International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

# Estimating the Future Input of Fossil Fuel CO2 into the Atmosphere by Simulation Gaming

Stahl, I. and Ausubel, J.H.

IIASA Working Paper

WP-81-107

July 1981

# ESTIMATING THE FUTURE INPUT OF FOSSIL FUEL $CO_2$ INTO THE ATMOSPHERE BY SIMULATION GAMING

Ingolf Stahl
Jesse Ausubel

July 1981
WP-81-107



INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS
2361 Laxenburg, Austria

## PREFACE

A question of considerable interest in assessing long-term energy options involves whether the burning of carbon, particularly the plentiful resources of coal, will continue to increase at a fairly rapid rate. If so, the level of carbon dioxide ($CO_2$) in the atmosphere may rise substantially, perhaps doubling around the middle of the next century. It is widely believed that such an increase would gradually lead to a significantly different climate, probably one warmer than the earth has experienced for roughly 100,000 years, and to important consequences for the economy and environment.

What are the likely societal responses to this prospect? Will nations try to prevent or reduce such change? Will they choose to accept the change and seek adaptive measures? During the past year an effort has been underway jointly between IIASA's Resources and Environment (REN) and Management and Technology (MMT) areas to explore the various policy options through a gaming approach.

This Working Paper is the fifth describing the research. "Carbon and Climate Gaming" (J. Ausubel, J. Lathrop, I. Stahl, and J. Robinson, WP-80-152) offers the basic arguments in favor of a gaming approach and outlines briefly the two proposed games. "$CO_2$: An Introduction and Possible Board Game" (J. Ausubel, WP-80-153) sketches the $CO_2$ issue in non-technical terms, describes the objectives and a possible design for a board game, and includes a tentative listing of spaces for the game. "An Interactive Model for Determining Coal Costs for a $CO_2$-Game" (I. Stahl, WP-80-154) explains reasons for emphasizing coal mining, combustion, and world coal trade in the $CO_2$ gaming, and presents a model which begins the incorporation of the coal economy into a more complex computer-based game. "A Framework for Scenario Generation for $CO_2$

**ABSTRACT**

Previous estimates of input of fossil fuel $CO_2$ into the atmosphere are reviewed, including those of NAS, IIASA, IEA, and Marchetti. Methods employed largely disregard that if $CO_2$-induced changes are indeed harmful then there may be efforts to prevent emissions. There is a need to include explicitly societal response to increasing $CO_2$ emissions in estimating future input as well as the strategic interaction among national energy policies. Economic theory of the general equilibrium type, game theory, and computer simulation (without humans) have disadvantages in this regard. Gaming, involving humans playing the roles of various nations, may be an illuminating approach to the problem. A simple game, focusing on coal, trade, and many nations is proposed as an initial effort.

Gaming" (J. Robinson and J. Ausubel, WP-81-34) develops a framework for the generation of integrated scenarios of carbon use and climatic impacts in the computer-based game and for strengthening the design of the board in the board game. It also begins the elaboration of the events which are an important basis for $CO_2$ scenarios. This Working Paper further develops arguments on how the proposed computer-based game may improve estimates of future input of fossil fuel $CO_2$ into the atmosphere.

The carbon and climate gaming effort has benefitted greatly from comments from people who have read the various working papers and played the early versions of the board game. The research is still evolving, and ideas about how to improve the approach continue to be most welcome.

**CONTENTS**

## ESTIMATING THE FUTURE INPUT OF FOSSIL FUEL $CO_2$ INTO THE ATMOSPHERE BY SIMULATION GAMING

Ingolf Stahl and Jesse Ausubel

### 1. PREVIOUS ESTIMATES

A question of fundamental importance in evaluating the carbon dioxide issue is how much $CO_2$ is likely to be put into the atmosphere from burning of fossil fuels over the next 50 to 100 years. A wide range of estimates has been offered. While the numbers have varied a great deal, there has been a similarity of approaches.

Often the approach is simply to take the current level of fossil fuel combustion and multiply it by an assumed constant rate of change. Rotty (1977) estimated that historically $CO_2$ emissions from fossil fuel burning and cement manufacture have increased 4.3% per year except for periods of the two world wars and the global economic depression of the early 1930s. This figure of 4.3% has commonly been used to project future levels of atmospheric $CO_2$. 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 seems to have been the one most often discussed in the literature (Munn and Machta, 1978; World Climate Programme, 1981), arguments are, of course, made for estimates on both sides of this number. At the low extreme, one finds the projections of Lovins (1980). With a slight decrease of use of fossil fuels, a $CO_2$ "problem" never comes about. With a zero growth rate, a doubling of atmospheric $CO_2$ is estimated to occur in 2119, almost 140 years from now. At the high extreme, one finds the 50 terawatt (TW) global energy scenario proposed as a limiting case by Niehaus (1979). This scenario analyses the consequences for atmospheric $CO_2$ if all of a high projected energy demand is covered by fossil fuels.

Most energy scenarios lie in between and project a continued growth of energy demand to between 20 TW and 35 TW over the next 50 years. (Estimated global primary energy supply in 1975 was about 8 TW (IIASA, 1981).) These include scenarios developed for studies by the US National Academy of Sciences (NAS), the International Institute for Applied Systems Analysis (IIASA), and the Institute for Energy Analysis (IEA). Whenever these 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. Let us briefly examine the character of these projections which are the basis of much of the concern about $CO_2$.

### 1.1. NAS

Perry and Landsberg (NAS, 1977) project world energy consumption and emissions to the year 2025. The projections are for 11 geographic regions, which are sometimes large nations and sometimes aggregates of nations, based on estimates of the supply of energy resources of various kinds and energy demand. Demand is derived from projections of population, GNP, and the relationship of GNP per capita and energy consumption. Energy resources produced in a region are used to supply regional demand to the extent that production has been estimated to be able to meet demand.

Emissions are calculated for two situations. On the one hand, if regional demand exceeds regional production, an estimate is made assuming a new renewable, nonpolluting energy resource would be available to meet the deficiency of nonrewable resources. On the other hand, an estimate is made for the situation where regional deficiency would be met by coal, the fuel in greatest supply. Based on these assumptions, annual world $CO_2$ emissions in 2025 would be about 14 gigatons of carbon (Gt C) in the first case and about 27 Gt C in the second case, or about 3 to 6 times current levels. There is no feedback between environmental change and energy strategy, other than the possibility of being on one or another path at the outset.

