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Greenhouse Warming: A Rationale for Nuclear Power?

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GREENHOUSE WARMING: A RATIONALE FOR NUCLEAR POWER?

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1. Introduction

Scientists have long recognized that small changes in the chemical composition of the Earth's atmosphere could result in potentially serious global climate variations. Most familiar is the possible climatic warming that could result from the so-called "greenhouse" effect associated with increased concentrations of carbon dioxide (CO_2). Certain trace gases in the earth's atmosphere, such as CO_2, absorb in the infrared wavelength region, and thus trap part of the earth's infrared radiation that would otherwise be radiated into space. This means that incoming solar energy is partially retained, causing the earth's temperature to rise -- hence the term "greenhouse" effect.[1] The effect was first identified over a century ago, and the earliest analytical work was done in 1896 by Svante Arrhenius, who estimated that a doubled concentration of CO_2 would lead to a 4-6 degree [Celsius] rise in the Earth's surface temperature.[2]

The atmospheric concentration of CO_2 has increased from a "pre-industrial" level of 275 ppmv in the mid-1800s to around 343 ppmv by 1984.[3] This increase is due primarily to anthropogenic activities, including both deforestation[4] and the combustion of fossil fuels. Between 1861 and 1984, the world experienced "a long time scale warming trend, with the three warmest years being 1980, 1981, and 1983, and five of nine warmest years in the entire 134-year record occurring after 1978."[5] The global mean temperature has increased by about half a degree Celcius during this period.[6] Serious attention to this issue increased during the 1950s and 1960s, and now in the late 1980s the greenhouse warming problem has become a household term.

Over the past decade there has been increasing political recognition of the urgency of the greenhouse problem. In 1986, the United States Congress appropriated $7.6 million to the U.S. Environmental Protection Agency (EPA) study the current status of greenhouse warming, and to analyze various policies to ameliorate the problem. The EPA is currently

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[1] For a review of the scientific theory, see "The Greenhouse Theory of Climate Change: A Test by an Inadvertent Global Experiment," Science 240:293-99, 15 April 1988.

[2] S. Arrhenius, "On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground," Phil. Mag. 41:237 (1896). For an historical account, see J. Ausubel, "Annex 2" in Changing Climate, National Research Council, 1983.

[3] B. Bolin et al., The Greenhouse Effect, Climatic Change, and Ecosystems, John Wiley, 1986, Chapter 1.

[4] G.M. Woodwell et al., "Global Deforestation: Contribution to Atmospheric Carbon Dioxide," Science 222: 1081-83 (1983).

[5] P.D. Jones, T. Wigley, and P. Wright, "Global Temperature Variations Between 1861 and 1984," Nature 322:430 (31 July 1986).

[6] R.A.Kerr, "Is the Greenhouse Here?" Science 239:559-61 (5 February 1988).

conducting several workshops on the topic, and expects to report back to Congress in early 1989.[7]

Recent studies have revealed rising atmospheric concentrations not only of CO_2, but also of *other* greenhouse gases such as methane, nitrous oxide, and chlorofluorocarbons (CFCs). These additional trace gases are expected to exacerbate the climatic warming trend considerably. Anthropogenic emissions of CO_2 into the atmosphere come primarily from the combustion of fossil fuels and from deforestation. Climate warming could produce a number of changes in the terrestrial biosphere that are irreversible and difficult to predict. Expansion of seawater together with the melting of polar ice caps could raise sea level enough gradually to flood coastal cities. Major shifts in precipitation patterns could profoundly change regional farm yields, dislocating global food supplies. A related environmental problem associated with fossil fuel combustion -- commonly referred to as "acid rain" -- involves acid deposition resulting from airborne emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x). The resulting acidification of lakes and forests has evidently already wreaked considerable damage upon trees, soils, and aquatic wildlife.

In view of these problems, it is widely recognized that continued fossil-fuel combustion on a large scale will accelerate future climatic warming and environmental degradation. Consequently it is essential to minimize our burning of these fuels in the future. Many people believe that this can only be done by replacing fossil fuels with another energy source. Moreover, it is often assumed that the only serious candidate for this new energy source is nuclear power, primarily because no other non-fossil supply technology can be developed on a sufficiently large scale. Thus, a growing number of individuals and institutions are coming to the view that the environmental hazards of burning fossil fuels will ultimately force us back to nuclear power, and that public perceptions of nuclear power will simply have to adapt accordingly.

In this paper, we explore the viability of a nuclear solution to the greenhouse warming problem from several perspectives. After summarizing the arguments for a nuclear solution in Section 2, we begin our analysis in Section 3 by explicitly assuming highly favorable conditions for nuclear power. We then analyze in detail two greenhouse scenarios that span the range from moderate to substantial future greenhouse warming. *The overall finding is that even a massive worldwide nuclear power program sustained over a period of several decades could not "solve" the greenhouse problem.*

Section 4 of the report takes a different tack, surveying historical experience and future prospects of nuclear power around the world. This section focuses particularly on developing countries, since the history of nuclear power in these countries is less well known. The basic finding is that the Third World cannot support a major expansion of nuclear power on the scale that would be required in an attempted nuclear solution to greenhouse warming.

In Section 5 we examine several low-energy scenarios in which the threat of greenhouse warming is greatly reduced. *The general finding is that the key to ameliorating future climatic warming caused by atmospheric release of carbon dioxide is to improve the efficiency of energy usage.* The degree of future energy efficiency is the greatest determinant of future CO_2 emissions. Even a sixfold expansion of nuclear power would have little impact on the greenhouse problem, unless that problem has already been largely solved by efficiency in the first place.

[7] "Funds for EPA in the Area of Ozone Depletion, The Greenhouse Effect and Climate Change," United States Congressional Record - Senate, S 14779-80, 2 October 1986.

Finally, we perform an opportunity cost analysis of a nuclear response to greenhouse warming. It is found that investing in nuclear power as a strategy for abating greenhouse warming actually makes the problem worse, by diverting funds away from improving efficiency. Per dollar invested, efficiency is nearly seven times more effective in abating CO_2 than nuclear power. Per kWh of electricity produced, nuclear power is effectively almost six times more carbon intensive than coal fired power (in terms of carbon that could have been displaced by an equivalent investment in efficiency).

The conclusion of this study is that nuclear power is a slow and ineffective response to the greenhouse warming problem, whereas improved energy efficiency is the opposite: quick, and highly effective. In addition, a "nuclear solution" would be economically infeasible for the developing world and is not the economically preferred solution in either industrialized or developing nations.

Following the conclusions are two Appendices that provide details of calculations in the text, and analysis of financing in developing countries.

2. Arguments for a Nuclear Solution

Nuclear power has long been viewed as a possible solution to the global greenhouse problem. As public awareness of the threat of climatic warming grew during the 1960s and 1970s, nuclear energy was frequently cited as an attractive alternative to fossil fuels.[8] In recent years, nuclear advocates have pointed to the growing urgency of environmental problems associated with fossil fuels as a major reason for revitalizing nuclear power.[9] Recent testimony to the U.S. Senate Committee on Energy and Natural Resources asserted that "The problems of climate change underline the importance of restoring the nuclear energy option."[10] And Alvin Weinberg, the grandfather of the pressurized-water reactor, argues that "Carbon dioxide, I believe, has emerged and continues to emerge as perhaps the central environmental issue. It seems to me...[to be] the strongest incentive to get back on track with nuclear energy."[11]

It is worthwhile to consider the reasons for this view. Nuclear power offers some attractive features as regards the greenhouse warming problem. Predominant among these, of course, is that nuclear electricity generation entails no direct emissions of CO_2 or of any other greenhouse gases.[12] Particularly when compared to coal-fired power, this is a distinct ad-

[8] See, for example, A.M. Weinberg, "Nuclear Energy at the Turning Point," IAEA CN-36/593, 1977, and the discussion in Chapter Six of Keeny, S.M. et al., Nuclear Power: Issues and Choices, Ballinger, 1977.

[9] See, for example, A.M. Weinberg, "A Nuclear Power Advocate Reflects on Chernobyl," Bulletin of the Atomic Scientists 43(1):58 (Aug./Sept. 1986), or quotation from H. Blix in Nucleonics Week, 16 Oct. 1986, p. 13.

[10] G. J. MacDonald, Relationship Between Current Energy Technologies and the Greenhouse Effect and Global Warming, statement before the Committee on Energy and Natural Resources, United States Senate, 10 November 1987.

[11] A.M. Weinberg, colloquium at Los Alamos National Laboratory, 7 December 1987, quoted in S. Doughton-Evans, "Safe Reactors Power of Future?," Los Alamos Monitor, 8 December 1987.

[12] Nuclear reactors and (especially) reprocessing plants emit a radioactive gas known as krypton-85, which may change the ionization level of the atmosphere. The consequences are not known, but it is supposed that important mechanisms of heat transfer between the tropics and temperate regions could be modified, with possibly serious

vantage. Moreover, nuclear power also entails no SO_2 or NO_x emissions, meaning that it makes no contribution to acid rain. Again, this advantage is especially relevant in comparison to coal-generated electricity. Finally, the breeder reactor can in principle produce more plutonium fuel than it consumes. In a nutshell, advocates of a nuclear solution to the greenhouse warming problem maintain that nuclear power is "clean," it is inexhaustible (in principle), and it can presumably make a sufficiently large contribution to replace fossil fuels.

Implicit Premises

It is important to point out that the notion of a nuclear solution to greenhouse warming entails a number of implicit premises and assumptions that we shall mention only briefly here. For example, there are numerous other non-fossil sources of energy (*e.g.*, hydroelectric, wind, and solar power), as well as many demand-reducing options such as end-use efficiency and conservation -- none of which emit CO_2. However, the usual assumption is that these other sources and options could not make sufficiently large contributions to be seriously considered as candidates for substitution of fossil fuels, even if they were all combined into a coherent grand strategy. A further implicit assumption is that future growth in energy and particularly in electricity demand will be substantial. Indeed, most nuclear scenarios assume relatively low energy price elasticities, along with rather strong correlations between energy demand and economic growth. The result is rapidly growing energy demand, [especially demand for electricity.] This, in turn, entails the assumption that electricity is well suited to most end-uses, and that its convenience and unusually high quality in many applications will outweigh its higher cost, even in developing nations. Finally, there is the host of well known health and safety issues associated with nuclear power, and the increased danger of proliferation of nuclear weapons. Nuclear proponents generally assume that these problems are either solvable or relatively unimportant.

There is considerable evidence to suggest that these implicit assumptions will not hold -- indeed, that they already do not hold.[13] Nevertheless, since our purpose is to assume favorable conditions for nuclear power, we will not examine these premises further here. In Section 5 we explore the potential for improved energy efficiency to curtail future energy demand growth and thereby to displace CO_2 emissions.

3. Feasibility of a Nuclear Solution

The essence of a nuclear solution to the greenhouse warming problem is the use of nuclear electricity to replace energy generated from the combustion of fossil fuels. Assuming that this strategy were to be adopted, it is natural to ask: how extensive a nuclear program would this require? How much would such a program cost? How effective would it be? To address such questions, it is necessary to turn to some representative scenarios of the

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climatic changes. The quantity of krypton currently being released is very small, but of course it would be much greater if the world vigorously pursued nuclear power as a response to the greenhouse problem. See W.L. Boeck, "The Meteorological Consequences of Atmospheric krypton 85," Science 193:195-198 (1976).

[13] See, for example, D. J. Rose, M.M. Miller, and C. Agnew, "Reducing the Problem of Global Warming," Technology Review May/June, 1984, pp 49-58; A.B. Lovins, L.H. Lovins, F. Krause, and W. Bach, Least-Cost Energy: Solving the CO2 Problem, Brick House, 1981; or J. Goldemberg et al., "An End-Use Oriented Global Energy Strategy," Annual Review of Energy 10, 1985, pp. 613-88, and...[WAI title].

world's energy future. A scenario is not a forecast, but rather a plausible evolution of future events, based on certain internally consistent assumptions.[14]

In this section, we focus specifically on two global energy scenarios that pose a serious threat of greenhouse warming due to CO_2 emissions. These are representative scenarios from the literature that foresee moderate to substantial growth in future fossil-fuel consumption. As such, these scenarios effectively bound the domain of serious global warming futures due to emissions of carbon dioxide into the atmosphere. In a later section, we treat separately those scenarios that project little or no growth in fossil fuel consumption, as they pose a much reduced climate warming risk.

Our goal in this section is to explore the prospects for nuclear power to solve the impending climate warming problem implicit in these two greenhouse scenarios. We begin by assuming economic and political conditions that are highly favorable to nuclear power. Then, within the context of each scenario, we suppose that the world pursues nuclear power vigorously as a means to eliminate the climate warming threat. Specifically, we assume that coal is entirely displaced by nuclear power over a period of a few decades. We then calculate rates of capital investment required for this transition, estimate the costs involved, and evaluate the effect on CO_2 emissions.[15] Since greenhouse warming in these two scenarios ranges from moderate to severe, conclusions common to both scenarios will be regarded as qualitatively robust for any scenario that anticipates substantial greenhouse warming due to fossil-fuel combustion.[16]

Assumptions

Any analysis of future costs for nuclear power plants ultimately boils down to guesswork, because actual nuclear plant costs can vary by a factor of three or four within a given country.

The capital cost of constructing nuclear power plants is currently around $2000 per kW installed in Britain, and more than $3200/kW in the United States. These figures would presumably be considerably lower in the event of a major nuclear power program, although plants under construction in both developed and developing countries have generally

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[14] Scenario analysis is a tricky business fraught with pitfalls. For political aspects, see A. Midttun and T. Baumgartner, "Negotiating Energy Futures: The Politics of Energy Forecasting," Energy Policy, June 1986, p. 219 ff. For methodological aspects, see B. Keepin, "Review of Global Energy and Carbon Dioxide Projections," Annual Review of Energy 11:357-92, 1986. For a case study illustrating both political and methodological issues, see B. Keepin and B. Wynne, "Technical Analysis of IIASA Energy Scenarios," Nature 312:691-95, 20 December 1984.

