Changing Climate

Report of the Carbon Dioxide Assessment Committee

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2.2 A REVIEW OF ESTIMATES OF FUTURE CARBON DIOXIDE EMISSIONS

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2.2.1 Introduction

In analyzing prospects and policies concerning future carbon dioxide buildup, it is necessary to begin with projections of levels of CO_2 emissions. Because of the long residence time in the atmosphere of CO_2 emissions, along with the potential for large and durable societal impacts of higher CO_2 concentrations, there is great interest in long-term projections--those extending a half-century or more. While it is clearly necessary to make global long-term projections in this area, the projections are intrinsically uncertain, and the uncertainty compounds over time.

This section reviews methods involved in making projections of carbon dioxide emissions, describes the major projections, and offers some comparisons and comments. It is intended to serve three purposes. First, it should help to acquaint the reader with the state of the art in CO_2 forecasting and the range of previous forecasts. Second, this review may help to identify shortcomings of current efforts and point to directions for new research. Third, it should establish the context of the forecasts developed by Nordhaus and Yohe (Section 2.1) for this report.

Projections of future trajectories of CO_2 emissions can be roughly divided into three categories: (A) projections that are no more than extrapolations and that are primarily intended to be used to initiate studies of the carbon cycle or the climate system; (B) those based on relatively detailed examination of global energy supply and demand in which CO_2 emissions are largely incidental; (C) projections deriving from analysis of the energy system in which changing levels of CO_2 are themselves taken into account. Leading examples of category A, in which CO_2 emissions are projected with little more than passing reference to energy modeling, are Keeling and Bacastow (1977) and Siegenthaler and Oeschger (1978). These papers extrapolate emissions in order to predict future atmospheric CO_2 levels. Such efforts also appear in numerous reports and papers concentrating on calculating climatic change, for example, JASON (1979) and Hansen et al. (1981). The projections consist of little more than extrapolating rates of fossil fuel emissions growth from recent decades out a century and more into the future. These extrapolations can be regarded as simplifications or summarizations of more complete projections; they are useful for studies of the sensitivity of the carbon cycle and climate system but unpersuasive as elements of a comprehensive CO_2 assessment.

The projections based on relatively detailed analysis of an uncontrolled global energy-climate system, (B), which are the most important for purposes of this section, differ greatly in their design, in the extent to which formal models are employed, and in detail with respect to fuels, geography, and other factors. Leading examples include those made by H. Perry and H. H. Landsberg (1977) for the NRC Geophysics Study Committee, the several projections by Rotty and by Edmonds and Reilly of the Institute for Energy Analysis (IEA) of Oak Ridge Associated Universities (Rotty, 1977; Rotty and Marland, 1980; Edmonds and Reilly, 1983a), the projections of Nordhaus (1977) and (1979), and those made for the Energy Systems Program of the International Institute for Applied Systems Analysis (IIASA) (Niehaus and Williams, 1979; IIASA, 1981).

Category (C) projections, which require the basic analysis of category (B) as input, seek additionally to take into account the changing level of atmospheric CO_2 (or the costs of climatic change) in the calculations. That is, CO_2 is included as a possible eventual constraint on the energy system. Projections incorporating this perspective are found in Nordhaus (1979, 1980), Council on Environmental Quality (CEQ) (1980), A. M. Perry (1982), Perry et al. (1982), and Edmonds and Reilly (1983a).

Almost all of the scenarios applied to studies of CO_2 that are based on reasonably in-depth analysis of the energy situation project a continued growth of energy demand (or consumption) to between about 20 and 40 terawatt (TW) years per year (yr/yr) over the next 40 or 50 years, an increase of two and a half to five times the recent level.* These include scenarios developed for studies by the National Research Council (NRC), the International Institute for Applied Systems Analysis (IIASA), and the Institute for Energy Analysis (IEA) of Oak Ridge Associated Universities and by Nordhaus (1979). Several other energy scenarios, like those of the Interfutures Project (1979), the Hudson Institute (Kahn et al., 1976), the World Energy Conference (1978), and Stewart (1981) are in the same range. Whenever such scenarios do not project a large share of nonfossil energy, they lead to relatively serious concerns about climatic change in the next 50 to 100 years.†

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*Estimated global primary energy supply in 1975 was roughly 8 TW yr/yr (IIASA, 1981).

†The market share of nonfossil energy sources (including noncommercial energy) is about 15% at present. The prominent scenarios

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Most of the estimates of CO_2 emissions from fossil fuels in the year 2030 lie in a range between about 10 and 30 gigatons of carbon (Gt of C). Thus, based on a review of past projections, it appears that the range of estimates of energy consumption 50 years hence is a factor of 2 or more, and consequent CO_2 emissions show a range of a factor of 3 or more.

It should become clear that the range of estimates is wider than the range of approaches. The large differences in the estimates are traceable in almost all cases to the sensitivity of the models to differences in estimates of the variables or parameters. Most prominent are assumptions about rates of population growth, economic growth, the ratio of energy demand to economic activity, and the mix of supply sources that will meet energy demand. Brief descriptions of the major projections in the three categories follow.

2.2.2 Projections Based on Extrapolations

The extrapolative (A) models are essentially one-equation global models. There are no nations, no economic sectors, no GNP or population projections. In these models, an idealized resource depletion function is customarily used to project the evolution of annual releases through future centuries. There are usually three key variables in the function. One is the total resource of carbon-based fuels. The second is the initial growth rate. The third is a parameter that embodies judgments about the future pattern of exploitation of the resource. It can be set such that peak exploitation occurs when the resource is, for example, 20% depleted, with the possible intention of reflecting a consumer response to rising prices. Or, it can be set to draw different patterns of exploitation, for example, short and intensive, or gradual.

In the very long run (past 2100), the key variable determining CO_2 buildup in this approach is the total carbon resource. The studies have typically taken a number in the vicinity of 5000 Gt of C for the total carbon resource. Such a figure is not out of line with estimates of ultimately available resources, although it is a factor of 10 larger than today's proved recoverable reserves (see World Energy Conference, 1980).

In the medium run (up to 2100), the central variable determining the CO_2 buildup in simple extrapolation models is the initial growth rate. It has been common in the literature to base this variable on work of Rotty (1977), who estimated from historical data that CO_2 emissions from fossil fuel burning (with a trivial addition for cement manufacture) increased 4.3% per year if one excludes the periods of the two world wars and the global economic depression of the early 1930s. This figure of 4.3% has been extremely influential and has been widely used to project future levels of atmospheric CO_2. Many papers and

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mentioned above generally foresee either an unchanged share for nonfossil sources or a moderate expansion of nonfossil sources, to about 20-35% over the next 50 years.

reports on CO_2-induced climatic change written in the past few years mention it prominently. For example, a JASON report (1979) opens with the statement, "If the current growth rate in the use of fossil fuels continues at 4.3% per year, then the CO_2 concentration in the atmosphere can be expected to double by about 2035. . . ."

While the 4.3% figure is the one most mentioned in the climate literature, increasing debate has grown around it (e.g., World Climate Programme, 1981). One reason for the recent skepticism is that energy growth has slowed considerably--to an average of little more than 2% annually--since 1973. Projections reviewed below range from that of Lovins (1980; Lovins et al., 1982), who suggests there might be a global decrease in use of energy and fossil fuels, to the 50 TW yr/yr case proposed by Niehaus and Williams (1979), in which energy demand grows at an average of about 4% in coming decades and all of this high projected energy demand is covered by fossil fuels.

It is worth noting that the highest projections of CO_2 emissions have generally come from the simple extrapolative models and rarely from studies that incorporate explicit supply and demand models for energy. To illustrate, the Keeling and Bacastow (1977) "preferred scenario" projects emissions somewhat larger than the high coal scenario developed by Niehaus (1979) as an upper limit scenario from the energy perspective, and the Siegenthaler and Oeschger (1978) "upper-limit" scenario generates emissions at about twice the rate of the Niehaus high scenario.