### 1.2. IIASA

The IIASA Energy Program (Niehaus and Williams, 1979; IIASA, 1981) analyzed several hypothetical energy strategies for the period up to the year 2100 for their implications for atmospheric $CO_2$. Distribution of energy supply among coal, oil, gas, solar, and nuclear is derived from a global energy model developed by Voss (1977). This model is structured into six sectors: population, energy, resources, industrial production, capital, and the environment. There is no geographic disaggregation. Proportions of fossil fuels used are determined by the Voss model, with some additional consideration of available resources.

Among the scenarios explored (Niehaus and Williams, 1979) are four in which global demand levels out to either 30 TW or 50 TW in 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 1 shows the reserves of fossil fuels used in each strategy.

Table 1. Reserves of fossil fuels used in different strategies.

| Strategy | Coal Gt C | Oil Gt C | Gas Gt 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 |

SOURCE: After Niehaus and Williams (1979).

The scenarios with reliance on nuclear and solar energy lead to peak $CO_2$ emissions of less than 10 Gt C per year, while the scenarios with reliance on fossil fuels lead to emissions of about 22 Gt C and 30 Gt C in 2025, increasing somewhat thereafter. While consideration is given to available fossil resources at the global level, no more detailed study is undertaken. As in the NAS study, the only feedback between $CO_2$-induced environmental change and energy strategy is the one implicit in choice between paths at the outset.

**1.3. IEA**

For several years, Rotty and co-workers at IEA (Rotty, 1977, 1978, 1979a; Marland and Rotty, 1979) emphasized extrapolation of figures in the vicinity of the 4.3% estimate of historic annual increase in $CO_2$ emissions. Based on demand and fuel share projections made for six world regions, an annual fossil fuel release of $CO_2$ containing 23 Gt C for 2025 is calculated. Arbitrary global fossil resource usage rates are applied for very long term tests of sensitivity of atmospheric concentrations.

A more recent paper (Rotty and Marland, 1980) begins to evaluate constraints on fossil fuel use. Three kinds of constraints are discussed: resource, environmental, and fuel demand. With respect to the resource constraint, Rotty and Marland (1980) conclude that the fraction of total resources already used 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 also dismissed as a constraint to fossil fuel use. "Although global warming of about 1°C to 1.5°C over a 50-year time span is enough to cause concern among climatologists, it is probably not enough to cause a revision in policy of fossil fuel use -- especially at the beginning of the 50-year period, and when fossil fuels play a major role in the global economy." Arguments other than the uncertainty about possible costs of climatic change are not presented to back this conclusion.

In contrast, Rotty and Marland (1980) discuss at some length that slower growth in fuel demand dictated by social and economic factors will limit fossil fuel use. Reduced economic growth is projected as a result of problems with capital and escalating costs and shifts toward conservation and less energy intensive industries. It is unclear whether international stress and threat of environmental change are themselves elements in causing the reduction in demand. In any case, summing up estimates for about a dozen countries and half a dozen aggregate regions results in a $CO_2$ release in 2025 of about 14 Gt C, an annual growth rate of 2% per year over the current level.

### 1.4. Marchetti

One other projection, employing a quite different logic, must be mentioned. Marchetti (1980) has made a forecast of the amount of $CO_2$ which will be emitted to the year 2050 based on a logistic substitution model of energy systems (Marchetti and Nakicenovic, 1979). This model treats energies 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 economies of scale associated with each energy source. The approach downplays the causal importance of resource availability, political arguments, and prices.

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 with Rotty (1979b) who finds that commercial energy supply, excepting times of world conflicts and depression, has grown at a rate of about 5.3% since 1860.) Applying a future growth rate of 3%, 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 quite important role for natural gas, and over the next 50 years a negligible role for new sources other than nuclear. The model predicts a cumulative increase in atmospheric carbon to the year 2050 of about 400 Gt, an amount below most other estimates, as well as a gradual reduction in atmospheric $CO_2$ thereafter.

## 2. COMPARING THE SCENARIOS

Comparison of the scenarios shows some features in common. Most prominent is an assumption that virtually all easily accessible oil and gas will be consumed. This assumption is difficult to argue with; the timing may be a point of contention, but these sources seem too attractive to remain underground.

However, the scenarios differ considerably, some suggesting an annual emission in 2025 of less than 10 Gt and others suggesting as much as 30 Gt. Since the scenarios differ so much, certain questions begin to arise. Is there some way to choose among them? Which is more likely? Is there a way to improve or bound the estimates generally? One way of choosing among the scenarios would clearly be to select on the basis of other assumptions, for example, about overall population or economic growth. Similarly, arguments can be made about lifestyle change or technical efficiency.

One perhaps more researchable means of both evaluating the scenarios and improving future forecasts may be to look for internal consistency. Do the various levels of emissions presuppose plausible patterns of international trade? Are they based upon distributions of natural resources which are in line with current estimates? Do they violate notions of national behavior?

### 2.1. A General Deficiency

The estimates above have a general deficiency when applied to analysis of the $CO_2$ issue. These are projections in which the estimates of ejected $CO_2$ are almost incidental; if the $CO_2$ issue is indeed trivial, then the estimates may be consistent. However, if the issue is more serious, than the method of estimation needs to take into account the changing level of $CO_2$ itself. That is, there is a need for feedback between environmental change and energy use.

If the emission of $CO_2$ is harmful in the long run for certain countries, possibly for many countries, then at some time interest in preventing $CO_2$ emissions will rise. Indeed, suppose that it becomes reasonably certain during the next one to three decades, either through results of more extensive research or by an actually experienced minor change in climate, that the effects of $CO_2$ emissions will be strongly negative for at least some countries. What would be the likelihood of reducing emissions? What forms of control might be feasible? What will be the effect of prevention efforts on emissions?

Focusing on this aspect of the issue indicates that a forecast of $CO_2$ emissions should not be a description of a mechanistic process but an analysis of the interaction between actual or perceived effects of $CO_2$ and the actions taken by various decision makers. Human decision makers largely determine how much $CO_2$ is added to natural sources and released to the atmosphere. In theory at least, governments and peoples could make the issue dissolve by deciding to reduce significantly the burning of carbon. It is their perception of the consequences of $CO_2$ emissions as well as their interaction with each other that will determine the decisions and thus the amount of $CO_2$ emitted.

