TECHNOLOGICAL FORECASTING AND SOCIAL CHANGE 23, 185–202 (1983)

A Brief Technology Assessment of the Carbon Dioxide Effect*

O.W. MARKLEY and THOMAS J. HURLEY III

ABSTRACT

Significant increases in atmospheric carbon dioxide are occurring as a result of fossil fuel combustion. More than a four-fold increase over preindustrial levels may occur by the year 2100. Heating of the atmosphere, changes in precipitation patterns and global storm paths, and other resulting effects are sure to cause significant social changes. This article is essentially a methodological case study demonstrating a useful but inexpensive type of technology assessment. It summarizes current research findings on "the CO_2 effect," and presents hitherto unpublished findings that resulted from a brief but systems-oriented approach. These findings suggest that most published forecasts of phenomena associated with a CO_2 buildup may be systematically low because various positive feedback relationships are not reflected.

Technology assessment (TA) is an increasingly important approach to futures-oriented policy analysis and planning. It is based on the assumption that technology (broadly interpreted) can and should be subjected to social controls for purposes of achieving societal objectives. In its complete form, the TA involves:

- describing and forecasting plausible technological developments
- identifying and assessing their impacts
- analyzing the relevant policy options available to decision makers

In general, an assessment may have numerous consequences, some of which include:

- support for a technological development
- stimulation of relevant research in scientific, technological, or social policy areas

---

*This article (and a complementary paper emphasizing the substantive results of the study reported in this methodological paper) were supported by the U.S. Department of Energy, under Contract No. 80EV10021. Based on work originally done for the U.S. Energy Research and Development Administration, under Contract No. EY76C030115, conducted at the Stanford Research Institute (now SRI International) by O.W. Markley, Alfred Webre, Buford Holt, and Richard Carlson. Any opinions, findings, and conclusions or recommendations expressed in this article are those of the authors and do not reflect the views of the Department of Energy.

O.W. MARKLEY is an Associate Professor at the Graduate Studies of Future Program, University of Houston/Clear Lake City. THOMAS J. HURLEY III is a graduate of the UH/CLC Studies of the Future Program, currently completing a futures research internship at the Institute of Noetic Sciences where he is Research Coordinator.

Address reprint requests to Dr. O.W. Markley, Associate Professor, Studies of the Future Program, University of Houston at Clear Lake City, 2700 Bay Area Boulevard, Houston, Texas 77058.

0040-1625/83/020185–17$03.00

- deferral or prohibition of the implementation of a given technology
- or more simply, provision of an information base for use by all interested individuals or groups

The latter result is often especially important. To the extent feasible, the comprehensive TA involves treatment of "higher order" as well as "direct" impacts, and seeks to evaluate them from the points of view of all interest groups involved, not only from those most prominently involved.

Such analytical objectives are obviously ambitious ones, and often they are neither feasible nor cost effective to attempt. Thus it is natural to think of a range of approaches to assessment having more limited objectives. Porter et al. [1] discuss such a "family" of assessment studies, summarized here in Table 1.

Still a different type of assessment study, however, is what may be termed a "brief" or a "focused" TA. Although perhaps not involving a difference worth naming as such (given the much criticized proliferation of jargon in the social sciences), these studies represent an important class of assessments whose singular characteristic is that they must be done quickly for a particular purpose—typically to inform a policy decision soon to be made. They require the formulation of a unique approach and methodology to fit their context, and usually focus quite specifically on the impacts or policy implications of interest to a given client or target audience. Although such abbreviated studies may often be conceptually located between the "mini" and the "micro" assessments identified in Table 1, they differ in that they may not attempt to involve all of the major stages of a TA (such as are listed in Table 2).

Such an approach is described in this paper, which uses the assessment of increases in atmospheric carbon dioxide (CO_2) as a case illustration of what, for convenience, we have termed a brief or focused technology assessment.

TABLE 1
A Family of Assessment Studies

Macroassessment (comprehensive, full-scale): Full range of implications and policies considered in depth (on the order of magnitude of 5 person–years work for technology-oriented to 10 person–years for problem-oriented assessments).

Miniassessment: Narrow in-depth, or broad but shallow focus (about an order of magnitude smaller than the macroassessment in work effort).

Microassessment: A thought experiment, or brainstorming assessment exercise, to identify the key issues or establish the broad dimensions of a problem (about an order of magnitude smaller than the miniassessment, say, 1 person–month of effort).

Monitoring: Ongoing gathering of selected information on a topic, e.g., radioactive emissions from a nuclear plant, or industrial energy use profiles. May be done formally or informally as a result of a prior assessment identifying critical uncertainties, and/or as a way to identify critical changes that warrant a new assessment.

Evaluation: Evaluation of ongoing projects and programs can determine whether alterations or new programs are needed. In addition, these can provide feedback as to the validity of previous TA/EIA predictions.

Source: Ref 1, based on A. F. Rossini, A. L. Porter, and E. Zucker, Multiple Technology Assessments, *J. Int. Soc. Tech. Assessment* 2, 21–28 (1976).

