply choose fuels, but rather choose a combination of fuels and end-use technologies.

The demand sector uses a least-cost algorithm to project consumers' decisions to invest in end-use equipment. Costs of end-use conversion and conservation technologies are combined with fuel prices to meet projected energy service demands at the lowest possible cost. Generally, this involves a tradeoff between a capital investment (for example, an energy-efficient furnace or additional insulation for a home) and paying annual energy costs: adding capital can lower the annual fuel bill. The least-cost combination depends on the cost and efficiencies of the technology alternatives, as well as the expected price of fuels. As prices rise, consumers invest in more energy-efficient capital equipment in order to save on energy bills.

Historical evidence indicates that consumers tend to invest in energy-related decisions as if they had a relatively short payback period (two to five years), or a relatively high "hurdle rate" for energy efficiency investments. The cumulative effect of these individual investment decisions through time determines the U.S. energy-using stock and potential energy consumption. Utilization of existing equipment can be modified by short-term behavioral responses, such as changing thermostat settings or practicing energy management. Thus there is both an immediate as well as a long-term response of demand to changes in prices in the FOSSIL2 model.

In the FOSSIL2 demand sector, each of the major energy-using sectors—residential, commercial, industrial, and transportation—is represented separately. Within each end-use sector, energy demand is further disaggregated by service demand category. Consumers are assumed to choose the least-cost combination of conservation and fuels to meet new service demand or to modify existing equipment. The conservation options are represented in cost/efficiency curves with a specific curve for each fuel and service demand category. The curves describe the cumulative energy savings that customers can purchase in conservation investments as a function of their cost per Btu saved. The technologies that comprise the curves are arranged in least-cost order, assuming that customers invest in the most cost-effective technologies first. The amount of conservation investment is dependent on expected fuel prices and the consumer's discount rate (hurdle rate for energy investments). As energy prices rise, consumers "move up the curves" and purchase more conservation. However, the conservation supply curves all show diminishing returns, and at some level more investment produces too little incremental savings to make the investment worthwhile.

For most energy service categories, there are several fuels that can provide the required energy—in addition to "conservation." In a few cases, such as lighting and appliances, only electricity can be used. For those where there are choices of fuels, a least-cost algorithm is used in FOSSIL2 to determine the fuel market share categories for new energy equipment. To determine market shares, energy service costs for each fuel/technology combination are compared. This cost is the sum of the capital cost, which includes a base equipment cost and additional conservation costs, and the fuel cost, which takes into account the base efficiency and conservation savings. Because the costs faced by all consumers are not exactly the same due to regional and site-specific differences, the fuel choice algorithm is based on distributions of cost rather than on single point estimates (AES, 1986).

Energy Supply

The FOSSIL2 energy model has four major supply sectors: oil, natural gas, coal and electricity. Renewables that produce electricity are incorporated in the electricity sector; nonelectric renewables are included in each end-use sector. The discussion here focuses on the sectors most relevant to the global warming study: oil, gas and electricity. The coal production sector produces little direct CO_2 (most CO_2 comes from coal burned in industrial or electric utility boilers).

Petroleum and Natural Gas Supply

The oil and gas sectors of the FOSSIL2 model project petroleum and natural gas production and imports; natural gas wellhead prices are also estimated. These sectors capture the long-term dynamics of fossil fuel discovery, production and depletion as well as the transition of the oil and gas industry from conventional resources to unconventional resources and production technologies. The model includes structures that represent the exploration for new resources, development of new reserves and installation of new production capacity in response to demand (determined by the demand sectors) and industry return on investment. Wellhead gas prices are calculated based on market equilibration between gas supply and demand. Oil prices are determined in the world market and are therefore input assumptions, although the model adjusts the oil price in response to changes in demand. These prices are then used to calculate product prices, which in turn are fed back in each time period to the demand sectors in order to equilibrate supply and demand.

The oil and gas sectors allocate joint oil and gas industry investment among extraction and conversion technologies on the basis of marginal production costs and industry return on investment. For extraction technologies, investment is allocated between wildcat and development drilling. Wildcat drilling discovers resources and increases proven and probable reserves; development drilling increases proven and probable reserves. Investment in conversion technologies (e.g. coal liquids) results in construction of synthetic fuel facilities. Resource categories included in the model are listed in Table 1.