[15] In this paper, we focus primarily on emissions of CO_2, since these are the most direct and relevant output from energy scenarios, and they are of greatest interest to energy specialists. CO_2 emissions are generally used as inputs to carbon-cycle models, which determine the resulting atmospheric concentrations of CO_2. These concentrations are in turn fed into climate sensitivity models which determine the warming that results from the increases in atmospheric CO_2. Both the carbon-cycle models and the climate-response models entail their own uncertainties, and thus we do not further complicate our analysis by including these components of global warming models. The interested reader should consult B. Bolin et al., "The Greenhouse Effect, Climatic Change, and Ecosystems, John Wiley, 1986.

[16] For a thorough analysis and discussion of these issues, see B. Keepin, "Review of Global Energy and Carbon Dioxide Projections," Annual Review of Energy 11:357-92 (1986).

experienced price escalation faster than inflation.[17] The least expensive nuclear costs worldwide are in France, where construction cost for a new 1000-MW (electric) plant is reportedly $1 billion in 1987 dollars.[18] Since we wish to make favorable assumptions, we shall adopt this figure as an optimistic global average for the cost of constructing a 1000-MW_e nuclear power plant, which is equivalent to $1000 per installed kilowatt (kW).

Two Greenhouse Scenarios

With these factors in mind, let us now imagine the following: In 1989, all nations on earth reach an unprecedented political accord that the greenhouse warming problem is extremely urgent, and moreover, that the best response to this problem is the reduction of CO_2 emissions via an immediate major buildup of nuclear power across the globe. This hypothetical nuclear program should meet the following two criteria to be most effective. First, it should be aimed at displacing coal, because coal is the "dirtiest" fossil fuel,[19] as well as the most substitutable. Because coal is used largely for electricity generation and process heat, it can be more readily displaced by nuclear energy (either electricity or heat) than can other fossil fuels, especially oil. Moreover, global reserves of coal are much greater than reserves of any other fossil fuel, and thus coal is often viewed as the primary source of future CO_2 emissions from fossil fuels. For these reasons, coal is a natural candidate to choose for displacement, and we focus on it in the analyses below.

Second, the program should begin as soon as possible, and be implemented relatively quickly, say over the next few decades (rather than the next century). To satisfy these conditions, we shall suppose that the world vigorously pursues a full transition from coal to nuclear power, completing it within four decades. Such a strategy yields the greatest possible reduction in CO_2 emissions for a given amount of nuclear power[20] (emissions of the greenhouse gas N_2O from coal combustion are also displaced). Moreover, accomplishing

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[17] A 1979 study indicated that nuclear costs, exclusive of inflation were rising at 16% per year. K.R. Shaw, "Capital Cost Escalation and the Choice of Power Stations," Energy Policy, Dec. 1979, pp. 321-328. For more recent figures, see Leonard Bennett and Robert Skjoeldebrand, "Worldwide Nuclear Power Status and Trends," IAEA Bulletin, Autumn 1986, p. 45. Cancelled plants tend to be among the most expensive nuclear units, biasing average remaining reactor costs downward. The 23 nuclear plants being completed in the United States in 1986 and 1987 have an average construction cost of over $3,200 per installed kW. On the other hand, construction costs in 1984 dollars are reported as around $2000 per kW installed in Canada and Britain, about $1400 in Japan and West Germany, and only $870 in France (from "Projected Costs of Generating Electricity from Nuclear and Coal-Fired Power Stations for Commissioning in 1995," OECD, Paris, 1986). See Chris Flavin, "Reassessing Nuclear Power," in State of the World, (W.W. Norton, New York, 1987), p. 70.

[18] This datum was supplied by the French Embassy in Washington, D.C., October 1987.

[19] Coal is the most carbon intensive fossil fuel, followed by oil and then gas. Carbon emissions per unit primary fuel combusted are 0.75 Ct/TW-y for coal, 0.62 Ct/TW-y for oil, and 0.43 Ct/TW-y for gas (from G. Marland, "The Impact of Synthetic Fuels on Global CO_2 Emission," in W. Clark (ed.), CO_2 Review 1982, Clarendon, Oxford: 1982. One $Ct=10^9$ metric tons.

[20] This assumes no major contribution from shale oil or tar sands.

this goal in only four decades provides for the greatest ameliorating effect on climate warming.[21]

Several technological assumptions about energy produced from nuclear and coal-fired plants must be made in the analysis that follows. The average construction lead time for a 1000-MW nuclear plant will be assumed to be six years, which is very short by most standards,[22] although such lead times have been achieved in France.[23] A short lead time is consistent with our assumed low capital cost of $1.0 billion per plant. This would allow a nuclearization program to begin yielding large increments of nuclear electricity by 1995. An average plant capacity factor of 65% and lifetime of 30 years will be assumed for all nuclear plants.[24] Since coal-fired power is to be displaced, it is necessary to make an assumption about the primary-to-secondary conversion efficiency for coal, which we take to be 33%.[25]

Finally, in the following analysis, we will omit any consideration of (i) nuclear waste treatment and storage, (ii) decommissioning costs,[26] (iii) the safety of nuclear plants, (iv) any environmental or health consequences that might result from the nuclear programs envisaged below, (v) the possible impact on proliferation of nuclear weapons, (vi)

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[21]Given that most studies of the greenhouse warming problem look forward 100 years or more, the reader may wonder why we consider only the next few decades here. Our purpose is to explore the prospects for a nuclear solution to the greenhouse problem under the most promising assumptions, and this requires a major transition to nuclear power over the next few decades. Beyond this time horizon, we simply assume for the sake of argument that all further growth in energy demand would be supplied by nuclear power (or some other CO_2-benign source). Hence our calculations do not extend beyond 2025; (if they did, the resulting average rates of nuclear capacity installation would be even higher than those calculated below.

[22]A recent MIT Global Energy Model with a relatively rapid nuclearization scenario uses a ten-year construction period (for 1.3-GW reactors). M.H. Khadani and David Rose, "Options in Planning Global Energy Strategies" Energy 10(8): 887-899 (1985).

[23]C. Flavin, "Reassessing Nuclear Power," in L.R. Brown et al., State of the World, W.W. Norton, 1987.

[24]Plant capacity factors vary considerably in practice, from under 15% to over 90%, but the average value for plants worldwide is around 63%, and has not changed appreciably in 20 years. See Operating Experience with Nuclear Power Stations in Member States in 1982, International Atomic Energy Agency (IAEA), Vienna, 1984.

[25]These technological parameter values are typical averages, and while they could change over time due to technological improvements, there is no way to predict this. Moreover, in our calculations such changes could tend to offset one another. For example, improved conversion efficiency for coal would tend to increase the calculated quantities of nuclear capacity required to displace the coal, whereas improved capacity factors in nuclear plants would tend to decrease these quantities. Rather than attempt to guess the future evolution of such details, we simply assume values that are known to be reasonable today.

[26]Jan Willem Storm van Leeuwen, "Nuclear Uncertainties: Energy Loan for Fission Power", Energy Policy, June 1985, p. 261, estimates decommissioning dismantling costs at 40% to 200% of original capital cost of $2700/kW$_e$ [in 1982$]). The author maintains that just the maintenance of the reactor during the post-shutdown period will cost at least 5-10% of construction cost. Dismantling the Shippingport reactor (not including cutting up and packing) is estimated at 29% of construction cost. Ibid., p. 262. California's Public Utility Commission ruled that Pacific Gas & Electric must set aside $3.89 billion for dismantling its Diablo Canyon reactor: The Wall Street Journal, 18 March 1987. Typical decommissioning estimates range from 20% to 100% of base capital cost. See C. Pollock, Decommissioning: Nuclear Power's Missing Link, Worldwatch Paper 69, Worldwatch Institute, Washington D.C., April, 1986.

vulnerability to terrorism, sabotage, or acts of war, and (vii) any other possible political or social impacts. In addition, we will ignore all the energy it takes to actually build the nuclear power plants envisioned in the scenarios below, which could be substantial.[27] Omission of these issues is typical in nuclear forecasts, and while we do not support this practice, for the sake of argument we again optimistically assume that all such issues would be happily worked out in the future so as not to become a factor in the scenarios considered below. Thus only first-order economic considerations are taken up below.

The two scenarios analyzed here will be labeled "high" and "medium" [emissions], and they span the range of the most problematic greenhouse futures. Both scenarios come from recent studies that represent some of the best work in the field, utilizing state-of-the-art mathematical models. The high scenario is taken from a recent assessment of the greenhouse problem carried out by the U.S. National Academy of Sciences, and the medium scenario is taken from a study carried out for the U.S. Department of Energy. The scenarios are selected to be representative of generic high-and medium-CO_2 emissions futures, and the results obtained below are broadly applicable to any scenarios having roughly the same fossil-fuel consumption rates.[28]

Our basic approach is to perform a sensitivity analysis in which a transition from coal to nuclear energy is completed by the year 2025.[29] Thus for each scenario, we determine the projected contribution to total primary energy from coal in the year 2025, and convert this to the equivalent installed nuclear capacity required to displace this coal. To this figure we add the nuclear installed capacity that already existed in the scenario to obtain the total requirements for installed capacity by the year 2025. This is then taken as the endpoint of an exponential growth curve that begins with today's global installed nuclear capacity[30] (see the Appendix for representative calculations). The details and results for each scenario are described below.

[27] A recent study concludes that large nuclear power systems would yield only a relatively small amount of net energy under optimistic assumptions, and negligible to negative net-energy under less optimistic assumptions. The study also reports that wind-powered electrical generating systems are not producers of net energy. See G. Tyner Sr., R. Costanza, and R.G. Fowler, "The Net-Energy Yield of Nuclear Power," Energy 13 (1):73-81, 1988.

[28] We chose scenarios from different studies to broaden the scope of the analysis. Since our focus is on displacing coal with nuclear power, any two scenarios having the same consumption levels of fossil fuel and nuclear power are effectively equivalent. Thus the particular studies we chose are rather arbitrary, and the "high" and "medium" scenarios could each have been selected from either the DOE or the NAS study. We make no judgment here as to the plausibility of these scenarios; they are chosen because they are representative of medium and high energy futures in the literature.

[29] This sensitivity analysis is not performed within precisely the same methodological context (i.e., using the actual model) that was employed in generating the original scenario. It is likely that some minor discrepancies would arise if the same sensitivity analysis were conducted using that original methodology. However such discrepancies would be small and are of little consequence, since we are employing the scenarios here as generic representations of high and medium emissions futures. In particular, when looking forward several decades, only major trends have any significance, and our analysis captures these trends.

[30] Note that the original scenario may include coal and nuclear data for intervening points in time (prior to 2025). However, it would be inappropriate to make similar substitution calculations using these data, because to do so would imply that the transition from coal to nuclear is completed before 2025, which would tend to make the required nuclear installations more stringent.

High Scenario

The "high" emissions case is taken from a study carried out for the National Academy of Sciences in 1983 by Nordhaus and Yohe.[31] They constructed a compact global model to perform a detailed statistical analysis of uncertainty in future values of global primary energy demand and CO_2 emissions. We choose their 95th percentile scenario as our "high" emissions case. In this scenario, global primary energy consumption reaches 35.7 TW by 2025, of which 26.9 TW is supplied by fossil fuels. Approximately 43% of this fossil contribution is supplied by coal, which means that nuclear power must displace 11.6 TW of coal (primary energy).

In addition to this, the nuclear contribution of the non-fossil component must be included. Given that we are positing essentially optimal conditions for global nuclearization, it would be appropriate to assume that all of the non-fossil energy growth would be supplied by nuclear power. However, we shall be conservative and assume that only half the non-fossil energy is supplied by nuclear power. This results in a total nuclear installed capacity of 8180 GW by the year 2025, equivalent to some 8,000 large nuclear power plants. This represents a 29-fold increase in world nuclear capacity, requiring that nuclear power plants be built at the average rate of one new 1000 MW plant *every 1.59 days for the next 38 years.*[32] At an assumed cost of $1.0 billion per 1000-MW installed, this results in a total cost of 8.7 trillion (1987) dollars, an average cost of $229 billion each year for 38 years. The required capital investment is economically infeasible for the developing world (see next section). Though economically possible for industrialized nations, this staggering nuclear investment would have to be weighed against alternatives such as efficiency, which we address toward the end of this paper.

It is instructive to determine how effectively the greenhouse problem would be ameliorated by this massive nuclear program. CO_2 emissions continue to grow from today's value of 5.3 Gt per year, reaching 8.29 Gt/y by the year 2025 (compared with 16.97 Gt/y in the original scenario). Thus, in this scenario, even bringing a new nuclear plant on line every day and a half for nearly four decades does not prevent annual CO_2 emissions from steadily increasing to a value 65% *greater* than they are today. Thus climate warming due to CO_2 would continue, exacerbated by other greenhouse gases (considered below). So in this scenario, despite the huge nuclear buildup, the greenhouse warming problem gets steadily worse.

This scenario is representative of high growth scenarios for fossil fuel combustion. To the extent that economic factors promote slower growth in demand, or concern over greenhouse warming motivates a change in consumption patterns, it seems unlikely that such a rapid growth in consumption will be realized. Thus we now turn to a more moderate scenario.

[31] W.D. Nordhaus and G.W. Yohe, "Future Paths of Energy and Carbon Dioxide Emissions," in Changing Climate, National Academy of Sciences, Washington, D.C., 1983. For a review of this model and its results, see B. Keepin, "Review of Global Energy and Carbon Dioxide Projections," Annual Review of Energy 11: 357-92 (1986).

[32] See Appendix for representative calculations, and for full details, see B. Keepin and G. Kats, Greenhouse Warming: A Rationale for Nuclear Power? forthcoming report, Rocky Mountain Institute, Snowmass, CO 81654.

Medium Scenario

For a medium scenario, we choose a recent middle-of-the-road "standard" scenario[33] published by the U.S. Department of Energy (DOE).[34] The principal inputs are assumptions about population and labor productivity growth, supply and demand schedules for each fuel type, and initial conditions.