TABLE 2
A Comparison of TA/EIA Strategies

Technology Assessment Study Strategies			Environmental Impact Statement Guidelines			
Porter et al.	Jones	J. Coates	Armstrong and Harman	U.S. CEQ Guidelines	U.S. Department of Housing and Urban Development Format	Zajic and Svrek
1. Problem definition	1. Define assessment task	1. Examine problem statements 7. Identify parties at interest	Ib. Bounding the assessment domain	1. Project description	1. Describe proposed project	1. Statement of objectives 3. Proposed actions
2. Technology description	2. Describe relevant technologies	2. Specify systems alternatives 8. Identify macro-system alternatives	Ia. Data acquisition	2. Land use relationships 4. Describe alternatives	3. Discuss impact of environment on project design 5. Discuss internal project environment 6. Discuss alternatives	2. Technical possibilities for achieving objectives
3. Technology forecast			Ic. Technology projection			
4. Social description	3. Develop state-of-society assumptions	9. Identify exogenous variables or events	IVa. Whole societal futures VIb. Societal values	1. Describe present conditions	2. Describe existing environment	4. Environment prior to proposed action
5. Societal forecast						
7. Impact analysis	5. Make preliminary impact analysis	4. Evaluate impacts	IIb. Predicting and assessing impacts	3. Describe probable impact 5. Describe adverse impact	7. Discuss short- and long-term impacts 9. Describe reactions to program developments	5. Impacts including magnitude and importance

(*continued*)

TABLE 2 (*continued*)

8. Impact evaluation			IIc. Impact comparisons and presentations	6. Short- vs. long-term impacts and their relationships 7. Irretrievable and irreversible impacts	4. Evaluate impact on environment	6. Assessment of impact
9. Policy analysis	6. Identify possible action options 7. Complete impact analysis	5. Identify decision apparatus 6. Identify action options for decision apparatus	III. Policy analysis	8. Other considerations offsetting adverse effects	8. Note actions taken to mitigate impacts	
10. Communication of results		10. Conclusions (and possibly recommendations	IVf. Validation, and public participation			7. Recommendations

Source: Table 4.3 of Porter et al. [1], which provides full references to these and to still other schemes.

Overview of the CO_2 Effect[1]

Since the beginning of the industrial era, the level of fossil fuel combustion has been increasing at an average rate of 4.3% annually, which means it has doubled approximately every seventeen years. This rise in fossil fuel combustion has been the major cause of an increase in atmospheric CO_2 from a preindustrial level of 290 parts per million (ppm) to a level in 1976 of 330 ppm. (Gaseous carbon dioxide is the principal byproduct of fossil fuel combustion.) Continued high levels of fossil fuel use until the depletion of fossil fuel reserves will cause further rapid increases. The specific rate at which such increases occur and the concentration of atmospheric CO_2 eventually achieved are significant because of the physical effects and sociopolitical impacts that will result. These effects and impacts can be very briefly summarized.

The principal components of the "CO_2 effect" are diagrammed in Figure 1. Approximately half of the CO_2 released by fossil fuel combustion remains airborne while the other half is absorbed in various natural reservoirs, chiefly the ocean. Increased absorption of CO_2 by the ocean increases its acidity, however, which if raised to sufficient levels would have severely negative impacts on the marine food chain.

Increased levels of atmospheric CO_2 have two major effects. First, atmospheric warming occurs because more of the infrared energy that would otherwise be reradiated from the earth into space is absorbed by the additional CO_2 in the atmosphere. Resulting changes in atmospheric temperature gradients (which occur as a function of both altitude and latitude) are expected to disrupt prevalent climate dynamics and, thereby, to have widespread impacts, both good and ill.

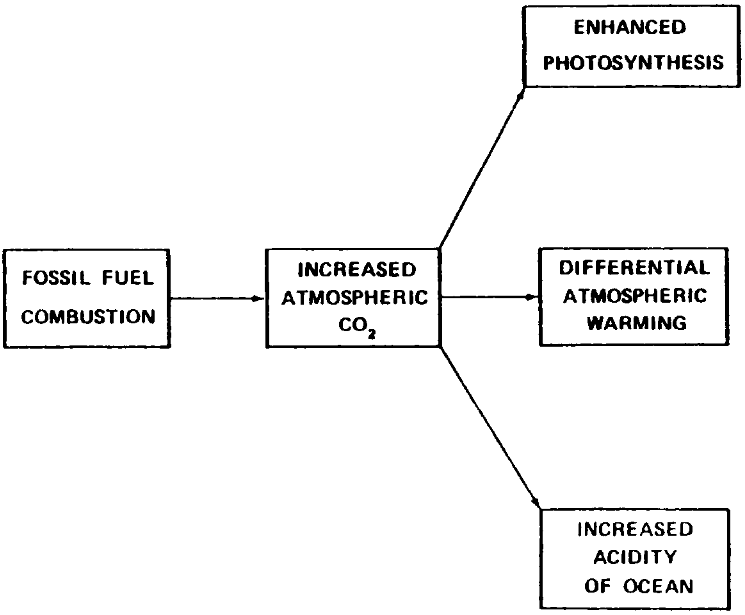


Fig. 1. Principal components of the CO_2 effect.

---

[1] Technical information about the "CO_2 effect" is necessarily brief in this methodological case study. References 2 and 3 provide good general introductions to the topic.

Second, basic plant photosynthesis will be enhanced—if other nutrients are plentiful—because of the increased proportion of ambient CO_2. If technologies are developed to exploit this effect, they might have beneficial consequences.

Knowledgeable forecasting of the CO_2 effect requires quantitative modeling of a number of complex phenomena. These include the amounts and types of fossil fuel ultimately economical to recover, the absorption capacity of the natural reservoirs, and the environmental impacts of increased ocean acidity, differential atmospheric warming, and increased photosynthesis. Although numerous uncertainties exist in such modeling exercises, there is agreement among scientists that accelerating fossil fuel use and the resulting large scale releases of CO_2 will have profound effects on the biosphere. The projected changes in atmospheric dynamics, which would lead to alterations in storm paths and global moisture distribution, are expected to be particularly significant. These and similar effects may seriously impact global patterns of social, economic, and possibly political organization. Not surprisingly, then, the CO_2 effect is receiving increasing attention not only from climatologists and other physical scientists, but also from social scientists and politicians attempting to understand the policy implications of this complex phenomenon as well.