The extrapolations might be best characterized as "gedanken experiments" devised for study of the carbon cycle: "suppose x thousand tons of carbon exist as fossil fuels and all will be used at a certain rate. . . ." While extrapolative models have been successful in drawing attention to the CO_2 issue, they are of limited interest in projecting likely outcomes for CO_2 emissions and concentrations. The main virtue of the approach is simplicity, for a constant growth or logistic curve has great transparency, particularly relative to the enormously complicated energy models. On the other hand, these models do not respect fundamental aspects of economic and energy sector behavior, such as conservation based on rising energy prices. It is not surprising that these models will, therefore, lack realism during periods (after 1973, for example) when changes in economic and political structures have been profound.

2.2.3 Energy System Projections

The major class of forecasts of CO_2 emissions arises from formal or informal energy modeling. Most of this work dates from the 1973 "energy crisis" and is only recently published. In general, it forms the most reliable basis on which to draw for projections. Note that only global studies are sufficient for projecting CO_2 emissions; the numerous national and regional energy studies may provide a consistency check on global studies, but they cannot be used independently to project CO_2 emissions.

2.2.3.1 Perry-Landsberg (NAS)

Perry and Landsberg (1977) assembled projections of world energy consumption and emissions to the year 2025 for the NAS report, Energy and Climate. The projections are for 11 geographic regions, which are sometimes large nations and sometimes groups of nations. Regional demand for energy is derived from projections of population, GNP, and the relationship of GNP per capita and energy consumption. A "high-population/low-economic-growth" situation is postulated for developing countries and a "low-population/low-economic-growth" situation for developed countries. Global population in 2025 is at 9.3 billion, about 20% higher than IIASA and Rotty. The net result is a total energy demand forecasted to reach about 39 TW yr/yr in 2025.

Emissions are calculated for two situations chosen to stress the contrast between a strategy based on "renewables" (i.e., noncarbon-based, abundant energy sources) and one based on coal. In the first case, if regional demand exceeds regional production, an estimate is made assuming the new noncarbon-based energy resource is available to meet the deficiency of nonrenewable resources. In the second case, an estimate is made for the situation for which regional deficiency would be met by coal. Based on these assumptions, annual world CO_2 emissions in 2025 would be between 13 and 14 Gt of C in the first case and about 27 Gt of C in the second, or about 2.5 to 5 times current levels.

The Perry-Landsberg study forms a careful baseline for comparison. It is comprehensible and plausible. A major shortcoming is that it omits any explicit role for prices to play in driving demand toward or away from energy in general or individual fuels in particular. In addition, while the total demand for energy grows out of a well-specified model, the fuel mix is based on arbitrary assumptions.

2.2.3.2 IIASA

2.2.3.2.1 Niehaus and Williams

The IIASA Energy Systems Program analyzed several hypothetical energy strategies for the period up to the year 2100 for their implications for atmospheric CO_2 (Niehaus and Williams, 1979; IIASA, 1981). As such, it could not directly employ the so-called "IIASA energy models," which were run only to the year 2030. Rather, distribution of energy supply among coal, oil, gas, solar, and nuclear is derived from a very-long-term energy model developed by Voss (1977). The Voss model employs principles similar to that of the Forrester-Meadows (system dynamics) school and is structured into six sectors: population, energy, resources, industrial production, capital, and the environment. It is global; there is no geographic disaggregation.

Among the strategies explored (Niehaus and Williams, 1979) are four in which global demand levels out to either 30 TW yr/yr or 50 TW yr/yr in the mid-twenty-first century and remains at that level to 2100. In both the lower- and higher-demand cases there is an analysis in which nuclear and solar energy play an important role and in which they do not. Table 2.19 shows the reserves of fossil fuels used in each strategy. The relation between total coal use and CO_2 emissions is characteristic of projections leading to high or low CO_2 emissions.

The scenarios with reliance on nuclear and solar energy lead to peak annual CO_2 emissions of about 8 to 10 Gt of C around the year 2000, while the scenarios with reliance on fossil fuels lead to emissions of about 22 and 30 Gt of C in 2030, increasing somewhat thereafter. While consideration is given to available fossil resources at the global level, there is no study of regional or national implications.

The Niehaus-Williams projections are based fundamentally on judgments external to economic analysis or modeling. Once the energy growth path and fuel mix are set, the outcome for CO_2 emissions is determined--the use of the system model plays but a small role in the outcome.

The most important issue is whether the *ex cathedra* judgments as to the ultimate levels of global energy demand (the 30 and 50 TW yr/yr levels discussed above) are reasonable. While such figures are conventional, and indeed so often used that they become comfortable assumptions, they have no grounding in a physical or economic constraint or in the outcome of an energy model. The notion of "saturation" at these levels is a popular idea that has no particular basis, other than the hope that human society will pass through a transition to a stable plateau over the next couple of generations. Thus, while the critical assumptions of energy demand and fuel mix in these studies do not appear implausible, their grounding is weak.

2.2.3.2.2 The IIASA Energy Models

IIASA used a set of extremely detailed models to delineate two scenarios, a "high" and a "low" case culminating in 2030 with world energy consumption at 35 and 22 TW yr/yr, respectively. The models are oriented toward engineering and technical considerations for specific demand sectors and global consistency of supply among the seven regions

TABLE 2.19 Reserves of Fossil Fuels Used in Different Outcomes (1975-2100)[a]

Strategy	Coal (Gt of C)	Oil (Gt of C)	Gas (Gt of C)
30 TW with solar and nuclear	170	170	110
50 TW with solar and nuclear	230	210	130
30-TW fossil fuel	1980	190	120
50-TW fossil fuel	3020	230	140

[a] After Niehaus and Williams (1979).

into which the world is disaggregated. The distribution of supply sources in the actual IIASA scenarios is quite different from Niehaus and Williams, even though the Niehaus and Williams runs were originally chosen to be broadly consistent with the global energy demand pattern. Both the high and low IIASA scenarios are hybrids, with expanded use of many supply sources, so that in 2030 11 TW yr/yr are coming from non-fossil fuel sources in the high case and 7 TW yr/yr in the low case. In the high case emissions are above 16 Gt of C in 2030, and in the low case they are nearing 10 Gt of C.

The IIASA models have probably been the closest existing approach to an appropriate disaggregated technique for forecasting CO_2 emissions. In principle, they are grounded in engineering and economic relations, with attention to feasibility and response of supply and demand to price. In practice, because of the need to accommodate differing views, world energy consumption was adjusted judgmentally to be "reasonable," as well as on the basis of the formal methods. In this respect, the outcome shares the problems outlined in the last paragraph of the discussion of the Niehaus-Williams approach.

Another issue raised by the IIASA model is whether a high degree of disaggregation is appropriate. Such an approach allows considerations such as those involving trade and national policies; however, it also makes the models difficult to comprehend, manipulate, change, and verify independently.

2.2.3.3 Rotty et al.

For several years, Rotty and co-workers at the Institute for Energy Analysis of Oak Ridge Associated Universities emphasized extrapolation of the 4.3% estimate of historic annual increase in CO_2 emissions and figures tapering off from this (Rotty, 1977, 1978, 1979a,b; Marland and Rotty, 1979). Based on demand and fuel-share projections made for six world regions, an annual fossil fuel release of CO_2 containing 23-26 Gt of C from energy use of 36-40 TW yr/yr in the year 2025 is calculated. The work is partly based on a more formal analysis by Allen et al. (1981) developed for the year 2000. In extension of the projections to 2025 Rotty assumes supply will meet demand without examination of balancing economic factors such as prices. For projections of emissions beyond 2025, a different extrapolative technique involving application of arbitrary global fossil resource depletion rates is employed (see Section 2.2.3.2 above).

A more recent paper (Rotty and Marland, 1980) includes some discussion of constraints on fossil fuel use. Three kinds of constraints are examined: resource, environmental, and fuel demand. With respect to resource supplies, Rotty and Marland conclude that "the fraction of total resources used up to the present is so small that physical quantities cannot yet be perceived as presenting a real constraint." However, it is mentioned that unequal geographic distribution of the resources probably will continue to be a source of international stress. Climatic change as an environmental issue is dismissed as a constraint to fossil fuel use.

In contrast, Rotty and Marland (1980) discuss at some length the likelihood that slower growth in fuel demand dictated by social and economic factors will limit fossil fuel use. Reduced rates of economic growth are projected as a result of very recent trends and anticipated problems with capital and escalating costs and shifts toward conservation and less energy intensive industries. No formal modeling is offered to substantiate the position. Regardless of the precise causes, summing up estimates for about a dozen countries and half a dozen composite regions leads Rotty and Marland to project CO_2 emissions in 2025 of about 14 Gt of C in a 26 TW yr/yr global energy scenario--an annual growth rate of 2% per year from today. Thus, the range of Rotty emission projections are quite similar to those of IIASA and Perry and Landsberg.