Table 1: Oil and Gas Categories

Oil Resources	Gas Resources
Conventional onshore	Conventional onshore
Stripper wells	Gulf of Mexico offshore
Gulf of Mexico offshore	Onshore associated
Thermal enhanced oil recovery	Gulf of Mexico offshore associated
Other enhanced oil recovery	Unconventional (coal bed methane, tight gas, Devonian shale and infill drilling)
Onshore natural gas liquids (NGL)	High Cost Unconventional (hydrates, very tight sands and deep gas)
Gulf of Mexico offshore NGL	Synthetic gas from coal
Tar Sands	Alaskan
Synthetic coal liquids	Pipeline imports
Alaskan	LNG imports
Imports	

Oil imports are equal to the shortfall in domestic supply. Natural gas imports (both pipeline and LNG imports) are determined on the basis of their cost and import capacity (EEA and AES, 1990).

Electricity Generation

The electricity supply sector of the FOSSIL2 model projects prices and the mix of electricity capacity and generation. It captures the long-term dynamics of capacity construction, use and retirement as well as the transition from more conventional fossil fuel capacity to advanced coal, nuclear and renewable generation technologies. The sector builds new capacity in response to expected future demand, dispatches capacity to satisfy current demand (determined by the demand sectors) and sets electricity rates in accordance with utility rate regulations. These prices are then fed back to the demand sectors in order to equilibrate future capacity and demand.

The sector estimates the quantity of new electricity generation capacity required in each time period based on a forecast of load growth and the levels of generating capacity both existing and under construction. Utility and non-utility generators then compete for a share of the market for new capacity. The model includes costs and performance characteristics for 23 different generation technologies (listed in Table 2). In addition to the technologies listed, the model can explicitly "life-extend" oil, gas and coal steam plants, "repower" coal plants using the atmospheric fluidized bed (AFB) or integrated gas combined cycle (IGCC) technologies and convert gas combined cycle or turbine plants to coal by installing a coal gasifier.

In order to allocate investment in new capacity among the large number of technologies, the levelized cost per kilowatt-hour is calculated for each technology in each time period based on capital costs, operating and maintenance costs, fuel costs and design capacity factors. New capacity construction decisions are then made on a least-cost basis weighted by a market allocation function. The model uses a logit-based market share algorithm; "knife-edge" construction decisions are therefore avoided. Electricity rates are then calculated based on capital and operating costs of the resulting capacity mix. (Detailed information on the technology assumptions, market share algorithm and electricity rate algorithm is available in AES 1990).

Table 2: FOSSIL2 Electricity Generation Technologies

Coal	Oil/Natural Gas	Nuclear	Renewables
Coal Steam	Oil steam	Light-water reactors	Hydroelectric
Coal steam w/FGD	Gas steam	Advanced light-water reactors	Photovaltaics
Atmospheric fluidized bed	Gas combined cycle	Second generation nuclear	Solar thermal
Pressurized fluidized bed	Combustion turbines		Wind
Integrated gasification combined cycle (IGCC)	Steam injected turbines (STIG)		Geothermal
Coal gasification ISTIG	Intercooled steam injected turbines (ISTIG)		Biomass
Coal gasification fuel cells	Gas fuel cells		

A national-level annualized load duration curve together with operating costs determine the capacity dispatching order. In a given time period, technologies within the capacity mix are dispatched on the basis of fuel and variable operation and maintenance costs. This typically translates into a dispatch order that baseloads nuclear, a large amount of coal, some oil and gas, and renewables. "Intermediate" coal and "intermediate" oil and gas are used for cycling loads, and pumped storage hydro and combustion turbines serve peaking needs. Capacity factors are determined from this dispatching order.

III. GLOBAL WARMING POLICIES

Virtually every part of the U.S. energy system produces carbon dioxide; however, some sectors produce disproportionate emissions. In 1990 the electricity generation industry is estimated to produce 38 percent of total energy-related carbon emissions, although it is important to note that end-use consumers are in effect emitting that carbon by consuming the electricity. Petroleum use in transportation accounts for about 29 percent of emissions, while industrial fossil fuel use represents 21 percent and residential and commercial buildings account for about 12 percent. Policies to reduce carbon emissions should focus on the major CO_2-emitting sectors but also consider the fact that all sectors contribute to this problem.