Context of the Brief Assessment

Early in 1977, an Inexhaustible Energy Resources Planning Study was initiated by the Energy Research and Development Administration (ERDA). This study was designed to assist in setting the agency's budget priorities, and its overall objective was to estimate the earliest feasible and latest prudent times at which the United States could safely make the transition from almost exclusive reliance on exhaustible energy resources (such as oil, natural gas, coal, and conventional nuclear fission) to those that are virtually inexhaustible (such as solar, geothermal, and nuclear fusion). Specifically, ERDA needed to know the levels and timing of investment that would be required to develop alternative inexhaustible sources in order to avoid what they termed societal "show stoppers"—energy shortages or other difficulties having catastrophic proportions. Initially it was known only that CO_2 accumulation in the atmosphere may lead to atmospheric warming and later to other environmental impacts. ERDA therefore asked whether anticipated CO_2-related impacts might prove a "show stopper," interfering with the projected long-term use of proven fossil fuel reserves, and necessitating an earlier transition to inexhaustible energy sources than would otherwise be the case.

Because of deadlines imposed by the Office of Management and Budget, only a few months were available in which to conduct the project. ERDA therefore contracted independent research centers to conduct several highly focused studies, which when synthesized would comprise the complete planning project.[2] The Center for the Study of Social Policy at Stanford Research Institute (now SRI International) was awarded one of these contracts, part of which called for a brief assessment of the long-range social and political impacts of CO_2 buildup as a result of fossil fuel consumption. Reflecting the overall schedule of the Inexhaustible Energy Resources Planning Study, the work plan for this study was tightly compressed. A briefing on the preliminary results was to be pre-

---

[2] ERDA later contracted with TRW Systems, Inc. to compile the working papers produced as part of the Inexhaustble Energy Resources Planning Study into several bound volumes available to the public. Although this work was completed, the Department of Energy has not approved its release and publication.

sented three weeks from the start of work and the final report and briefing about five weeks later. Overall, only 3.5 person–months of work were budgeted for the brief assessment.

Initial Methodology and Results

One of the considerations in initiating the brief assessment was to avoid duplicating work that had already been done. Because the National Academy of Sciences/National Research Center was currently sponsoring an extensive study of energy and climate, focusing on the physical effects of CO_2 accumulation, the objectives of the SRI study as initially conceived were to:

1. Identify the major impacts (including the social, economic, and political consequences) resulting from physical effects of the CO_2 buildup, assuming no curtailment of fossil fuel use for reasons other than depletion of fossil reserves.
2. Assess the sociopolitical impacts of implementing various fossil fuel curtailment schedules (e.g., 50% reduction in 10 years as compared with 10% reduction in 50 years) designed to avoid creating undesirable CO_2-related impacts.

The initial research methodology was strongly shaped by three major constraints—the project team's relative lack of prior knowledge about the CO_2 effect; the relatively large amount of unpublished work on the topic that existed in connection with the NAS/NRC study; the short time in which the assessment was to be conducted. In view of these constraints, it was decided to begin the study by conducting what is sometimes called a "snowball survey." This is a procedure in which one or more persons who are knowledgeable about a given field are contacted (typically by telephone) and asked to identify the leading work and workers on a given topic. By subsequently posing the same general set of questions to the experts suggested by earlier respondents (thereby achieving the snowball effect), an investigator having a compelling "need to know" can often very quickly and accurately become familiar with the state of the art in a given area of knowledge.

As is so often the case in exploratory studies, the conclusions stemming from the initial inquiry indicated that the initial assessment methodology should be reconceptualized. The following two factors made this necessary.

UNCERTAINTIES INHERENT IN FORECASTING OF CO_2 EFFECTS

First, it was found that although existing studies provided detailed analysis and estimates about the nature of CO_2-induced changes in the biosphere, sizable uncertainties remain about the intensity, timing, and sometimes the direction of specific effects. Three examples illustrate.

A first type of uncertainty pertains to the levels and timing of the peak atmospheric concentration of CO_2 associated with different estimates of the ultimate amount of recoverable fossil fuel reserves, the rates at which they are to be exploited, and the absorption characteristics of the natural reservoirs. Various forecasts of the peak level in atmospheric CO_2 range from 5–14 times the preindustrial level.

Second, although it is generally accepted that atmospheric CO_2 accumulation will cause differential atmospheric warming (with greater increases at high than at low latitudes), the degree of warming for given levels of CO_2 above the preindustrial level is uncertain by at least a factor of two. Furthermore, although it is certain that mean cloudiness will change as CO_2 concentration rises, it is not now possible to predict with confidence how large the change will be nor even which direction it will take.

As a third example, assuming that a doubling in atmospheric CO_2 results in a temperature increase of 10°C at latitudes greater than 80°, it is not known whether polar snow cover will increase because of higher levels of water vapor in the atmosphere in the polar regions, or decrease because of accelerated melting.

Such uncertainties obviously limit the specificity of analysis and interpretation that is possible.

INFEASIBILITY OF A U.S. CUTBACK POLICY

A second factor that led to modification of the initial methodology was the finding that even if the United States and other non-Communist industrialized nations were to drastically reduce fossil fuel consumption (a conservation strategy), the buildup of atmospheric CO_2 would be affected only negligibly. The expected increases in consumption by other nations, particularly by developing nations, are so great that the levels of CO_2 accumulation that would otherwise occur could be delayed only a few years by such conservation.

Thus the assessment of differential impacts resulting from curtailment of fossil fuel use was not sensible. And although it could be argued that various CO_2-abatement schemes would lead to the same effect as curtailment, no such schemes were found to be plausible. Hence any attempts to assess deliberate reductions in future levels of atmospheric CO_2 were abandoned. (A recent paper by Chen, et al. [4] nicely summarizes these points.)

Alternative Methodological Approaches

Forecasts of the nature, timing, and direction of plausible developments of the technology are usually central to a TA. In this study, given the uncertainties noted above, an innovative methodological approach was obviously required to satisfy the overall objectives of the Inexhaustible Energy Resources Planning Study for which the brief TA was being done.