The question of $CO_2$ emissions should not be regarded as only a technical one, but rather as one involving societal responses, where decision makers are a central focus. By focusing on the decision making processes and the effect of information on these processes, one can also hope to advance discussion of other important questions. For example, can we wait to take preventive action on $CO_2$ until we know with certainty about the effects of $CO_2$? Is the time lag among perceived effects, decisions, and adjustments so long that recommendations for action should be given quite soon?

## 3. WAYS TO STUDY SOCIETAL RESPONSES TO THE $CO_2$ ISSUE

Having established the reason for studying societal responses to the $CO_2$ issue, the question becomes what research strategy may shed light on the problem.

### 3.1. Do Not Study at All

The first possible answer is not to study the question at all. Many would stress the enormous complexity and long time perspective, implying that all findings would be uselessly hypothetical. Others would say, continue to leave the problem entirely as a concern of physical scientists. We do not, however, subscribe to these attitudes. That a problem is difficult, complex, and long-term does not mean that research will have no value. If the question is potentially important, serious attempts to explore it are worthwhile from several points of view. It is evident that we will not come up with correct predictions about what will happen half a century from now. However, we may make substantial progress over the scant picture currently available. And, by attempting better descriptions now, we may be able to develop useful means for organizing information so that as time evolves one can give gradually better and better answers. Moreover, having a more reliable forecast 5 or 10 years from today of impending climatic change will be of little value, if we have not made progress in analysing societies' concerns about and responses to climatic change.

Another group would say that at the present time it is simply unnecessary to worry about a long-term issue like $CO_2$. Before it becomes an acute problem, technological innovations like the "giga-mixer" (Marchetti, 1977) will take care of it. We are not certain that such a technologically optimistic view is justified. We by no means rule out the possibility of such solutions, but the probability of the absence of such solutions is large enough that thinking about a world with increasing $CO_2$ in the atmosphere is an important research task.

Hence we proceed with looking for concrete proposals on how to study societal responses to the prospect of high levels of burning of carbon.

### 3.2. Optimization

One approach is that of optimization, searching for the best possible outcome of exploitation of carbon and climatic resources. In simplest terms, one makes some best estimate of the impact of $CO_2$ and climatic change on economic activities and maximizes the present value of the benefits of burning carbon and the costs and benefits of the impacts caused by resulting levels of $CO_2$ in the atmosphere. Nordhaus (1979) has tried to determine an optimal path for the whole world to follow in burning of carbon with respect to the potential effects of $CO_2$ on the environment and economy.

There is a considerable problem with this approach. Global optimization implicitly assumes the existence of some kind of single benevolent world ruler, an entity capable of implementing the policies which the global objective function suggests. While we do not know the geopolitical configuration of the 21st century, this appears to be an unrealistic assumption, or at least an extreme one. It seems more likely that the world, even as integration and interdependence increase, will continue to consist of many sovereign states. Indeed, our major working hypothesis is that in the future there will be many independent nations, often having conflicting aims in regard to factors which form the $CO_2$ issue, particularly energy policy.

### 3.3. Game Theory

To advance our understanding of the likely evolution of the $CO_2$ question, it appears to be of fundamental importance to develop an analysis which can portray dynamically the conflict potentially inherent in the situation. Hence, we turn to the theory and playing of games, and the analysis of a situation involving conflicting interests in terms of gains and losses among opposing players. The conflict situation embodies at least two different kinds of games.

#### 3.3.1. The "Tragedy of the Commons" Game.

One way of seeing the $CO_2$ issue is as a long term game involving a tragedy of the commons (Hardin, 1968), where the potential tragedy is use of the atmospheric common for waste disposal to the extent that a catastrophic change of climate takes place. For the sake of simplicity of exposition, this game can be represented as a kind of "Prisoners' Dilemma" (Rapoport 1974), with interaction between two players or nations. In the $CO_2$ case, each nation regards itself as small, with its actions having a minor effect on climate, and regards other nations as one big nation, "the outer world," with a large effect on global climate.

If we let nations A and B represent many nations in the eyes of the other party, the game can be studied in the form of a simple matrix. The numbers in the matrix imply a ranking of the outcomes for each player. A player prefers an outcome with as high a number as possible, that is, a payoff of 4 is best and a payoff of 1 is worst.

We look more closely at the matrix, starting with A's decision. Recall that A sees B as a big player. If A believes that B will burn, then A will think that the climate will be ruined anyway in the long run, regardless of whether he himself will burn. A faces a choice between an outcome of 2 for burning and 1 for not burning, and A will then burn and get the short term benefits of burning.

Alternatively, suppose that A believes that B will not burn. Since A regards himself to be small and hence only a marginal factor in the climate, tnen A will still burn. In this way A achieves his best outcome, 4, with the benefits of both burning and essential conservation of the climate. A prefers the short term benefits of burning to marginally affecting the climate in a beneficial way.

Table 2. Prisoners' Dilemma Game.

| | | B: Burn | B: Not Burn |
|---|---|---|---|
| A | Burn | 2, 2 | 4, 1 |
| | Not Burn | 1, 4 | 3, 3 |

Since we assume that B has a similar view of the world, in this symmetric game the same decisions will be made by B. Each party will burn regardless of what he thinks that the other party will do. Hence, they will together reach the outcome 2,2 in spite of the fact that they would both prefer the result 3,3, that is, that no one burns.

This is the general problem of the tragedy of the commons. If the players were committed to pursuing a strategy of cooperation, in this case of not burning, everyone would be better off. If possibilities of forming binding agreements or establishing mutual trust are lacking, then each party will act contrary to the common interest. (See Godwin and Shepard, 1980, for a discussion of the influence of specific incentive structures on the outcome of commons dilemmas.)

An advantage of presenting the commons problem in the Prisoners' Dilemma format is that it focuses on the question of whether legally binding or morally committing agreements on not burning can be reached. Furthermore, it helps relate the analysis to the extensive experimental gaming work done on the Prisoners' Dilemma. (See, for example, Guyer and Perkel, 1972.) These advantages should outweigh the argument (see Dasgupta and Heal, 1979) that the Commons problem is not formally equivalent to the many player version of the Prisoners' Dilemma game in the sense that the strategies of the equilibrium solution are not generally formed by dominating strategies.

**3.3.2. A Game of Opposing Interests.**

While the Tragedy of the Commons (Prisoners' Dilemma) game deals with the longer term problem of a catastrophic change of the climate, for example, in the form of a sea level rise induced by collapse of of the West Antarctic ice sheet, there is another game situation arising from impacts obtainable in a shorter time perspective, perhaps within a few decades. It seems quite likely that already at a global average warming of 1'C, considerable changes in agricultural conditions would be experienced. (See Flohn, 1980.) Such changes could well be beneficial for some regions and adverse for others.