As with the Nordhaus-Yohe model discussed above, detailed sensitivity and uncertainty analyses have been conducted with the IEA/ORAU model, including a probabilistic scenario analysis utilizing sophisticated Monte Carlo techniques.[35] These tests have shown that the output results are very sensitive to certain input variables, most notably labor productivity growth, rate of improvement in end-use energy efficiency, and income elasticity of demand for energy in developing countries. Not surprisingly, a wide range of scenarios has been produced with this model, and recent studies applying the model have acknowledged the inherent uncertainties about the future by offering several plausible scenarios.

A number of researchers have applied the IEA/ORAU model to analyze different aspects of the global energy future, focusing primarily on the greenhouse warming problem.[36] For our purposes, we focus on a study carried out for the DOE that investigates likely future rates of future CO_2 emissions.[37] Three scenarios were analyzed in this study; a "standard" scenario, and two extreme scenarios intended to span the range of uncertainty about future CO_2 emissions. We choose the "standard" scenario[38] to be our medium emissions scenario. This scenario was obtained by setting all model parameters to median estimates, and the results are typical of middle-of-the-road energy/CO_2 projections. Global primary energy demand reaches 21.3 TW by the year 2025, of which 9.4 TW are supplied by coal, 4.0 TW by oil, 3.6 TW by gas, and 0.7 TW by nuclear power. CO_2 emissions are 10.3 Gt/y in 2025.

Our modification to this scenario consists of a transition from coal to nuclear power that is completed by the year 2025. Apart from this, the scenario remains unchanged. As shown in the Appendix, this requires that the world build nuclear capacity at the equivalent average rate of one 1000-MW plant every 2.4 days until 2025. This comprises one plant every 4.1 days in the developed countries, and one every 5.7 days in the less developed countries (LDCs). Total cost is $5.8 trillion (1987 $), or an average of $151 billion annually.

[33] J. Edmonds and J. Reilly, "Global Energy and CO2 to the Year 2050," Energy Journal 4(3) 21-47 (1983). A detailed description of this model is given in this reference, along with J. Edmonds and J. Reilly, "A Long-Term Global Energy-Economic Model of Carbon Dioxide Release from Fossil Fuel Use," Energy Economics 5:74-88 (1983). A review in provided in Keepin (op. cit. supra).

[34] Edmonds and Reilly, op. cit.; S. Seidel and D. Keyes, Can We Delay a Greenhouse Warming?, Washington, D.C., U.S. Environmental Protection Agency, 1983; D.J. Rose, M.M. Miller, and C. Agnew, "Reducing the Problem of Global Warming," Technology Review 83(7):(1984); and I. Mintzer, A Matter of Degrees: The Potential for Controlling the Greenhouse Effect, World Resources Institute, Washington, 1987.

[35] J.M. Reilly et al., "Uncertainty Analysis of the IEA/ORAU CO_2 Emissions Model," Energy Journal 8(3):1-30(1987).

[36] For a review of these efforts, see B. Keepin, "Review of Global Energy/CO_2 Projections," Annual Review of Energy 11:357-[illegible] (1986).

[37] J. Edmonds, J. Reilly, J.R. Trabalka, and D.E.Reichle, An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2, TR013, DOE/OR/21400-1, U.S. Department of Energy, Washington, D.C., September 1984.

[38] This is "case B" in the reference in previous footnote.

of which LDCs are responsible for \$64 billion. As discussed in the next section, such a financial commitment is especially infeasible in LDCs for a variety of economic and political reasons. By 2025, the global installed capacity reaches 5200 GW, an 18-fold increase over today's capacity. Of this, 2330 GW are in LDCs, which would mean a staggering 155-fold increase over today's installed capacity of 15.02 GW.[39] In Latin America alone, which currently has only 1.7 GW operating, the required capacity is 334 GW by 2025 -- substantially more than all the nuclear power in the world today (see Appendix for details of calculations).

The CO_2 emissions in this nuclearized scenario grow from today's value of about 5.0 Gt/y to 6.48 Gt/y at the turn of the century, and then decline to 5.27 Gt/y by 2025.[40] Thus, even in this scenario of moderate energy growth coupled with a massive nuclear program, future CO_2 emissions per year remain consistently above today's values. Thus the rate of growth in global warming in this scenario is slowed somewhat, but nonetheless continues to grow, despite the massive nuclear investment.

Other Greenhouse Gases

As mentioned in the introduction, a number of greenhouse gases other than CO_2 are expected to contribute to future global warming. Studies of these additional gases are still in their infancy, but with the aid of a one-dimensional climate model, Ramanthan *et al.* have shown that methane (CH_4), nitrous oxide (N_2O), ozone (O_3), $CFCl_3$, and CF_2Cl_2 account for more than 90% of temperature changes due to greenhouse gases other than CO_2.[41] Modeling the combined warming effects of these gases and CO_2 is very difficult. Complications include partially overlapping spectral absorption bands, and photochemical reactions that effect the mixing ratio of most non-CO_2 greenhouse gases, leading to a more rapid decrease of the cooling rate at higher altitudes (between 15 km and 35 km). Full accounting of the warming effects of non-CO_2 greenhouse gases requires the use of global circulation models (GCMs), and has not yet been done. Current practice is to estimate the climate effects due to increasing concentrations of non-CO_2 gases in comparison with those calculated for increasing CO_2 concentrations.[42] This has been done using one dimensional models, with the general result that the warming contribution from non-CO_2 gases is of about the same order of magnitude as the warming caused by increased CO_2 concentrations.[43]

Additional uncertainty arises because of potential political success in reducing greenhouse gas emissions -- primarily CFCs -- through such measures as the pending UNEP treaty to

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[39] Moreover, in developing countries, plant capacity factors have tended to be low, which would mean that even more installed capacity might be required in practice.

[40] Thereafter, in this scenario, CO_2 emissions would grow steadily due to increased oil and gas combustion.

[41] V. Ramanthan et al., "Trace Gas Trends and Their Potential Role in Climate Change," J. Geophysical Research 90:D35547-66 (1985).

[42] I. Mintzer, A Matter of Degrees: The Potential for Controlling the Greenhouse Effect, Research Report No. 5, World Resources Institute, Washington, D. C., April 1987. The emission data are estimated from Figure A-1, and the warming data are interpolated linearly from Tables 15 through 18, and indicate that the warming contribution from CO_2 and N_2O combined is roughly the same size as the warming from CO_2 alone.

[43] R.A. Kerr, "Trace Gases Could Double Climate Warming," Science 220:1364-5 (1983).

reduce CFC usage. In addition, Dupont is committed to a ten year phase out of CFC production. More concretely, US manufacturers of styrofoam containers, cups and plates have committed to stop using CFCs in these products by the end of 1988.[44] The likely effect of these government and private initiatives is to dampen or reduce CFC emissions, thereby decreasing non CO_2 greenhouse gas contribution to global warming and making CO_2 emissions the predominant future cause of global warming. This could make future CO_2 emissions relatively more important in determining the rate and extent of global warming.

For our purposes, we assume that reducing CO_2 emissions by displacing coal with nuclear power will not affect the emissions of other greenhouse gases, apart from N_2O, which is negligible. In both the high and medium scenarios, CO_2 emissions are cut roughly in half from what they otherwise would have been. Considering these factors, and assuming rough linearity,[45] we estimate that in both scenarios, the massive nuclear programs would reduce total global warming by 20 to 35 percent (from what it otherwise would have been). Thus, in absolute terms, both CO_2 emissions and global warming continue to *increase* under either scenario, despite the massive nuclear programs.

Summary of Greenhouse Scenarios

A summary of the two nuclear scenarios is given in Table 1 below, including indications of the capital investment rates involved, and also estimated average costs. As mentioned earlier, the cost figures are optimistic estimates that are meant to be indicative only.[46] The overall conclusion in this section is that any scenario having modest to rapid growth in energy demand leads to increased CO_2 emissions that no conceivable nuclear power program could alleviate.

[44] B. Rosewicz, "Big Packagers Using CFCs Agree to Stop, Citing Chemicals' Effect on Ozone Layer," The Wall Street Journal, 12 April, 1988, p. 16.

[45] See B. Keepin and G. Kats, Greenhouse Warming: A Rationale for Nuclear Power? forthcoming report, Rocky Mountain Institute, Snowmass, CO 81654.

[46] We have not analyzed these numbers in detail, and thus we do not present them as projections. Note also that these estimates are for the total cost of the nuclear programs envisioned (rather than the net additional cost over and above what the displaced coal-fired power plants would cost in these scenarios).

Table 1. Nuclear Amelioration of Greenhouse Warming

	High Scenario	Medium Scenario
Av. Nuclear Commissioning rate	1.59 days/GW_e	2.42 days/GW_e
Average annual cost (1987 $) @ $1,000/$kW_e$	$229 billion	$151 billion
Increase in installed nuclear capacity (2025)	29-fold	18-fold
Greenhouse warming ameliorated (2025), % reduction compared to base case with modest nuclear contribution	20-35 percent	20-35 percent

4. Nuclear Experience to Date

In this section we briefly review the nuclear power experience in both developing and industrialized nations. Examination of actual experience with nuclear power programs to date constitutes our only empirical guidance in assessing the feasibility of very large scale nuclear programs. Whereas our purpose in the previous section was to make optimistic assumptions about nuclear power, the purpose here is to offer a realistic assessment of historical experience and future prospects for nuclear power.

<u>Less Developed Countries</u>

In the past two decades, less developed countries (LDCs) have spent tens of billions of dollars on nuclear reactors, their single largest technological investment to date. Because of more rapid population growth in LDCs and likely higher rate of growth in per capita electricity usage in developing than in developed nations, global nuclearization would imply faster growth of nuclear power in LDCs than in industrialized nations. In regard to greenhouse warming, replacing wood fuel with [nuclear] electricity would slow deforestation, itself a potentially significant source of both CO_2 release[47], as well as N_2O emissions.[48]

[47] Stephen H. Schneider, "Deforestation and Climatic Modification--an Editorial", <u>Climatic Change 6: (1984).</u>

[48] W.N. Bowden and H.F. Borman, "Transport and Loss of Nitrous Oxide in Soil Water After Forest Clear-Cutting", <u>Science</u> 233:867-869 (1986), cited in Irving Mintzer, <u>op. cit.</u>, p. 10.

An LDC nuclearization scenario is consistent with International Atomic Energy Agency (IAEA) calls for a rapid expansion of nuclear power in Asia, Africa, and Latin America.[49] Some twenty developing countries have undertaken nuclear programs, with almost half of these investing in large scale commercial nuclear reactors. Several decades of nuclear experience in developing nations to date is worth reviewing because it constitutes a concrete, empirical assessment of the technological, economic, and political feasibility of a rapid expansion of nuclear energy in the developing world.

The major developing nations that now have nuclear power -- Argentina, Brazil, and Mexico in Latin America; China, India, South Korea, and Taiwan in Asia; and Egypt and Iran in the Middle East -- have shared roughly the same historical pattern of nuclear power investment. In the late 1950s and early 1960s, most of these countries were given small research reactors. During the late 1960s and early 1970s, the IAEA (working together with nuclear vendors and LDCs) published optimistic cost projections for nuclear power in LDCs. Highly ambitious nuclear power programs were launched in developing countries on the basis of these estimates, which turned out to be unrealistically low. By the late 1970s, most of these programs had either been terminated or sharply cut back, due to steeply rising costs and construction delays.

Latin America

By 1960, research reactors were installed in Brazil, the major power of Latin America, and by the early 1970s, most Latin American countries were planning for large nuclear programs to be in place by the year 2000: 30 GW for Argentina, up to 50 GW for Brazil, and 25 GW for Mexico.[50] (By way of comparison, Great Britain now has 13 GW, Canada 11.3 GW, and Italy 1.3 GW of installed nuclear capacity.)[51]

Since the mid-1970s, these ambitious nuclear plans have been beset by delays and cost overruns. Argentina's 600-MW Embalse plant was completed in 1983 at over three times the original cost estimate. Argentina's 250 metric-ton-per-year Arroyito heavy water plant has quadrupled in cost to $1 billion. Construction delays and cost increases have led the country to cancel four planned nuclear reactors, and prompted the Argentine nuclear trade union to declare that the country's nuclear industry "was on the brink of collapse."[52]

Like Argentina, Brazil and Mexico have experienced repeated construction delays and cost escalations and have also sharply cut back nuclear funding. Brazil's first nuclear plant, the 626-MW Angra I, was completed eight years late in 1985 for $1.8 billion -- four and a half times the original estimated cost.[53] The plant was closed for most of 1986 because of

[49] For example, see comments by IAEA Director, Dr. Hans Blix, in IAEA release "Promotion of International Co-operation" (IAEA, Vienna, 23 March 1987).

[50] John Redick, Military Potential of Latin American Nuclear Programs (California, Sage Publications, 1972), p. 14. For slightly lower figures see Nuclear Engineering International, Sept. 1971, pp. 750-751.

[51] Nucleonics Week, 9 April 1987, p. 6.

[52] Reported on São Paolo Radio network, Sept. 1985, translated in Foreign Broadcast Information Service (FBIS), 10 September 1985, pp. D1-2.

[53] Nucleonics Week, 25 October 1984, pp. 3-4.

widespread concern over safety and adequacy of evacuation procedures. In 1986, Brazil scrapped plans for five of eight planned reactors and suspended work on Angra III after spending $300 million on it. Then in June 1987, Brazil suspended work on Angra II for six months as part of its response to continued financial crisis.[54] Brazil had already spent $1.1 billion on the 626-MW plant, now 60% complete, indicating a final construction cost of $2,930 per MW. With no operating nuclear plants, Mexico cancelled its third and fourth reactors, suspended construction on its second reactor, and may not complete Laguna Verde I, already under construction for 14 years.[55] The reactor cost has increased tenfold (due substantially to inflation) to $3 billion.[56] Additional reactor construction in Mexico and Brazil now appears unlikely in the foreseeable future.