Two of the most promising alternatives that were considered are as follows. One approach was to delineate and "combine" all major alternative assumptions regarding potential physical effects, their interactions, and the consequent impacts. Taking but one of the uncertainties noted above as an example, assuming that increasing cloud cover did prevent a substantial temperature increase, it might also prevent widespread deployment of solar energy technologies. This would decrease the possibility of avoiding high levels of fossil fuel use and therefore of avoiding severe CO_2 effects. Figure 2, formulated by Buford Holt, depicts significant interrelationships among the major physical phenomena constituting the CO_2 effect. It was constructed to understand the CO_2 effect in an holistic fashion, something that to that time had not been done, and to help evaluate whether a "contingency analysis" of uncertainties might be feasible. That approach quickly proved impractical, given project constraints. Although it could appropriately be used in a more comprehensive decision-analytic effort that would be directly concerned with the uncertainties and with the estimated benefits and costs of reducing them by specific research studies, its requirements far exceeded the limited resources of the brief assessment.

A second, simpler approach that was more feasible for this study was to bracket the ranges of plausible variation using a high impact and a low impact case, creating the conceptual equivalent of the "error bands" often used in engineering design calculations. Particularly in view of ERDA's overall goal of determining whether the effects of CO_2 accumulation would constitute a "show stopper," this proved to be an economical way of dealing with the uncertainties involved.

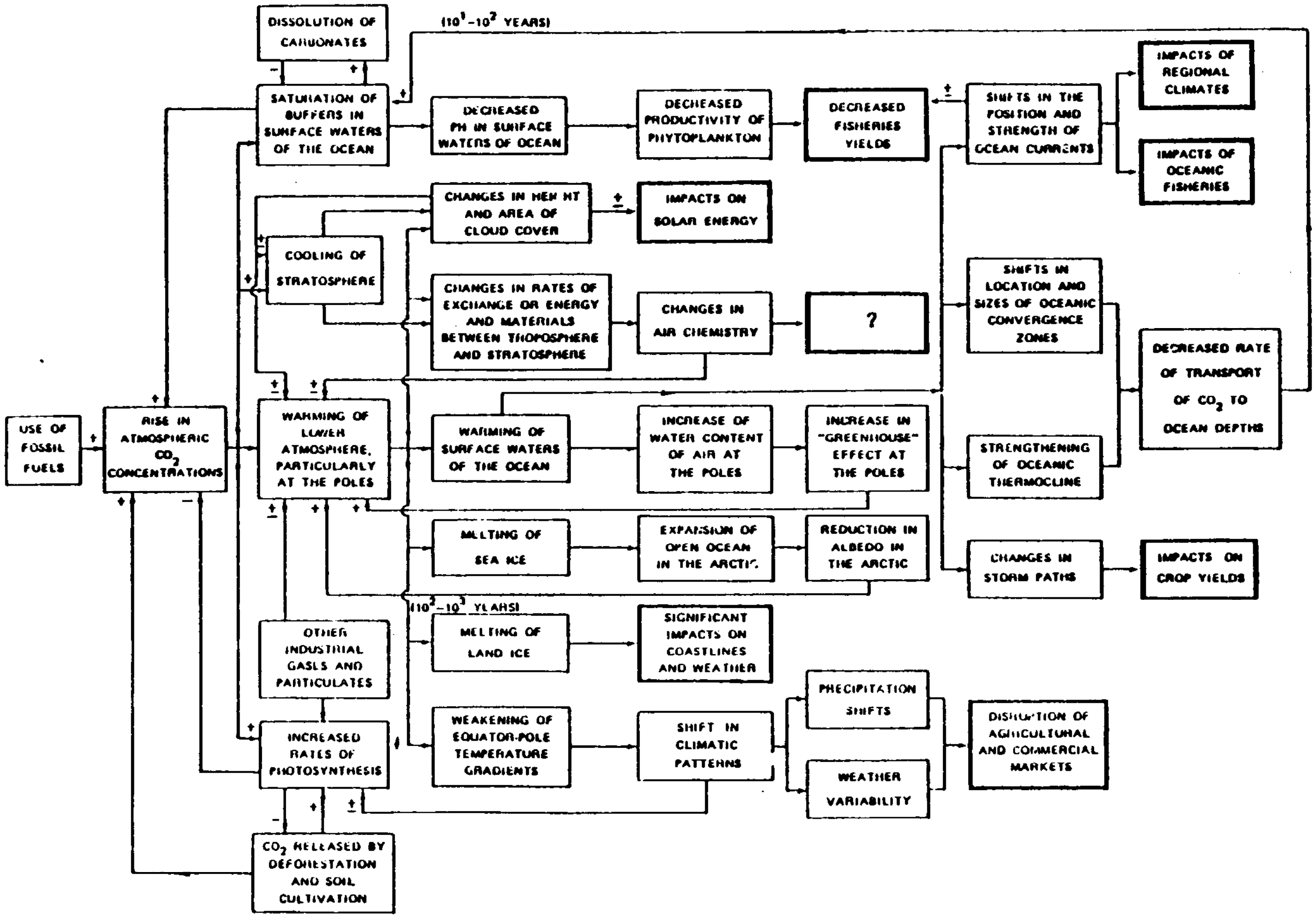


Fig. 2. Interrelations among phenomena associated with the CO_2 effect.

Revised Methodology and Results

The objectives of the study were therefore revised. The new emphases were to:

1. Identify the maximum range of plausible effects to be expected from both a high and a low fossil fuel use case (with associated assumptions regarding uncertainties).
2. Identify significant patterns of sociopolitical impacts to be expected at different times as the CO_2 effect unfolds regardless of which scenario ultimately proves to be most accurate.