Policies that address the rising rate of carbon emissions can take a number of approaches depending upon the availability of appropriate technology as well as the feasibility of implementation. Measures that decrease the carbon intensity of energy consumption seek to provide the same level of energy production at lower carbon levels. For example, the promotion of energy-efficient production technologies and energy conservation through standards causes users to use less fuel input for the same energy output. Financial incentives (such as fees or taxes) might also be used to discourage the use of carbon-intensive energy systems and encourage more environmentally benign ones. Such fees or taxes, based either on carbon content or the use of particular fuels or technologies would allow energy users to trade off the relative merits of paying the penalties versus adopting new fuels or technologies to avoid carbon emissions. If these fees are set appropriately, commensurate with the carbon content of the fuels, the market will pursue emission-reducing and economically efficient measures. In conjunction with reducing carbon emissions, sequestering those emissions by planting trees (or developing other carbon sinks) could prove worthwhile as well.

Our study seeks not to recommend a particular course of action, but rather to examine a wide range of policy options, to explore the potential costs of pursuing those options, and to identify feedback effects which could improve or offset the effectiveness of these policies. The FOSSIL2 model includes end-use technology costs as well as energy production costs, so it is able to account for the total energy service costs. Both capital and fuel components of costs are considered, so that new equipment, conservation investment and fuel price changes can be balanced as economic choices are made to invest in one or another technology. The costs of these policies can be compared with their effectiveness in reducing emissions to arrive at measures for policy cost-effectiveness. Relating these costs to their effects on the energy system and carbon emissions will give policy makers measures of the relative cost-effectiveness of alternative policy options.

Energy Efficiency Standards

Residential, commercial and industrial conservation investments in FOSSIL2 are made in each end-use category on the basis of fuel prices, consumer discount rates, and conservation equipment costs and efficiencies (represented in conservation "supply curves"). Given these parameters, each end use arrives at a least-cost matrix of energy conservation and fuel consumption in a given period. It is important to note, however, that the least-cost solutions for such consumers are often not the least-cost solution for society as a whole. For example, consumers who make decisions based on average energy prices and use a two to three year payback period are reluctant to invest one thousand dollars per kilowatt in energy conservation. However, utilities that see marginal prices and use a 30-year payback period may spend two to four thousand dollars per kilowatt on new capacity. Policies that could reduce energy consumption therefore also result in society-level least-cost solutions and are leading candidates for an effective CO_2 mitigation strategy.

Energy efficiency standards mandate higher conservation levels through efficiency standards for each end use. This is accomplished in the model by racheting up the conservation supply curves in 1990 to the standards levels. Thus the standards force new buildings and capital stock to meet the new efficiency levels. As a result, the capital costs rise substantially in the short term relative to the reference case without the standards; however, added fuel savings are realized in the longer term. Standards are incorporated similarly in the transporation sector. CAFE standards are specified over time and all new autos and trucks are required to meet the standards.

This paper reviews two standards cases that bound the buildings and industrial conservation potential in the conservation supply curves. The very high standards are set in the uppermost region of the curves; they represent extremely high but non-economic levels of conservation. The high conservation case represents approximate mid points on the curves between the reference and very high conservation cases. Hypothetical extensions of vehicle CAFE standards in both cases are taken from recent work at Argonne National Laboratory. Average on-road auto fleet efficiency reaches 26 mpg by 2000, 32 mpg by 2010, and 48 mpg by 2030.

Carbon Taxes

The prices of fossil fuels do not reflect the carbon content of those fuels. In fact, the fuel highest in carbon (coal) has the lowest price ($/MMBtu). Policies that tax fuels proportional to their carbon content can adjust the energy prices seen by the end-user to better reflect the fuel's contribution to global warming. Such a pricing scheme would favor non-carbon emitting fuels over fossil fuels and natural gas over oil and coal. This tax would be applied based on the carbon content of the primary fuel, rather that actual carbon emissions. Ostensibly, an emissions tax would provide the user more flexibility in reducing carbon output, because of the additional option of removing carbon from the process before it is emitted. However, the present high cost of CO_2 removal and the lack of permanent CO_2 disposal possibilities make an emissions tax essentially no different than a carbon content tax from the end-user's perspective, and a tax based on carbon content is much more easily implemented.