Original plans for nuclear power in Latin America called for some 105 GW of installed capacity by the year 2000, implying a growth rate roughly comparable to those envisioned in the two scenarios of the preceding section. However, the total capacity is now only 1.7 GW and is likely to reach no more than 3 or 4 GW by the turn of the century,[57,58] falling short of original goals by 96 percent or more. Moreover, the ameliorating effect of this nuclear capacity on greenhouse warming will be minuscule indeed. For perspective, recall that in the medium scenario analyzed in the previous section, just to displace coal in Latin America required that some 334 GW of nuclear capacity be installed by 2025.

Asia, Africa and The Middle East

In Asia, nuclear power has had a mixed record. For South Korea and Taiwan, countries with centralized political control and relatively advanced industrial infrastructure, nuclear power has provided an economically competitive compared with other options for electricity generation. In the four less-industrialized nations with nuclear programs, China, India, Pakistan, and the Philippines, nuclear power programs have been less successful. China has postponed its nuclear program indefinitely -- once targeted to reach 10 GW in 2000 and almost 40 GW in 2010 -- in favor of developing domestic energy sources, especially hydropower.

Inability to obtain external financing, rising reactor costs, and vendor concerns about military intentions led Pakistan to postpone indefinitely bid submission dates for its planned 10 to 20 nuclear power plants. Though completed, the Philippine's single nuclear plant appears unlikely to operate, and future Philippine nuclear investment appears improbable. And India, with its three-decade-old nuclear program -- the first substantial nuclear program in the developing world -- has only 1.2 GW of installed nuclear capacity. India is likely to reach only 2 to 3 GW of the 10 GW of nuclear power projected for the

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[54] Nucleonics Week, 18 June 1987, p. 3.

[55] For an analysis of the economics of Mexico's nuclear plant and an evaluation of alternatives, see Gregory Kats, "An Assessment of Mexico's Laguna Verde Plant," completed under USAID grant through the Conservation Foundation/World Wildlife Fund for Federacion Conservacionista Mexicana, fall 1986.

[56] Nucleonics Week, 9 October 1986, p. 11.

[57] Nucleonics Week, 9 April 1987, p 6.

[58] Restoration of civilian governments to Argentina and Brazil has allowed sharply increased public political involvement and opposition to nuclear power on grounds of economics and safety. Continued democratization in these nations make a renewed massive commitment to nuclearization decreasingly likely.

year 2000.[59] The Indian nuclear program is experiencing increasing cost overruns, construction delays, safety problems, and growing domestic opposition.[60] One of India's operating nuclear plants, 235 MW RAPS I reactor has experienced so many problems that it is being considered for premature decommissioning.[61]

In Africa, only South Africa has a commercial nuclear reactor installed or under construction. In the Middle East, Egypt has postponed a bid decision on nuclear plants for the past four years, and despite an original goal of 8 GW and ongoing nuclear negotiations, Egypt seems unlikely ever to purchase a commercial nuclear reactor. Kuwait and Saudi Arabia have both shelved nuclear energy programs.

Nuclear Costs and Finance in Developing Countries

Nuclear reactors are the most complex and demanding electricity-generating system in terms of required infrastructure, port and transportation facilities, etc. (The IAEA has recommended that a single generating plant not constitute more than 15% of the electric grid capacity.) Thus, a developing country that does not have existing sophisticated electricity infrastructure and trained personnel must invest in infrastructure and training in order to construct and run nuclear plants successfully. These investments are generally omitted from nuclear cost estimates but are required nonetheless.[62]

Exact nuclear power costs are very hard to obtain for a number of reasons, including pride, secrecy, and incomplete reporting of full costs. Following are some developing nation nuclear power costs, just for plant construction:[63]

- Argentina's 698-MW Attucha II reactor is now estimated to cost $6017 per kW.[64]
- Brazil's 626-MW Angra I reactor cost $2874 per kW.[65]

[59] Although capacity factors were designed to be 75%, actual capacity achieved is about 45%. In 1983 the Chairman of India's Atomic Energy Commission commented that: "Viewed in the context of performance so far, this [10 GW goal by 2000] appears as a very optimistic target." "AEC Chairman's Article, "The Hindu, 23 July 1983, p. 17. Reaching 10 GW by 2000 would require India to commission over 30 new 235-MW reactors by 1995.

[60] For example, see "Tarapur Reported Crippled by High Radioactivity," The Times of India (Bombay), May 1983, pp. 1 & 9, and Tomar Ravindra, "The Indian Nuclear Power Program: Myths and Mirages," Asian Survey, May 1980.

[61] Nucleonics Week, 11 June 1987, p. 6. According to the IAEA's Operating Experience with Nuclear Power States, in 1979 7,963,000 man hours were required to refuel Tap I, in large part because high radiation exposure required very rapid cycling through of workers to prevent radiation overexposure.

[62] Gregory Kats, "Problems Associated with the Development of Nuclear Power in Developing Countries," International Journal of Energy Research, Vol. 7, 1983.

[63] Nuclear power costs of Taiwan and South Korea are significantly lower. However, the level of industrialization of these newly industrialized countries (NICs) makes their nuclear reactor cost experience less similar to the average LDC nuclear program than the countries cited.

[64] Nucleonics Week, 10 October 1985, p. 9.

[65] Nucleonics Week, 25 October 1984, pp. 3-4.

- In Egypt, current nuclear reactor bids are officially quoted at about $1800 to $2000 per kW. However, an internal 1984 Ministry of Electricity report projected full nuclear reactor costs to be $4000 per kW.[66]
- Iran's reactors would, if completed, have cost $3000 to $4,000 per kW, according to the Chairman of Iran's independent Commission on Nuclear Power, established before the Shah's fall.[67]
- Philippine's 620-MW reactor cost $3387 per kW.

Recall that in our analysis, a construction time of six years is assumed, along with a cost estimate of $1,000 per kW for construction of a 1000-MW nuclear reactor. In view of actual cost experience with nuclear power in LDCs, these figures are very optimistic indeed.[68]

Even supposing that our rosy cost estimates could be realized in the event of a major nuclear program, LDCs would still have to borrow most of the money to finance their nuclear programs, because they simply do not have the foreign export earnings to purchase the reactors. LDC access to foreign capital has declined since 1981, while interest payment obligations have risen. New loans from banks now barely offset interest payments on outstanding loans. Therefore, most of the money would have to come from the public sector, and public financing for electricity in all LDCs totaled $7 billion in 1986/87, most of which was not applicable to nuclear power plants. Moreover, even if this entire $7 billion *were* applicable to nuclear development (leaving nothing for the grid to deliver the nuclear output), it is but a small fraction of the $64 billion required annually by LDCs in the Medium Scenario above to finance their buildup of nuclear capital.

Finally, assuming that the foreign financing were somehow made available, the current debt burden of LDCs strongly suggests that massive additional debts would be insupportable. During the early 1980s, capital transfer to LDCs averaged $70 billion a year, and now LDC interest obligations are running in the low $80 billion range. Thus nuclearization on the scale of the Medium Scenario above would require LDCs to essentially double their current indebtedness in order to finance just one element of the economic landscape -- nuclear generated electricity.

In summary, despite very high early growth projections, most major developing nations with nuclear programs have either cut them back sharply or phased them out altogether, because nuclear plants have been too costly and too slow to build. Thus, nuclearization programs on a scale sufficient to reduce CO_2 emissions significantly in LDCs have already been tried in those countries, and have demonstrably failed. Rapid future expansion of nuclear power in LDCs seems entirely infeasible and unrealistic in view of (a) experience to date, (b) LDC access to capital to finance nuclear purchases, and (c) LDC ability to support massive additional debt burdens. Because of a shortage of foreign exchange, resulting largely from massive interest obligations, and the uniquely high foreign exchange cost of nuclear plants, large-scale nuclear investment by developing countries (and the associated

[66] "Financial Requirements for the Nuclear Program," Al-Ahram Al-Iktisadi, 28 May 1984, p. 10, translated in Gregory Kats, "Egypt," Non-Proliferation: The Why and the Wherefore, SIPRI (London, Taylor & Francis, 1985), p. 186.

[67] Dr. Fereidun Fesharaki, Revolution and Energy Policy in Iran (London, Economist Intelligence Unit, 1980), p. 91.

[68] $1000 per installed kW just for construction is well under a third of the lowest cost case of $3780 per installed kW in Van Leuwen, op. cit. The author includes such costs as decommissioning and waste handling. A figure of $2000 per Kwe may be a more realistic "optimistic" cost projection, just for construction, in developing nations.

subsequent need to pay for imported fuel and expertise) can perhaps be more accurately viewed as an alternative to -- rather than as a prerequisite for -- economic development.

Industrialized Nations

Experience with nuclear power in industrialized countries is well publicized, so this section will be brief. The accident at Chernobyl in the Soviet Union on 26 April 1986 bought home to many the dangers inherent in nuclear power."[69] Even before the Chernobyl accident, nuclear power was in trouble in most developed countries. Public and political opposition have grown in response to concerns about rising costs, health and safety issues, waste treatment and storage procedures, etc. Since 1974, the International Atomic Energy Agency's (IAEA) projections for nuclear capacity installed worldwide by the year 2000 have dropped nearly 90 percent.[70] In the United States, there has not been a single order for a nuclear plant in the past decade, while 108 orders for nuclear plants -- including all orders placed since 1973 -- have been cancelled.[71] Meanwhile, construction lead times for U.S. nuclear plants grew from six or seven years in the early seventies to more than 12 years for large plants. During the same period, the annual rate of growth in electricity consumption fell from 7 percent (in the early 1970s) to 1.8 percent since 1980.

Nuclear power has suffered major setbacks in the United States over the past decade, due primarily to economics, and safety issues.[72] Construction costs soared from $200 per kW installed in the early 1970s to over $3200 per kW in 1986/87.[73] Indeed, a recent article in the American business magazine *Forbes* summed up the situation as follows: "The failure of the U.S. nuclear power program ranks as the largest managerial disaster in business history, a disaster on a monumental scale...It is a defeat for the U.S. consumer and for the competitiveness of U.S. industry, for the utilities that undertook the program, and for the private enterprise system that made it possible."[74]

Nuclear power has not fared well abroad either, especially since Chernobyl. Austria has decided not to bring its only plant on line, Greece has abandoned plans to build its first plant, and the Swedish government is considering proposals to accelerate the planned

[69] Some 300 people received sufficiently large doses of radiation to be hospitalized, and 29 of them subsequently died (as of September 1986). And more disconcerting, specialists have concluded that "the short-term health consequences may be only the visible tip of a very large iceberg. Because of the radioactive pollution of Europe by the Chernobyl accident, thousands to tens of thousands of people may develop thyroid tumors or cancer over the next few decades. F. von Hippel and T.B. Cochran, "Estimating Long-term Health Effects," in "Chernobyl: The Emerging Story," special section in Bulletin of the Atomic Scientists, Aug./Sept. 1986, p. 24. It should be noted that pollution from coal-fired power plants is estimated to kill thousands of people every year via heart or respiratory disease, or cancer.

[70] See Annual Reports, International Atomic Energy Agency, Vienna, 1974 and 1984. 1974 projection: 4,450 GW, and 1984 projection: 605 GW. Quoted in C. Flavin, op. cit.

[71] C. Flavin, "Nuclear Power's Burdened Future," Bulletin of the Atomic Scientists, July/August 1987, pp. 26-31.

[72] R. Weiss, "Nuclear Reactor Safety Assailed in Report," Science News, 3 October 1987.

[73] U.S. Department of Energy, Nuclear Power Plant Construction Activity 1985, Energy Information Agency. These figures are given in current dollars, and thus they exaggerate the increases. Nevertheless, real costs grew more than six-fold during this period.

[74] J. Cook, "Nuclear Follies," Forbes, February 11, 1985.

phaseout of its nuclear program. Yugoslavia has postponed construction of plants pending safety evaluation, Finland has postponed new orders, and in Italy all major parties have turned against the country's nuclear program.[75] Even before Chernobyl, the Soviet nuclear program was plagued by the same delays and mishaps that have impeded other programs around the world, and the country has fallen at least ten years behind its early nuclear goals.[76] Although official Soviet response to the Chernobyl accident is that it will have no effect on further nuclear development, General Secretary Gorbachev recently stated that "It is not secure when the development of atomic engineering is justified by unacceptable risks....They say that one thorn of experience is worth more than a whole wood of instructions. For us, Chernobyl became such a thorn."[77]

Indeed, even nuclear programs that are generally viewed as success stories have encountered difficulties. Although Japan's program appears relatively successful overall, its nuclear capacity forecasts for the year 2000 were scaled downward by 31 percent in 1984. The much-touted French program is beset with a debt of $32 billion -- a result of ordering more plants than were needed. The excess nuclear capacity has forced the state-run utility Electricité de France (EDF) to promote electricity consumption domestically and to market electricity in neighboring countries. Overcapacity is expected to persist well into the '90s.

In sum, nuclear power has not fared anywhere near early expectations in most developed countries throughout the world. Reactors are now generally being ordered only in nations where the free market plays little or no role in energy policy decisions.[78] Prospects for a concerted global program on a scale sufficient to ameliorate future greenhouse warming seem very remote at present, and are likely to diminish even further in the foreseeable future.

5. Low-Energy Scenarios

In this section, we examine scenarios that project little or no growth in future fossil fuel consumption. A representative example is the global scenario recently developed by Goldemberg *et al.*, which is based on detailed end-use analyses in four nations: Brazil, India, Sweden, and the United States.[79] In this scenario, due to a combination of various state-of-the-art energy efficiency improvements and a shift toward less materials-intensive economies, the industrialized nations are able to cut per capita demand for final energy in half by the year 2020, while maintaining annual growth rates of 1% to 2% in GDP per capita. Meanwhile in LDCs, total per capita energy demand grows only slightly (though commercial energy use per capita doubles), and substantial rates of economic growth can be sustained, depending on the extent of investment in energy efficiency. The result is that global primary energy grows only slightly from 10.3 TW in 1980 to 11.2 TW by 2020, and

[75] C. Flavin, "Reassessing Nuclear Power," in State of the World 1987, Worldwatch Institute, Washington, D.C., Table 4.2.

[76] C. Flavin (1987), op. cit.