The following steps comprised the method of approach to fulfill the revised objectives:

1. Reviewing the literature on the CO_2 effect and compiling all known physical effects and their functional relationships, describing their intensity if possible.
2. Constructing a flow chart portraying the interactions and feedback networks among the physical effects, and leading to environmental, economic, and sociopolitical impacts.
3. Computing or adapting from the literature "error band" ranges of plausible magnitudes for:
   - fossil fuel combustion as a function of time
   - atmospheric CO_2 as a function of fossil fuel combustion rate with time
   - temperature rise as a function of latitude (high, low, and average) and atmospheric CO_2 concentration.
4. Identifying physical effects and major environmental or economic impacts as a function of CO_2 concentration, and hence time, for both the high impact and low impact cases.
5. Describing patterns of sociopolitical impacts due to the CO_2 effect.

To develop the "error band" ranges of atmospheric CO_2 concentration and warming, existing work was adapted from the literature. The curve selected for use as the high impact case was taken from Keeling and Bacastow [5] and corresponds to a 4.5% average growth rate in fossil fuel use, assumed to continue until depletion-related price increases reduce overall levels of fossil fuel use. For the low impact case a curve adapted by Rotty [6] from Keeling's work was chosen, because it most closely resembled the SRI team's estimate of the lowest feasible use case.[3]

To forecast the degree of temperature change that would result from increasing atmospheric CO_2 in both cases, research done by Manabe and Wetherald [7] and Ramanathan [8] was synthesized. Manabe and Wetherald, using a three-dimensional mathematical model of general atmospheric circulation, had forecast the differential temperature increase that would occur at different altitudes and latitudes for given increases of

---

[3] Although the study methodology dictated that we assume surface and deep water carbonate dissolution in the low use case (which would involve more rapid oceanic absorption of atmospheric CO_2 than had been assumed by Rotty), the complexities involved prevented adjusting the forecast for this assumption. The projections of observed atmospheric CO_2 beyond the year 2000 were therefore too high for a true lower bound—by perhaps 30%—but this indifference would not substantially affect the results of the assessment.

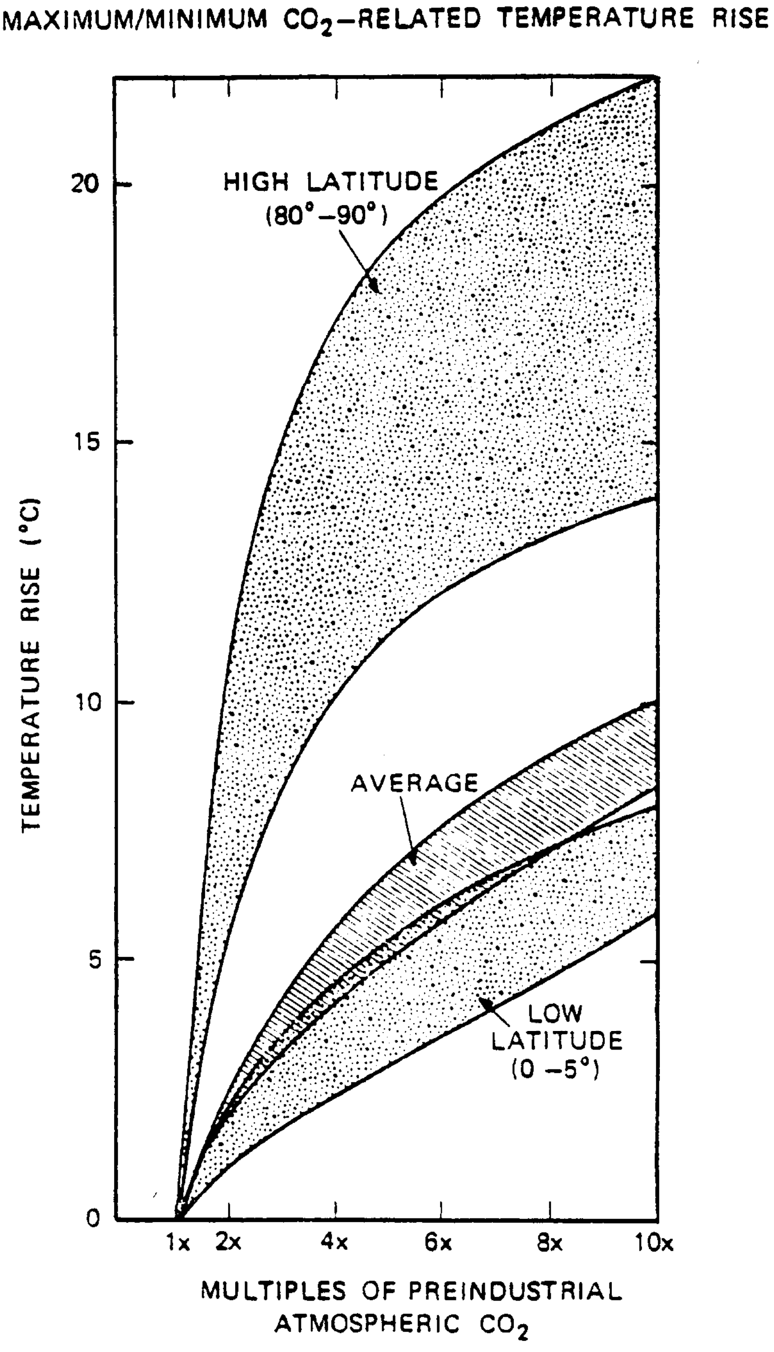

MAXIMUM/MINIMUM CO_2-RELATED TEMPERATURE RISE
HIGH LATITUDE (80°–90°)
AVERAGE
LOW LATITUDE (0 –5°)
TEMPERATURE RISE (°C)
20
15
10
5
0
1x
2x
4x
6x
8x
10x
MULTIPLES OF PREINDUSTRIAL ATMOSPHERIC CO_2