The strengths and weaknesses of the Rotty approach are partly those of the extrapolative models and partly those of the Perry-Landsberg approach. The repeated adjustment of assumptions is evidence of the uncomfortably arbitrary nature of the endeavor.

2.2.3.4 Nordhaus

Nordhaus (1977, 1979) estimated the uncontrolled path of CO_2 emissions in a modification of a model developed for studies of efficient allocation of energy resources (or of a competitive market for energy). Nordhaus's approach was fundamentally based on economic modeling and assumptions--with interaction of forces of supply and demand leading to a path of prices and energy consumption over time. By comparison, prices play a lesser role in the IIASA and Perry and Landsberg approaches and virtually no role in Rotty's projections.

Nordhaus employs a medium-sized linear programming model, with basic components being an objective function (based on demand functions for energy) and a supply function centered on geological considerations and technology. The outcome is calculated by finding the lowest cost way of meeting the demand function, using a linear programming (LP) algorithm. The demand function (technically, the objective function) for the LP is drawn from data on market behavior. It is built up from four energy sectors (electricity, industry, residential, and transportation), with demand in each sector a function of population, per capita income, and relative prices. The technology or constraint set is derived from engineering and geological data on resource availability and costs of extraction, transportation, and conversion. The model incorporates constraints on new technologies, adaptation of demands, and upper bounds on rates of growth.

Running the model involves balancing supply and demand over time, with prices playing the central role of equilibration. Results are given in terms of both activity levels (for example, production of coal or oil in a given period) and prices. The calculation provides for six different fuels used in the four energy sectors, for two different regions (United States and rest of world), for ten time periods of 20 years each. The macroeconomic assumptions are that rapid growth in GNP per capita will continue in both regions, but at a diminishing rate after 2000, and that population will also slow to reach a world level of 10 billion in 2050.

Nordhaus calculates that the uncontrolled path leads to large changes in the level of atmospheric CO_2. In the uncontrolled case, annual emissions are at 18 Gt of C in 2020 and steeply increasing, so they reach 40 Gt of C in 2040. Global energy demand is about 40 TW yr/yr in 2030. A key in these high projections is high initial GNP growth rates; for 1975-1990 the assumed growth per year is 3.7% in the United States and 6.5% in the rest of the world.

The results of the Nordhaus analysis exhibit the strengths and weaknesses of pure (nonjudgment-based) economic modeling. On the one hand, the outcome is based on objective data (such as market prices and resource availability) and is thus reproducible and can be easily modified over time. On the other hand, results are very sensitive to assumptions about future price and growth trends. The actual model runs were based on an assumption of rapid future economic growth and low fuel prices--leading thereby to rapid estimated growth of CO_2 emissions and atmospheric concentrations.

2.2.3.5 Edmonds and Reilly

Rotty's work is now being followed at IEA by a more formal CO_2 emissions model developed by Edmonds and Reilly. The model takes as inputs key economic, resource availability, and demographic variables such as income, energy costs, resource constraints, labor force, and population. From these it calculates consistent energy-use paths. Consistency is defined as a balancing of supply and demand in the face of resource constraints, with energy prices adjusting to assure an equilibrium solution. Energy use is disaggregated into nine world regions and all major possible fuel types, including oil, gas, coal, coal liquefaction, and shale oil. The model is intended to be applicable out about 100 years, with calculations feasible at intervals that the user selects, for example, 10 or 20 years. The model is extensively documented (Edmonds et al., 1981; Reilly et al., 1981; Edmonds and Reilly, 1983c), and a base case is now being developed (Edmonds and Reilly, 1983a,b).

Initial results show a quite steady increase in energy demand of about 2.5% per year from now to 2050, so that demand has reached about 29 TW yr/yr in 2025 and 50 TW yr/yr in 2050. CO_2 emissions increase by 1.5% per year from now to 2000, and by 2.3% per year between 2000 and 2025, reaching 12 Gt. Because of increasing reliance on coal, oil shale, and synthetic fuels, emissions then rise quite steeply, by more than 3% per year, and reach an annual rate of 26 Gt of C by 2050.

The Edmonds-Reilly model has the potential of being an extremely useful follow-up to earlier detailed studies, such as that of IIASA. It contains sufficient regional and sectoral disaggregation that experts in individual areas (such as analysts specializing only in the U. S. economy or a particular fuel source) can evaluate the detailed forecasts and assumptions. It also appears to be flexibly designed, so that results of different assumptions can be examined easily.

At the same time, the current effort contains some of the problems that have plagued earlier large-scale energy models. Perhaps the most important is the decoupling of energy demand from output. The current model has energy demand sensitive to prices and incomes, but incomes and outputs are not directly related to energy, labor, and other inputs. (Technically, energy is not treated as a derived demand, that is, derived from a production function relating inputs to output.) A second problematic feature is the extensive use of logistic curves that are not sensitive to prices for determining supply.

It should also be noted that the Edmonds-Reilly model is quite large and somewhat forbidding for a casual user. The benefit from technological and regional detail is partially vitiated by the difficulty of understanding the structure and workings of the model. As in many large-scale models, the size makes identification of critical parameters or assumptions a formidable task.

Notwithstanding these reservations, the Edmonds-Reilly work stands out today as the only carefully documented long-run global energy model operating in the United States.

2.2.3.6 Other Projections

Marchetti (1980) has made a forecast of the amount of CO_2 that will be emitted to the year 2050 based on a logistic substitution model of energy systems (Marchetti and Nakicenovic, 1979). This model treats energy sources as technologies competing for a market and applies a form of market penetration analysis. A logistic function is used for describing the evolution of energy sources and is fitted to historical statistical data. The driving force for change in this model appears to be the geographical density of energy consumption, and the mechanisms leading to the switch from one source to another are the different technical characteristics associated with each energy source. For example, in the Marchetti view oil succeeded coal primarily because of the advantages achievable by a system operating on fluids.

With data on energy consumption back to 1860 and including both commercial and noncommercial (wood, farm waste, hay) energy sources, the slope of the fitted curve of energy demand implies an annual growth of 2.3%. [This contrasts strongly with Rotty (1979b), who emphasizes that commercial energy supply, excluding times of world conflicts and depression, has grown at a rate of about 5.3% since 1860.] Applying a future growth rate of 3% per year, Marchetti calculates energy consumption for the various sources for the period 1975-2050 based on the logistic equations. The model predicts a relatively rapid phaseout of coal, a dominant role for natural gas, rapid growth of nuclear power, and a negligible role for new sources other than nuclear over the next 50 years. The model implies an increase in annual CO_2 emissions to about 14 Gt of C in 2030, an amount close to the lower estimates of Perry and Landsberg, IIASA, and IEA, and a cumulative emission of carbon to the atmosphere between the years 1975 and 2050 of about 400 Gt of C [to somewhat less than 450 ppm(v)]. Perhaps more important, it predicts a gradual reduction in emissions and atmospheric CO_2 thereafter, rather than continuing increase.

While Marchetti's projection of fuel shares is singular, his analysis of the long-term pattern of energy demand is not. Stewart (1981) also uses an empirical approach leaning on application of logistic growth curves, chosen to fit historical data extending back to 1850. Stewart argues additionally that energy growth is likely to evolve in surges or cycles rather than monotonically. Stewart identifies historical "cycles" in energy use with periods of around 50 years (perhaps a manifestation of the frequently cited Kondratieff cycle of economic activity) and notes that deviations of plus or minus 20% around a long-term logistic growth curve were experienced.

On the basis of an assumed stable cyclical structure, Stewart projects world energy consumption to the year 2025. For the period 1975-2000 a 40% growth is indicated; this breaks down into zero energy growth in the United States and a 60% growth for the world outside the United States. This overall projection for 2000 is lower than most. However, Stewart's projection for 2025 is close to other high values. After the relatively depressed period between 1975 and 2000, world energy growth between 2000 and 2025 is projected at a rate of about 4%, increasing from about 13 TW yr/yr to almost 36 TW yr/yr.

