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MANAGING ATMOSPHERIC CO_2: POLICY IMPLICATIONS

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Abstract—In a previous study, the impact on atmospheric CO_2 concentration and globally-averaged climatic change of various CO_2 emission-reduction strategies was estimated using a coupled climate–carbon cycle model. Scenarios in which fossil-fuel CO_2 emissions increased by 0–1% yr^{-1} until 2000–2020, followed by a gradual transition to a rate of emission decrease of 1–2% yr^{-1}, were considered and found to result in peak atmospheric CO_2 concentrations of 400–500 ppmv, depending on rates of deforestation and the effect of various climate–carbon cycle feedbacks. Here, it is shown that a rate of decrease of fossil-fuel CO_2 emissions of 1–2% yr^{-1} is consistent with reasonable assumptions concerning global population growth, feasible future *per capita* primary energy demand in the industrialized and developing countries, and attainable rates of installation of non-fossil fuel energy supply. It is thus concluded that stabilizing atmospheric CO_2 at a concentration of 400–500 ppmv is a credible option. Attaining this target requires both greatly improved efficiency of energy use and a redirection of energy policy toward non-fossil-fuel energy sources.

INTRODUCTION

Emissions of CO_2 from the combustion of fossil fuels, deforestation, and other human activities have caused the atmospheric concentration of CO_2 to increase from a pre-industrial value of about 280 ppmv (parts per million by volume) to its current value of about 350 ppmv. It is almost universally assumed that fossil fuel emissions of CO_2 will continue to grow or at least remain near their present level, such that atmospheric CO_2 will double in concentration sooner or later. However, many studies[1–4] have shown that substantial reductions in total energy use and hence in CO_2 emissions are possible in the industrialized world through improved efficiency of energy generation and use, and that the Third World need not follow the industralized world's path of high energy use as it undergoes development. There is therefore considerable scope for reducing emissions of CO_2.

A doubling of atmospheric CO_2 concentration above its pre-industrial concentration and the associated climatic changes and sea-level rise would have significant but as yet uncertain impacts on global food production, forests and other terrestrial ecosystems and coastal regions, as well as on marine productivity. The final statement of the Toronto conference on *The Changing Atmosphere*: *Implications for Global Security* contains the following: "Humanity is conducting an unintended, uncontrolled, globally pervasive experiment whose ultimate consequences could be second only to global nuclear war" and further advocates that "energy research and development budgets must be massively directed to energy options which would eliminate or greatly reduce CO_2 emissions".[5] An assessment of the impacts induced by the continuing CO_2 increase may be found in Ref. 6, which contains the background papers that ultimately provided the scientific basis for the Toronto conference statement.

Because of concurrent increases of other greenhouse gases, the climate will experience the radiative heating equivalent of a CO_2 doubling by the time atmospheric CO_2 reaches a concentration of 400–450 ppmv, depending on how rapidly other greenhouse gases increase in concentration. To stabilize atmospheric composition at the equivalent of CO_2 doubling therefore requires limiting CO_2 to substantially less than a doubling. However, most scenarios project atmospheric CO_2 rising to several times its pre-industrial concentration.[7–9] Thus, *even if* the net global impact of a CO_2 doubling or its equivalent should be beneficial, human societies could still face significant negative consequences associated with even higher CO_2 concentrations. Given that significant changes in the use of fossil fuels will require several decades, policies must be set in place soon merely to prevent the equivalent of more than a CO_2 doubling.

Projection of future atmospheric CO_2 concentrations for a given emission scenario requires the use of a global carbon cycle model to compute the partitioning of emitted carbon between the oceans, potential biotic sinks, and the atmosphere. The response of both the oceans and the biosphere to increases of atmospheric CO_2 will be modulated by concurrent changes in temperature resulting from the buildup of CO_2 and other greenhouse gases. A coupled climate–carbon cycle model, which takes into account the effect of CO_2 and other greenhouse gases, is therefore needed to account for the feedback between climate and the storage of carbon in the oceans and biosphere.

In an earlier study,[10] such a model was used to investigate the effect on atmospheric CO_2 concentration and on global mean temperature of various CO_2 emission reduction strategies. This model included the effect of warmer temperatures in reducing the oceanic ability to hold CO_2, enhancement of plant and soil respiration by warmer temperatures, a weak enhancement of photosynthesis by warmer temperatures and, in some sensitivity tests, enhancement of photosynthesis by higher atmospheric CO_2. For scenarios in which fossil fuel emissions were either constant or increased by 1% yr^{-1} until A.D. 2000 or 2020, followed by a 10–15 yr transition to a rate of emission decrease of 1–2% yr^{-1}, atmospheric CO_2 concentration reached a peak concentration in the range of 400–500 ppmv. This range includes the effect of a variety of assumptions regarding future rates of deforestation and the response of the terrestrial biosphere to temperature and CO_2 increases, and is therefore a robust result.

An important parameter in determining future atmospheric CO_2 concentration is the so-called airborne fraction—the ratio of atmospheric CO_2 increase during a given time interval to the total emission during that interval. Currently, about half of the CO_2 emitted into the atmosphere in any given year is absorbed by the oceans (and possibly other sinks), so that the airborne fraction is about 0.5. The oceanic absorption of CO_2 in any given year depends on the ocean–air difference of CO_2 partial pressures and the vertical gradient of CO_2 within the ocean, which in turn depends on *previous* CO_2 emissions. If CO_2 emissions were to begin decreasing, the oceanic absorption of CO_2 would initially stay approximately constant, so that the airborne fraction—corresponding to the difference between emission and absorption—would fall. Once emissions fall to the level of absorption by the oceans and any other sinks, the airborne fraction would be zero and atmospheric CO_2 would cease to increase. Figure 1 illustrates the variation of atmospheric CO_2, fossil fuel emission, and CO_2 absorption by the oceans and other sinks, as computed in Ref. 10, for scenarios in which fossil fuel emissions increase by 1% yr^{-1} until 2020,