As a hypothetical case, let us follow Gribbin (1981), who suggests the possibility that a global warming might lead in general to problems for areas producing wheat and corn, while improving prospects in rice growing areas. Such a scenario might hold if findings about warming being associated with drier conditions in middle and high latitudes (Manabe and Wetherald, 1980) turn out to be correct. If one looks at the situation from a global perspective and regards population as completely mobile, one might well find that the deteriorated conditions in some areas are offset by improved conditions in other areas. However, one must recognize that many attach a high negative value to large scale population movements. If one assumes limitations on or great costs of both internal and international migration, then the situation becomes one of opposing interests between players, that is, regions or nations.

Returning to our hypothetical case, a rice player may prefer burning of carbon, not only "domestically," but also elsewhere, since it may lead to a more favorable climate. A wheat player, in contrast, will not only dislike the burning carried out by others, but might even find his own burning detrimental, if he is a large enough player. This example leads to a matrix like the one in Table 3. In order to emphasize the difference from the Prisoners' Dilemma matrix described earlier, we here assume that the player Wheat is relatively large. In this matrix we see that Rice prefers the situation when both burn carbon, while Wheat prefers the situation when nobody burns. The result will be that Rice burns, while Wheat does not burn.

Table 3 could very well have other forms. The important point is that in the medium term (that is with a time horizon before a catastrophic possibility the $CO_2$ issue may have a different character than in the long term. In particular, in the shorter perspective some parties might actually prefer a higher level of $CO_2$ in the atmosphere. Both game situations described here and other plausible ones, involving, for example, distribution of benefits from direct $CO_2$ "fertilization" of plants or opening of arctic transport routes, stress that it is important to have an analysis of the $CO_2$ issue that focuses on the fact that different countries have different perceptions regarding the character of a $CO_2$-induced warming and various societal responses may be warranted.

Table 3. Game of opposing interests.

| | | Wheat | |
|---|---|---|---|
| | | Burn | Not Burn |
| Rice | Burn | 4 \ 1 | 3 \ 2 |
| | Not Burn | 2 \ 3 | 1 \ 4 |

## 4. STUDYING THE GAME SITUATION

Having established that the $CO_2$ issue involves a game situation, the more specific question of how to study such a situation arises. In particular, focusing on the first kind of game problem, that of the Tragedy of the Commons, how does one begin to explore if there will be some agreement on international cooperation to limit carbon burning and if in the absence of such agreements a tragedy will occur.

### 4.1. Economic Theory

One possible approach would be to employ economic theory of the general equilibrium type. We would then assume the existence of a great many, small, independently acting countries. This assumption in itself, however, implies the answer the analysis would give. With each nation acting independently, cooperation would not take place. The basic assumption precludes analysis of strategic interdependence existing between various nations.

It should be stressed that it is by no means without interest to carry out this type of economic analysis. It may provide an extreme value for what could happen if there is no cooperation at all. One might then come to understand better how serious a "tragedy" could result from the total absence of cooperation.

### 4.2. Game Theory

To incorporate considerations of interdependence among nations, we turn to game theory, which focuses on strategic relationships between rational actors. (Rationality generally implies that each actor is maximizing his individual utility and has correct expectations about the other actors.) Broadly speaking, game theory can be divided in two categories, cooperative theory and noncooperative theory. (See, for example, Bacharach, 1976.)

Cooperative theory implies that the parties first find and decide on a jointly optimal strategy and then proceed (if side-payments are allowed) to divide the jointly optimal result. Much of cooperative theory consists of schemes for dividing the results. Cooperative theory could thus build on the global optimization model of Nordhaus and examine the question of how to share the results of a non-tragedy outcome. In contrast, noncooperative theory does not allow any commitment to agreements. As in the Prisoners' Dilemma situation presented above and traditional economic theory, an outcome with no cooperation, most likely leading to a tragedy, is obtained. A critical problem for exploring the $CO_2$ question is which body of game theory to apply, cooperative or noncooperative, when the reality might lie between the results produced by the two extremes of complete cooperation and complete lack of cooperation.

There is little higher level theory helping to identify which of these two main bodies of theory is appropriate. The little theory there is indicates that the total number of players is one factor of importance for determining whether stable cooperation is feasible or not. The fewer the players are, the more likely one is to get some cooperative agreement on a set of jointly optimal strategies. This has been shown mainly for games with players of equal size. The idea is that belonging to a cartel is advantageous, but that in certain cases it will be more advantageous to be a party outside of the cartel, when all other parties are in the cartel. In some very simple games, with players of equal size, simple demand and cost functions, and complete information, the critical number of players has been shown to be around 4 to 6. (Selten, 1973; see also Guyer and Cross, 1980, p. 131.) In games where there are players of different sizes and complex demand and cost functions and a dynamically evolving state of information for the players, the aid which game theory can provide in estimating the outcome is quite limited.

### 4.3. Simulation

Realizing the complexity of the $CO_2$ situation, we next consider using computer simulation, not involving humans as players. The advantage of computer simulation is that it allows complexity in cost and demand conditions, as well as stochastic characteristics regarding the state of nature. Furthermore, in contrast to game theory, one is not required to assume complete rationality and correct expectations by the actors. Finally, computer simulation models can be run a great number of times, testing how sensitive results are to changes in various parameters.

There is, however, a major obstacle to direct use of this type of computer simulation for studying the $CO_2$ issue. We do not know how to specify the equations representing the behavior of the nations to be represented. For example, how will a large country respond when some smaller country starts to defect from an agreement? Will it also defect to punish the other country? Or, will it continue to play cooperatively for awhile, hoping to bring the other country back to cooperation? Whether we get stable international cooperation or a tragedy of the commons can depend largely on how these behavioral equations are specified.

It has been shown in other game situations that it is difficult to formulate behavioral equations for players without studying first the actual behavior of human players in several runs of a game. Even for a game as simple as the Prisoners' Dilemma played many times in a row, it has been difficult to construct reasonable simulation models without using information from a great many actual gaming experiments. (See Stahl, 1975.)

