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THE EFFECTS OF CHANGES IN EXPECTED NEAR-TERM FOSSIL FUEL PRICES ON LONG-TERM ENERGY AND CARBON DIOXIDE PROJECTIONS

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Two surveys of near-term energy related projections produced thus far by the International Energy Workshop have produced two different views of the world through the year 2000. This paper considers the effects of these differences on long-term forecasts of global energy consumption and corresponding emissions of carbon dioxide. The lower growth forecast of the more recent survey portends lower economic activity in the next century, but carbon emissions of nearly the same dimension. Slower growth can, in particular, be expected to slow the price induced substitution into non-fossil fuels so that the income effect of slower growth is balanced by a slower, less vigorous substitution effect.

1. Introduction

Under the leadership of Professor Alan Manne of Stanford University, a series of plenary meetings of the International Energy Workshop was initiated in 1981. The first meeting produced a survey of expert opinion on the likely trend through the year 2000 for the international price of crude oil, among other variables of significant worldwide interest. Based upon an index number scheme that set the 1980 price of crude equal to 100, the expectations of the experts attending the 1981 workshop displayed mean crude oil price indices of 127.2 and 166.7 for the years 1990 and 2000, respectively. The standard deviations of the survey results around those means were 5.8 and 10.6, respectively. A second survey has now been conducted at a subsequent plenary meeting held at the International Institute for Applied Systems Analysis in June of 1983. The 1983 survey produced lower mean estimates for 1990 and 2000 (111.3 and 143.6, respectively), but surrounded those means with larger standard deviations (27.7 and 36.6).

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These numbers were, of course, also based on the 1980 = 100 indexing scheme.

Even though the scopes of the two surveys differed dramatically (the 1983 survey being much wider), it is clearly quite interesting to ponder the source of these dramatic changes in the experts' opinions. Why have the mean projections fallen? Why has disagreement across experts risen? Why do projections differ at all? One of the ongoing objectives of the Workshop is, in fact, to uncover answers to these types of questions. Preliminary planning for the 1985 plenary session is currently focused on constructing mechanisms with which to pursue just that objective. It is not, however, the purpose of this paper to contribute to that effort. It is, instead, to initiate discussion around a second set of questions that is, arguably, just as interesting and just as important.

The new survey represents the current state of our knowledge about the near-term future; the disagreement it records reflects some of the uncertainty with which we look forward even a short distance. Some of the policy issues of the day require, however, that we look beyond the near term into the more distant future. What, for example, is the likely date of the arrival of serious problems associated with the greenhouse effect of increasing atmospheric concentrations of carbon dioxide. The questions that I would like to pose are based upon our need to try to see far into the future with a knowable degree of (in)accuracy. If the new survey results represent the current state of our knowledge about the near-term future, what effect does incorporating that new knowledge into our modeling have on our long-term view of the world? What changes should we make in our predictions of the long-term growth of world GNP, world energy consumption, world consumption of fossil and non-fossil fuels and the world price of fossil fuel relative to non-fossil fuel on the basis of the new short-term projections? Does the new information alter our view of the carbon dioxide problem? Is doubling of carbon dioxide concentrations more likely to occur earlier or later than was formally expected?

The present paper will begin the discussion of this type of question by applying the methodology of probabilistic scenario analysis to trace out two likely ranges of trajectories for the major exogenous variables listed above — one each for the two alternative near-term forecasts identified by the Workshop surveys. Comparisons of these trajectories will lead to conjectures about the impacts that differences across the surveys might have on the range of long-term possibilities. Professor Manne has already expressed the concern that the two surveys might not be exactly comparable. The 1983 meeting was more widely attended, and the scope of its survey was considerably broader than the 1981 effort. The survey questions were, moreover, not asked in precisely the same way. Still, consistency in scope and questions is a goal that the Workshop has set for itself as it plans for its own future. Comparison and application of the different results that it will generate across time will thus become increasingly germane as the Workshop achieves its goal. While the results recorded here might be a bit suspect because of some degree of survey incompatibility, it is nonetheless hoped that both the identification of an applied line of questioning and the methodological approach outlined here will be an initial contribution to a growing field of inquiry.