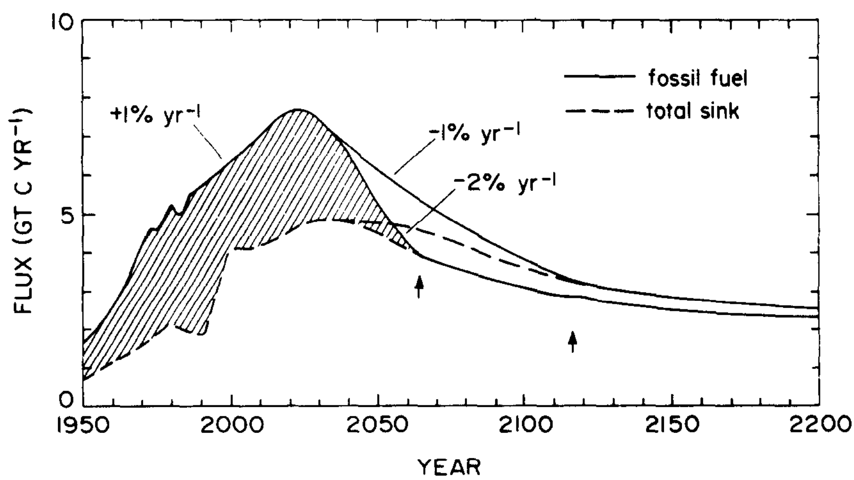

Fig. 1. Variation of fossil fuel CO_2 emission and CO_2 absorption by oceanic and other sinks for scenarios in which fossil emissions increase by 1% yr^{-1} until 2020, then begin a transition to rates of decrease of 1 or 2% yr^{-1}. The airborne fraction is given by the difference between the emission and absorption curves (cross-hatched) divided by the emission.

followed by a 1 or 2% yr^{-1} decrease. The airborne fraction corresponds to the cross-hatched area in Fig. 1. For these scenarios, the airborne fraction drops rapidly once emissions begin to decrease, so that emissions need drop to only about half their peak value in order to equal absorption by the sinks. Once emissions fall to the CO_2 sink strength, subsequent reductions of CO_2 emissions could proceed more slowly, as the sink strength gradually decreases (Fig. 1).

The purpose of this paper is to determine sets of assumptions regarding (i) population growth and *per capita* primary energy demand in the industrialized and developing countries, (ii) rates of introduction of non-fossil fuel energy supplies, and (iii) the mix of fossil fuels used, under which fossil fuel emission reduction rates of 1–2% yr^{-1} could be achieved. This permits an assessment of the feasibility of these emission reduction targets and the associated atmospheric CO_2 ceilings, and of the policies that would be needed to keep atmospheric CO_2 below or near a given ceiling.

POPULATION, ENERGY DEMAND, AND DEFORESTATION ASSUMPTIONS

Projections of future global energy demand can be classified as supply-oriented or end-use oriented. In the supply-oriented approach, future energy demand is projected based on various assumptions concerning population growth and either *per capita* energy demand or factors affecting *per capita* energy demand, such as energy prices and rates of improvement in the efficiency with which energy is used. The primary emphasis, however, is in calculating a mix of energy sources that will satisfy the projected demand and various other constraints. In the end use approach, the emphasis is on the demand for energy end-use services and the computation of the least energy intensive, cost effective means of providing the desired level of energy services. The end-use approach generally leads to dramatically less primary energy demand than the supply-oriented approach because of the much greater efficiency of energy use assumed in the former case, but represents a technical feasibility study rather than a projection.

A widely cited supply-oriented projection of future energy use is the IIASA study,[11] which contains two projections of global primary energy demand to the year 2030, a high projection in which global demand grows from 10 TW ($1\,TW = 10^{12}\,W$) in 1980 to 36 TW, and a low projection in which global energy demand grows to 22 TW. These scenarios have been criticized as being unrobust[12,13] and unrealistic,[3] the latter because they require pushing all energy-supply options, including nuclear and coal, to near their limits, and would have significant environmental impacts and security implications. Edmonds and Reilly[14] have developed a widely used, supply-oriented econometric model to project future global energy use under alternative sets of assumptions. In their most recent study using probabilistic scenario analysis,[15] 50% of their scenarios gave a global commercial energy demand of 16 TW or less in 2030.

A recent end-use oriented study is that of Goldemberg et al,[2,3] in which it is argued that *per capita* primary energy demand in the industrialized† countries could be cut almost in half by the year 2020 using currently available, cost-effective technologies, while the developing world could be brought up to the 1970s Western European standard of living with little change in total (commercial plus non-commercial) energy use. Global primary energy demand grows from 10.3 TW in 1980 to 11.2 TW in 2020 while population grows to 7 billion in their analysis. The 1980 global energy demand includes 1.5 TW of non-commercial biomass energy, primarily in the developing world, while the 2020 energy demand is assumed to be entirely commercial energy. *Per capita* commercial primary energy demand decreases from 6.3 kW in 1980 to 3.5 kW in 2020 in the industrialized world, while increasing from 0.54 to 1.2 kW in the developing world. Goldemberg et al assumed a 50% increase in *per capita* consumption of goods and services in the industrialized world in deriving the 3.5 kW *per capita* energy consumption for 2020.

†Industrialized countries here and in Goldemberg et al include Canada and the U.S.A., all of Europe, U.S.S.R., Japan, Australia, and New Zealand.

Goldemberg et al[2,3] show that their scenario is consistent with reasonable values for the price elasticity of energy demand (−0.7 to −1.0), income elasticity of energy demand (0.8–1.0) and non-price-induced rate of efficiency improvement (0.5–1.0% yr^{-1}) in the industrialized world if energy prices in 2020 are 2–3 times their 1972 values. Recent work by Mintzer[16] indicates a convergence of the supply-oriented and end-use oriented approaches to estimating possible future energy demand. Mintzer examined the impact using the Edmonds and Reilly model of various policy options designed to limit emissions of CO_2 while still permitting economic growth and development, and obtained global commercial primary energy use in 2075 ranging from no increase over present use to 19 TW for strong to modest policy scenarios.