### 4.4. Gaming

Gaming, the playing of games involving several humans, appears to be a method well-placed for gaining insights into the $CO_2$ question. (See Shubik, 1975 and 1980, for basic discussion of gaming.) It is a method which has been used with success for a variety of problems, for example, in the military and in business, in countries with different economic systems. (Brewer and Shubik, 1979; Marshev, 1981) While maintaining several of the advantages of simulation and game theory, it overcomes the problem of performing a simulation without a behavioral basis. By involving human players in the game, we can observe human responses in specific situations and begin to learn about the critical variable, namely the propensity of humans in this situation to build trust and to respond to noncooperation. In the exploration of societal responses to the $CO_2$ issue, gaming thus would seem logically to precede simulation without humans. While gaming appears to have certain advantages as a research tool for the $CO_2$ question, it also has benefits from the points of view of education and collection of information (Ausubel and others, 1980; Stahl, 1980; Robinson and Ausubel, 1981).

Several objections can also be raised to the use of gaming. These center on the the question of whether a game played by a small number of players in an "experimental" setting in a short time can have any validity as regards a long-term problem of enormous complexity.

It must be stressed first that gaming can give only extremely tentative answers and that we see gaming as an appropriate method for our problem, not in an absolute sense, but in a relative sense as compared to other methods. With respect to the specific game proposed in this paper, we believe there are ways to respond to some of the most common criticisms of the methodology of gaming. These objections include the following.

[1] The relationship between the "level" of the actor in reality and the player in the game. The classic example of this problem in the gaming literature is the American college student playing the role of the Chinese foreign minister. The problem for the $CO_2$ game is probably less drastic. Given the international character of IIASA, it should be possible to have players from most of the nations covered in the game. Secondly,players will include both scientists in the energy field and people from government and industry, who, although not on the top decision level, have a good feeling for the real decision making process. In this regard experience with a IIASA regional water cost allocation game played with water and regional planners in Bulgaria, Italy, Poland, and Sweden is encouraging (Stahl and others,1981). It should be mentioned that the positive experience in

obtaining qualified participants is due to a great extent to the fact that the gaming experiments are designed to be completed in about three hours, or a single evening. The $CO_2$ game is being designed to be similarly attractive from the point of view of desirable players.

[2] The relationship between how a certain person would behave in reality and how he would behave in a game. How seriously does a person behave when playing in a game? In this respect we are again hopeful based upon experience with the water game. The fact that water planners in several quite different countries played in a similar manner (different from how students in these countries played) indicates that their playing was not random, but rather reflected careful professional thinking.

[3] The relationship between the real decision environment, for example, with respect to resources, technological development, and changing scientific information, and how this is covered by the institutional assumptions of the game. Clearly, there will be a tremendous discrepancy. We believe, however, that the game can still be used as an acid test for various hypotheses and theoretical models about the decision process. These hypotheses or models are generally built on at least as simplified a set of institutional set of assumptions as the game. If the players do not behave according to the model in the simple game with an institutional set up of the same simplicity as the model, they are not likely to behave according to the model in the more complicated reality either. The gaming should at the least be helpful in indicating what kind of hypotheses and models one should devote more research to.

## 5. MAIN CHARACTERISTICS OF THE PROPOSED GAME

While several games based on the $CO_2$ situation could be envisaged, the game under development focuses on the question of how much carbon may be burnt, as more information becomes available regarding the environmental and economic impacts of $CO_2$. The main structure of the game can be characterized in brief by coal, trade, and many countries.

### 5.1. Why Coal?

The *sine qua non* of a severe $CO_2$-induced climate problem seems to be the burning of coal.

We here take a doubling of atmospheric $CO_2$ as a level which warrants considerable concern. This choice is quite arbitrary. Both greater and lesser increases could have very costly -- or beneficial -- consequences. However, an increase of 50%, which might be associated with a degree of warming similar to the Medieval warm phase 1000 years ago, seems on the conservative side, while placing a threshold as high as a tripling definitely seems imprudent, given possibilities for changes of sea level and so forth (Flohn, 1980).

As shown in Table 4, current estimates of total reserves and resources of oil, gas, coal, and other forms of carbon indicate that a doubling of the present level of atmospheric carbon dioxide within the next 50 to 100 years will only be reached with substantial burning of coal. Even allowing for the considerable uncertainty of these estimates, it comes

Table 4. Potentially available carbon resources.

| | Best current estimates (Gt C) | Upper limit speculation (Gt C) |
|---|---|---|
| Ultimately recoverable conventional petroleum resources[1] | 230 | 380 |
| Ultimately recoverable conventional natural gas[1] | 140 | 230 |
| Ultimately recoverable conventional coal[1] | 3500 | 6300 |
| Unconventional oil and gas[2] | hundreds of Gt | thousands of Gt |
| Biospheric (forests, etc.)[3] | — | ~200 |

SOURCE: 1) Rounded from Rotty and Marland (1980); 2) See IIASA (1981), Rotty and Marland (1980); 3) Cumulative release in high deforestation scenario (Chan and others, 1980).

across strongly that non-coal carbon resources are not large or accessible enough to be exploited to a degree that is highly threatening from a $CO_2$ perspective. Total oil and gas resources, even with the addition of high rates of deforestation, amount to only about half the 1500 gigatons of carbon (Gt C) roughly necessary for a doubling, given present models of the carbon cycle (NAS, 1977; Bolin and others, 1979). It should be noted that some estimates of unconventional gas and oil resources, especially oil shale, are quite large (Rotty and Marland, 1980). However, exploitation of these resources on a scale which could be significant for $CO_2$ seems unlikely for until well past the year 2000 (Sundquist and Miller, 1980; IIASA, 1981). In contrast, coal could readily account for two-thirds or more of $CO_2$ emissions in a scenario of doubling in the early to middle decades of the next century (Marland and Rotty, 1980; Ausubel, 1980). Moreover, the extremely desirable characteristics of oil and gas make their exploitation appear less "optional" than exploitation of coal. Because coal plays this indispensable role in the $CO_2$ issue, it is logical to begin game development with the emphasis on coal.

### 5.2. Why Trade?

Why the game explicitly deals with trade in coal is evident from Table 5, which shows the approximate distribution of coal reserves and resources.