The paper is organized as follows. Section 2 will review the methodology of probabilistic scenario analysis briefly in an attempt to put the application that follows into its proper context. The specific model, based upon an economically consistent aggregate model of the world economy, will then be presented in section 3. The data employed will be recorded in section 4 before the results of the analysis for each of the two surveys are outlined in the next two sections. Section 7 will compare the results of the analysis in the near and long term, and section 8 will extend the comparison to include carbon dioxide emissions and atmospheric concentrations. A summary of the major findings will then conclude the paper. Even as we start, though, it should be emphasized that those conclusions will not simply be based upon some interesting scenario or other. A full range of scenarios based upon current knowledge of ten random variables will produce not only a most likely path for each of the major variables, but also a probability distribution of possible outcomes around that path. Conjectures will be advanced, therefore, about not only the effect of the different surveys on most likely paths, but also about the confidence with which we can advance those paths as projections of the future.

2. Methodology

Scenarios have beome fixtures in the collection of techniques with which we try to understand and predict the future. As useful as these exercises have been, however, they have generally suffered from one of two major shortcomings. Some have been based upon extrapolative techniques that have not allowed researchers to assess the degree of precision with which their forecasts can be advanced. This is surely a serious omission for the many policy issues in which it is essential that the best scientific judgement be expressed in a way that clearly delineates the extent to which that judgement is precisely or vaguely known. Cases in which policy decisions are irreversible spring to mind as examples in which the best decision in the face of existing uncertainty might simply be to gather more information. Such a conclusion would certainly be difficult to reach if the uncertainty of the prediction were not accurately reflected in the analysis.

A second type of shortcoming has arisen in modeling that has attempted to correct for spurious precision by carefully delineating a hypothetical scenario. In these studies, time paths for important variables are tracked under assumptions that are arguably interesting. But without care in constructing the scenario, these types of studies can be interesting but essentially useless. They have almost no chance of actually describing what will happen. They are difficult to update and alter as events unfold that take society off the predicted path. They provide, in short, little more than answers to hypothetical questions of the 'what if' genre.

The present paper attempts to address both of these shortcomings in a systematic way. To escape the latter difficulty, modern developments in economic theory are employed to construct a transparent model of the global economy. Care is taken to assure that the model is consistent, reasonable, and flexible. The structure is not, in other words, specific and rigid; it is, instead, general and malleable. Moreover, the modeling described here recognizes the intrinsic uncertainty with which we contemplate the future. The most important uncertain parameters in the model are identified and the range of current knowledge and disagreement about these parameters examined. A corresponding range of possible future outcomes for each on the basis of that disagreement is then produced. The attempt is not to resolve these uncertainties, but rather to represent them as accurately as possible. Combining the general model with the important uncertainties allows projection of not only a 'best guess' of the future path of some important variables, but also alternative trajectories of outcomes that cannot be ruled out on the basis of current knowledge.

This entire process can be represented mathematically as follows. Suppose that the endogenous variables that are of interest, denoted by the vector $Y(t)$, are systematically related to exogenous variables $X(t)$ and parameters $K(t)$ according to

$$Y(t) = G[X(t); K(t)].$$

The idea is to use subjective probability distributions $f[X(t)]$ and $h[K(t)]$ in conjunction with the function $G[-,-]$ to produce a distribution $g[Y(t)]$ that describes the range of possible trajectories for $Y(t)$ through time. The problems to be confronted immediately therefore involve both the specification of the general form of $G[-,-]$ and the estimation of the distributions $f[-]$ and $h[-]$. In the work presented here, the $Y(t)$ vector includes consumption of fossil and non-fossil fuels, their relative prices, and world GNP. As a result, the $G[-,-]$ function represents the workings of a set of energy markets for which an aggregate production function produces the derived demand side and production based supply schedules provide the supply side. Exogenous variables include rates of Hicks-neutral productivity growth and labor growth; the critical parameters include elasticities of substitution, depletion factors and technological change in the supply of energy. To provide ranges for these variables and parameters, the literature has been surveyed, summarized and represented by discrete, subjective probability distributions. The desired distribution of the $Y(t)$ vector is then produced by sampling among the various possible combinations of values for the exogenous variables and other parameters.