[77] M.S. Gorbachev, "Reality and Guarantees for a Secure World," supplement to Moscow News issue No. 39 (3287), 1987. Translated from Gorbachev's article in Pravda, 17 September 1987.

[78] Continued nuclear plant ordering is highest in the Soviet Union, Eastern Europe, Taiwan, and South Korea.

[79] J. Goldemberg et al., "An End-Use Oriented Global Energy Strategy," Annual Review of Energy 10:613-88 (1985).

CO_2 emissions decline slightly from 5.17 Gt/y to 4.85 Gt/y, because of a shift away from coal and oil toward natural gas.

The goal of this study was not to forecast economic growth, but rather to provide a kind of "existence proof" of the startling fact that living standards as high as those of Western Europe could be attained in the third world by 2020 *without* major growth in energy consumption (or associated pollution), provided sufficient investment in energy-efficient technologies and services were made. It is clear that large amounts of capital would be required to bring about this scenario. Though the authors do not estimate this, they do state that "our analysis suggests strongly that for a wide range of plausible sets of activity levels and for a wide range of end-use technologies, it would be ~~less~~ costly to provide energy services with conventional, less efficient end-use technologies than to provide the same services with conventional, less efficient end-use technologies and increased energy supplies." Indeed there is considerable evidence to suggest this, as discussed below.

Additional Low Energy Scenarios

A number of other future energy/CO_2 studies have reached essentially the same or similar conclusions. The earliest of these was by Lovins *et al.*[80] who showed that ambitious economic growth projections for the world (a fivefold increase by 2080 could be achieved with far lower consumption of energy than had been hitherto assumed -- with the important benefit of greatly reduced CO_2 emissions. The global projections were based on extrapolation from a detailed case-study of the Federal Republic of Germany (FRG), in which some 120 different efficiency improvement measures were incorporated into 15 different sectors of the economy, saving 70% of end-use energy with no reduction in living standard. A long-term energy/CO_2 study carried out for the National Science Foundation was published in 1983 by Rose *et al.* of the MIT Energy Laboratory.[81] Using the IEA/ORAU model discussed in Section 3, Rose and his colleagues sought to explore the policy options available for holding down the growth of CO_2 emissions. Eleven different scenarios were investigated, incorporating a broad range of assumptions. The overall conclusion was that the CO_2-climate problem could be "much ameliorated." Regarding the role of energy efficiency, the authors concluded that

> ... the effectiveness of energy use on a global scale can be increased by about 1 percent per year for decades without any social strain. This seemingly small figure leads to a halving of energy use by the year 2050 and a 60 percent reduction in [annual] CO_2 emissions. This result is quite independent of the effect on CO_2 of any shifts to non-fossil sources for primary energy supplies.[82]

[80] A.B. Lovins, L.H. Lovins, F. Krause, and W. Bach, Least-Cost Energy: Solving the CO_2 Problem, Brick House, Andover MA, 1981.

[81] D.J. Rose, M.M. Miller, and C. Agnew, "Reducing the Problem of Global Warming," Technology Review 83 (7):49-58 (1984). For the full technical report, see D.J. Rose, M.M. Miller, and C. Agnew, Global Energy Futures and CO2-Induced Climate Change, MITEL 83-015, MIT Energy Laboratory, Cambridge, MA.

[82] D.J. Rose, M.M. Miller, and C. Agnew, "Reducing the Problem of Global Warming," Technology Review 83 (7): (1984).

Another study using the IEA/ORAU model was recently conducted by Mintzer at the World Resources Institute.[83] Four scenarios were investigated to explore policy options for reducing global warming. The first two, called the "high emissions case" and the "base case," are roughly comparable to those we selected above (in Section 3) to represent high and medium emissions scenarios, respectively. The remaining two scenarios incorporate measures to abate greenhouse gases. A "modest policies" scenario includes such measures as improved energy efficiency, enhanced contributions from renewable sources of energy, and tropical reforestation efforts, with the result that CO_2 emissions remain roughly constant through 2025. CO_2 emissions are substantially reduced in the "slow build-up" scenario, which incorporates a strong emphasis on improving energy efficiency, high environmental costs internalized to discourage use of solid fuels, rapid introduction of solar energy, and a major global commitment to reforestation. Despite this dramatic reduction in CO_2 emissions, the contribution from nuclear power remains roughly fixed at today's level.[84]

The Key Role of Efficiency

What these low energy scenarios all have in common is substantial growth in the efficient use of energy. In fact, end-use energy efficiency is the single most important technological factor determining future energy consumption levels, and therefore also future CO_2 emissions. This has been shown repeatedly in a number of sensitivity analyses and uncertainty studies with global models.[85] Opportunities for efficiency gains are so compelling that they suggest that global warming can best be avoided by concentrating on efficiency rather than on a rapid expansion of nuclear power. Heating, cooling, and lighting of buildings produces 17 percent of today's global carbon emissions, and new buildings often require 75 percent less energy than earlier counterparts.[86] A typical incandescent light bulb consumes 75 watts, whereas a recent fluorescent replacement uses only 18 watts, produces higher quality light, and lasts ten times as long (greatly reducing maintenance costs). Advances in industrial drivesystems and residential appliances also offer dramatic opportunities for saving electricity.

Improved efficiency of energy use is also the key to reducing global CO_2 emissions. The data in Table 2 show that most countries have a long way to go before they are anywhere near the efficiency achievable with existing technologies. Of particular interest are the centrally planned economies, which are highly energy-intensive. This is due in part to their stage of development, which is still industrial and inherently materials-intensive, rather than service-oriented. Nevertheless, the industries themselves employ outmoded inefficient technologies in many cases. The Soviet Union is the world's largest producer of steel, and yet is almost the least efficient. Soviet steel mills consume an average of 31 gigajoules (GJ) per ton of steel produced, compared with 19 GJ in Japan. Most COMECON countries could reduce their CO2 emissions substantially while implementing sorely needed efficiency improvements.

[83] I. Mintzer, A Matter of Degrees: The Potential for Controlling the Greenhouse Effect, Research Report No. 5, World Resources Institute, Washington D.C., April, 1987.

[84] By 2025, the supply mix is shifted toward increased contributions from natural gas (21.5%), hydropower (16.2%), and solar (6.1%), and reduced contributions from oil (30.0%) and solid fuels (22.3%).

[85] See J.M. Reilly et al., "Uncertainty Analysis of the IEA/ORAU CO_2 Emissions Model," Energy Journal 8(3):1-30 (1987). This paper summarizes a very detailed and sophisticated analysis of uncertainty in the iea/orau model. The three most important determinants of variation in CO2 emissions turned out to be labor productivity, rate of improvement in end-use efficiency, and the income elasticity of demand for energy in the developing world.

[86] C. Flavin and A. Durning, "Raising Energy Efficiency," Chapter 3 in State of the World 1988, W.W. Norton, 1988.

Table 2. Energy Efficiency and CO_2 Emissions[87] in 1983

	Energy intensity primary (megajoules per dollar GNP)	CO_2 Emissions from fossil fuels (million metric tons)	CO_2 emissions share (percent)
Market Oriented			
United States	19.3	1,138	23
United Kingdom	17.2	141	3
Italy	12.9	91	2
West Germany	11.8	179	4
Japan	9.7	224	4
France	8.6	103	2
Centrally Planned			
China	40.9	440	9
Soviet Union	32.3	911	18
East Germany	29.0	82	2
Poland	26.9	113	2
All Other	-	1,591	32
Total	-	5,013	100

The Role of Efficiency in the United States

The United States emits more carbon emissions from the combustion of fossil fuels than any other nation in the world. As shown in Table 2, the U.S. share is 23 percent of the world's total. This portion would be substantially higher if it were not for major efficiency gains (and significant increases in CO_2 benign supply) already made. Since 1973, total energy use has remained roughly constant, while real GNP has increased by 40%, demonstrating that economic growth has become decoupled from growth in energy consumption.[88] Indeed, if the U.S. economy were as energy-intensive as it was just 15 years ago, we would be importing four times as much oil, and paying an additional $150 billion each year for energy.[89]

[87] Data are for 1983, taken from Tables 10-1 and 11-4 of L. Brown et al., State of the World 1987, Worldwatch Institute, Washington D.C., 1987.

[88] Annual Energy Review1986, Energy Information Administration, Washington, D.C., 1986.

[89] H. Geller, J.P. Harris, M.D. Levine, and A.H. Rosenfeld, "The Role of Federal Research and Development in Advancing energy Efficiency: A $50 Billion Contribution to the US Economy," Annual Review of Energy 12:357-95 (1987).

Despite these dramatic successes, there is still a very large potential for further efficiency gains in the U.S. As just one example, it now costs no more to build an energy-efficient office building than to build an inefficient one, and if these commercial building improvements are adopted, then in fifty years time, 85 power plants *and* the equivalent of two Alaskan pipelines will have been avoided.[90] Studies have shown that by investing in efficiency, the U.S. has the means to reduce its annual energy bill by a net $220 billion.[91] Federal investments in energy efficiency have been relatively small, yet have produced outstanding results. One analysis finds that seven Federal investments totaling $16 million for building components and equipment yielded a total savings of $68 billion -- a return of 4400:1 on the taxpayers' dollars.[92] However there is much farther to go, especially if U.S. industry is to regain its competitive edge in the international marketplace.[93] As shown in Table 2, for each dollar of GNP produced, the U.S. currently consumes some 19.3 MJ of energy, compared with 11.8 MJ for the FRG, and only 9.7 MJ for Japan.[94]

Efficiency in Less Developed Countries

The perception that the ratio of energy consumption to GNP growth is not fixed and can in fact be sharply reduced, primarily through increasing end-use efficiency, is becoming widely accepted in industrialized countries, but has only recently become known in the developing world. Hence, energy planners in developing countries continue to project rates of secondary energy use that grow in lockstep with projected economic growth.

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[90] A. H. Rosenfeld and D. Hafemeister, "Energy Efficient Buildings," Scientific American 258 (4), April 1988, pp. 78-85.

[91] Id.

[92] H. Geller, J.P. Harris, M.D. Levine, and A.H. Rosenfeld, "The Role of Federal Research and Development in Advancing energy Efficiency: A $50 Billion Contribution to the US Economy," Annual Review of Energy 12:357-95 (1987).

[93] A few examples serve to illustrate the large scope for efficiency improvement in the U.S. Quite apart from the tremendous potential for retrofitting existing buildings, a typical new building, which will be in service for next 50 to 75 years, uses twice the energy of the most efficient building available. The efficiency of new gas and electric appliances in the U.S. is typically 30-40% below that of the best available units, which are themselves often suboptimal. A single year's sales worth of electric appliances currently requires some six 1000-MW power plants to operate. This could be cut down to two plants if only the most efficient appliances were sold. Amory Lovins estimates that all told, some 50% of all U.S. electricity can be saved at zero net cost, and that about 75% can be saved at an average cost certainly below one cent and probably near 0.5 cents per kW-h -- less than the cost of just operating an existing coal or nuclear plant even if building the plant were free (documented in Competitek[SM] quarterly update service provided by Rocky Mountain Institute, Snowmass, CO 81654). And finally, the efficiency of new cars could be raised from an average of 26 miles per gallon (mpg) to 40 mpg, at a cost of less than one dollar per gallon of gasoline saved. Not only would this be cost effective, but it would save 34% of fuel use in new cars (D. Blevis, Testimony on Post-1985 Fuel Economy for Light Vehicles, House Subcommittee on Energy Conservation and Power, Committee on Commerce, 31 July 1984, quoted in Geller et al., op. cit). Considerably bigger savings will ultimately be possible, as efficient cars being developed by Toyota, Fiat, Peugeot, Renault, Volkswagen, Ford, etc. become commercially available. Composite on-road fuel efficiencies between 70 and 121 mpg are already being achieved in prototypes.

[94] W.U. Chandler, "Designing Sustainable Economies," in State of the World 1987, Washington, D.C., Worldwatch Institute, 1987, Table 10-1.

Energy modelling has generally been based on energy output and has not explicitly considered consumer decisions as energy inputs. However, this ignores the fact that energy demand is shaped by political and economic structures.[95] Individual and industrial consumers have a broad choice of investments in equipment and appliances that commit them to greatly differing levels in efficiency and energy usage for the same services. The input measure in energy modelling should therefore reflect those elements over which the consumer has a choice.[96]

A growing number of studies in the developing world show that investment in efficient appliances, motors, etc., is a much less expensive way to provide the energy services required to meet growing economic needs. A 1986 study of Brazil, performed by the American Council for an Energy-Efficient Economy and Brazil's main utility, found that a $10 billion investment in efficiency would offset a roughly $40 billion investment required to generate the 22 GW that could instead be saved through the efficiency investments.[97] Recent studies of the Indian industrial sector show investment in efficiency to provide a significantly higher energy yield than investment in domestic energy sources.[98] In fact, developing nations have been turning increasingly to energy efficiency, and particularly in electricity usage, as a way to provide required commercial and residential needs with lower capital investment.[99]

Lower electricity and energy demand growth means lowered borrowing, reduced environmental degradation, and more resources to invest in other infrastructure, education, agriculture, etc. Despite the greater return on investment in energy efficiency than in building new generating plants (and lower LDC borrowing and environmental degradation), most aid institutions still spend very little on promoting efficiency.[100] A major impediment to efficient use of energy is very high energy subsidies, which encourage investment in inefficient plants, equipment, and appliances, and discourage investment in efficiency. However, encouraged by loan conditions of the International Monetary Fund (IMF), developing nations are dismantling energy subsidies, with a consequent dampening in growth of energy demand. This implies a higher price elasticity of demand for energy than is generally calculated for LDCs.[101]

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[95] Michael Drohan, "Energy Futures for Oil-Importing Developing Countries," Energy Policy, June 1985.

[96] E.R. Berndt and G. Watkins, "Modelling Energy Demand: The Choice Between Input and Output Energy Measures," The Energy Journal, April 1986, pp. 69-79.

[97] Howard S. Geller et al., "Electricity Conservation Potential in Brazil," American Council for an Energy-Efficient Economy, Washington, D.C., March 1986.