Table 5. Approximate world distribution of coal resources (in gigatons carbon).

| Huge holdings | | Large Holdings | | Small Holdings | |
|---|---|---|---|---|---|
| USSR | 3300 | Australia | 180 | Czechoslovakia | 12 |
| U.S. | 1700 | FRG | 170 | Yugoslavia | 7 |
| China | 1000 | UK | 110 | Brazil | 7 |
| | | Poland | 80 | GDR | 7 |
| | | Canada | 80 | Japan | 6 |
| | | Botswana | 70 | Colombia | 6 |
| | | India | 40 | Zimbabwe | 5 |
| | | South Africa | 40 | Mexico | 4 |
| | | | | Swaziland | 3 |
| | | | | Chile | 3 |
| | | | | Indonesia | 2 |
| | | | | Hungary | 2 |
| | | | | Turkey | 2 |
| | | | | Netherlands | 2 |
| | | | | France | 2 |
| | | | | Spain | 2 |
| | | | | North Korea | 1 |
| | | | | Romania | 1 |
| | | | | Bangladesh | 1 |
| | | | | Venezuela | 1 |
| | | | | Peru | 1 |

SOURCE: Based on data from World Energy Conference (1978). Very rough estimate of carbon wealth in Gt has been obtained by multiplying coal resources in $10^9$ tons coal equivalent by carbon fraction of 2/3.

More than four-fifths of the resources are held by three countries, the USSR, US, and China (henceforth regarded as "big" players). The total holdings of the remaining countries, including a few gigatons for countries with holdings smaller than one gigaton, amount to around 800-900 gigatons, or somewhat more than half the carbon base required for a doubling. As it is unlikely that a major part of this will be used within the next few generations, it seems reasonably assured that a serious $CO_2$

problem will arise only with substantial use of the coal resources of the three big players. If these big players do not export large amounts of coal and also keep their own coal combustion low, a severe $CO_2$ problem should not arise. The $CO_2$ issue arises in scenarios, like the ones proposed in the World Coal Study (WOCOL, 1980), where over the next 20 years roughly a ten-fold increase in steam coal trade is envisaged (from 60 million tons in 1977 to 680 million tons in 2000). Coal trade could become important for coal consumption in the way that oil trade is today for oil consumption. Without a substantial world coal trade, the physical quantities of carbon required for a $CO_2$ problem are unlikely to be used.

Trade in coal is also of importance for the estimation of future coal usage from another point of view. Coal usage will depend partly on the price of coal. Although total consumption of energy in the short run is fairly insensitive to price, consumption of a specific energy source in the long run will be sensitive to the price of the resource, since in the long run there are possibilities of substitution between various sources of energy. (See, for example, Nordhaus, 1977.) The extent to which there can be substitution between coal and other sources of energy is a major aspect of the $CO_2$ question, and our working hypothesis is that reasonably good possibilities of substitution exist. The price of coal traded on world markets thus becomes important for coal usage. If a country either has to import or can export coal, then the world market price of coal will influence the country's consumption of coal.

We foresee a world market price of coal, much in the same way as one talks today about a world market price of oil, not only in the market economies but also in the socialist countries. Three broad levels of coal prices can be envisaged.

[1] A cost based price. Price would be close to long term average costs of marginal producers. This price is compatible with the idea that the coal market is characterized by pure competition, that is, a market with a great many sellers. This resembles the oil price situation prior to 1973.

[2] Monopoly price. The price would maximize the joint result of the producers. The sellers forming a cartel would be better coordinated than the buyers. This is a situation similar to that of oil prices since 1973. For reasonable values of price elasticity, this would imply a price several times higher than marginal costs. (Let us, for example, assume that price elasticity $E = 1.5$, implying that a lowering of price by 10 per cent will increase long term usage by 15 per cent. Maximizing profits, that is, setting marginal revenue equal to marginal costs, we would then have $p = E * MC / (E-1) = 1.5MC / 0.5 = 3MC$, or a price three times marginal cost.)

[3] A price above monopoly price. Such a price could reflect concern for the environmental effects of coal, in particular a $CO_2$ problem. On top of the ordinary price, there would be a tax to lower the consumption of coal to that level which is optimal if the cost of coal also includes the costs caused by the $CO_2$ effects on climate. This price is thus a kind of shadow price. As pointed out by Nordhaus (1979) such a "carbon tax" could become quite high, especially at the time when the $CO_2$ level in the atmosphere has gone up. ( Such a price can of

course also be below the monopoly price, but always above the cost based price, if the environmental effects of $CO_2$ are not so strong or immediately felt.)

Which kind of price prevails will be established largely by trade structure, that is, by the number and relative strengths of the exporters and importers.

Trade in coal is also of interest in connection with different schemes of international cooperation for reducing or preventing $CO_2$ emissions. The possibility for the larger countries to limit the supplies of coal either on the world market generally or to specific countries can give teeth to attempts at enforcing international agreements to limit the usage of coal.

### 5.3. Why Many Countries?

The basic reason for inclusion of more than a very few nations is that the $CO_2$ issue in reality concerns a world where many nations, able to act with some independence from one another, affect the problem. If we limit ourselves to only a handful of actors in all phases of development of the game, certain scenarios would be excluded where international cooperation is impeded by the actions of relatively small nations. This kind of possibility is also the reason that it is not appropriate to deal with aggregate energy regions, likely to contain several countries with quite different characteristics from the point of view of the $CO_2$ issue. Of course, it is also not necessary to represent every nation in order to capture the essence of the $CO_2$ issue.

Which nations or kinds of nations are critical? Obviously, the three big players are of great importance. At the same time, a major portion of energy consumption will be taking place outside these countries. Large future users of energy like Japan, Brazil, and Italy are among the nations with relatively small holdings of coal, and the behavior of such potentially large importers will be of interest. Players which can affect cartel efficiency are also of great significance. Even if the three big players account for around 80 per cent of total coal resources, the resources of some smaller holders are large from an absolute point of view. As Table 5 shows, another eight countries have substantial holdings, holdings currently estimated at more than 40 Gt. 40 Gt corresponds roughly to total global carbon emissions during the past decade. Such players can affect cartel efficiency.

Furthermore, there are some countries, although neither large coal consumers nor producers, that are important due to the fact that a severe $CO_2$ problem would be particularly imposing for them. For example, collapse of the West Antarctic ice sheet and ensuing rise of the world oceans (Schneider and Chen, 1980) could constitute a true catastrophe for low-lying countries like the Netherlands and Bangladesh.

While the "reality" of the situation is one reason to include more than just a few players, the other major reason is that answers to the question about likelihood of cooperation are dependent on the number of players involved in the game. For example, with only three players cooperation in the game is quite likely. As mentioned earlier, in some very simple games with all players of equal size 4-6 seems to be the boundary between few and many. In games with players of different sizes the boundary will probably lie higher.