Carbon taxes have already been proposed in a number of countries and are usually expressed in dollars per ton of carbon emitted. Finland has gone the furthest by introducing a $6/ton tax on fossil fuels in its 1990 Finance Act; Sweden is considering a much larger tax of $40/ton (The Economist, March 17, 1990). Even so, taxes of greater magnitudes will most likely be required to achieve the dramatic reductions called for by Congress. Our study explores four tax cases: $100/ton, $250/ton, $400/ton and $625/ton.

Coal Power Plant Efficiency Standards

Coal consumption in the electric utility sector represents over 85 percent of all U.S. coal consumption, and therefore the promotion of more efficient coal-fired generation should help to reduce carbon emissions. Included in our study is a set of coal power plant efficiency standards that imposes a penalty on the capital cost of new coal-fired power plants not meeting the standards. This penalty is based on the difference in conversion efficiencies between each coal technology and a chosen state-of-the-art technology. The best commercially available technology is considered the standard; this target changes as new clean coal technologies develop. Atmospheric fluidized bed issued as the most efficient available technology in 1990, but is then replaced by the Integrated Gasification Combined-cycle (IGCC) technology in 2000 and then by coal fuel cells after 2010. The penalty is $800 per 1000 Btu/Kwhr difference in the heat rates between the standard and target technologies; this translates into 30 to 50 percent increase in capital costs for the affected technologies.

Reforestation Offsets

The potentially high cost of limiting carbon emissions suggests that policies for removing carbon from the power plant emissions should be considered. Technologies exist to scrub carbon dioxide from the effluent stream of power plants, but costs are extremely high and disposal poses a substantial problem. Currently the most cost-effective method of "scrubbing" CO_2 after burning the fuel is the planting of fast-rotation trees and other forms of biomass. Carbon emitted by fossil fuel combustion can be "fixed" (i.e. removed from the atmosphere and stored in the biomass) during the growth cycle of such crops.

One reforestation offset case is considered in this paper. In this reforestation policy case, tree planting is mandated to fix the lifetime carbon output of all new fossil-fueled power plants and industrial boilers and cogenerators. Although such offsets are conceptually straightforward, major uncertainties are connected with the costs of such a policy (Moulton, 1989). This paper estimates that 160 million acres of marginal agricultural land are available for reforestation in the U.S. and that carbon uptake with appropriate crops and climate conditions is about 2.5 tons/acre/year (Reilley, 1989). The acreage limit is assumed to be an economic rather than a absolute constraint; additional land is available, but only at a much higher cost. These costs start at about 10 dollars per ton of carbon removed, and rise as high as 90 dollars per ton removed (Moulton, 1989). This translates into into cost additions of up to a third of the capital cost of a new fossil-fueled power plant and almost double the cost of life extensions. In industry, the cost is 8 percent of a new boiler.

IV. RESULTS

With no major changes in policy, the annual rate of carbon emissions from the U.S. energy system is projected to grow from an estimated 1320 million metric ton per year (MMT/yr) in 1987 to 1772 MMT/yr in 2010 and 2267 MMT/YR in 2030--the 2030 rate being over 70 percent higher than in 1990. In this "business as usual" case, virtually all growth occurs in electricity generation and in transportation fuels.