Legasov and Kuz'min of the Atomic Energy Institute of the USSR have also made a projection employing a logistic approach. The key variable in their function is one that describes the level of stabilization of per capita energy consumption (Legasov and Kuz'min, 1981; Report of the US/USSR Workshop, 1982). Legasov and Kuz'min explore two cases, one in which global average annual per capita energy consumption by 2100 reaches 10 kW (roughly the level in the United States today) and one in which it reaches 20 kW. Population, meanwhile, stabilizes at a level of 12 billion people. Under these assumptions global energy use in 2020 is either 50 or 60 TW yr/yr, with a population of 8.8 billion. Legasov and Kuz'min project coal and nuclear power as the principal energy sources for the coming decades, with nuclear power gradually becoming dominant. Under these assumptions, CO_2 emissions in 2020 are about 15 Gt in the lower case and 18 Gt in the upper case and roughly stable for several subsequent decades.

The three approaches described above are more sophisticated than the extrapolation approach (see Section 2.2.3.2), but the underlying methodology is similar. All assume that there is a stable underlying dynamic (exponential, logistic, or logistic-cum-sinusoidal) and forecast off that base. These approaches allow for no structural relation between exogenous variables like population and resources and endogenous variables like energy consumption. Such autoregressive or inertial models do relatively well at prediction in the short run, but their level of aggregation is so high that for most purposes one must still turn to the more structural models.

A final source is Lovins (Lovins, 1980; Lovins et al., 1982), who projects very low CO_2 emissions because of a shift to conservation and renewable (nonfossil) sources. With a 4.6-fold increase in global economic activity during 1975-2080 and a doubling of world population, total energy needs will, according to Lovins, be below the 1975 level, indeed dropping over the next century to less than half the present level. A projected increase in energy efficiency in end uses along with renewable sources for energy production might, according to Lovins, largely or wholly eliminate the global use of fossil fuels. A case study of the Federal Republic of Germany, a diverse heavily industrialized economy in a rigorous climate, is used as an "existence proof" (basis for extrapolation) for the efficiency and renewables strategy.

Lovins's results appear to be wishful with respect both to rapid development and diffusion of solar technologies and to lifestyle changes involving energy conservation. He does not present a formal model or develop the implications of the analysis for capital and labor needs. In addition, some of the trends identified, such as increasing efficiency of end-use devices, may raise the demand for energy, an outcome not accounted for. While Lovins may turn out to be correct, the analytical basis for his views remains elusive and characterized by strong cultural bias.

2.2.4 Projections with CO_2 Feedback to the Energy System

The energy projections reviewed in Section 2.2.3 share a potential deficiency when used to generate long-term CO_2 emission trajectories. Calculation of the ejected CO_2 is largely incidental. An energy path is plotted for a variety of reasons, and CO_2 is merely the outcome of the chosen path.

There are two ways in which such an approach may be deficient. First, by focusing on CO_2 directly, it may be possible to get more accurate CO_2 forecasts, as secondary issues (such as coal versus oil) can be ignored. Second, if a CO_2 buildup takes place and leads to serious social consequences, there may be some impact on the economy directly (through output) or indirectly (through policy reactions). Put differently, models that allow very high CO_2 but do not allow feedback from environmental change to energy policy must be regarded with caution; they mask significant assumptions about the behavior of people and governments (Stahl and Ausubel, 1981).

Projections that include increased CO_2 levels as a possible eventual constraint on CO_2 emissions include Nordhaus (1979, 1980), Edmonds and Reilly (1983a,b), CEQ (1980), and Perry (1981; Perry et al., 1982). These projections generally require that some threshold concentration of CO_2 (or similar constraint) be set, presumably by political intervention. Trajectories are then calculated that keep ambient levels from exceeding this threshold. Thus, in these approaches, rather than begin from high- and low-energy scenarios, the approach is to work backward from a desired or specified terminal condition to defining energy demand and fuel mix patterns that satisfy it.

2.2.4.1 Nordhaus

Along with estimating the uncontrolled path described earlier, Nordhaus (1977, 1979) also estimates time paths of emissions given particular carbon dioxide constraints. Efficient allocation of energy resources is calculated using the model described earlier under the assumption that it would be necessary to prevent atmospheric CO_2 from exceeding either 1.5, 2, or 3 times the preindustrial level [about 450, 600, or 900 ppm(v)].

The optimal path does not differ from the uncontrolled path for the first period (up to 1990). Abatement measures become necessary only in the second period (1990-2010) for the stringent control (450 ppm) and in the third period (2010-2030) for the milder control programs. To illustrate, in 2020 emissions for the uncontrolled case and the tripling are identical at 18 Gt of C, and the doubling case is only marginally lower at 16 Gt of C, but the 50% increase limit requires emissions of only 4 Gt of C. In 2040 the stringent-case emissions have trailed off to barely more than 2 Gt of C, the doubling case leaves carbon emission steady at 16 Gt of C, while the tripling and uncontrolled case have both reached the vicinity of 40 Gt of C per year. This technique allows estimates of the costs of controlling CO_2 emissions as well as the "carbon taxes" necessary to induce such responses.

Nordhaus (1980, 1982) also develops an optimal control framework, which seeks to identify the most economical way to balance the exploitation of both carbon fuels and climatic resources. The analysis is at a highly aggregate, global level; implications for sectors or for regional or national policies are not explored. Nordhaus weighs CO_2 control strategies according to two criteria: their effects on the paths of consumption that are generated by the control strategy and maximization of the discounted value of consumption streams, where the discount rate combines both a temporal and a growth factor.

The framework consists of four simple equations. These are a description of the carbon cycle and climatic effects of CO_2 elevation, estimates of the costs of reducing or abating CO_2 emissions, an equation that incorporates estimates of economic impacts of CO_2 buildup, and an equation that represents intertemporal choice between consumption paths.

Since there is great uncertainty about the economic and social impact of elevation of CO_2 concentration, Nordhaus tests the sensitivity of the model to different sets of costs. These are described by a "loss parameter," which indicates the fractional loss of consumption per doubling of CO_2. By varying this and other parameters, a set of emissions trajectories is calculated. The outcome of the model was considered at best illustrative given the uncertainty surrounding key parameters (such as the economic impact of climate change). A major result, however, was that the best degree of CO_2 control was extremely sensitive to important uncertain parameters, that is, no obvious control strategy stood out.

2.2.4.2 Edmonds and Reilly

Edmonds and Reilly (1983a,b) have also begun to explore the effect of taxation policies of various kinds on CO_2 buildup. One question asked is what consequences a substantial CO_2 tax in the United States would have on the level of atmospheric CO_2. They find that global carbon emissions are reduced by much less than the U.S. reduction owing to the fact that decreased U.S. energy demand resulting from the CO_2 tax lowers world energy prices, which in turn spurs energy consumption in other regions. In contrast, when a global tax is combined with a U.S. embargo on coal exports, there are substantial reductions in U.S. and non-U.S. CO_2 emissions.

While all the studies on taxation of CO_2 are still quite tentative, the three sets of tax experiments that we have reviewed--the Nordhaus results discussed in Section 2.2.4.1, the Nordhaus-Yohe results in Section 2.1, and the Edmonds-Reilly results--appear broadly consistent. This finding is striking, given that the three approaches are very different.

2.2.4.3 CEQ

The CEQ study (1981) derives several curves to yield a buildup of atmospheric CO_2 equal to 1.5, 2.0, and 3.0 times the preindustrial level (slightly less than 450, 600, and 900 ppm, respectively). It employs a simple, two-equation global model consisting of a differential equation to explain buildup of atmospheric CO_2 and a logistic equation to forecast CO_2 emissions. The major unknown parameter is the initial growth rate of fossil fuel combustion. The model is run backward to calculate global fossil fuel releases that would produce the assumed buildups of carbon dioxide. Curves preferred for further analysis correspond in 2030 to fossil fuel energy production of about 8, 13, and 17 TW yr/yr and emissions of 6, 10, and 13 Gt of C, respectively.