Here, *per capita* energy demand in the industrialized world is assumed to remain constant from 1986 until 2000, and to initially increase at 2% yr^{-1} in the developing world. Beginning in 2000, the following policies are implemented which are aimed at achieving a target rate of CO_2 emission decrease of 2% yr^{-1}: (i) reduction of *per capita* energy use in the industrialized world; (ii) accelerated introduction of non-fossil fuel energy supply; and (iii) increased use of natural gas at the expense of coal.

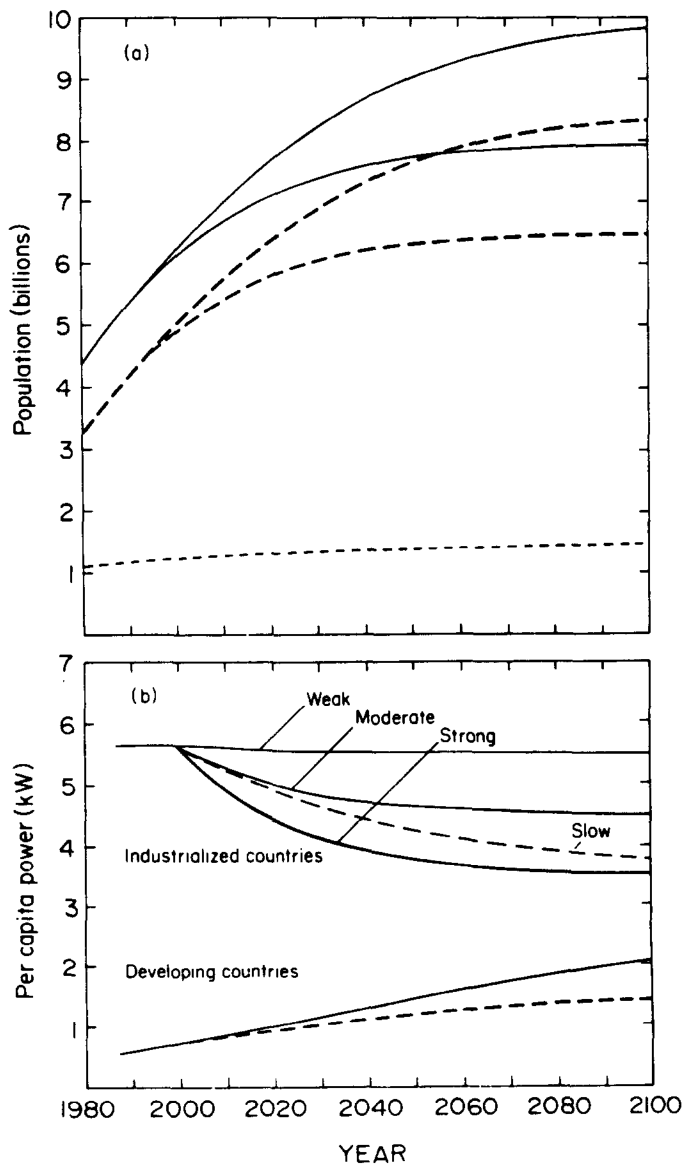

Fig. 2. (a) Industrialized and developing country population scenarios; (b) scenarios of *per capita* rate of energy use for industrialized and developing countries.

All scenarios begin in 1986, with industrialized and developing world populations of 1.18 and 3.76 billion, respectively, and with corresponding *per capita* commercial energy use of 5.58 and 0.55 kW,[17] giving a global commercial primary energy use in 1986 of 273.2 EJ (1 EJ = 10^{18} J). In all scenarios the population of the currently industrialized world is assumed to increase to 1.5 billion by 2100, while that of the developing world increases to 6.5 or 8.5 billion by 2100, corresponding to the moderate and rapid fertility reduction scenarios of the U.S. Population Reference Bureau.[18] The population growth scenarios are illustrated in Fig. 2(a).

It is assumed that the difference between the current and achievable *per capita* energy use in the industrialized world decreases by 4% yr^{-1}; the achievable *per capita* energy uses are assumed to be 5.5, 4.5, and 3.5 kW, reflecting weak, moderate, and strong energy efficiency improvements. A scenario is also considered in which the industrialized *per capita* energy use asymptotes at 3.5 kW, but in which the gap between current and asymptotic energy use decreases by 2% rather than 4% yr^{-1}. For the developing world, two scenarios are considered, in which *per capita* commercial energy use rises logistically to 1.5 or 2.5 kW. The resultant *per capita* energy use scenarios are illustrated in Fig. 2(b), and summarized in Table 1. Industrialized world *per capita* energy use is assumed to remain higher than that of the developing world even for the high efficiency scenario because of greater heating needs in industrialized countries and lower population densities, resulting in greater transportation energy use.

The two deforestation scenarios of Ref. 10 are assumed here. Accurate data on rates of deforestation since 1980 are currently lacking, but it was assumed in Ref. 10 that the 1987 rate of deforestation was 1.5 times the 1980 rate. In the high-deforestation scenario, this rate continues until 2035, while in the low deforestation scenario this rate continues until only 1990. Details are given in Table 2.

Finally, one scenario is considered in which reduced deforestation is accompanied by reforestation. In this scenario the estimated 1980 carbon absorption of 0.1 Gt yr^{-1} (gigaton, or 10^9 metric tonnes) due to reforestation linearly increases to 1.0 Gt yr^{-1} between 1990 and 2000, is held constant until 2040, then decreases back to 0.1 Gt yr^{-1} by 2050. The Tropical Forestry Action Plan of 1987 identifies the need to rehabilitate 1.6 million square kilometers of forest and woodland for erosion and flood control alone.[19] Taking a rate of CO_2 absorption of 10 ton C ha^{-1} yr^{-1} out of a range of 5–25 ton C ha^{-1} yr^{-1} for a growing tropical forest,[20] this gives a CO_2 sink of 1.6 Gt C yr^{-1}. The 1 Gt C yr^{-1} assumed here is about two-thirds of this value.

Table 1. Alternative asymptotic *per capita* energy use and population scenarios for the developing world and for industrialized countries.