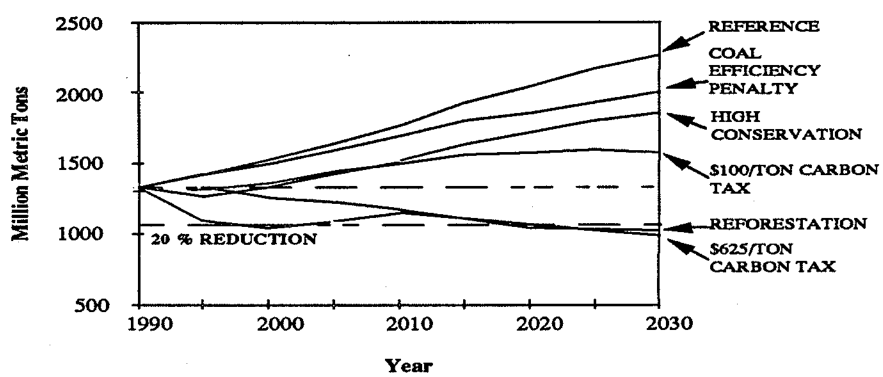
Our discussion first explores the CO_2 emissions reduction potential of the policy cases, then fuel switching and energy end-use implications, and finally discusses costs and cost-effectiveness. This set of policies illustrate that absolute reductions in carbon emissions are possible, but will not be easy.

Emissions

The eight policy cases examined involve significant changes in fuel use and technology choice and rely on consumers' responsiveness to higher prices. The substitution of more efficient technologies both at the end-use and in electricity production can help decrease our energy intensity, but the direct impact of efficiency improvements reduces greenhouse gas emissions only modestly. Significant carbon reduction comes about primarily through price-induced cutbacks in demand and wholesale switching towards carbon-free technologies.

Figure 2 illustrates annual carbon emissions for the reference case and selected carbon mitigation policies. Most notably, only the extreme carbon tax case ($625/ton) and the reforestation policy nears the goal of 20 percent reduction in total carbon emissions. Most of the reductions in emissions shown in Figure 2 occur in the electricity sector and to a lesser extent in industry. These not only represent the largest contributing sectors of carbon emissions, but are the sectors with the most technology and fuel alternatives. Conservation standards are the most effective means of reducing emissions in the residential and commercial sectors, whereas carbon taxes affect all sectors, (especially electric generation).

Figure 2: ANNUAL CARBON EMISSIONS

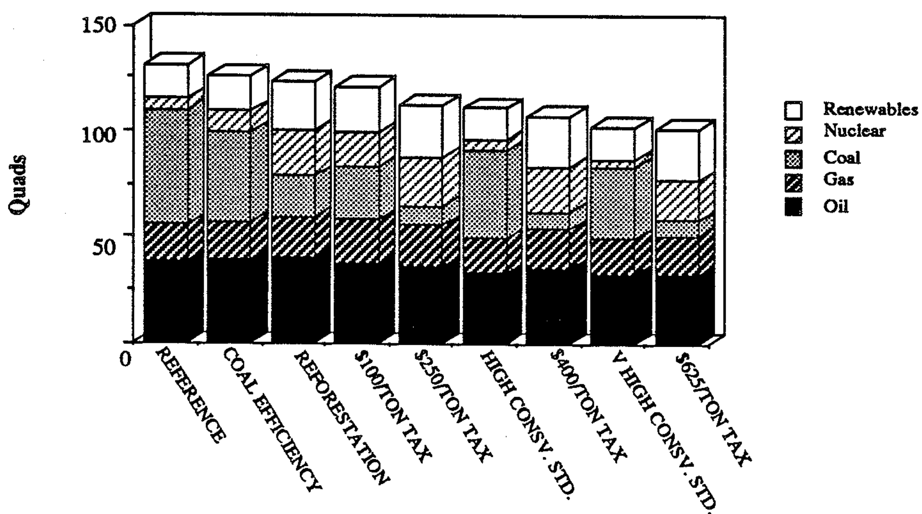


Reforestation is unique in offering sustainable carbon reductions. Because this policy fixes carbon output from all new generating plants, it decouples emissions from electricity demand. The potential reduction in emissions is quite large--emissions from electric generation represent 54 percent of total 2030 CO_2 emissions in the reference case but amount to only 5 percent with reforestation. With the prospect of increased electrification in the economy, this policy provides a potentially effective way to reduce emissions while maintaining growth in electricity usage, provided enough acreage is found to support the required biomass.