The controlled curves are compared with two overall energy projections. The high global energy demand scenario is for a world whose population has leveled off at 10 billion by the year 2100 and an average per capita energy use equal to two thirds the present U.S. level. Energy use in 2030 is about 35 TW yr/yr (similar to the IIASA high scenario) and rises to about 75 TW yr/yr by 2100, a ninefold increase over current levels, with about one fourth accounted for by population growth. A lower world energy use scenario represents a world whose population has leveled off at about 8.5 billion by 2100 at an average per capita level of one third present U.S. consumption. In 2030 energy use is about 20 TW yr/yr (similar to the IIASA low scenario) and reaches a plateau well before 2100 of about 30 TW yr/yr, about a fourfold increase over current consumption in which one half the growth is attributable to population increase.

The CEQ study evaluates the significance of the gap between overall energy demand and the three assumed CO_2 limits. For example, to avoid exceeding a 50% increase in global CO_2 concentration and to meet the low-energy-demand scenario (a low growth, environmentally cautious world), nonfossil fuel sources would be required to increase from about 1 TW yr/yr today to more than 4 TW yr/yr by the year 2000, or about a 9% growth per year. By 2020 nonfossil fuel sources would have to contribute about 10 TW yr/yr, with their growth averaging 4%

between 2000-2020. The 10 TW yr/yr are more than the current total global annual energy use, and more than the nonfossil (solar and nuclear) supply estimated for 2020 in the IIASA high scenario. The CEQ study estimates that together hydropower and nuclear power could probably provide between 2 and 3 TW yr/yr (fuel equivalent) by the year 2000. Thus, with low-energy growth but also a low ceiling on CO_2 levels, a contribution of about 1 to 2 TW yr/yr would be needed by 2000 from other renewables, with rapid increases thereafter as hydropower potential is exhausted.

2.2.4.4 A. M. Perry et al.

Perry and colleagues (1982; Perry et al., 1982) begin by adopting global energy projections from IIASA, the World Coal Study (1980), and others as reference scenarios. The novel parameter in their analysis is the date when global fossil energy use must begin to deviate from the reference scenarios in order to meet various atmospheric CO_2 limits. This date is referred to as the action initiation time (AIT). All the analyses so far are at the global level; that is, they refer to when a global policy (national policies summing to a global policy) would need to begin to be followed.

The approach built around action initiation times stresses that the rate of change of energy strategies is extremely important. If some CO_2 limit were approached along the kinds of curves normally drawn, the limit would certainly be passed, because of the inertia or momentum of the energy system. If the ceiling were not to be exceeded, CO_2 production would have to fall abruptly to zero, a virtual impossibility. Thus, Perry (1982) proposes anticipatory scenarios, which involve a gradual slowing of growth of fossil fuel use, followed by an eventual slow decline. With a high initial growth rate or a late AIT, the transition required in order to remain below a given CO_2 target may be too rapid and the subsequent decline too steep--the required transition may be infeasible.

According to arbitrary feasibility criteria relating to historic evolution and behavior of energy systems, several scenarios are drawn that should allow sufficient time for the necessary changes in energy demand patterns and supply technologies. Table 2.20 lists some AITs thought to be of intermediate difficulty.

In the Perry study, as well as the CEQ study, it is apparent that by fixing only a few parameters, principally energy growth, CO_2 limits, and a few characteristic times like market penetration, the overall trends of fossil and nonfossil energy use become approximately determined. With further work it may be possible to judge more reliably whether the different patterns of energy use designed to limit CO_2 concentrations would be easy or difficult to attain. Without such information, it seems premature to employ these models for prescriptive purposes.

TABLE 2.20 Required Action Initiation Times for Various CO_2 Ceilings[a,b]

CO_2 Limit (ppm)	Initial Growth Rate of Annual Carbon Emissions 1.5%/yr	2.5%/yr	3%/yr
500	2005	1995	1990
600	2025	2010	2000
700	2040	2025	2010
800		2035	2020

[a] Source: Perry (1982).

[b] For example, if a global limit for CO_2 in the atmosphere of 500 ppm is to be met, and emissions are growing at the outset by 1.5%/year, actions to reduce the share of fossil fuels would need to begin in the year 2005. If emissions are growing by 3% in the coming decade and we wish to meet a limit of 500 ppm, policies to discourage use of fossil fuels might need to become effective as early as 1990. These action initiation times are for transitions away from fossil fuels judged by Perry to be of intermediate difficulty.

2.2.4.5 General Comments

Studies that attempt to include feedback from CO_2 concentrations to energy policy are in their infancy. A particular problem is the confusion and combination of "positive" and "normative" approaches. In a "positive" model, the attempt is to describe how a system will behave under given boundary conditions. In a normative approach, one sets up a policy goal or objective function and then asks how the system ought to behave in order to optimize the objective function. While the distinction is seldom clearly delineated in global energy models (see particularly the comment on Lovins above), potential confusion is most likely to arise concerning the class of models discussed in this section. For the most part, the best interpretation would seem to be the following: the energy systems are based on a positive description, and CO_2 constraints are viewed as alternative normative policy constraints. However, assumptions of inaction (or absence of feedback) at very high levels of CO_2 emissions are also in a sense normative.

A second issue concerns the actual limits imposed. While the limitation of a doubling of CO_2 is the policy most often analyzed, it does not arise from a well-developed line of reasoning. An ideal (or even a "good") set of CO_2 policies will depend on the costs and benefits of climate change and CO_2 controls; costs and benefits are so poorly understood that no clear line of policy stands out as appropriate (see Schelling, Chapter 9).

In terms of conclusions, the Nordhaus, CEQ, and Perry studies seem to be largely consistent in their projections of what emission trajectories would look like under particular CO_2-induced constraints. As long as fossil fuel growth rates continue at the low level of the past few years and concentrations of 400-450 ppm are judged acceptable, there is little urgency for significant reductions in CO_2 emissions below an uncontrolled path before 1990. Emissions would need to be reduced below an uncontrolled path around 2000 if a limit in the vicinity of 450-500 ppm is desirable. To limit concentrations to 600 ppm (a doubling from preindustrial levels) would require that serious reductions be initiated in the 2010 to 2030 period. These long lead times before CO_2 reductions are necessary may be misleading, however. To effect a significant reduction of CO_2 emissions in an orderly and efficient way probably requires planning and policy measures decades in advance, for the infrastructure and capital stock associated with fossil fuels cannot quickly be scrapped and replaced without high economic cost. Also, it is probably necessary to consider policies with regard to climatic change on the basis of possible combined effects of CO_2 and other greenhouse gases.

2.2.5 A Note on the Biosphere

In the past the biosphere may have been a cumulative source of CO_2 as a result of human activities within a factor of 2 as great as burning of fossil fuels (Clark et al., 1982; Woodwell, this volume, Chapter 3, Section 3.3). However, it appears that in projecting future CO_2 emissions resulting from human activities the role of the biosphere is swamped by the potential contribution of fossil fuel combustion.*

An estimate for the maximum possible future addition from all biospheric sources is 240 Gt of C (Revelle and Munk, 1977). Baumgartner (1979) estimates that clearing of all tropical forests might contribute about 140 Gt of C. The total carbon content of the Amazon forest is estimated at about 120 Gt of C (Sioli, 1973). Chan et al. (1980) develop a high deforestation scenario in which total additional transfer of carbon from the biosphere to the atmosphere by the year 2100 is about 100 Gt of C. The World Climate Programme (1981) group of experts adopted a range of 50 to 150 Gt of C for biospheric emissions in the 1980-2025 period. Machta (this volume, Chapter 3, Section 3.5) estimates that massive oxidation of the biota might increase atmospheric CO_2 by 75 ppm by A.D. 2100.

Projections of future atmospheric CO_2 concentrations embracing both burning of fossil fuels and terrestrial sources have all been dominated by growth rates in fossil fuel emissions, except in cases where fossil fuel emissions are extremely low or in cases like that described by Woodwell (Chapter 3, Section 3.6), where all the world's forests are entirely destroyed in a few decades. While annual bio-

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*While the role of the biosphere may be marginal in projecting future emissions, it is, of course, important in calculating how the emissions are distributed among ultimate reservoirs.

spheric emissions from human activities may average as high as 1 to 3 Gt of C per year in future decades, fossil fuel emissions are typically projected to be an order of magnitude larger. From a different perspective, Schelling (Section 9.2.4) estimates that massive destruction or plantation of forests might accelerate or retard the growth of atmospheric CO_2 to a particular level by a decade or so during the second half of the next century.