Ultimately one would probably wish to include about twenty countries of different sizes and characteristics to catch fully the strategic problem. While the roles of only seven or eight countries would be played by human players, the remaining dozen nations would be played by computer programs, "robots." (See Ausubel and others, 1980.)

### 5.4. General Structure of the Game

The initial design of the game is oriented toward what may happen a generation from now, if there is confirmation of a $CO_2$-induced global warming. With the decades around 2010 - 2020 as critical, the game needs to cover a period of half a century and possibly longer. There will be up to about 10 rounds of decision, each representing 5 or 10 years. Since the game should be playable in roughly three hours, the number of decisions in each 15-20 minute round must be strictly limited.

The general structure of the game is shown by Fig. 1.

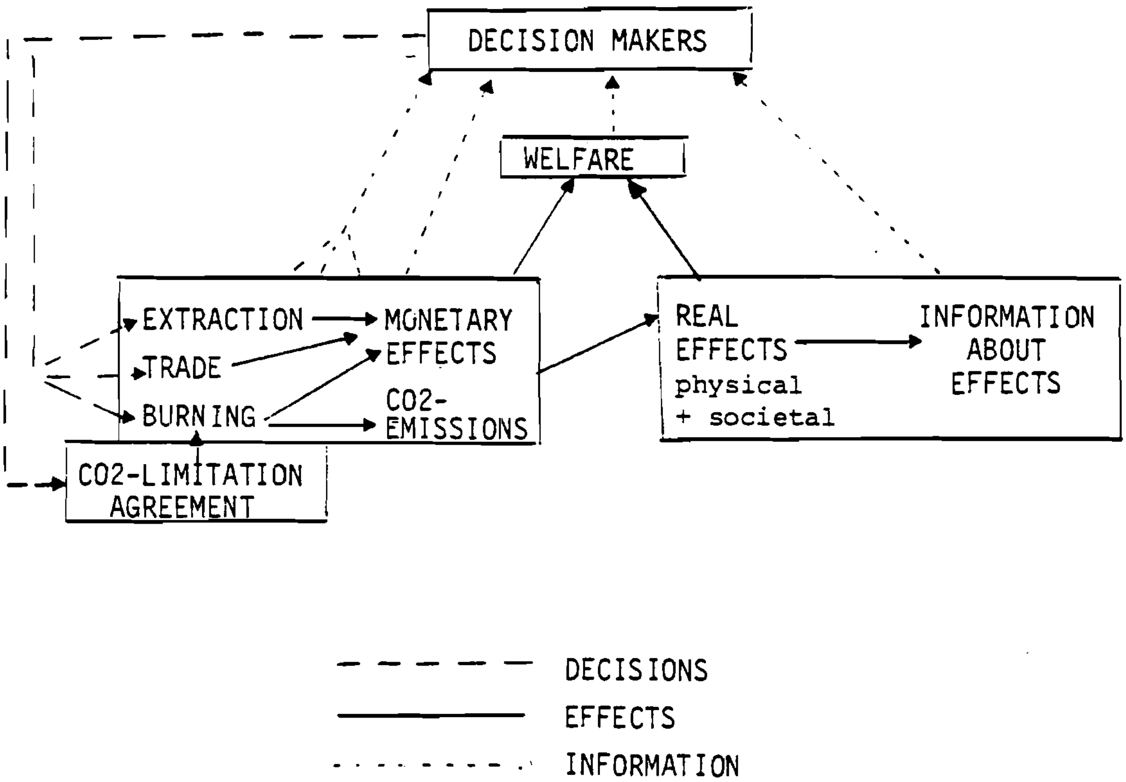


Figure 1. Main structure of the game.

Decisions are represented by dashed lines extending from the decision makers. Each player will have four principle decisions in a round.

[1] An extraction decision: How much coal shall be mined?

[2] A trade decision: How much coal shall be demanded or supplied on the world market at various prices?

[3] A burning decision: How much coal shall be combusted?

[4] A decision on $CO_2$-limitation: How much shall one pay in order to get other nations to agree on burning less coal?

Extraction, burning and trade decisions will have monetary consequences, while the burning decision also will have effects on climate. The welfare of the player is influenced by both these shorter term monetary effects and the longer term climatic effects of $CO_2$. Players will base their decisions not only on information about their own economic welfare, but also on information about mining, trade, and coal burning by other players and information which will develop gradually over time about actual and anticipated $CO_2$ effects. (For more information on game design see Ausubel and others, 1980; Stahl, 1980; Robinson and Ausubel, 1981.)

## 6. CONCLUSIONS

In the beginning of the paper various estimates for the input of fossil fuel $CO_2$ into the atmosphere were presented. These estimates may well be inadequate, since the methods underlying them do not take into account societal responses that $CO_2$-induced changes may bring about. Experimental gaming, focusing on development of international coal trade, may provide an approach which overcomes some of the deficiencies of other methods. On the basis of designing and playing a $CO_2$ and coal game with experts in energy and other fields, one should be in a better position to evaluate previous estimates of future $CO_2$ emissions and improve on these estimates.

Of course, one should not look to gaming for an authoritative forecast; the uncertainties inherent in the $CO_2$ issue will continue to mean that there is a fragile foundation to all forecasts. Rather, the application of simulation gaming to this problem should be seen as part of the necessary contribution of many disciplines and methodologies to the building up of a satisfactory assessment of the $CO_2$ issue.

**REFERENCES**

Ausubel, J. (1980). Climatic change and the carbon wealth of nations. Working Paper 80-75. IIASA, Laxenburg, Austria.

Ausubel, J., J. Lathrop, I. Stahl, and J. Robinson (1980). Carbon and climate gaming. Working Paper 80-152. IIASA, Laxenburg, Austria.

Bacharach, M. (1976). *Economics and Theory of Games*. MacMillan, London.

Bolin, B., E.T. Degens, S. Kempe, and P. Ketner (1979). *The Global Carbon Cycle*. Wiley, Chichester.

Brewer, G.D. and M. Shubik (1980). *The War Game*. Harvard University Press, Cambridge, Mass.

Chan, Y.-H., J. Olson, and W. Emanuel (1980). Land use and energy scenarios affecting the global carbon cycle. *Environment International*, Vol. 4, pp. 189-206.

Cross, J. and J. Guyer (1980). *Social Traps*. U. of Mich. Press, Ann Arbor.

Dasgupta, P.S. and G.M. Heal (1979). *Economic Theory of Exhaustible Resources*. Nisbet and Cambridge University Press, Cambridge.