Energy Consumption

Since carbon emissions are closely linked to energy consumption, policies should be evaluated from this perspective as well. The goal of each policy in this context is to decrease the total fossil fuel consumption, and especially coal consumption, since coal emits twice as much carbon as natural gas. Figure 3 shows primary energy consumption in the year 2030 for each of the policies tested. Total oil and gas consumption in these cases is similar to the reference case, but total energy consumption as well as the mix of coal, nuclear, and renewables varies substantially. This model, prepared for the Department of Energy, assumes that over this 40-year time frame, viable "advanced" nuclear technology options will be developed. It is clear from Figure 3 that when coal use is cut back, these advanced nuclear technologies make up most of the difference, with some increase in renewable energy and conservation as well. This is logical since coal and nuclear power are assumed to be the two major energy sources which provide long-term, reliable and inexpensive baseload capacity for electricity generation. Natural gas provides a short-term solution (to the year 2000 or so), but as conventional gas resources are depleted, the energy system must rely on expensive unconventional supplies to meet gas demand. This causes the price of gas to rise substantially, making the nuclear option more economically attractive in the longer term.

Figure 3: PRIMARY ENERGY CONSUMPTION IN 2030



In the increased coal efficiency case, the average efficiency of coal power plants in 2030 increases from 40 percent to 45 percent. Although this change is relatively modest, the cost penalty associated with this policy substantially raises the cost of most coal-fired capacity and results in substantial shifts to nuclear, renewable and advanced high-efficiency coal capacity (e.g. coal gasification fuel cells) in the long term. Total coal use is reduced by almost 12 quads by 2030, 42 percent of which is due to increased efficiency; the remaining 58 percent is attributable to conservation and fuel switching (by both consumers switching away from electricity and electricity generators switching to other fuels). In general, the end-use fuel mix in this scenario is not significantly different from the reference case, although coal use in industry increases slightly, thus mitigating some of the emissions reductions achieved in electric generation. This is in response to a decrease in the delivered price of coal resulting from reduced coal demand. This price-demand feedback effect has also been observed in other policies examined in the DOE study but not discussed here. In the end-use efficiency standards cases, end-use consumption for all fuels drops; by 2030, oil falls 15 percent, gas 8 percent, coal 50 percent and electricity 16 percent. The reforestation case shows a substantial switch from coal to nuclear and renewable energy in the long term, with some conservation as well. This adjustment is caused by the requirement to offset emissions with tree planting, which acts like a tax on coal-fired power plants and discourages coal use. In addition, a large portion (86 percent) of the carbon emissions from the remaining fossil fuel use is offset by this policy. The total energy consumption and fuel mix in the $100/ton carbon tax case looks similar to the reforestation case, but the more extreme carbon tax cases ($400/ton and $600/ton) show an even greater shift away from coal, with nuclear and renewables making up 43 percent of total fuel consumption in the $625/ton tax case, as compared to 16 percent in the reference case.

In order to understand the reasons behind the differences in fuel mix and levels of conservation in these different policy cases, it is helpful to look at the policies in terms of the energy consuming sectors which are being affected. Industry, transportation and electric generation consume the most energy: the electric sector uses 47 percent of total fuel consumption in the reference case in 2030, industry uses 22 percent, transportation uses 23 percent, and the remaining 8 percent is consumed by the residential and commercial sectors. Effective policies might focus on reducing energy consumption in each of the three energy intensive sectors, or encouraging a switch to non-fossil fuel sources of energy within these sectors. Table 3 below shows each policy and the sector or sectors affected by the policy. The coal efficiency case affects only the electricity producers, which explains why the policy is relatively ineffective. The reforestation case offsets emissions for both electric generators and industrial users, but does not affect the transportation sector. Both the conservation standards cases and the carbon tax cases affect all of the energy consuming sectors, and are generally effective at reducing total energy consumption as a result. The conservation standards cases, however, act upon each fuel equally, regardless of its carbon content. Since coal has the highest carbon content and the electric producers and industrial consumers use the greatest amount of coal (95 percent of total coal consumption in the reference case), these policies might be made more effective if higher conservation standards were placed on industrial coal boilers and electricity consuming end-uses (such as appliances). Therefore from an <u>energy</u> perspective, the carbon tax cases are the most effective in reducing emissions because these policy cases affect all energy consuming sectors and apply the tax based on the carbon content of the fuels.