Region	Case	*Per capita* energy use or population
Asymptotic per capita energy use		
Industrialized world	Weak efficiency improvement	5.5 kW
	Moderate efficiency improvement	4.5 kW
	Strong efficiency improvement	3.5 kW
Developing world	High	2.5 kW
	Low	1.5 kW
Equilibrium population		
Industrialized world	All	1.5 billion
Developing world	Low	6.5 billion
	High	8.5 billion

Table 2. Years in which gross emissions of CO_2 due to forest clearing are assumed to reach prescribed fractions of the assumed 1980 values, for the low and high deforestation scenarios. The values of the prescribed fractions, given in the the body of the table, are the same for low and high deforestation scenarios, but are attained at different times.

		Year			
	Low deforestation:	1980	1987-2035	2070	2100
Process	High deforestation:	1980	1987-1990	2000	2100
Forest harvesting		1.0	1.5	0.75	0.75
Cropland expansion		1.0	1.5	0.50	0.00
Pastureland expansion		1.0	1.5	0.00	0.00

NON-FOSSIL FUEL ENERGY SUPPLY

United Nations data[17] indicate that of 273.2 EJ primary commercial energy consumed in 1986 (corresponding to 8.66 TW power), only 13.0 EJ came from non-fossil fuel energy sources. In the scenarios considered here, the non-fossil fuel energy supply E_N is assumed to grow at a rate of 2% yr^{-1} from 1986 until 2000. To estimate how rapidly non-fossil fuel energy supply might be able to grow after 2000, the renewable energy potential estimated in the Goldemberg et al analysis is used. They estimate the technically and economically usable hydroelectric potential to be 1.1 TW, of which 0.2 TW were utilized in 1980 and 0.5 TW were assumed for 2020. The organic waste stream had an energy potential of 2.8 TW in 1980 and a projected potential of 4.1 TW in 2020, of which 0.8 TW were assumed to be used. Similarly, 0.8 TW from forest plantations were judged to be feasible by 2020. Nuclear energy was assumed to grow from 0.22 TW in 1980 to 0.75 TW in 2020. Goldemberg et al assumed that wind and solar together provided only 0.09 TW in 2020. According to a IIASA study,[11] the global technical potential for wind energy is 3 TW; if one-fifth were developed by 2020 this would amount to 0.6 TW. Recent dramatic improvements in the efficiency of amorphous-silicon solar panels indicate that 2% of the global desert area could displace the present fossil fuel energy use of 8.4 TW if combined with a hydrogen energy carrier.[21] Developing one-fifth of this potential by 2020 would provide 1.7 TW. The total non-fossil fuel power supply in 2020 would then be 5.2 TW. If this were achieved over a 30 yr period, it would amount to a rate of installation of non-fossil fuel power supply $\dot{E}_N$ of about 170 GW (gigawatt) yr^{-1}.

Here, we consider the impact on fossil fuel CO_2 emissions of assuming maximum rates of installation of non-fossil fuel power supply $\dot{E}_N$ of 75 and 150 GW yr^{-1}. This is substantially less than the peak rates of 400–1200 GW yr^{-1} found to be necessary for CO_2 stabilization in a previous study.[22] Since a typical large coal or nuclear power plant has an output of about 1 GW, we are assuming the *equivalent* of 75–150 new power plants per year. However, most of the non-fossil fuel power sources which were considered in deriving this estimated feasible rate of installation involve small scale, widely dispersed power sources.

Also of importance is the second time derivative of non-fossil fuel power supply, $\ddot{E}_N$, which corresponds to the rate at which factories for building new power plants would have to be built. This quantity is given a value of 5 or 10 GW yr^{-2} beginning in 2000 and continues until the maximum rate of installation of new non-fossil fuel capacity is achieved. In a previous study,[23] peak values for this quantity associated with a 2000 starting date for policies to limit CO_2 and a 500 ppmv ceiling were about 20–30 GW yr^{-2}, depending on the initial rate of growth in coal use.

Figure 3 shows the variation of global primary commercial energy demand for 1986–2100 for the weak, moderate, and strong industrialized efficiency scenarios, assuming the high developing world population scenario and low developing world energy demand scenario. Also shown in Fig. 3 is the growth of non-fossil fuel energy use for $\dot{E}_N = 75$ and 150 GW yr^{-1}. For $\dot{E}_N = 150$ GW yr^{-1}, non-fossil fuel energy as a share of total energy rises from insignificance in 2000 to 50% by 2045–2052. This is consistent with Marchetti's market penetration concept,[24]