Flohn, H. (1980). Possible climatic consequences of a man-made global warming. Research Report 80-30. IIASA, Laxenburg, Austria.

Godwin, R.K. and W.B. Shephard (1980). The use of the commons dilemma in examining the allocation of common resources. RFF reprint 179, Resources for the Future, Washington, D.C.

Gribbin, J. (1981). The politics of carbon dioxide. *New Scientist*, April 9, pp. 82-84.

Guyer, M. and B. Perkel (1972). Experimental Games: A Bibliography

1945-1971. Communications Nr. 293, Mental Health Research Institute, U. of Mich., Ann Arbor.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, 16, pp. 1243-1248.

International Institute for Applied Systems Analysis (IIASA) (1981). *Energy in a Finite World: A Global Systems Analysis*. Ballinger, Cambridge.

JASON (1979). The long term impact of atmospheric carbon dioxide on climate. Technical report JSR-78-07. SRI International, Arlington, Virginia.

Lovins, A.B. (1980). Economically efficient energy futures. In Bach, W., J. Pankrath, and J. Williams (eds.), *Interactions of Energy and Climate*. Reidel, Dordrecht. pp. 1-31.

Manabe, S. and R. Wetherald (1980). On the distribution of climate change resulting from an increase in $CO_2$ content of the atmosphere. *J. Atmos. Sci.*, *37*, 99-118.

Marchetti, C. (1977). On geoengineering and the $CO_2$ problem. *Climatic Change 1*, p. 59ff.

Marchetti, C. (1980). On energy systems in historical perspective. IIASA, Laxenburg, Austria.

Marchetti, C. and N. Nakicenovic (1979). The dynamics of energy systems and the logistic substitution model. RR-79-13. IIASA, Laxenburg, Austria.

Marland, G. and R. Rotty (1979). Atmospheric carbon dioxide: implications for world coal use. In M. Grenon (ed.), *Future Coal Supply for the World Energy Balance*, Third IIASA Conference on Energy Resources, Nov. 28 - Dec. 2, 1977. Pergamon, Oxford. pp. 700-713.

Marshev, V. (1981). Gaming in the USSR. Collaborative Paper 81-13. IIASA, Laxenburg, Austria.

Munn, R.E. and L. Machta (1979). Human activities that affect the climate. In WMO, *Proceedings of the World Climate Conference*, World Meteorological Organization, Geneva.

National Academy of Sciences (NAS) (1977). *Energy and Climate*. NAS, Washington DC.

Niehaus, F. (1979). Carbon dioxide as a constraint for global energy scenarios. In Bach, W., J. Pankrath, and W. Kellogg (eds.), *Man's Impact on Climate*, Elsevier, Amsterdam. pp. 285-297.

Niehaus, F. and J. Williams (1979). Studies of different energy strategies in terms of their effects on the atmospheric $CO_2$ concentration. *J. of Geophysical Res. 84*, pp. 3123-3129.

Nordhaus, W.D. (1977). *International Studies of the Demand for Energy*. North-Holland, Amsterdam.

Nordhaus, W.D. (1979). *The Efficient Use of Energy Resources*. Yale University Press, New Haven.

Rapoport, A. (1974). Prisoner's Dilemma - recollections and observations. In Rapoport, A. (ed.), *Game Theory as a Theory of Conflict Resolution*. Reidel, Dordrecht.

Robinson, J. and J. Ausubel (1981). A framework for scenario generation for $CO_2$ gaming. Working Paper 81-34. IIASA, Laxenburg, Austria.

Rotty, R. (1977). Present and future production of $CO_2$ from fossil fuels. ORAU/IEA(O)-77-15. Institute for Energy Analysis, Oak Ridge.

Rotty, R. (1978). The atmospheric $CO_2$ consequences of heavy dependence on coal. In J. Williams (ed.), *Carbon Dioxide, Climate and Society*, Pergamon, Oxford. pp. 263-273.

Rotty, R. (1979a), Energy demand and global climate change. In Bach, W., J. Pankrath, and W. Kellogg (eds.), *Man's Impact on Climate*, Elsevier, Amsterdam. pp. 269-283.

Rotty, R. (1979b). Growth in global energy demand and contribution of alternative supply systems. *Energy 4*, pp. 881-890.

Rotty, R. and G. Marland (1980). Constraints on fossil fuel use. In Bach, W., J. Pankrath, and J. Williams (eds.), *Interactions of Energy and Climate*. Reidel, Dordrecht. pp. 191-212.

Schneider, S. and R. Chen (1980). Carbon dioxide warming and coastline flooding : a problem review and exploratory climatic impact assessment. *Annual Review of Energy*, *5*, 107-140.

Selten, R. (1973). A simple model of imperfect competition, where 4 are few and 6 are many. *International Journal of Game Theory*, pp.141-201.

Shubik, M. (1975). *Games for Society, Business and War*. Elsevier, New York.

Shubik, M. (1980). State-of-the-art survey. In Stahl, I. (ed.), The Use of Operational Gaming as an Aid in Policy Formulation and Implementation. CP-80-6. IIASA, Laxenburg, Austria.

Stahl, I. (1975). The Prisoners' Dilemma paradox, bargaining theory and game theoretic rationality. Working Paper. EFI, Stockholm.

Stahl, I. (1980). An interactive model for determining coal costs for a $CO_2$-game. Working Paper 80-154. IIASA, Laxenburg, Austria.

Stahl, I., R. Wasniowski, and I.Assa (1981). Cost allocation in water resources - six gaming experiments in Poland and Bulgaria. Working Paper. IIASA, Laxenburg, Austria.

Sundquist, E. and G. Miller (1980). Oil shales and carbon dioxide. *Science*, Vol. 208, 16 May 1980, pp. 740-741.

Voss, A. (1977). *Ansätze for Gesamtanalyse des Systems Mensch-Energie- Umwelt*. Birkhauser, Basel.

World Climate Programme (1981). On the assessment of the role of $CO_2$ on climate variations and their impact. Report of a WMO/UNEP/ICSU meeting of experts in Villach, Austria, November 1980. World Meteorological Organization, Geneva.

World Coal Study (1980). *Coal - Bridge to the Future*. Ballinger, Cambridge, Mass.

World Energy Conference (1978). *World Energy Resources 1985- 2020, An Appraisal of World Coal Resources and Their Future Availability*. IPC Science and Technology Press, Guildford, UK.