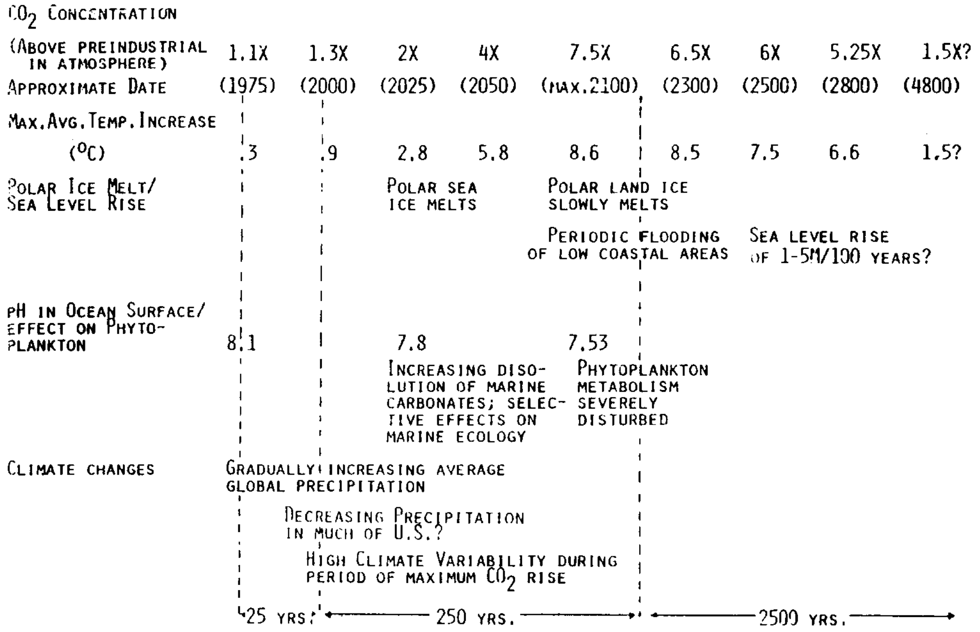
Fig. 3

CO_2, but only up to 2× the preindustrial level. Ramanathan, using a one-dimensional radiative–convective model, had simulated average global surface temperature increases attending increases in atmospheric CO_2 up to 10× the preindustrial level. Changes in surface temperature influence numerous subsidiary physical effects and impact, so it was thought important for planning in the face of uncertainty to integrate Ramanathan's findings with those of Manabe and Wetherald, especially since one of the key findings of Manabe and Wetherald was that increases at high latitudes may be far greater than those at lower latitudes or those usually cited as average global temperature increases. These findings, which were checked for plausibility by such climatology experts as Keeling, Ramanathan, Manabe, and Mitchell, are plotted on Figures 3, 4, and 5. A range of sociopolitical impacts relevant to ERDA in its planning were then derived, on the assumption that knowing any of the specific effects likely to occur was less important than having a sense of the overall pattern of probable impacts.

In the final stage of the assessment, an analytical framework for the identification of intermediate impacts and subsequent identification of sociopolitical impacts was constructed. In summary, the steps involved in developing the matrix were:

1. Detailing the major expected physical effects resulting from selected increasing levels of concentration of atmospheric CO_2.
2. Isolating those significant societal processes that appear to be most vulnerable and responsive to CO_2-related effects.
3. Describing the likely intermediate impacts on significant societal processes resulting from CO_2-related effects.

The Intermediate Impact Matrix showing the major physical effects anticipated and the societal processes effected are presented in Figure 6. The linkages between the two



CO_2 CONCENTRATION (ABOVE PREINDUSTRIAL IN ATMOSPHERE)	1.1X	1.3X	2X	4X	7.5X	6.5X	6X	5.25X	1.5X?
APPROXIMATE DATE	(1975)	(2000)	(2025)	(2050)	(MAX.2100)	(2300)	(2500)	(2800)	(4800)
MAX.AVG.TEMP.INCREASE (°C)	.3	.9	2.8	5.8	8.6	8.5	7.5	6.6	1.5?
pH IN OCEAN SURFACE/ EFFECT ON PHYTOPLANKTON	8.1		7.8		7.53				

Fig. 4. Approximate timing of major CO_2-related effects (high impact case).

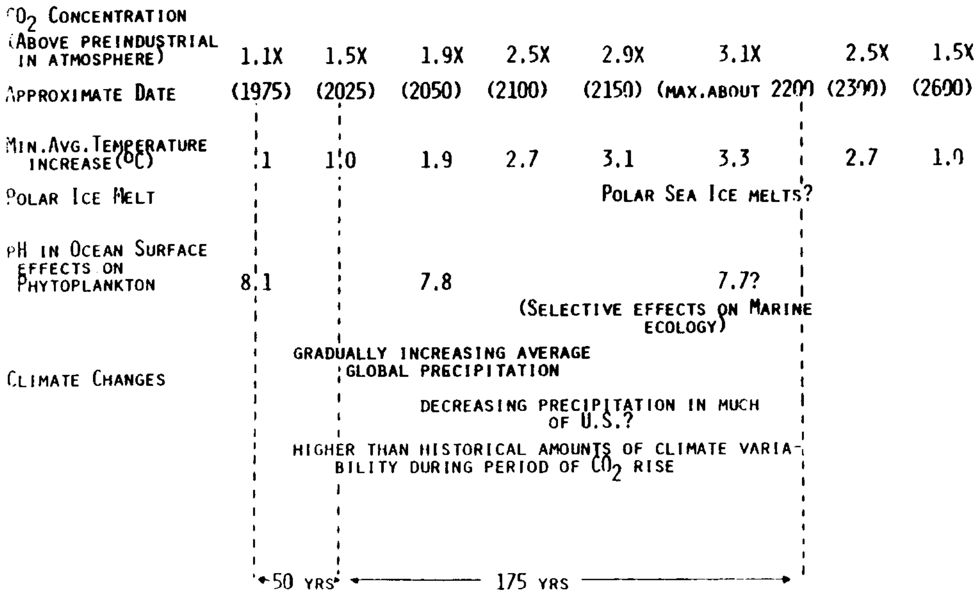


Fig. 5. Approximate timing of major CO_2-related effects (low impact case).