3. The economic model

The demand for fossil and non-fossil energy is derived entirely from a production function that, for any year, assumes the form

$$X(t) = F_t[L(t), E^c(t), E^n(t)]$$

$$= A(t)L(t)^{d(t)}[bE^c(t)^r + (1-b)E^n(t)^r]^{[1-d(t)]/r}, \tag{1}$$

where

$X(t)$ = world GNP at time t in constant 1975 U.S. dollars,
$A(t)$ = $A_0 \exp[a(t)t]$ = level of labor productivity at time t in U.S. dollars of output per capita,
$L(t)$ = $L_0 \exp[l(t)t]$ = world population at time t,
$E^c(t)$ = consumption of fossil fuel at time t in metric tons of coal equivalent,
$E^n(t)$ = consumption of non-fossil fuel at time t in metric tons of coal equivalent, and
$d(t)$ = the share of GNP devoted to paying for non-energy inputs.

The function $F_t[\text{-},\text{-},\text{-}]$ is, of course, a nested CES schedule in which the elasticity of substitution between fossil and non-fossil energy sources is represented by $s_1 = 1/(1-r)$; the parameter b depends upon the initial share of GNP devoted to each type of energy. It should be noted, though, that we are setting

$$d(t) = [kP(t)^{q/q-1} + 1]^{-1} \tag{2}$$

with

$$P(t) = [P^c(t)E^c(t) + P^n(t)E^n(t)]/[E^c(t) + E^n(t)]$$

representing the aggregate price of energy [i.e., the $P^j(t)$ denoting the price of the $E^j(t); j = c, n$] and k reflecting the initial relative share of energy and non-energy inputs. In this way, the intertemporal elasticity of substitution between energy and non-energy inputs can be set equal to any arbitrary $s_2 = 1/(1-q)$. Put another way, specifying the share devoted to labor endogenously according to eq. (2) allows (1) to approximate a more general production schedule with arbitrary values prescribed for both the elasticity of substitution between energy sources and the elasticity of substitution into and out of energy.[1]

The demand side of the energy markets derived entirely from (1) can now be summarized at any point in time by two equations:

$$P^n(t)E^n(t)+P^c(t)E^c(t)=[1-d(t)]X(t) \tag{3a}$$

and

$$[E^c(t)/E^n(t)]=[(1-b)P^c(t)/bP^n(t)]^{1/r-1}. \tag{3b}$$

And this demand specification allows for four sources of uncertainty to be explicitly modeled:

$a(t)$ = the rate of growth in the Hicks-neutral measure of labor productivity,
$l(t)$ = the rate of growth of the worldwide labor force,
s_1 = the elasticity of substitution between fossil and non-fossil energy, and
s_2 = the elasticity of substitution between aggregate energy and labor.

The supply conditions for fossil fuel are meanwhile specified mathematically by

$$P^c(t)=P^c_d+[g_0+g_1(R(t)/(\bar{R}-R(t))]\exp(h_1(t)t), \tag{4}$$

where

P^c_d = the distribution cost of fossil fuel in constant 1975 U.S. dollars,
g_0 = the initial primary price of fossil fuel in constant 1975 U.S. dollars,
g_1 = a depletion factor reflecting the scarcity rent of a fixed supply of fossil fuel,
$\bar{R}$ = fixed world reserves of fossil fuel in metric tons of coal equivalent,
$R(t)$ = $E^c(0)+\ldots+E^c(t-1)$ = cumulative consumption through year $t-1$ of fossil fuel in metric tons of coal equivalent, and
$h_1(t)$ = the inverse of the rate of technological change in the energy sector.