2.2.6 Projections of Non-CO_2 Trace Gases

Changes in atmospheric concentrations of several infrared absorbing gases besides CO_2 may result from human activities (see Machta, Chapter 4, Section 4.3). These activities include the following:

(a) Stratospheric flight. Increasing supersonic air traffic may lead to changes in the O_3 and H_2O content of the stratosphere.

(b) Use of nitrogen fertilizers. Denitrification of fertilizers in the soil releases nitrous oxide (N_2O) to the atmosphere. Less significant increases in NH_3 and HNO_3 may also result.

(c) Use of chlorofluorocarbons (CFCs)--CCl_2F_2 and CCl_3F--as refrigerants and propellants in aerosol spray cans, for example.

(d) Extraction and burning of fossil fuels. Methane (CH_4) may be released as a result of mining of coal and extraction of oil and gas. CH_4 is also a conversion product of CO, and its presence is thus correlated with burning of fossil fuels.

(e) Agricultural and livestock production. Increasing methane emissions may be associated with large livestock herds and expansion and intensification of rice production.

Projections of future emissions of these non-CO_2 trace gases are generally at a more primitive stage than are CO_2 projections.* Researchers studying biogeochemical cycles and the atmosphere typically have used simple assumptions of linear increase or exponential growth based on a short segment of recent years (see Flohn, 1980, pp. 22-23). Wang et al. (1976), in a widely cited article, assumed that by 2020 stratospheric H_2O, N_2O, and CH_4 would all double and that the CFCs would increase by a factor of 20. Alternatively, projections may be extrapolated from more detailed studies, like the Climatic Impact Assessment Program (CIAP, 1975), which developed scenarios of stratospheric flight. The time horizons of the studies of stratospheric flight, agricultural production, industrial use of chemicals, and other activities vary, and the macroeconomic assumptions employed vary as well. There is a lack of studies of the combined greenhouse effect that use assumptions consistently in generating both CO_2 emissions

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*In addition to the references given in the text of this section, see Hameed et al. (1980), Lacis et al. (1981), Logan et al. (1978), Ramanathan (1980), and Rowland and Molina (1975).

and emissions of other infrared-absorbing trace gases. Given the very large inertia and modest rate of technological change in energy systems, projection of CO_2 emissions over periods of 50 years and longer has large but manageable error bounds. In human activities--like use of CFCs or stratospheric flight--where more rapid technological change is occurring, and where less inertia is imposed by a large and expensive capital stock, projections extending many decades are much more hazardous.

2.2.7 Findings

2.2.7.1 The State of the Art

2.2.7.1.1 Recent Progress

Few serious attempts at global long-range energy perspectives were undertaken before the 1970s. There has been rapid methodological progress in methods of making energy and CO_2 projections over the last decade. Much important work is a spinoff from energy analysis spurred by the 1973 oil shock. With some exceptions, methods developed independent of CO_2 studies in energy modeling, statistics, and econometrics should be adequate for the task of projecting future anthropogenic CO_2 emissions, when brought together with knowledge from geology, engineering, and other relevant fields.

2.2.7.1.2 Nature of Modeling Exercises

Modeling is a way of organizing thinking about a problem, one that should allow improved scrutiny of data, assumptions, and relationships. There is unlikely to be one "correct" approach to energy modeling for CO_2 applications. The systems involved are too complex, too uncertain; questions we ask may differ; methodological improvements occur frequently.

Moreover, there are cultural factors that influence forecasting. It is obvious to even a casual observer of the energy scene that there are deeply held and diverse views about energy futures, which are, after all, views of the character and relationship of man, nature, and society. Even if all could agree on a single model to use, we would certainly disagree on values for many variables. This is not merely a question of uncertainty; it is a question of coexisting contradictory certainties, points about which different groups and individuals hold highly assured but also highly different views.

Historical fashions in forecasting may be equally significant. It would be myopic to think that the current set of projections is free of today's implicit assumptions or biases. One cannot help but notice the tendency in energy forecasting to extrapolate the most recent past, whether one of relatively rapid or slow growth, far into the future. When the price of electricity was going down in the 1950s, people spoke of nuclear electricity becoming too cheap to meter; when the price of oil increased in the 1970s, people spoke of a barrel rising to a price of $100 or $200. The tendency of many forecasters to move in parallel (so that when one makes an upward or downward turn, all do) is also noteworthy.

How historical trends and trendlines in forecasts should affect both choice of method and our interpretation of contemporary forecasts and the spread of forecasts remains to be explored further. Probabilistic approaches, like that of Nordhaus and Yohe (Section 2.1), are one natural response. However, in view of the fickleness of forecasts, it is clearly useful to encourage a variety of approaches: large and small; formal and informal; stochastic and deterministic.

A pervasive question in research in CO_2 and energy is how much disaggregation is useful for accurate predictions of future CO_2 emissions. (A similar question arises, indeed, in climate modeling, where the question of the optimal level of refinement of spatial grid and time steps also occurs.) It is often assumed that more disaggregation is better. Careful investigation of the issue shows, however, that no general result holds. The potential improvement from disaggregation depends on the purposes of the study, the structure of microrelations, and the quality of the microdata. (See Grunfeld and Griliches, 1960.)

There are at least two possible reasons why disaggregation in CO_2 projections might not produce more reliable estimates. First, disaggregated data may be less reliable than aggregated data. This problem can lead to errors in variables and biased statistical estimates of microrelations. For example, we might have a good estimate of global energy production and, therefore, consumption but not of the distribution of global consumption. Second, there may be interdependence across regions that would be taken into account in aggregate models but not in disaggregated models. An example is the constraint that the balance of trade of the world be zero (or the net oil imports of the world be zero). A pasting together of studies of individual countries would generally not respect the constraint. In both cases, it is possible that aggregate models could provide superior prediction to disaggregated models.

2.2.7.1.3 Assessment of Current Efforts

The current modeling and knowledge of future CO_2 emissions appears marginally adequate today; we have a general idea of likely future trends and the range of uncertainty. It may be that further effort could increase the accuracy of our forecasts substantially. Given the large uncertainty that future energy growth and energy projections are contributing to the CO_2 issue, this area may well merit more research attention and support than it has received in the past. Future research efforts might be designed with four points in mind.

1. In general, the most detailed and theoretically based projections of CO_2 have been a spillover from work in other areas, particularly energy studies. This fact suggests that continued support of energy modeling efforts will be of importance in further pushing out the frontier of knowledge about future CO_2 emissions, as well as the interaction between possible CO_2 controls and the economy.

2. We have identified a serious deficiency in the support of long-run economic and energy models in the United States. There is not one U.S. long-range global energy or economic model that is being developed and constantly maintained, updated with documentation, and usable by a wide variety of groups. This shortcoming is in stark contrast to climate or carbon cycle models, where several models receive long-term support, are periodically updated, and can be used by outside groups. Another striking contrast is with short-run economic models, which are too plentiful to enumerate.

3. The bulk of CO_2 projections have been primitive from a methodological point of view. Work on projecting CO_2 emissions has not drawn sufficiently on existing work in statistics, econometrics, or decision theory. There has been little attention to uncertainties and probabilities. Also, considerable confusion of normative and positive approaches exists in modeling of CO_2 emissions.

4. Application of models for analysis of policies where there are, for example, feedbacks to the economy from climatic change or CO_2 control strategies is just beginning. Efforts to evaluate the effectiveness for CO_2 control of energy policies of particular nations or groups of nations in a globally consistent framework have been lacking.

2.2.7.2 Likely Future Outcomes

It is possible to synthesize past work to obtain a likely range of future CO_2 emissions. Before doing so, it is important to reiterate the inhomogeneous character of the projections surveyed.

Some studies, like those of Rotty, Perry and Landsberg, and Marchetti, seek to be best guesses or forecasts of future energy demand; others, like IIASA, posit scenarios, seek to fill out the descriptions, and avoid making claims about probability. Not only do the studies vary in intent, they are also of limited comparability in structure. The studies differ widely in levels of detail, time horizon, data base, and geographical aggregation. While projections of CO_2 emissions may extend to the year 2100, few energy studies offer detailed analysis beyond the year 2000, and fewer still offer detail past 2025 or 2030. The relative reliance on economic, engineering, and ecological logic varies. In addition, the studies are not independent. For example, researchers who participated in the IIASA work also participated in IEA and Interfutures research; both Lovins and IIASA rely on Keyfitz's population projections.