IMPACT CATEGORY	1 Altered Climate Patterns	2 Cryospheric Effects	3 Oceanic Effects	4 Increased Weather Variability	5 Altered Hydrology
A. Location/ viability shifts					
B. Supply/cost Facters					
C. Demographic migration					
D. Health and well-being					
E. Governance, regulation and planning					
F. Systemic: Interregional and International relations					

Fig. 6. Intermediate impact matrix of CO_2-related effects.

were then analyzed for each cell of the matrix. Three illustrative results will suffice to convey the flavor of this analysis:

A-1: *Location/viability shifts due to altered climate patterns.* Low but significant probability of increased precipitation at high and equatorial latitudes, and decreased precipitation in midlatitudes. Regional shifts in large production farming areas, and in water-intensive energy production, resource extraction, and industry for dry (midlatitude) to wet (tropics and northern latitude) areas. Shift in viable food crops, for example, use of present high-yield hybrid grain in much of continental United States is less viable.

E-1: *Governance, regulation, and planning effects due to altered climate patterns:* Probable increases in governmental regulation regarding social relief and welfare, food allocation, water allocation, and permissible energy and resource consumption across all jurisdictional levels.

F-2: *Systemic responses due to cryosphere effects:* In the long term, regional and transnational conflict and conflict management regarding migration, territorial boundaries, and national sovereignity.

Finally, using the Intermediate Impact Matrix as a framework for informed speculation, significant sociopolitical impact patterns were identified. Although other impacts could also be foreseen, the following list illustrates the scope and variation in the types and intensity of impacts that may attend the CO_2 effect, and can usefully be seen as a set of "planning issues" such as those used in strategic planning:

- *large persistent fluctuations in global food supply* (high probability coverage of population, within 25–50 years)
- *shifts in power balance among nations* (high probability, high coverage of population, within 50–100 years)
- *disruption of U.S. economic system due to chronic water shortfalls below needs for agriculture and energy technologies* (uncertain probability, high coverage of population, within 50 years)
- *increasingly regulated demographic migration between regions and across national boundaries* (high probability, low coverage of population, within 50–100 years)
- *widespread concern and political dissension about prevention of CO_2 buildup* (high probability, uncertain coverage of population, uncertain timing)
- *infusion of capital and human resources into newly exploitable, increasingly habitable, and accessible land* (high probability, medium coverage of population, within 50–100 years)
- *emergence of responsive multinational social inventions* (low probability, high coverage of population, within 50–100 years)
- *dislocation of major coastal metropolitan areas and coastline settlements* (medium probability, high coverage of population, 300–10,000 years)

Overall, the brief assessment of the CO_2 effect indicated that fossil fuel resources cannot be exploited at maximum possible use without incurring CO_2-related impacts that may come to be defined as intolerable, and that significant, unavoidable CO_2-related sociopolitical impacts appear likely even if global demand for fossil fuel were reduced to minimum feasible usage. Some potentially unavoidable impacts are of uncertain probability but are so severe as to require present contingency planning, for example, chronic U.S. water shortfall due to global precipitation shifts. Other of these impacts, though longer range, are so grave that if further research were to reduce present uncertainties about the probabilities, one could expect social or political activity to prevent them. Examples of the latter type of impact include disruptive climate effects on climate and/or marine ecology.

Policy Implications and Conclusions

As Table 2 depicts, there are a variety of TA models, each with its own categories for setting forth the important parts of an assessment. Beyond their differences, however, all seem to agree that, at a minimum, a TA should include some type of technology description and forecast, an analysis of probable impacts on all major interest groups, and the assessment of the policy implications that derive from those impacts and interests. In a brief assessment such as this, the impact analysis and the assessment of policy implications must necessarily be done at a relatively high level of abstraction or aggregation, except for those impacts and implications of particular interest to one's specific target audience or client.

Two types of implications are of concern here: substantive and methodological. The primary substantive implications of this brief assessment are summarized in Table 3, which was prepared to accompany Figures 1, 3, and 4 as a compressed summary or essential conclusions.

The first conclusion/implication suggests that, when viewed holistically, the feedback paths involving the basic mechanisms of atmospheric warming may be predominantly positive, or deviation-amplifying, so that the magnitudes of various CO_2 effects as estimated in current studies could be systematically low. When combined with the uncertainties noted above, this feature of the CO_2 effect implies that the overall impacts of increasing atmospheric CO_2 may lie considerably beyond the levels being publicly discussed at present.

At least one policy analyst has suggested that although the CO_2 effect is admittedly of concern, it is not of pressing concern to most policy makers (science policy is an exception) because the projected occurrence of virtually all CO_2 effects, twenty years or more in the future, lies beyond the planning horizon of most institutions. Although probably true for the types of effects considered just above, it ignores another feature of the CO_2 effect. The second conclusion/implication noted on Table 3 suggests that, from a cybernetic systems viewpoint, a relatively rapid forced change in a complex, nonlinear system is sure to destabilize that system to some degree. Furthermore, the magnitude of the destabilization tends to be proportional to the rate of change induced by the forcing function. Because the rate of change in atmospheric CO_2 concentration is expected to be greatest between 2000 and 2060, these decades may be accompanied by chronic and severe weather variability. This might have immediate and profound impacts. For instance, traditional farming methods, especially in poorer and less developed regions, could well become ineffective and result in massive starvation, well before the types of effects noted in Figure 2 are observed.