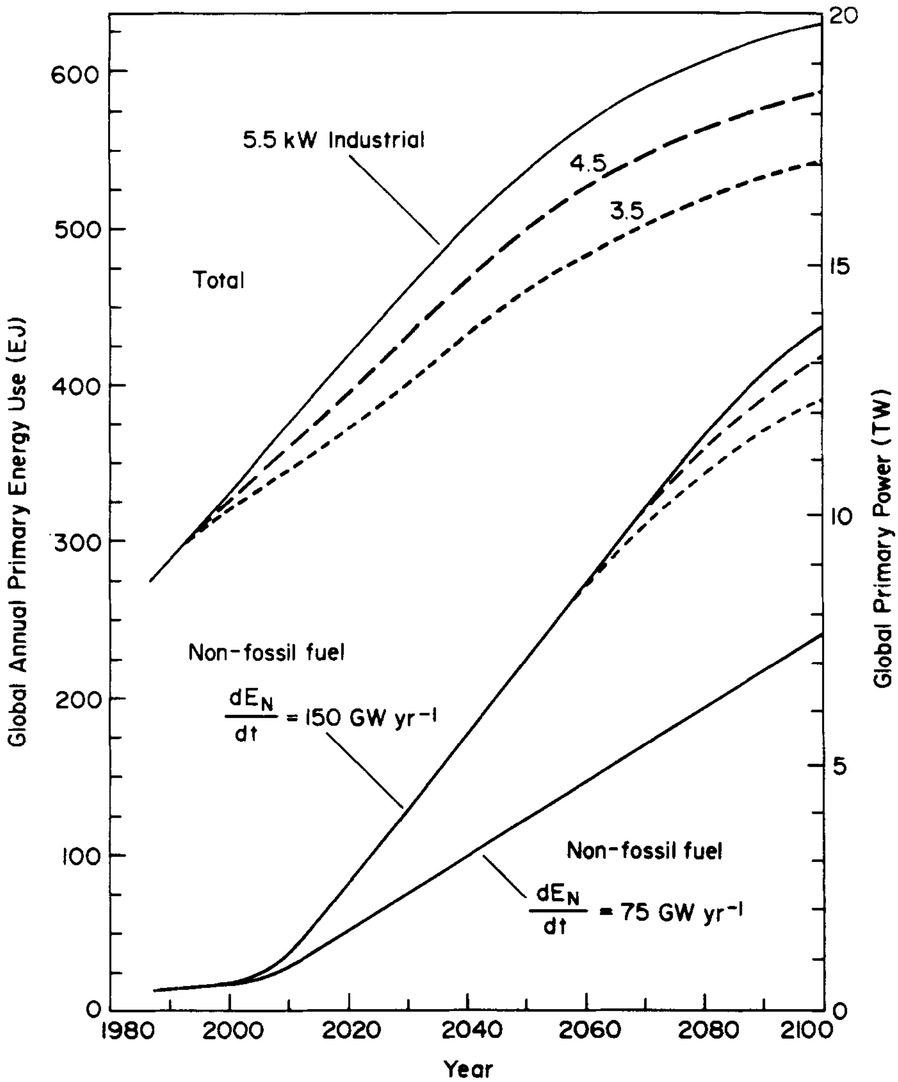

Fig. 3. Variation of global primary commercial energy demand 1986–2100 for scenarios in which developing world population approaches 8.5 billion, developing world *per capita* energy use reaches 1.5 kW, and industrialized world *per capita* energy use reaches 5.5 kW (——), 4.5 kW (– – –) or 3.5 kW (-----). Also given is the growth of non-fossil fuel energy supply for rates of installation E_N of 75 and 150 GW yr^{-1}.

whereby major new energy sources have historically required about 50 yr after their initial introduction to capture 50% of the market. A global non-fossil fuel energy installation rate of 150 GW yr^{-1} therefore seems to be realistic.

FOSSIL FUEL ENERGY SUPPLY

It is assumed that oil and gas production after 1986 are given by logistic functions, such that production of both fuels rises to a broad peak, then gradually declines. In generating the logistic curves, the total recoverable oil and gas energy resources are assumed to be 13,000 and 11,000 EJ, respectively, and the cumulative production up to 1986 is taken to be 3472 and 1693 EJ, respectively, based on Refs. 25 and 26. The assumed recoverable oil and gas resources are near the means of estimates summarized in Refs. 3 and 26. The resulting supply curves are given by solid lines in Fig. 4.

An enhanced gas use scenario is also considered, in which the gas supply increases from that given by the logistic function in 2000 to twice that given by the logistic function from 2010

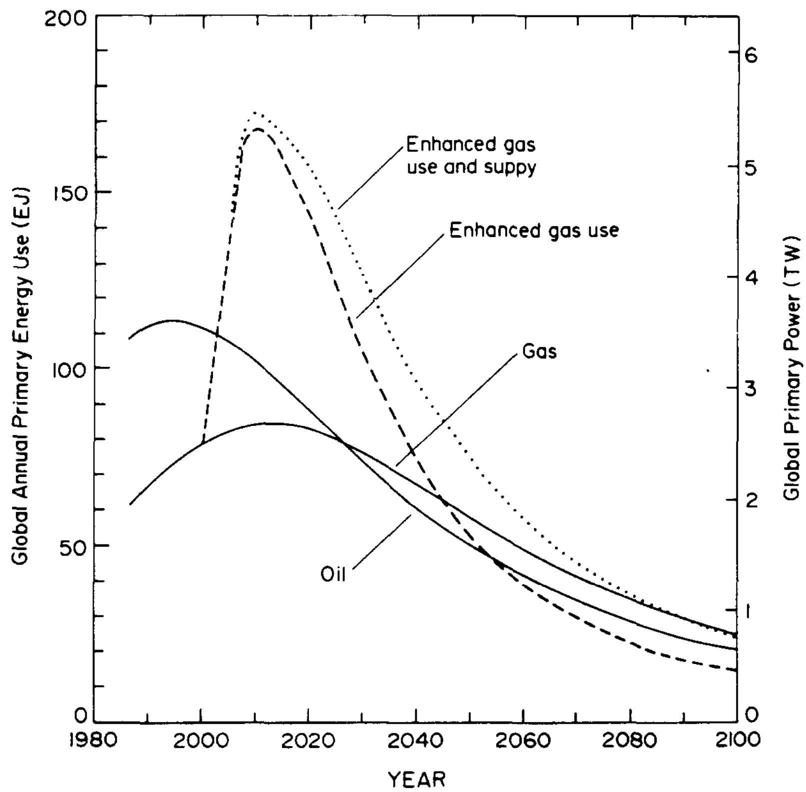

Fig. 4. Base case oil and gas supply scenarios (——) as well as gas supply with enhanced use but a fixed recoverable resource (---) and with enhanced use and expanded recoverable resource (...).

onward. This scenario is shown by the dashed line in Fig. 4. Once gas use is enhanced, this alters the subsequent path of the logistic function; hence, the dashed curve is not a simple multiplicative scaling of the solid curve for gas. If no change is assumed in the size of the recoverable gas resource, enhanced gas use has the effect of depleting gas supplies sooner. In reality, enhanced gas use would drive up prices, thereby increasing the size of the economically recoverable resource. Thus, a further scenario is considered in which it is assumed that the size of the recoverable gas resource increases each year by half of the enhancement in gas supply beyond that given by the logistic curve for that year. The resultant gas supply curve is given by the dotted line in Fig. 4. The enhancement of gas supply assumed here might be larger than what is achievable in reality, but is intended to indicate a likely upper limit to the decrease in CO_2 emissions possible through fuel switching alone.

Coal use is computed as the difference between global energy demand, oil and gas supply, and the non-fossil fuel energy supply. Thus, it is implicitly assumed that enhanced gas use displaces coal, that energy savings through reduced *per capita* energy demand ultimately lead to reduced coal use, and that new non-fossil fuel energy supplies ultimately displace coal. If non-coal energy supply exceeds energy demand, then coal use is zero and the use of oil is reduced. If, on the other hand, the growth of energy demand and non-fossil fuel energy supply are such as to give a $>2\%\ yr^{-1}$ reduction of CO_2 emissions, then growth of non-fossil fuel energy is reduced and some coal use is permitted.