Table 3: Energy Sectors Affected by Each Policy

Policy	Residential Commercial	Industrial	Transportation	Electric Generation
Coal Efficiency Penalty				√
Reforestation		√		√
Conservation Standards	√	√	√	√
Carbon Tax Cases	√	√	√	√

Note: Conservation Standards Cases act upon the electric generating sector indirectly by reducing electricity use by consumers.

Costs

The previous sections detailed the effects of the greenhouse policies on carbon emissions and on energy consumption. This section focuses on the costs of those policies, using total energy service costs to determine cost-effectiveness of each policy. Energy service costs, which sum the end-use capital and fuel costs associated with using energy are calculated explicitly in FOSSIL2 and totals can be compared across cases. The cost of energy services varies depending on the fuels and technologies chosen and these costs feed back to overall economic output as measured by GNP.

Table 4 compares the average cost per ton of carbon reduction and the total amount of carbon reductions for each policy over the 40 year period. An effective policy would have a low (or even negative) cost of reduction and hopefully the potential to eliminate a large percentage of future carbon emissions. According to this analysis, the high conservation standards are the most cost-effective way to reduce CO_2 emissions. In fact, long term costs are negative. A negative cost suggests that consumers would be better off making the additional conservation investments anyway. That is to say, cost-effective conservation opportunities exist that would decrease energy usage, and hence emissions, without diminishing energy services or increasing long term costs. These opportunities are not pursued now, though, because of the short time horizons consumers have for calculating returns on investment. The very high conservation case mandates investments that are too expensive to be cost-effective even in the long term—the savings in fuel costs do not offset the high cost of

Table 4: Incremental Cost of Reduction

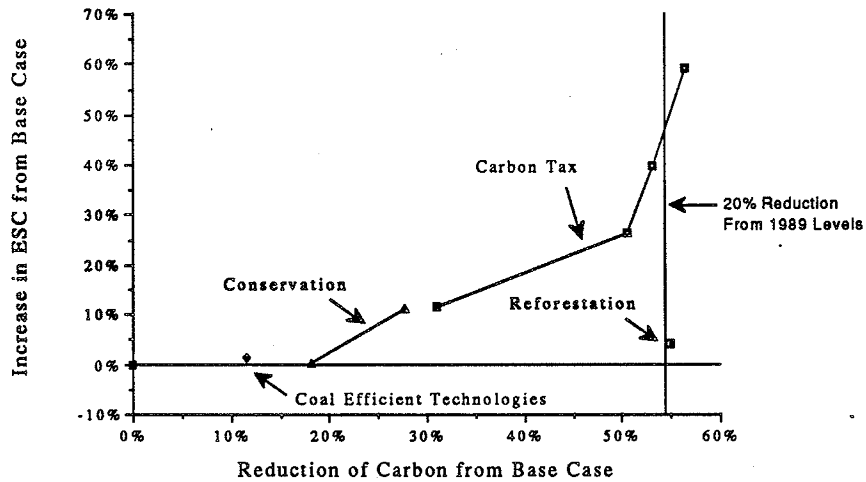
	Dollars/ton Removed*	Carbon Reduction (% from Reference)
Conservation		
High	negative	18%
Very high	280	28%
Reforestation Offsets	88	55%
Coal Efficiency Tax	260	12%
Carbon Tax		
$100/Ton	565	31%
$250/Ton	710	51%
$400/Ton	885	53%
$625/Ton	1100	57%

installing additional energy-saving devices. Reforestation offsets provide both a low cost carbon reduction policy and can achieve perhaps the highest absolute reduction in emissions (55 percent). The coal efficiency standards cost more than three times the reforestation case yet reduces emissions only 12 percent; although coal efficiency rises, large quantities of coal are still consumed in the electricity industry. The carbon tax cases have high costs of carbon removal and appear to have diminishing returns after the $250/ton case.

Incremental costs cannot explain the whole picture. Figure 4 is a "supply curve" of carbon reduction options. Both axes are relative to the reference case and compare the change in cumulative discounted energy service costs to changes in emission levels. Annual energy service costs are not simply summed over time, but are discounted based on a social discount rate of 3 percent. Expenditures in the near future are given more weight in this metric than are those further off in time, because money spent in the present is more highly valued than that spent in the future.