2.2.7.2.1 Energy Growth

Figure 2.22 summarizes the energy consumption forecasts to the year 2030.

Projections of CO_2 emissions are basically products of projections of energy demand and fuel mix. Projections of growth in energy use involve, more or less explicitly, assumptions or estimates concerning population growth, changes in per capita production of goods and services, and changes in the primary energy input required per unit of

TABLE 2.22 U.S. Energy Demand Projections by Various Studies[a]

Energy Study	Period of Projection	Population at End of Period (millions)	Average Annual Growth, GNP (%)	Average Annual Rate of Growth, Consumption (%)	Total Energy in Final Year of Projection (quads)
Ford Foundation[b]	1975-2000				
Historical		265	3.02	3.4	186.7
Technical fix		265	2.91	1.9	124.0
Zero energy growth		265	2.92	1.1	100.0
Edison Electric Institute[c]	1975-2000				
High		286	4.2	3.8	179
Moderate		265	3.7	3.2	155
Low		251	2.3	1.6	105
Exxon[d]	1977-1990	--[e]	3.6	2.3	108
Bureau of Mines[f]	1974-2000	264	3.7	3.1	163.4
EPRI[g]	1975-2000				
Baseline[h]		281	3.4	3.37	159
High electricity[i]		281	3.4	4.21	196.1
Conservation		281	3.4	2.97	145.6
Five times prices		281	3.4	1.98	114.3
CONAES	1975-2010				
I_2		279	2.0	-0.29	64
II_2		279	2.0	0.45	83
III_2		279	2.0	1.04	102
IV_2		279	2.0	1.95	140
I_3		279	3.0	0.52	85
II_3		279	3.0	1.38	115
III_3		279	3.0	1.95	140
IV_3		279	3.0	2.82	188

[a] Source: National Academy of Sciences (1979). Energy in Transition, 1985-2010, Final Report of the Committee on Nuclear and Alternative Energy Systems (CONAES). National Academy of Sciences, Washington, D.C.

[b] Source: Ford Foundation (1974). Energy Policy Project, A Time to Choose: America's Energy Future. Ballinger, Cambridge, Mass.

[c] Source: Edison Electric Institute (1976). Economic Growth in the Future, Committee on Economic Growth, Pricing and Energy Use. Edison Electric Inst., New York.

[d] Source: Exxon Company, U.S.A. (1978). "Energy Outlook: 1978-1990." Available from Public Affairs Department, P.O. Box 2180, Houston, Tex. 77001.

[e] Not specified.

[f] Source: U.S. Bureau of Mines (1975). United States Energy Through the Year 2000, rev. ed. U.S. Govt. Printing Office, Washington, D.C.

[g] Source: Electric Power Research Institute, (1978). Demand '77: EPRI Annual Energy Forecasts and Consumption Model. EPRI (EA-621-SR), Palo Alto, Calif.

[h] With restriction on the availability of natural gas.

[i] With no restrictions on the availability of natural gas.

lower energy costs. These and other factors having to do with either the macroeconomic environment or the energy sector can be combined in various proportions to form a slower growth in the energy system.

One additional component in declining energy supply and demand projections is probably the reduction in the projected role of nuclear energy. Figure 2.23 shows the steady lowering of projections made between 1970 and 1978 for 1985 nuclear generating capacity in countries of the Organization for Economic Cooperation and Development (OECD) (CIA, 1980). Of course, withdrawal of nuclear energy from the supply picture may mean substitution of other sources rather than a reduction in demand.

It is interesting to note that none of the major energy-centered projections has estimated 4% per year energy demand growth beyond the year 2000. This contrasts with the 4.3% figure for growth in CO_2 emissions that prevailed for a time in the carbon cycle and climate modeling literature. Most of the studies looking beyond 2000 project energy growth between about 2% and slightly above 3% per year.

The absolute range of projections spreads strikingly as the time horizon is extended. For example, the range of the more detailed projections in the year 2000 is between about 14 TW yr/yr (IIASA low) and 21 TW yr/yr (OECD A), while the range in 2025 is between about 20 TW yr/yr (IIASA low) and about 40 TW yr/yr (Perry and Landsberg, Rotty), an increase from 7 to 20 TW yr/yr, almost tripling with one generation. In fact, in the case of the IIASA low and high scenarios (which are not even presented as lower and upper bounds), the divergence increases from about 3 TW yr/yr in 2000 to 13 TW yr/yr in 2030.

While an individual or group may have a particular preference, the review of estimates shows no strong signs of convergence toward a single, widely accepted projection or set of assumptions. The analysis of Lovins et al. (1981) suggests that the "hard" path of high-energy consumption is as far from the "soft" path of low-energy consumption as when the energy debate began 10 years ago. While there has been a trend downward during the last decade, it appears to be more a parallel movement of camps than a convergence (Ausubel, 1982).

2.2.7.2.2 Fuel Mix

While the balance between carbon and noncarbon fuels is obviously key to projection of CO_2 emissions, it is one of the weak points of many studies. Only IIASA (1981), Nordhaus (1979), and Edmonds and Reilly (1983c) make careful attempts to calculate the balance. Other studies are notably arbitrary in assigning fuel shares. Of course, the fuel mix is likely to have a high degree of intrinsic uncertainty. Over a period of 50 years or more, substantial substitution is possible. While we know there will still be a need for transportation or home heating, how it is accomplished will depend critically on the relative prices and availabilities of different fuels.

Estimates for shares of nonfossil fuel 40 to 50 years hence range from 10% (Rotty, 1978), to 13% (World Energy Conference), to 25% (Marchetti), to 30% (Edmonds and Reilly), to almost 35% in the IIASA low scenario. The Perry and Landsberg study, where a case of almost