It should be noted that both of these conclusion/implications are derived from a holistically designed, brief technology assessment, and were overlooked by the inquiry methodologies of conventional science and science policy analysis. Although they should be viewed only as suggestive hypotheses until evaluated in a more detailed way, they are indicative of what a brief TA can contribute.

TABLE 3
Three Analytical Conclusions Derived from a Brief Technology Assessment of the CO_2 Effect

Analytical Conclusion	Policy Implication
1. From a cybernetic systems viewpoint, the interacting phenomena forming a possible CO_2-induced climate shift are seen to form a complex nonlinear multiple feedback system with a decided dominance of positive, i.e., deviation amplifying, feedback loops (see Figure 2).	The magnitudes of many phenomena previously studied by means of relatively compartmentalized simulation models, e.g., temperature rise, are *systematically underestimated*—the combined effects being greater because of multiple positive feedback interactions than would otherwise be the case.
2. Similarly, increase in climatic variations may be seen as a CO_2-induced disruption of the complex nonlinear system interactions that have for millenia approximated dynamic stability. Unlike many phenomena whose magnitude is expected to be a direct function of the *degree* of change in atmospheric CO_2 from preindustrial levels, the severity of climatic disruptions will most likely be a function of the first derivative (rate of change) of atmospheric CO_2.	Although sizable uncertainties exist regarding the magnitude and sometimes the direction of significant phenomena attending increases in atmospheric CO_2, chronic and severe weather variability may be confidently predicted during the period of maximum CO_2 buildup—a period that comes well before maximum CO_2 level, temperature rise, and other attendant effects.
3. Although a CO_2-induced climate shift has enormous potential impact, it is a "distant" concern for most interested parties. Thus, it is likely to be strongly discounted as a priority concern in the public policy arena by all interest groups except those who are well informed and concerned.	CO_2 science policy analysis needs to be especially attentive to the information needs of various audiences other than the scientific community itself, and to the differential value of information that alternative strategies and studies would produce for each. Widely based participation in development of CO_2 science policy recommendations is essential.

The final conclusion/implication is that CO_2 science policy analysis needs to be attentive to the information needs of all major interest groups and systematically to evaluate the costs and benefits to each group of different inquiry methodologies. This follows both from the observation that the conventional methods of science and science policy analysis need to be augmented by holistic and futures-oriented methods such as those employed in technology assessment, and from the insights of TA researchers such as Harold Linstone [9] that people tend to discount the future and impending problems until too late. In this light, the CO_2 problem may be seen as an opportunity for significant innovations in the art and science of social policy development. These could occur in conjunction with a comprehensive TA of the "CO_2 effect" and other anthropogenic (human-caused) climate changes.

The methodological implications of this study are significant in that they demonstrate that although done quickly and on a low budget, a brief technology assessment can accomplish many of the objectives of a more comprehensive TA. In light of evidence that many important TAs have been neither widely known nor applied [10], the brief TA may in many situations even be the preferable strategy for technology forecasting and inquiry into the resulting social change, although the various components of a comprehensive TA (see Table 2) should be used at least as a methodological check list.

To summarize, the "brief" TA may be characterized as:

- *preliminary and incomplete* (as contrasted with the conventional TA) regarding the technology description and forecast, the impact analysis, and the assessment of policy implications

- *tightly constrained* (to the needs of the client or primary interest group and to overall context) regarding focus, role, and scope
- *recursive* (as are many comprehensive assessments) using an adaptive, "cut and try" strategy of inquiry
- *often quite rushed* (as are many studies whose results will quickly be used in pressing policy decisions) requiring the analysts to find relevant experts and information fast, and then to analyze and synthesize tentative results in a rapid sequence of interactions with both the client and the expert informants.

References

1. Porter, Alan L., Rossini, F. A., Carpenter, S. R., and Roper, A. T., *A Guidebook for Technology Assessment and Impact Analysis*, North Holland, New York, 1979.
2. National Research Council, Overview in *Energy and Climate*, NRC Panel on Energy and Climate, National Academy of Sciences, Washington, D.C., 1977.
3. Baes, C. F. Jr., Goeller, H. E., Olson, J. S., and Rotty, R. M., The Global Carbon Dioxide Problem, Report ORNL-5194, Oak Ridge National Laboratory, Oak Ridge, Tennessee (August 1976).
4. Chen, Kan, Winter, R. C., and Bergman, M. K., Carbon Dioxide From Fossil Fuels: Adapting to Uncertainty, *Energy Policy*, 318–330 (December 1980).
5. Keeling, Charles D. and Bacastow, R. B., Impact of Industrial Gases on Climate, in *Energy and Climate*. National Academy of Sciences, Washington, D.C., 1977, Chap. 4.
6. Rotty, Ralph M., Uncertainties Associated with Future Atmospheric CO_2 Levels, draft report for the ERDA Inexhaustible Energy Resources Planning Study, Institute for Energy Analysis, Oak Ridge, Tennessee (July 15, 1977).
7. Manabe, S., and Wetherald, R., The Effects of Doubling the CO_2 Concentration on the Climate of a General Circulation Model, *J. Atmos. Sci.* 32 (3) 15 (1975).
8. Ramanathan, V., Radiative Transfer Within the Earth's Troposphere and Stratosphere: A Simplified Radiative–Convective Model, *J. Atmos. Sci.* 33, 1330–1346 (1976).
9. Linstone, Harold, On Discounting the Future, *Technol. Forecast. Soc. Change* (4) 335–338 (1973).
10. Berg, Mark R., Brudney, J. L., Fuller, T. D., Michael, D. N., and Roth, B. K., Factors Affecting Utilization of Technology Assessment Studies in Policy-Making, Center for Research on Utilization of Scientific Knowledge, University of Michigan, Institute for Social Research (1978).

Received 25 February 1982, revised 18 May 1982