This analysis suggests that achieving the targeted level of reductions in carbon emissions can be expensive. The high conservation case is important because of its savings (negative cost) in total energy service costs relative to the reference case. But this level of conservation only achieves a 20 percent reduction relative to the 55 percent needed to meet the target. The reforestation case stands out because of its ability to meet the target reduction level by 2030 at relatively low cost. In contrast, the $625/ton carbon tax also achieves the target, but only at a huge cost, with total cumulative energy service costs increasing by over 50 percent. Reforestation programs might increase total costs by about 5 percent (or perhaps less if non-U.S. acreage were used for planting), but has large and sustainable emission reduction potential. The practical effectiveness of this policy remains unknown because of uncertain costs and total acreage availability. Nevertheless, reforestation offsets show enough promise to warrant further consideration as an effective policy for carbon mitigation.

Figure 4: 2030 CARBON REDUCTION VS. ENERGY COSTS



V. CONCLUSION

This study has attempted to focus policy-makers on the cost and energy impacts of suggested measures to reduce carbon emissions. This discussion has seen reforestation emerge as a promising alternative to taxes or standards. More analysis and debate will be needed before an acceptable policy or combination of policies is found, and we hope to forward this search by presenting insights gained from the analysis presented here.

As has often been recommended, there are considerable opportunities for conservation to limit the growth of energy use and carbon emissions. Our analysis highlights possible cost savings (reductions in energy service costs) associated with at least one such case we tested (the "high conservation standards" case). It is clear that a policy that effectively promotes these cost-effective conservation measures would be worthwhile to implement and should be given a role in any global warming or energy policy strategy. A set of mandated efficiency standards is not necessarily the best method to advance these savings; a program that better informs people of conservation options and the potential savings from those options might go far in accomplishing the same result. More effort needs to go into understanding the non-cost related factors present in consumers' decisions and into addressing those factors in the design and sale of efficient equipment. Incentives (regulatory or otherwise) for manufacturers to develop and produce more energy-efficient equipment (such as CAFE standards) may also be necessary to achieve the desired level of conservation.

In the electricity sector, this analysis portrays a significant long-term switch from coal to nuclear power and renewables for many of our policy cases. An obvious key assumption in this conclusion is the existence of a viable, cost-effective nuclear option (here called "advanced nuclear generation"). Advanced nuclear plants are chosen as the inexpensive baseload technology to substitute for coal in the long-term. Natural gas provides a short-term solution for electricity generation, but it too is carbon-based and it is also a finite resource. The desire to reduce coal consumption encourages gas use in the near term in this analysis which depletes gas resources and drives up the price of gas. Nuclear power and renewables then become the cheaper options in the long-term. Gas-fired generation, therefore, provides a transition from the present coal-dominated electricity sector to one in which nuclear power and renewables play an increasing role. Whether this future for nuclear power is realistic depends upon its cost and more importantly its public acceptability, but policy-makers will need to address the issue of finding an inexpensive, reliable and environmentally-benign fuel source to replace coal in electric generators.

The natural "feedback" interaction of energy supply, demand and price has illuminated another important insight regarding policy design. By having policies address only one sector and ignoring their ramifications on other sectors, unintended results may occur. For example, in the policy promoting coal efficiency, a penalty was assessed against inefficient coal plants. This resulted in a significant reduction in coal consumption by this sector. This reduction in demand brought down coal prices and made coal more attractive to industrial users. Policy-makers must concern themselves with this potential for policies to "backfire" in this manner.

Because of the limitations of most of these single policies to achieve significant reductions in a cost effective manner, policy-makers might need to seek a combination of policies that would be cost-effective and target the major carbon emitting sectors. One such combination would impose a carbon tax whose collection would be applied towards planting trees and increasing conservation investment and information. Other combinations might also be devised to take advantage of energy market interactions and consumer behavior.

A more thorough examination of policies and their results and insights can be found in the forthcoming DOE report to Congress. The global warming issue presents a significant challenge to both scientists and policy-makers, and system dynamicists are playing a role in providing important insights to both.

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