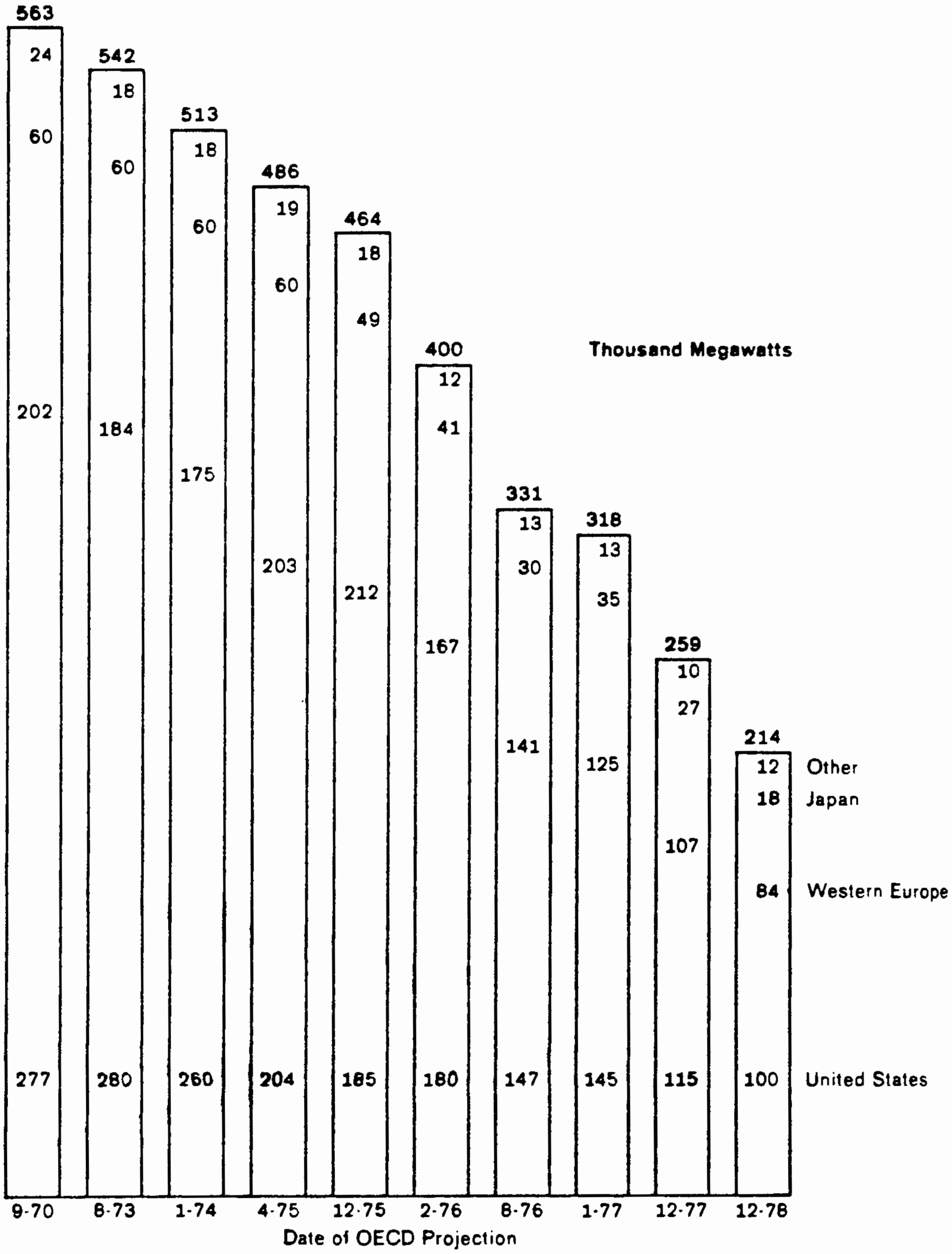

FIGURE 2.23 OECD: Past projections of year-end 1985 nuclear generating capacity. (Source: CIA, 1980.)

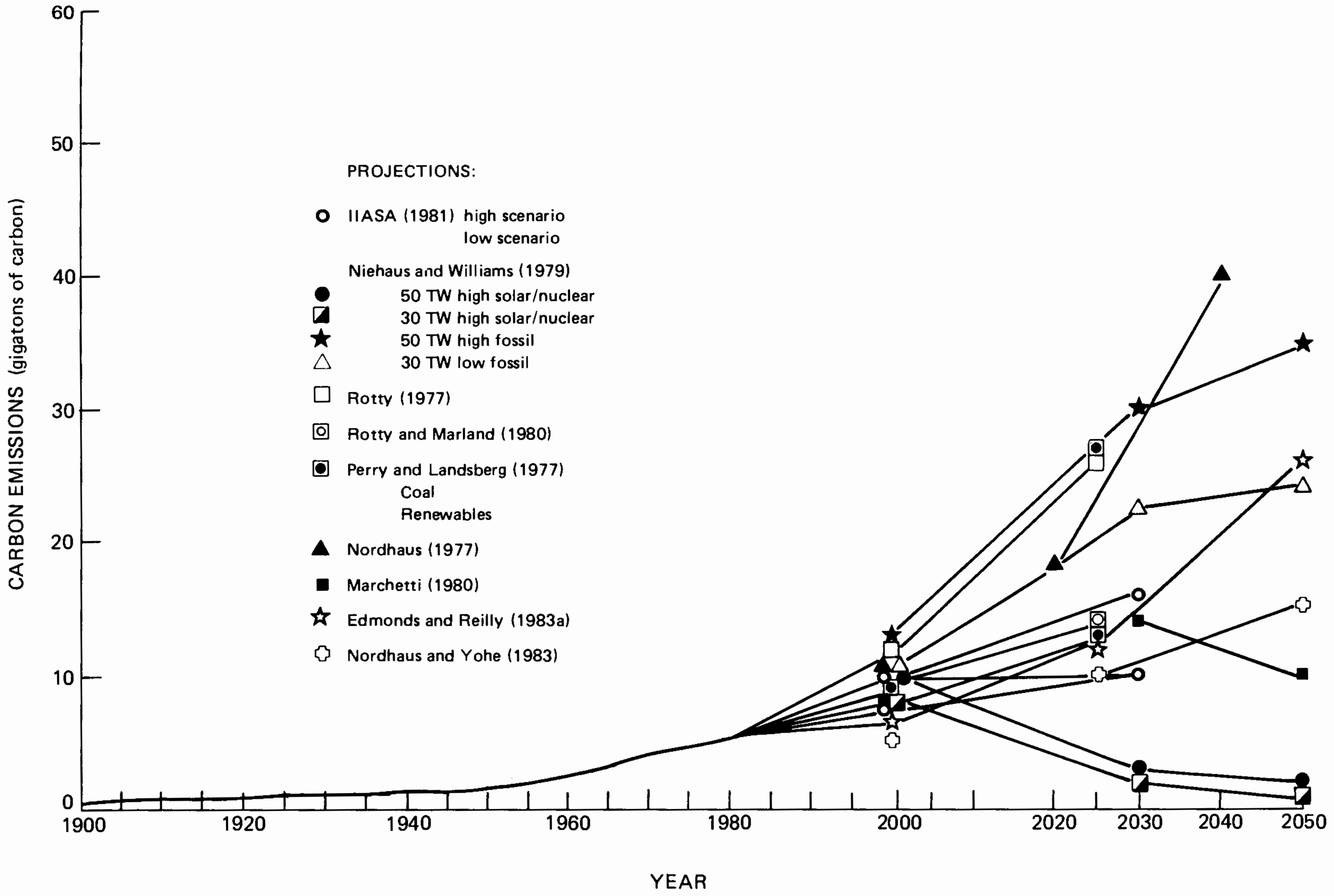

FIGURE 2.24 CO_2 emissions derived from long-range energy projections and historic production from fossil fuels. Sources: Historic data to 1949: Keeling (1973); 1950-1980: Rotty (1982). For data for projections see Table 2.23 and references.

TABLE 2.23 Some CO_2 Emission Projections Derived from Long-Range Energy Projections

Projections	2000	2020	2025	2030	2040	2050
IIASA (1981)						
High scenario	10			16		
Low scenario	7.5			10		
Niehaus and Williams (1979)						
50 TW high solar/nuclear	10			3		2
30 TW high solar/nuclear	8			2		1
50 TW high fossil	13			30		35
30 TW low fossil	11			22		24
Rotty (1977)	12		26			
Rotty and Marland (1980)	9		14			
Perry and Landsberg (1977)						
Coal			27			
Renewables			13			
Nordhaus (1977)	10.7	18.3			40.1	
Marchetti (1980)	8			14		10
Edmonds and Reilly (1983a)	6.9		12.3			26.3
Nordhaus and Yohe (this volume) 50th percentile	5		10			15

total reliance on coal is contrasted with a strategy where regional shortfalls in supply are met by an undefined noncarbon source, is also indicative. Here the fossil shares are 96% and 53%, respectively.

In conjunction with discussion of fuel shares, one other prominent feature of long-range energy studies should be mentioned: it is assumed or calculated that virtually all easily accessible oil and gas will be consumed. While there is contention over rates of depletion, these sources are generally posited as too attractive to remain underground. (Marchetti, who foresees a phase out of oil before exhaustion of resources, and Lovins, who argues for reduced demand and renewable substitutes, demur.) Thus, in most studies the estimates of oil and gas resources form a minimum expected increase of atmospheric CO_2; the degree of extraction of coal and shales determines how much further the atmospheric buildup of CO_2 will rise.

2.2.7.2.3 CO_2 Emissions

Combining estimates of energy and fuel mix leads to projections of CO_2 emissions. Figure 2.24 and Table 2.23 show CO_2 projections derived from long-range energy projections. Average annual rates of increase in CO_2 emissions to 2030 range from about 1% to 3.5%. Estimated annual emissions range from the past studies between about 7 and 13 Gt of C in the year 2000 and, with a couple of exceptions, between about 10 and 30 Gt of C in 2030.

2.2.8 Conclusion

Careful analysis of the economy, of energy, and of CO_2 emissions is vital. Such efforts are a key to better understanding of how the future atmosphere will evolve and what the likely costs and benefits of alternative CO_2 control or adaptation strategies will be. Considerable progress has been made over the last decade in developing more reliable and theoretically grounded models. As in other aspects of the issue of climate change, in economic and energy modeling a strong fundamental research program is a prerequisite for responding in an agile way to the concerns of today and images of the next century.

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