[98] G. Anadalingam, "Energy Conservation in the Industrial Sector of Developing Countries," Energy Policy, June 1985. See also, for a similar conclusion on residential and small-c lighting,

[99] Gregory Kats, "The Chill of Chernobyl: Developing Nations Turn to Energy Efficiency," Development International, March/April 1987, pp. 52-53.

[100] At least one author maintains that failure to support energy efficiency discredits OECD energy policy advisors in the eyes of LDC leaders. Andrew MacKillop, "Energy Sector Investment in LDCs: The Credibility Gap Widens," Energy Policy, August 1986, p. 322.

[101] Gregory H. Kats, "Energy Subsidies: Time for a Rethink in Cairo," The Middle East Economic Digest (MEED), August 1984.

In sum, the scenarios examined in this section all have one element in common: improved efficiency of energy use. While energy efficiency is not a panacea, it offers the greatest promise to reduce global CO_2 emissions substantially, while also ameliorating other problems such as acid rain, and economic inefficiency. Moreover, rather than being just a theory, this efficiency potential has also been demonstrated in practice. Since 1973, the energy used per unit world economic output has declined by 12 percent, primarily in response to increased oil prices. This has occurred in the absence of vigorous efforts to promote increased efficiency in most nations, and only gives a hint of what would be possible in the event of a concerted effort to implement improved energy efficiency worldwide.

6. Comparison Between Efficiency and Nuclear Amelioration

Given that efficiency holds great promise for reducing global CO_2 emissions, it is of particular interest to compare efficiency and nuclear strategies in terms of their efficacy and economics. A systematic global comparison of the costs of abating CO_2 emissions via improved efficiency versus expanding nuclear supply would be quite difficult to carry out, and in fact has not been done. However, specific regional examples of such comparisons provide a good basis for performing a few basic calculations.[102]

Before proceeding with these calculations, it should be pointed out that most efficiency improvements can in principle be implemented very quickly, whereas the CO_2 emissions targeted for displacement by a nuclear power plant continue unabated throughout the construction period of the plant -- which is a minimum of six years. Not only is CO_2 abatement via efficiency much more expeditious, but it is also far more effective than nuclear power at reducing CO_2 emissions, as the next example shows.

Plausible Nuclear Amelioration

The nuclear programs envisioned in the High and Medium Scenarios of Section 3 were so extreme as to be economically infeasible in LDCs, and highly unlikely in developed nations. It is worthwhile to ask what a major -- yet much more plausible -- nuclear program could do to ameliorate CO_2 emissions. Alvin Weinberg, a prominent nuclear advocate, recently suggested that in order to make a dent in CO_2 emissions, production of electricity by nuclear power around the world should be increased by at least sixfold.[103] Let us consider this possibility for a moment, assuming that a sixfold expansion of nuclear power were commissioned in 1988 and completed by 2025. As shown in the Appendix, this requires that new nuclear capacity be brought on line at the average rate of 1000 MW (equivalent to one large plant) every 7.5 days for the next 37 years. For comparison, during the period between 1970 and 1985, global nuclear capacity increased at the rate of 1000 MW every 23.5 days, so a sixfold expansion by 2025 is about three times more intensive than recent historical development of nuclear power. This rate of capital development is very high, but not implausible, given a major global commitment to nuclear power.

[102] As one example, in 1983 the Pacific Gas and Electric Company (PG&E) of California invested $80 million for energy saving devices and incentives. The company's economists calculate that this saved 240 megawatts, at a cost of $350 per kilowatt. By comparison, PGE's recently completely nuclear plant cost $2,760 per kilowatt -- almost eight times higher.

[103] S. Doughton-Evans, "Safe Reactors Power of Future?," Los Alamos Monitor, 8 December 1987.

To what extent would such a program reduce CO_2 emissions? By 2025, 2.594 TW of primary nuclear energy is produced, which displaces (if all coal-fired) 1.945 Gt/y of CO_2 emissions from coal. Incorporating this into the original scenarios in Section 2, annual emissions are reduced by 11.5% in the high scenario, and 18.9% in the medium scenario. When non-CO_2 greenhouse gases are taken into account in these scenarios, *the overall effect of the sixfold nuclear expansion on reducing greenhouse warming is roughly six percent in the high case, and at most ten percent in the medium case.* In contrast, in the Goldemberg *et al.* efficiency scenario discussed in Section 4, the total contribution from coal in 2020 is 1.95 TW. Thus this sixfold nuclear expansion is enough to displace all the coal plus 0.644 TW of oil in this scenario (by 2025), which reduces CO_2 emissions from 4.85 Gt/y to 2.98 Gt/y.[104]

For ease of comparison, CO_2 emissions displaced by the six-fold nuclear expansion are shown in Figure 1 for the high, medium, and Goldemberg (low) scenarios. The cross-hatched area sitting atop the three columns in 2025 represents the emissions displaced by the six fold expansion of nuclear power. This figure illustrates a key point. Amelioration of CO_2 emissions due to nuclear power is barely noticeable in the high scenario (12%), and quite modest (19%) in the medium scenario. Only in the low scenario does the nuclear program result in a substantial reduction in CO_2 emissions (38%), and then *only because the overall magnitude of emissions has already been reduced by efficiency.* Thus, in the low scenario, the size of the greenhouse problem has been scaled down to such an extent that nuclear power's modest contribution can be noticed.[105] Thus Figure 1 gives an indication of the relative magnitudes of the amelioration effects due to efficiency and to nuclear power. The total height of each column is determined by the degree of efficiency improvement, and the much smaller cross-hatched adjustment perched atop each column is determined by the sixfold nuclear expansion.

The conclusion is that a sixfold expansion of nuclear power, while costing a very optimistic 1.43 trillion (1987) dollars, or an average of $39 billion per year for 37 years,[106] can only take a small bite out of the greenhouse warming pie -- unless the pie itself is pre-shrunk by improved energy efficiency.

Global Opportunity Cost

To what extent does this sixfold nuclear expansion scenario effectively *contribute* to the greenhouse warming problem, in the sense of diverting funds away from the most promising CO_2 abatement strategies? To estimate the size of this "opportunity cost," we calculate the total CO_2 displaced under this nuclear scenario, and then compare this with the total CO_2 that *would* have been displaced if the same investment been made in efficiency improvement. Consistent with our analyses above, we again make highly

[104] Since the Goldemberg scenario has a time horizon of 2020, for purposes of this analysis, we extrapolate to 2025, assuming that all primary energy values remain constant between 2020 and 2025. This is not an unreasonable assumption, because the total primary energy and supply mix change very slowly in this scenario. Furthermore, a five-year difference does not matter much when looking 35 to 40 years into the future.

[105] Strictly speaking, in making this argument, the global population and economic output should be identical in the high, medium, and low scenarios, but since these quantities are broadly equivalent in these three scenarios, the required adjustments are negligible.

[106] Here we again make highly optimistic assumptions, but in this case we assume an operating cost (rather than just capital cost) of 5 ¢/kWh.

optimistic assumptions for nuclear power, and we shall also make rather pessimistic assumptions for efficiency. The cost of electricity generated from new nuclear power plants is assumed to be just 5 cents per kWh (see Appendix). We shall assume U.S. cost estimates are roughly applicable worldwide, and we shall ignore the fact that efficiency improvements generally have very short lead times. Thus for the purposes of this exercise, neither efficiency improvements nor nuclear power will begin to displace carbon emissions before 1995. Since the marginal cost of efficiency will presumably rise with increased investment in efficiency, we assume that the cost of efficiency will increase linearly, doubling over the thirty year period from 1995 to 2025. Specifically, the cost of efficiency is assumed to rise steadily from the figure cited below of 2 cents per kWh in 1995[107] to 4 cents per kWh in 2025. Meanwhile, nuclear costs will be held fixed (all calculations are done in 1987 $).

As shown in Figure 2, even under these optimistic assumptions for nuclear power (and pessimistic assumptions for efficiency?), the nuclear scenario still dumps 17.27 Gt more carbon into the earth's atmosphere than the efficiency scenario (see Appendix). This is an average of 0.575 Gt/yr between 1995 and 2025, representing over 10% of today's global carbon emissions. Thus, a sixfold expansion of nuclear power would actually exacerbate the greenhouse warming problem by diverting funds away from efficiency -- thereby effectively causing an additional 17.3 Gt of CO2 emissions to be added to the earth's atmosphere.

Marginal Opportunity Costs of Nuclear Power in U.S.

The U.S. is the principal emitter of carbon emissions in the world, and it is therefore of particular interest to compare efficiency and nuclear strategies for abatement of CO_2 emissions in the U.S. Specifically, for each dollar invested in nuclear power, how much carbon is emitted into the earth's atmosphere that would *not* have been emitted, had that dollar been invested in improved efficiency?

To calculate this, we need estimates of the cost of saving electricity via improved efficiency, and the cost of generating electricity via new nuclear power plants. A recent study analyzes the cost and savings potential of several electrical efficiency improvements, including solid state ballasts, improved refrigerators, and water heaters.[108] As shown in the Appendix, the weighted average cost of these various improvements is approximately 2 cents per kWh of electricity saved. Meanwhile, the cost of electricity generated from new nuclear power plants (in 1987 $) is currently around 13.5 cents per kWh (see Appendix). Thus one dollar buys 50 kWh of saved electricity, and only 7.4 kWh of nuclear electricity. Assuming a strategy of displacing coal-fired power, efficiency is therefore 50/7.4 = 6.76 times more cost-effective in displacing carbon emissions than nuclear power.

More importantly, for each dollar invested in nuclear power, (50 - 7.4) kWh_e = 42.6 kWh_e of electricity savings are forgone. This represents an additional 42.6 kWh_e of coal-fired power that could have been displaced at no extra cost, had the dollar been invested in efficiency instead of nuclear power. Since the carbon intensity of existing coal-fired power plants is 2.57×10^{-4} t/kWh_e, then for displacing carbon emissions (from coal-fired electricity), every dollar invested in nuclear power adds (42.6 kWh_e)(2.57×10^{-4} t/kWh_e) = 0.011 tonnes of carbon to the atmosphere that *could* have been avoided, had that dollar been invested in efficiency. Put simply, *every $100 invested in nuclear power effectively*

107 This assumes no increase in the marginal cost of efficiency between now and 1995, which is a reasonable assumption for this exercise because efficiency is presumed not to be able to make a contribution before 1995.

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releases an additional tonne of CO_2 into the atmosphere. This provides a measure of the environmental opportunity cost of nuclear power.

These results are illustrated in Figure 3, which compares the efficacy of nuclear power and efficiency for abating CO_2 emissions at the margin. As shown, efficiency displaces 6.75 times more carbon per dollar invested than does nuclear power. Moreover, the opportunity cost of each dollar invested in nuclear power is shown as the lighter gray area, representing the additional carbon that could have been displaced, had that dollar been invested in efficiency.

The opportunity cost of nuclear power can be computed in another way that is also of interest. Let k represent the carbon intensity of existing coal-fired power plants [t/kWh_e].[109] Further, let c_n be the cost of producing one kWh_e of electricity from new nuclear power [\$/kWh_e], and let c_e be the cost of displacing one kWh_e of electricity with improved efficiency [\$/kWh_e]. Then one dollar buys $1/c_n$ [kWh_e/\$] of new nuclear electricity, and assuming that this displaces existing coal-fired power (at constant demand), then the direct carbon displaced per dollar invested in new nuclear power is given by k/c_n [t/\$]. Parallel calculations hold for efficiency: one dollar buys $1/c_e$ [kWh_e/\$] of displaced electricity, which displaces k/c_e [t/\$] carbon.

For each dollar invested in nuclear power, we now calculate the foregone carbon displacement, denoted by S [t/\$]. Here, S represents the *additional* carbon - over and above the carbon displaced due to direct replacement of coal-fired power by nuclear power - that *could* have been displaced, had that dollar been invested in efficiency. This is simply given by $S = k/c_e - k/c_n$. Note that $S > 0$, since $c_n > c_e$. Thus S may be regarded as the quantity of carbon "released" to the atmosphere for each dollar invested in nuclear power. Since that same dollar buys $1/c_n$ kWh_e of nuclear electricity, the effective carbon intensity of new nuclear power is given by $S/(1/c_n)$, which simplifies algebraically to $k(c_n/c_e - 1)$.

This expression becomes particularly interesting when we plug in numerical values for the costs. Using the figures cited above of c_n = 13.5 ¢/kWh_e and c_e = 2 ¢/kWh_e, we find that the effective carbon intensity of nuclear power is nearly six times *greater* than the direct carbon intensity of coal fired power.[110]

6. *Summary and Conclusions*

Given the increasing threat of greenhouse climate warming, many people have assumed that the world will eventually be forced to turn to nuclear power as the most viable response to this threat. To explore this possibility, we began by examining future scenarios in which greenhouse warming is likely to be a major problem; namely, representative scenarios that

[109] For this discussion, units of all quantities are given in square brackets. The symbol t stands for metric tons.

[110] This number should be interpreted cautiously. For example, note that assuming a cost of 7 cents per kWh for electricity generated from coal, the equivalent number for the efficiency opportunity cost of investing in coal fired power is 6.42×10^{-4} t/kWh, which is 2.5 times greater than the direct carbon intensity of coal fired power.

project moderate to heavy consumption of fossil fuels. We then posited the optimistic hypothesis that a global transition from coal to nuclear power could be completed over the next four decades. This is an extreme but highly favorable scenario for a successful nuclear response to greenhouse warming. Coal was selected as the target for displacement because it is the "dirtiest" and most readily substitutable fossil fuel. We found that nuclear power plants must be built at the average rate of one new plant (1000 MW) *every one to three days* for nearly four decades, costing an average of between $151 billion and $229 billion each year. However, even these massive nuclear programs sustained for four decades do not prevent an increase in CO2 emissions, and global warming continues in both scenarios. Moreover, the economic impact of such programs on developing nations would probably be catastrophic, while the effect on the global economy would be severe.