COMPUTATION OF CO_2 EMISSIONS AND ATMOSPHERIC CO_2

Fossil fuel CO_2 emissions are computed by multiplying the gas, oil, and coal energy use by emission factors of 0.01356, 0.02114, and 0.02495 Gt/EJ, respectively. These were obtained by comparing data on global CO_2 emissions from these fuels[25] with global primary energy use[17] for

1984 for the corresponding fuel, and include emissions associated with the extraction, refining, distribution, and end-use of these fuels.

Emissions of CO_2 due to deforestation are determined from the specified change since 1980 in the rates of land clearing due to harvesting of forests and expansion of cropland and pastureland, scaled by the estimated emission in 1980. The estimated net emission for 1980 ranges from 0.5 to 2.5 Gt C.[27–29] Here, the emissions due to deforestation are scaled by an assumed 1980 net flux of 1.0 Gt C. By using a scaling factor near the low end of the range of uncertainty, the impact on atmospheric CO_2 concentration of reducing the rate of deforestation is minimized.

The fossil fuel and deforestation CO_2 emissions serve as input to the coupled carbon cycle–climate model. The carbon cycle model computes the increase of atmospheric CO_2 which, along with increases of other greenhouse gases [methane (CH_4), nitrous oxide (N_2O), chlorofluorocarbons (CFCs) and tropospheric ozone], leads to a continuously changing heating perturbation. This perturbation drives a globally averaged climate model which computes, among other things, globally averaged ocean surface and surface air temperature changes. The temperature increases then feed back on the carbon cycle model by reducing the oceanic ability to hold CO_2, and by altering the exchange of CO_2 between the atmosphere and terrestrial biosphere. Full details of the coupled climate–carbon cycle model, extensive sensitivity tests, and assumptions concerning the increase of non-CO_2 greenhouse gases, may be found elsewhere.[10]

One of the parameters of the climate model is the globally averaged temperature increase, ΔT_{2x}, which would accompany a CO_2 doubling, if CO_2 were to remain constant at the doubled level long enough for the climate to fully equilibrate. This parameter is estimated to range from 1.5 to 4.5°C.[30] Here, $\Delta T_{2x} = 4.0$°C is used, rather than a value near the low end of the above range. Using a larger equilibrium sensitivity maximizes the buildup of CO_2 due to climate–carbon cycle feedback. The results presented below are, in this respect, conservative rather than overly optimistic.

RESULTS

Figure 5 shows the computed fossil fuel CO_2 emissions for selected scenarios, and Fig. 6 gives the associated coal use. Table 3 gives the global energy use in 2020 and 2100, the years in which fossil fuel emission reduction rates of 1 and 2% yr^{-1} are achieved (or the rate of reduction in 2100 if not achieved), the peak atmospheric CO_2 concentration (which occurs after 2100 for some scenarios), and the peak globally averaged climatic warming after 1980 assuming $\Delta T_{2x} = 4.0$°C. The globally averaged post-1980 warming ranges from 1.2 to 3.2°C. Using $\Delta T_{2x} = 2.0$°C reduces the peak warmings by about 40–45%, as the smaller equilibrium sensitivity is partly compensated by a faster transient response. Note that many climate models indicate that the climatic warming would be 2–3 times greater at mid- to high-latitudes than in the global mean, and greater still in winter at mid- to high-latitudes.[31]

Based on Table 3, the 2% yr^{-1} target emission reduction rate cannot be achieved by 2100 if $\dot{E}_N = 75$ GW yr^{-1}, even under the most optimistic assumptions. Rather, $\dot{E}_N = 150$ GW yr^{-1} is required. For the low developing world energy demand scenario, the year in which this target is achieved ranges from 2077 to 2096 as industrialized energy efficiency improvement ranges from strong to weak.

Peak atmospheric CO_2 varies by only 41 ppmv for the range of industrialized energy scenarios if $\dot{E}_N = 150$ GW yr^{-1}, but varies by 85 ppmv if $\dot{E}_N = 75$ GW yr^{-1}. Assuming the slow approach to the 3.5 kW *per capita* energy demand cause peak atmospheric CO_2 to be only 10 ppmv higher and delays the attainment of a 2% yr^{-1} emission reduction by 1 yr for the $\dot{E}_N = 150$ GW yr^{-1} case. The rate of introduction of non-fossil fuel energy supply would appear to be more important to atmospheric CO_2 than the rate of improvement of industrialized country energy efficiency. This does not imply that improving energy efficiency in the industrialized world is unimportant, for two reasons: (1) the analysis on which these scenarios is based assumes a 50% increase in the industrialized country consumption of goods and