The term in the share brackets of eq. (4) measures the depletion effect on the price of fossil fuel of gradually running out of a finite resource. It must be noted, though, that this term does not yet represent true economic scarcity rents. Instead, it is included to approximate their effect on the real price of fossil fuel. To complete the model, the supply conditions for non-fossil fuels

[1]The need for the elaborate iterations with the $d(t)$ parameter is derived from a theorem demonstrated by Uzawa (1962). To maintain constant elasticities of substitution between more than two inputs, it is generally necessary that either (1) all of the elasticities be identical or (2) the elasticity between at least one pair of inputs be unity. Neither condition was attractive, so an approximation procedure to allow constant, arbitrary elasticities was developed.

are summarized similarly by

$$P^n(t) - P^n_d + P^n_0 \exp[h_1(t)t + h_2(t)t], \quad (5)$$

where

P^n_d = the distribution cost of non-fossil fuel in constant 1975 U.S. dollars,
P^n_0 = the initial primary price of non-fossil fuel in constant 1975 U.S. dollars,
$h_1(t)$ = the inverse of the rate of technological change in the energy sector, and
$h_2(t)$ = the bias in the rate of technological change in the energy sector that favors (or does not favor) non-fossil energy.

From these equations, four more sources of uncertainty are captured: $\bar{R}$, g_1, and the $h_i(t)$. All of the other parameters are again determined by initial conditions.

4. The data

Two types of data were required to fully specify the model. Initial conditions were first of all, certainly necessary. Table 1 records the requisite estimates for world GNP, world population, world fossil and non-fossil fuel consumption in 1975, and world fossil and non-fossil fuel prices in 1980. Since these initial conditions were based upon historical evidence, consensus was not difficult to achieve. Existing studies and comparisons with published data were generally sufficient to generate consistent estimates for the first four rows. Initial energy prices were a bit more problematical. Aggregate prices based upon the historical distribution of fossil fuel consumption

Table 1
Initial data.[a]

	Item	Notation	Value
(A)	World population	L_0	4×10^9
(B)	World GNP (1975 U.S. dollars)	$X(0)$	$\$6.4 \times 10^{12}$
(C)	Fossil fuel consumption (mtce)	$E^c(0)$	8.1×10^9
(D)	Non-fossil fuel consumption (mtce)	$E^n(0)$	0.7×10^9
(E)	Primary energy prices (1975 U.S. dollars)		
	Fossil fuel (1980)	g_0	\$76/mtce
	Non-fossil fuel (1980)	P^n_0	\$118/mtce
(F)	Distribution costs (1975 U.S. dollars)		
	Fossil fuel (1980)	P^c_d	\$40/mtce
	Non-fossil fuel (1980)	P^n_d	$\$137 \times 10$

[a]Values for 1975 unless otherwise noted.

between coal, oil and gas were required, and it is these prices that are recorded in rows (E) and (F). They are the product of a rather straightforward aggregation procedure. Notice, too, that primary and distribution costs are recorded; the corresponding secondary price of either type of energy is, of course, simply the sum of these two components.

Data were also required to set the long-term context of the study — a more involved function. Projections of the various important parameters and exogenous variables identified in section 3 into the near and distant future were compared, but the uncertainties inherent in those projections made consensus impossible. Indeed, it would have been extremely suspicious if consensus had emerged for any of these variables. It was, instead, expected that a review of projections would produce a range of possibility for the critical variables. These ranges were treated not as spurious disagreement among researchers, but as reflections of the inherent uncertainties. The technical response to this treatment was to assume that each projection was an observation from an underlying probability distribution around the true value of the parameter. The collection of projections for each variable was then used to compute a mean and a variance for each variable. Subsequently, each distribution was assumed to be fully described by these statistics. Discrete, three cell approximations of each were then defined with weights of 25%, 50% and 25% being assigned to high, middle and low values, respectively. The values for each cell were computed to preserve both the computed means and variances of their continuous antecedents. This procedure guaranteed, by application of the Central Limit Theorem, that using samples of sufficient size would generate the same expected outcomes as would have been observed if the continuous representations had been employed.

To put this procedure more intuitively, managable distributions for each variable were constructed to mirror the level of uncertainty presently surrounding the various analysts' projections that were sampled. In deference to the tendency of individuals to underestimate uncertainty, however, the procedure did not stop there. Particularly when the estimated variances declined over time so that estimates of far distant values appeared to be more certain than estimates of near values, future variances were occasionally expanded beyond their computed ranges. This secondary procedure was employed only when it was apparent that the larger near-term variance was not the result of short-term white noise — that could be expected to 'wash out' over the long haul.