These nuclear scenarios are then considered in the light of recent experience with nuclear power around the world. In most industrialized nations, the future of nuclear power continues to be bleak, and prospects for a major reversal appear very remote -- a situation that has been widely publicized. Nuclear experience in less developed countries (LDCs) is much less well known. Developing nations have the fastest rate of population growth, the lowest installed electricity generation capacity, and most rapid projected rate of growth of electricity consumption. In the early 1970s, nuclear programs were initiated in LDCs on a large scale -- comparable to what would be required in an attempted nuclear solution to the greenhouse problem. Despite export financing and subsidies, and a substantial LDC political and economic commitment to nuclear energy, the nuclear programs have failed in the majority of cases. Current massive interest obligations of debtor nations leave little foreign exchange left over for expensive imports, and LDCs simply cannot obtain the credit and capital that would be required to finance a major nuclear buildup. Moreover, even if the requisite financing and political will were available, the additional debt incurred from major nuclearization in LDCs would roughly double the already crippling debt burden, spelling economic disaster for most LDCs. The conclusion is that prospects for major nuclear development in LDCs on a scale sufficient to significantly abate CO_2 emissions are thin to vanishing.

Having explored scenarios of moderate to heavy fossil fuel consumption, we next examined energy scenarios that project low growth in future consumption of fossil fuels. In most of these scenarios, greenhouse warming is not nearly so serious a threat. Low growth in energy consumption is achieved via improving energy efficiency, permitting substantial economic growth. For example, in one scenario, the entire world attains Western European living standards by 2020, yet annual CO_2 emissions decline and nuclear power is unnecessary.

Given that the nuclear programs analyzed earlier were so extreme as to be infeasible we next explored the effects that a major but feasible nuclear program would have on ameliorating greenhouse warming. This involved a sixfold expansion of nuclear power by 2025, and it was found to have rather little effect on greenhouse warming -- *unless* the magnitude of the problem were sufficiently reduced by improved energy efficiency. Thus nuclear power's contribution to solving greenhouse warming is inherently small, and could only be significant if the overall problem is shrunk by efficiency in the first place.

Finally, we compare the economics of efficiency and nuclear strategies for abatement of CO_2. It is found that in the U.S., efficiency displaces nearly seven times as much CO_2 (per dollar invested in abatement) as new nuclear power does. This means that nuclear power as a strategy for reducing greenhouse warming carries a heavy opportunity cost for every $100 invested in nuclear CO_2 abatement, one tonne of CO_2 is released into the earth's atmosphere that could have been avoided, had that $100 been put into efficiency. In this sense, the pursuit of nuclear power as a response to greenhouse warming actually exacerbates the problem by diverting funds away from the most promising approaches.

We conclude that the dream of a nuclear solution to the greenhouse warming problem is precisely that -- a dream. Nevertheless, we share a sense of urgency about the greenhouse problem with many advocates of nuclear power. Precisely because of this urgency, it is self-evident that the nations of the world should pursue those energy policies that will ameliorate the greenhouse problem as quickly and effectively as possible. This means going for the most effective correctives first, and in this case those correctives happen to be the cheapest ones as well. Not only is nuclear power slower and far more expensive than efficiency improvement, but its overall potential for displacing CO_2 emissions is also much smaller. The fastest, least expensive, and above all, most effective response to CO_2-induced greenhouse warming is to curtail the emission of CO_2 by improving the energy efficiency of the global economy.

Appendix: Details of Calculations

Details of selected calculations reported in the text are provided below. For full details, see B. Keepin and G. Kats, *Greenhouse Warming: A Rationale for Nuclear Power?* forthcoming report, Rocky Mountain Institute, Snowmass, CO 81654.

Medium Scenario

The scenario is case "B" from J.A. Edmonds and J. Reilly, *An Analysis of Possible Future Atmospheric Retention of Fossil Fuel CO_2*, U.S. Department of Energy DOE/OR/21400-1, September 1984, hereafter abbreviated ER.

From Table B-6 in Appendix B of ER, we find global primary energy consumption in 2025 to be 673.2 EJ/y, which is 21.34 TW (since 1 TW = 31.54 EJ/y). Of this, 297.67 EJ/y, or 9.44 TW, is from coal. From the same table, we find that 53% of this coal is consumed in developed countries, with the remainder consumed in LDCs. Converting the total 9.44 TW to secondary energy gives 3.15 TW, which requires 4.84 TW of installed nuclear capacity (assuming 65% capacity factor).

The nuclear contribution already existing in the scenario in 2025 is given in Table B-6 of ER as 21.78 EJ primary, which is 0.23 TW secondary, requiring 0.354 TW installed capacity. The fraction of this component in developed countries is 85%.

Thus the total installed capacity required by 2025 in this scenario is 0.53 x 4.84 TW + 0.85 x 0.354 TW = 2.87 TW in developed countries, and 0.47 x 4.84 TW + 0.15 x 0.354 TW = 2.33 TW in LDCs. The schedules for completing installed capacity in developed and developing countries are shown in Tables A.1 and A.2, respectively, assuming exponential growth of the form

$$A\, e^{k(t-1990)}$$

with initial conditions for developed countries being 340 GW in 1990, and 2870 GW in 2025. We select 1990 as the initial point because the six year lead time for construction of power plants means that the impact of the nuclear scenario could not be felt before 1995 (hence the global installed capacity for 1990 is fixed[111]). The exponential growth constant (k) turns out to be 0.061 for the developing countries, and 0.133 for the LDCs (these translate into annual growth rates of 6.3% in developed countries and 14.2% in LDCs).

The entries in the second column of Tables A.1 and A.2 (labeled "Change in Inst. Cap.") are simply the difference of two successive entries from the first column. The data in the "Retired Capacity" column are adapted from industry decommissioning plans,[112] and the final column (labeled "New Additions to Capacity") is obtained by adding the entries from the previous two columns. All figures are rounded to the nearest whole GW.

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[111] Boundary conditions for 1990 are 340 GW in developed nations, and 22 GW in LDCs, taken from "World List of Nuclear Power Plants, Nuclear News, February 1986, quoted in C. Pollock, Decommissioning: Nuclear Power's Missing Link, Worldwatch Paper No. 69, Worldwatch Institute, Washington, D.C., April, 1986.

[112] Id. For details of past and present global commitment to nuclear power, and current plans for the future, see Appendix A of B. Keepin and G. Kats, Greenhouse Warming: A Rationale for Nuclear Power? forthcoming report, Rocky Mountain Institute, Snowmass, CO 81654.

Table A.1 Installed Nuclear Capacity in Developed Countries (GW)
(*Medium Scenario*)

Year	Installed Capacity	Change in Inst. Cap.	Retired Capacity	New additions to Capacity
1985	236	109	0	109
1990	340	104	1	105
1995	461	121	4	125
2000	625	164	11	175
2005	848	223	54	277
2010	1150	302	57	359
2015	1560	410	109	519
2020	2116	556	105	661
2025	2870	754	125	879

Table A.2 Installed Nuclear Capacity in LDCs (GW)
(*Medium Scenario*)

Year	Installed Capacity	Change in Inst. Cap.	Retired Capacity	New additions to Capacity
1985	13	9	0	9
1990	22	9	0	9
1995	43	21	0	21
2000	84	41	0	41
2005	164	80	0	80
2010	318	154	4	158
2015	618	300	9	309
2020	1200	582	9	591
2025	2330	1130	21	1151

Total global installed nuclear capacity reaches 5200 GW by 2025, which is an 18.2-fold increase over today's capacity of 283.6 GW. In LDCs, the current capacity is 15.02 GW,[113] meaning that installed capacity must increase 2330/15.02 = 155-fold by 2025.

Summing the final columns of these tables, we obtain 3209 GW to be built in developed countries (equivalent to 3,209 large power plants), and 2369 GW in LDCs. The corresponding average capital investment rates over the 37 year period are one new (1000 MW) power plant every (37 x 365)/3209 = 4.21 days in developed countries, and every 5.70 days in LDCs. The global capacity to be added in this scenario is 5578 GW, which means a new plant every 2.42 days.

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[113] Nucleonics Week, 4 June 1987, pp. 14-16.

The contribution from Latin America mentioned in the text is computed from the data given in Table B-6 of ER. Primary coal and nuclear consumption are 19.07 EJ and 1.45 EJ, respectively. Thus 19.07 EJ + 1.45 EJ = 20.52 EJ = 0.651 TW (primary) = 0.217 TW (secondary), which requires 0.334 TW installed nuclear capacity, or 334 GW.

Opportunity Costs of Nuclear Power

To calculate the marginal cost of efficiency quoted in the text, we begin with the cost data shown in Table 4 of Geller, *et al.*,[114] reproduced in Figure A.1 below. The four electricity saving technologies considered are solid state ballasts,[115] high efficiency refrigerator compressor, high efficiency refrigerator/freezer, and heat pump water heater. The cost of conserved electricity is calculated as the ratio of the entries in row 5 to those in row 1 (eg for solid state ballasts (SSB), the result is ($1.70/y)/(133 kWh/y) = 1.28 ¢/kWh). The total annual electricity savings are obtained as the product of the entries in row 1 with those of row 10 (again, for SSB, the result is (600 x 10^6 units)(133 kWh/unit/y) = 79,800 x 10^6 kWh/y. This number is used as a weight in calculating the weighted average cost of conserved electricity. The corresponding figures are obtained for the remaining technologies, and the weighted average is given by (1.28(79,800) + 0.62(14,904) + 3.57(18,480) + 2.96(58,800))/171,984 = 2.043 ¢/kWh. This figure is rounded to 2 ¢/kWh in the text, and provides a measure of today's average marginal cost of electrical efficiency in the United States.

The cost of electricity generated from new nuclear power plants in the U.S. is obtained in consultation with Charles Komanoff of Komanoff Energy Associates in New York City.[116] The result is 13.3 ¢/kWh, which is consistent with the experience of many utility companies.[117]

Sixfold Expansion of Nuclear Power

Using data from the end of 1986, the global installed nuclear capacity is 273.715 GW, and the total nuclear electricity generated in 1986 is 172.90 GW-y (this gives a capacity factor of 0.63 for 1986).[118] Multiplying the nuclear electricity generation by six, we have 1037.4 GW-y of electricity to be generated in 2025. At a capacity factor of 65%, this requires (1037.4 GW)/0.65 = 1596 GW of installed capacity by 2025. Assuming exponential growth from 1990 to 2025, the schedule for installed capacity is shown in Table A.3. Summing the figures in the final column of Table A.3 from 1990 onwards gives 1800 GW, which requires an average investment rate of (365 x 37)/1800 = 7.5 days/GW.

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[114] Geller et al.

[115] Figures used here include feedback dimming control, as described in footnote "a" of the table.

[116] Komanoff Energy Associates, 270 Lafayette St., Suite 902, New York, NY 10012.

[117] See, for example, "Cost Outlook for Nuclear Power Plants Under Construction," Public Utilities Fortnightly, 21 March 1985, p. 40.

[118] Nucleonics Week, 9 April 1987, p. 6.

Table A.3 Global Installed Nuclear Capacity (GW)
(Sixfold Expansion of Nuclear Power)

Year	Installed Capacity	Change in Inst. Cap.	Retired Capacity	New additions to Capacity
1985	249	118	0	118
1990	362	113	1	114
1995	448	86	4	90
2000	553	105	11	116
2005	684	131	54	185
2010	845	161	61	222
2015	1045	200	118	318
2020	1291	246	114	360
2025	1596	305	90	395

Opportunity Costs of Sixfold Expansion

As discussed in the text, a sixfold expansion of nuclear power actually *contributes* some 17.27 Gt of carbon to the earth's atmosphere that could have been avoided, had the same investment been made in efficiency. This is a conservative calculation made under the highly optimistic assumption that future nuclear electricity will cost only 5 ¢/kWh$_e$.[119] We assume that this figure applies globally (note that this is about one third of the current marginal cost of new nuclear power in the U.S.). Since nuclear power plants ordered now could not come on line before 1995, we conservatively assume that no costs are incurred before 1995, and that the cost remains fixed thereafter at 5 ¢/kWh. Meanwhile for the sake of this exercise, we assume that efficiency could also not displace electricity before 1995, and that the cost of displacing electricity through efficiency improvement will increase linearly from 2 ¢/kWh to 4 ¢/kWh between 1995 and 2025. The resulting calculations are summarized in Tables A.4 and A.5.

We begin by computing the net increase in nuclear capacity (as a function of time) that would be required in the sixfold expansion scenario. This is obtained by subtracting existing and currently planned nuclear capacity[120] from the "Installed Capacity" column in Table A.3, and the result is shown in the first column of Table A.4. Hence, this column shows the *additional* nuclear capacity that would have to be built, over and above all existing and planned nuclear power plants.[121] Assuming a 65% capacity factor, the second column of Table A.4 shows the resulting electricity generation, and the third column shows the associated cost (at 5 ¢/kWh). Finally, the last column of Table A.4 shows the CO_2 emissions (from coal fired power) that would be displaced by this nuclear capacity.

[119] This figure is calculated assuming a capital cost of $1000 per installed kW, and optimistic assumptions about operating costs, see Appendix A of B. Keepin and G. Kats, Greenhouse Warming: A Rationale for Nuclear Power? forthcoming report, Rocky Mountain Institute, Snowmass, CO 81654.

[120] See Appendix A of B. Keepin and G. Kats, Greenhouse Warming: A Rationale for Nuclear Power? forthcoming report, Rocky Mountain Institute, Snowmass, CO 81654.

[121] It is important to use these net increases in installed capacity, since otherwise the calculations would not make a fair, direct comparison between new investments in nuclear power and new investments in efficiency. To use absolute figures (ie. first column of Table B.5) rather than these net figures would make efficiency look better than it really is.

To calculate the CO_2 that could be displaced by an equivalent investment in efficiency, we begin with the assumed marginal cost (as a function of time) of displacing electricity (via efficiency improvement), shown in the first column of Table A.5. We then divide the annual cost figures in Table A.4 (third column) by the marginal cost entries in the first column of Table A.5, to obtain the total electricity displaced, shown in the second column of Table A.5. Again assuming that coal fired power is displaced, this results in CO_2 displacement as shown in the third column of Table A.5.