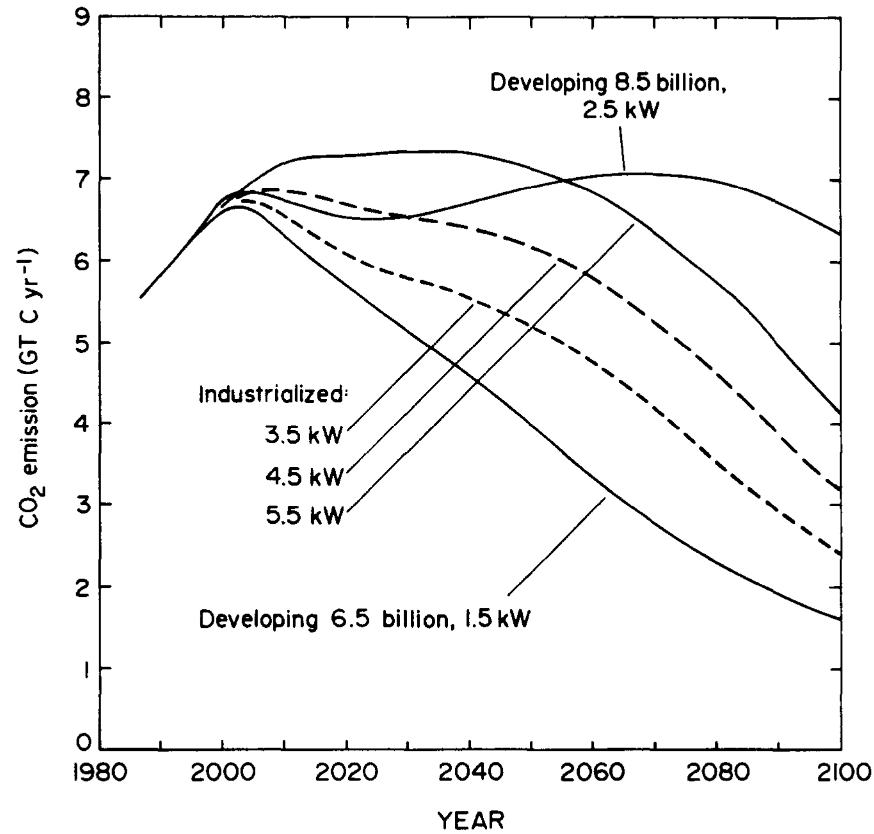

Fig. 5. Variation of fossil fuel CO_2 emissions 1986–2100 for the following scenarios: 8.5 asymptotic developing world population and 1.5 kW *per capita* energy demand with asymptotic industrialized *per capita* energy demands of 3.5, 4.5, and 5.5 kW; developing world asymptotic population of 6.5 (or 8.5) billion and asymptotic *per capita* energy demand of 1.5 (or 2.5) kW with the strong efficiency improvement in the industrialized countries.

services, so that even for the "weak" scenario, GNP/(energy use) rises substantially; (2) slower growth in energy demand will make it easier to meet the capital demands needed to maintain the rate of installation of non-fossil fuel energy supply assumed here.

Assuming that developing world *per capita* energy demand rises to 2.5 kW rather than 1.5 kW, all else being equal, increases the peak atmospheric CO_2 concentration by about 70 ppmv. However, higher developing world energy demand implies a greater degree of the development and hence a smaller growth of population. Assuming an equilibrium developing world population of 6.5 rather than 8.5 billion with 2.5 kW *per capita* energy results in peak atmospheric CO_2 only 6 ppmv higher than the 8.5 billion, 1.5 kW case for the particular patterns of energy demand growth assumed here. Indeed, if energy aid leading to 1.5 kW *per capita* demand were directed to the satisfaction of basic human needs, as discussed in Refs. 2 and 3, a 6.5 billion developing world equilibrium population could be consistent with 1.5 kW *per capita* energy demand.

Surprisingly, enhanced gas use, even with expansion of the recoverable resource, has a small effect on peak atmospheric CO_2 (Table 3). Given the problem of emissions of fugitive methane (which is a 25 times stronger greenhouse gas than CO_2 on a molecule-per-molecule basis) associated with gas use, expanded use of natural gas needs to be carefully evaluated.

Finally, going from the high to low deforestation scenario reduces peak atmospheric CO_2 by about 15 ppmv, while concurrent reforestation gives a total reduction of peak CO_2 by about 25 ppmv. As discussed above, these effects were obtained assuming the 1980 net emission due to deforestation to be 1 Gt C, and would be larger assuming the upper limiting estimate for the 1980 flux of 2.5 Gt C.

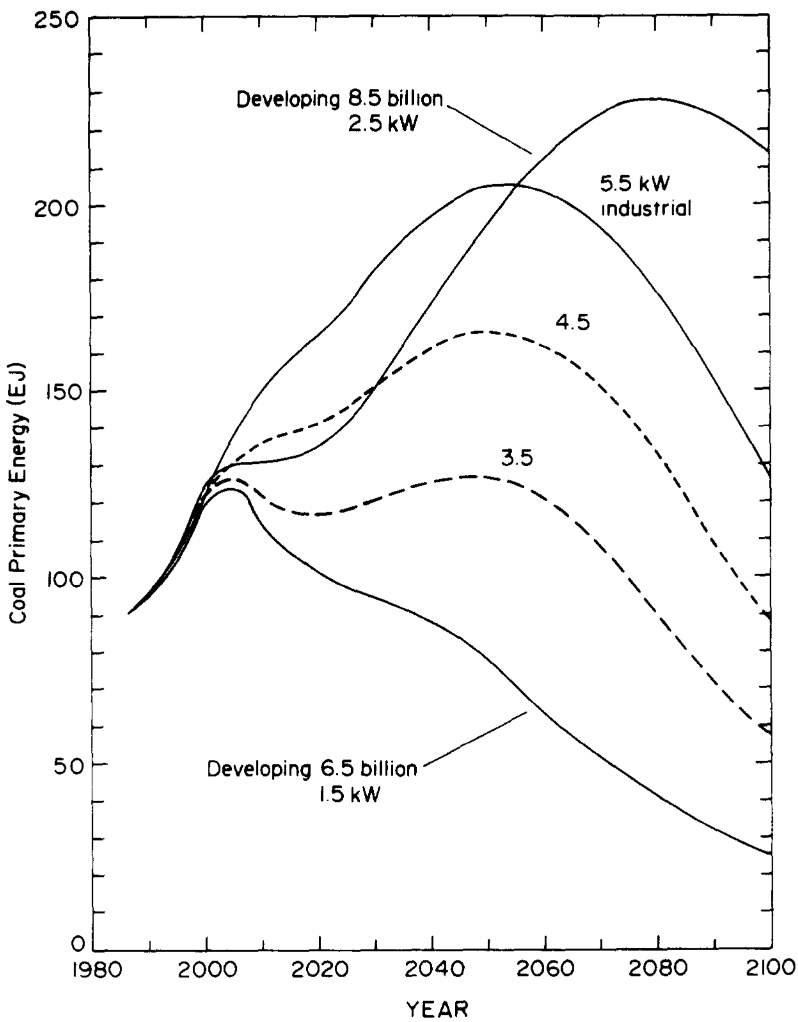

Fig. 6. Global coal use for the same scenarios as shown in Fig. 5.

CONCLUSIONS AND POLICY IMPLICATIONS

The simplified analysis presented here indicates that rates of fossil fuel CO_2 emission decrease of 1–2% yr^{-1} could be attained by the middle to end of the next century or sooner, and atmospheric CO_2 could be stabilized at 400–500 ppmv. Such targets are consistent with reasonable assumptions concerning industrialized and developing country population growth and feasible *per capita* primary energy demand, and would not require excessively large rates of installation of non-fossil fuel power supply.

The rate of non-fossil fuel power expansion found to be necessary, on the order of 150 GW yr^{-1}, almost certainly requires deliberate policy intervention on the part of government, particularly if it is to be achieved within the first two decades of the 21st century, as assumed here. Vigorous promotion of improved energy efficiency is also required in order to keep total energy demand, and capital requirements, low enough that non-fossil fuel energy supply can make a large enough contribution to total energy supply to bring about the target emission reductions.

For non-fossil fuel energy sources to gradually displace fossil fuel sources requires development of a storable energy carrier to complement electricity. In technologically advanced countries, hydrogen would be a suitable carrier,[29] whereas methane or methanol produced from renewable biomass might be more suitable in developing countries, at least in the short term. Modest programs of hydrogen research currently exist in a number of OECD

Table 3. Global primary energy use (EJ) in 2020 and 2100, years in which fossil fuel CO_2 emission reduction rates of 1 and 2% yr^{-1} are achieved, peak atmospheric CO_2 concentration (ppmv), and peak global mean warming (°C) after 1980. If a 1 or 2% emission reduction per year target is not achieved by 2100, the rate of reduction in 2100 is given.

Scenario	Energy use 2020	Energy use 2100	Year Target Achieved 1%	Year Target Achieved 2%	Peak CO_2	Peak ΔT after 1980
Developing world high population and low energy use						
(a) E_N=150 GW yr^{-1}						
Strong industrial efficiency	371	541	2058	2078	441	1.6
Moderate industrial efficiency	394	586	2066	2087	460	1.7
Weak industrial efficiency	418	632	2074	2097	482	1.9
Strong efficiency, slow improvement	391	552	2058	2079	451	1.6
(b) E_N=75 GW yr^{-1}						
Strong industrial efficiency	371	541	0.5%	0.5%	547	2.5
Moderate industrial efficiency	394	586	0.4%	0.4%	588	2.8
Weak industrial efficiency	418	632	0.3%	0.3%	632	3.2
Strong industrialized country efficiency and E_N=150 GW yr^{-1}						
(a) *6.5 billion developing world population limit*						
High developing world energy	367	594	2077	2098	447	1.6
Low developing world energy	355	457	2013	2056	426	1.3
(b) *8.5 billion developing world population limit*						
High developing world energy	383	716	0.7%	0.7%	508	2.2
(c) *8.5 billion developing world population and low developing world energy*						
Enhanced gas use	371	541	2061	2079	438	1.5
Enhanced gas use and supply	371	541	2061	2078	435	1.4
Low deforestation	371	541	2058	2078	426	1.3
Low deforestation + reforestation	371	541	2058	2078	416	1.2

countries, coordinated by the International Energy Agency.[3] Funding for these programs, and cooperation in hydrogen research among IEA member countries, needs to be dramatically increased if non-fossil fuel energy sources are to make a significant contribution to total energy supply.

Third World population and *per capita* energy demand are of central importance to future atmospheric CO_2 concentrations. The scenarios considered here assume moderate to rapid decreases in Third World fertility, a large share of sustainable biomass energy in the Third World (coupled with a suitable energy carrier), and very efficient use of energy, so that *per capita* energy demand levels out at 1.5 or 2.5 kW. Under these assumptions, atmospheric CO_2 can be stabilized at under 500 ppmv, possibly substantially below 500 ppmv. The assumptions regarding the Third World are inter-dependent and, in order to be realized, requires two major thrusts for Third World energy aid: (1) one thrust must be directed toward the satisfaction of the basic needs (cooking, heat, light) of the rural poor; and (2) the other thrust must be directed toward providing the most energy efficient technologies available for use by industry and the more affluent members of Third World societies.

Most of the energy consumed in the Third World is non-commercial biomass energy used for heating and cooking. This energy is used with efficiencies as little as 10%, whereas 50% efficiency is possible using wood stoves, and 80% efficiency is possible if the fuelwood were gasified and used in a gas stove.[3] A top priority of Third World aid must be to improve the efficiency with which biomass energy is used. This will lessen pressures on forests, thereby permitting reforestation programs which will otherwise almost certainly fail, and permitting silvicultural techniques to increase yields to the point where biomass could play the role implicit in the scenarios considered here.

Similarly, the energy efficiency of individual industries in Third World countries is often far below the average for the same industries in developed countries, which in turn is often far below that of the current state-of-the-art technology. An example is steel making, where 38 GJ are used on average per ton of steel in China, compared to an average of 24 GJ per ton in the U.S.A. and 10 GJ per ton for state-of-the-art technology.[34] Bilateral and multilateral lending institutions need to explicitly consider the energy efficiency and resultant emissions of CO_2 in providing credit, with more credit available for technologies which may have a larger initial cost but which would be less energy intensive and have smaller life-cycle costs.

Finally, the present analysis does not support the assertion that resolution of the greenhouse problem requires massive development of nuclear energy. The analysis presented above assumed a rate of growth of nuclear power supply of about 18 GW yr^{-1} out of an originally estimated potential for expansion of non-fossil fuel power supply of 170 GW yr^{-1}, something which could be absorbed by other supply options if so desired. Furthermore, over-reliance on nuclear energy could be counter-productive if it consumes capital which could be more effectively used in improving energy efficiency.[35] The particular mix of non-fossil fuel energy sources needed to replace fossil fuels will vary from region to region, and is something to be decided and based on nation-specific economic, social, and environmental considerations.†

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†For those wishing to carry out further sensitivity studies, an extensively documented FORTRAN code of the complete energy supply–carbon cycle-climate model is available upon request. Requests can be sent by electronic mail to harvey@geog.utoronto.ca, or by regular mail if accompanied by a 5 in. floppy diskette.

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