Finally, to compute the difference in carbon displacement between the nuclear and the efficiency scenarios, we subtract the entries in the last column of Table A.4 from those in the third column of A.5. This yields the excess CO_2 displaced in the efficiency scenario, shown in the last column of Table A.5. To obtain the total excess carbon displaced in the efficiency scenario, we compute the time integral of this column, which yields 17.27 Gt. Over the thirty period from 1995 to 2025, this is an average of 0.576 Gt/y, which is more than 10% of today's emissions.

Table A.4 Carbon Displacement - Nuclear Scenario
(Six-Fold Expansion of Nuclear Power)

Year	Excess Inst. Cap. (GW)	Elec. Gen. (10^6 GWh)	Cost ($\$10^9$/y)	CO_2 Displaced (Mt/y)
1985	0.0	0.0	0.0	0
1990	0.0	0.0	0.0	0
1995	71.6	0.41	20.5	105
2000	187.5	1.07	53.5	275
2005	372.8	2.12	106.0	545
2010	595.3	3.39	169.5	871
2015	912.8	5.20	260.0	1336
2020	1272.9	7.25	362.5	1862
2025	1596.0	9.09	454.5	2335

Table A.5 Carbon Displacement - Efficiency Scenario

Year	Efficiency cost (¢/kWh)	Elec. Displ. (10^6 GWh)	CO_2 Displ. (Mt/y)	Ex. CO_2 Displ.
1985	2.00	0.0	0.0	0
1990	2.00	0.0	0.0	0
1995	2.00	1.03	265	160
2000	2.33	2.29	588	313
2005	2.67	3.97	1020	475
2010	3.00	5.65	1451	580
2015	3.33	7.80	2003	667
2020	3.67	9.88	2538	676
2025	4.00	11.36	2918	583

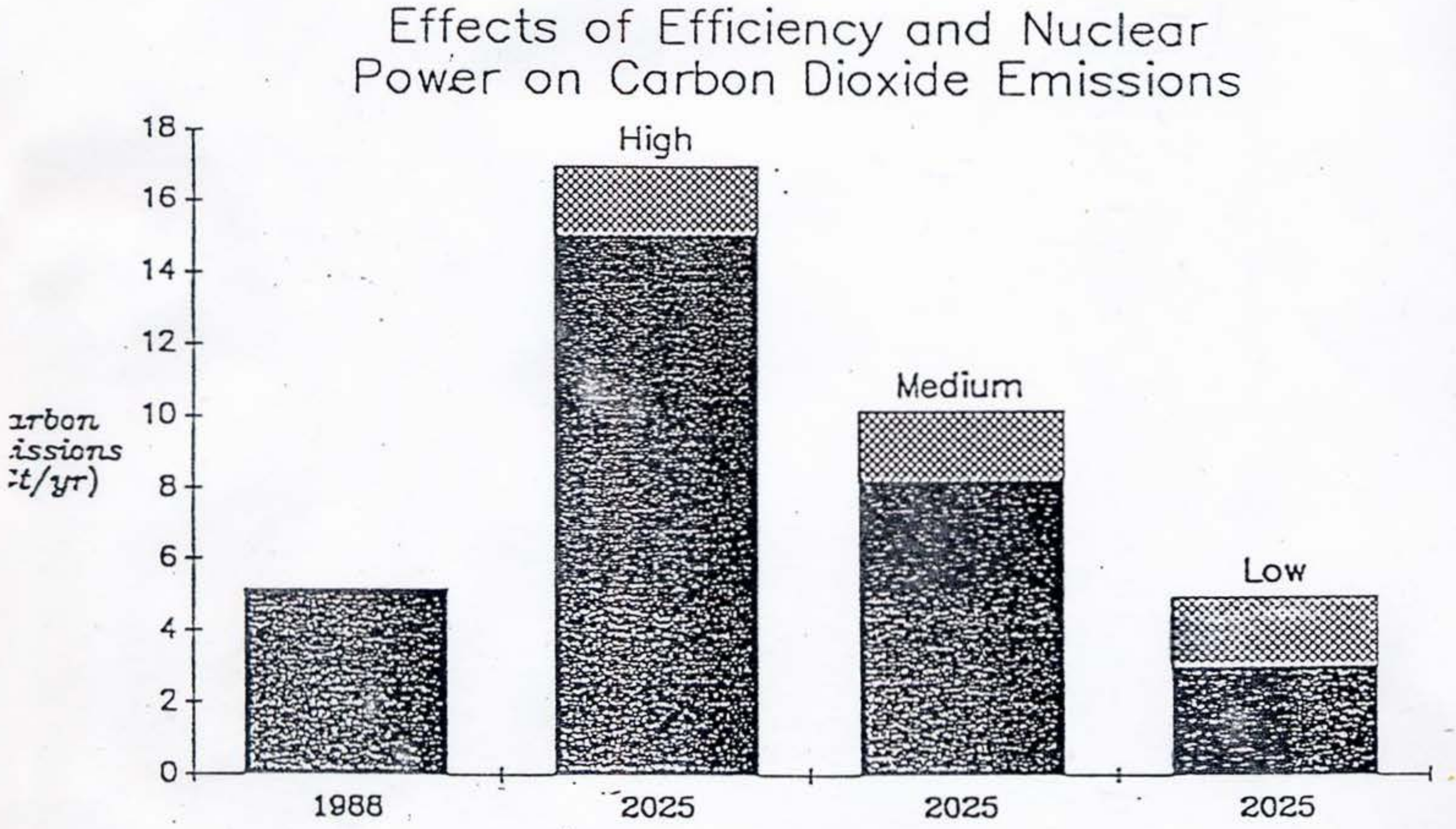
Effects of Efficiency and Nuclear
Power on Carbon Dioxide Emissions
High
Medium
Low
18
16
14
12
10
8
6
4
2
0
1988
2025
2025
2025

Figure 1

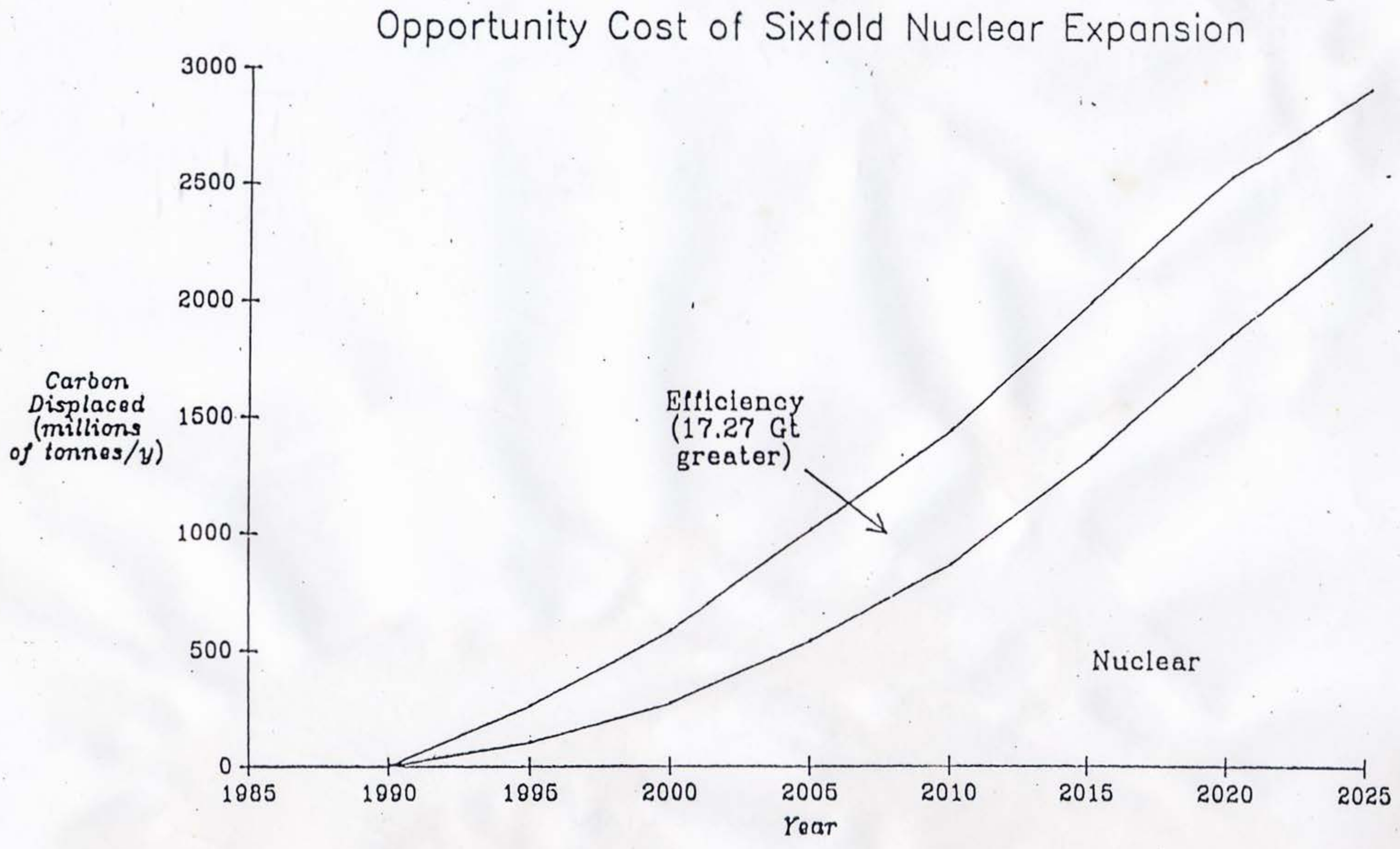
Opportunity Cost of Sixfold Nuclear Expansion
Carbon Displaced (millions of tonnes/y)
3000
2500
2000
1500
1000
500
0
1985
1990
1995
2000
2005
2010
2015
2020
2025
Year
Efficiency (17.27 Gt greater)
Nuclear

Figure 2

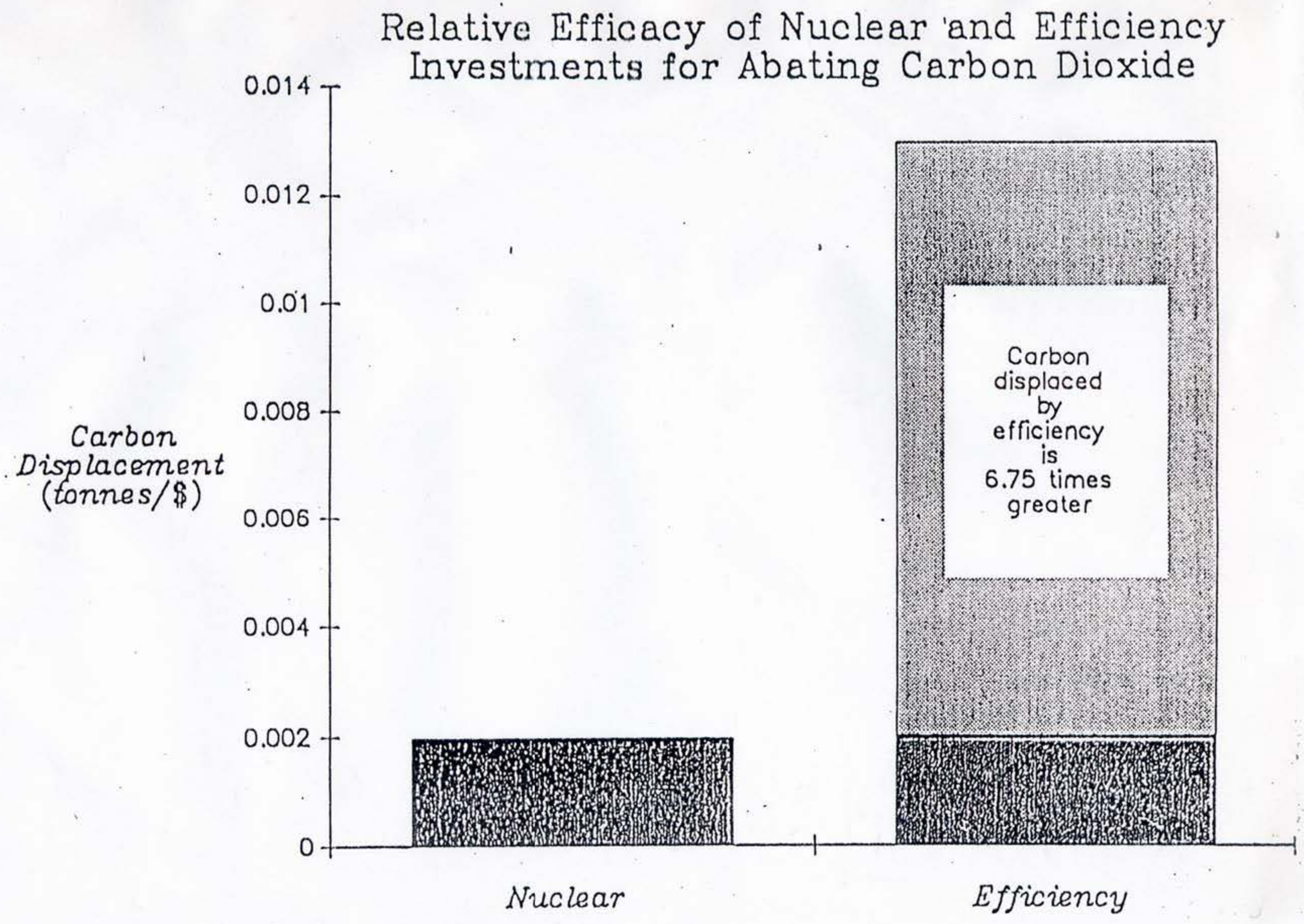
Relative Efficacy of Nuclear and Efficiency
Investments for Abating Carbon Dioxide
Carbon
Displacement
(tonnes/$)
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
Carbon
displaced
by
efficiency
is
6.75 times
greater
Nuclear
Efficiency

Figure 3