The first four categories of table 2 record the ranges employed for four variables whose values changed over time. Recall that the high and low values were assigned probabilities of 25%, so that, under assumptions of normality, it is expected that slightly less than 7% of the underlying continuous probability distribution would fall below the low value and about

Table 2
Uncertain parameters.[a]

	Item	1975–2000	2000–2025	2025–2100
(*A*)	*Population growth* [$l(t)$]			
	High	2.0	1.6	0.8
	Middle	1.7	1.1	0.3
	Low	1.4	0.6	−0.2
(*B*)	*Productivity growth* [$a(t)$]			
	High	3.4	2.3	1.9
	Middle	2.3	1.6	1.0
	Low	1.2	0.9	0.1
(*C*)	*Technological change in the energy sector* [$h_1(t)$][b]			
	High	2.0	1.0	1.0
	Middle	0.5	0.0	0.0
	Low	−1.5	−1.0	−1.0
(*D*)	*Technological bias in non-fossil energy* [$h_2(t)$][c]			
	High	2.0	1.0	1.0
	Middle	0.5	0.0	0.0
	Low	−1.5	−1.0	−1.0

(*E*) *The depletion of parameter in the fossil fuel supply equation*

World fossil fuel resources	Price of fossil fuel at $R(t)=1100$	g_1	Probability
3200	$43/mtce	13.8	0.06
3200	$73/mtce	65.0	0.13
3200	$103/mtce	118.0	0.06
11000	$43/mtce	72.0	0.13
11000	$73/mtce	342.0	0.24
11000	$103/mtce	612.0	0.13
21000	$43/mtce	145.0	0.06
21000	$73/mtce	687.0	0.13
21000	$103/mtce	1230.0	0.06

(*F*) *Elasticity of substitution between fossil and non-fossil fuel*

High	−2.0
Middle	−1.2
Low	−0.5

(*G*) *Elasticity of substitution between energy and labor*

High	−1.2
Middle	−0.7
Low	−0.4

[a]All of the values recorded here are in units of percent of annual rate of change.

[b]This variable reflects the inverse of the rate of change in the price of energy caused by technological advances, or the lack thereof, in the supply conditions of energy.

[c]This variable reflects the bias in the rate of technological advance represented by $h_1(t)$ toward or away from non-fossil energy sources.

7% would fall above the high value. The remainder of table 2 records the ranges of the variables whose values were fixed over the entire time horizon. Notice, in particular, that three possible values each for total world resources of fossil fuels and anticipated fossil fuel prices around the year 2025 were plugged into eq. (4) to produce nine distinct values for the depletion factor g_1.

5. Results using the 1981 survey

Eqs. (1) through (5) produce a consistent aggregate model of world energy consumption. Eight sources of uncertainty are identified in these equations, and each is represented by a discrete probability distribution of 3 cells. Sampling from the resulting total of $3^8=6561$ possible combinations of these values thus produces distributions of the future trajectories of the important endogenous variables of the model: world GNP, world fossil and non-fossil fuel consumption, world prices for fossil and non-fossil fuel, and total world energy consumption. The present section records the results of this exercise when the distribution of world oil prices projected for 1990 and 2000 during the 1981 International Energy Workshop held at Stanford are used to frame the early prices of fossil fuel.

It should be noted that, in fitting the index of the price of fossil fuel to the distribution of the index generated at Stanford for world crude oil prices, an assumption is being made about equilibrium in the markets of the various types of fossil fuel: coal, oil and natural gas. Disaggregate energy markets across the world are, in particular, assumed to interact sufficiently to guarantee that their prices reflect the BTU equivalence of the respective fuels. Alternatively, application of the procedure requires only an implicit assumption that any existing distortions be perpetuated over time. In as much as this study extends over 125 years, accepting either version of this assumption should not do serious damage to reality.

Table 3 records the results of an initial set of runs. They produce a mean index for the price of fossil fuel equal to 128.7 and 166.3 in the years 1990 and 2000, respectively; i.e., they match the average expectation of the 1981 Workshop within one percentage point. They do, however, produce estimated standard deviations of 11.4 and 28.9 for those two benchmark years, and these numbers are well above the statistics computed from the original survey. Unless one believes that some of the sources of uncertainty incorporated into the aggregate model presented above are negatively correlated, however, the results of these runs suggest that the 1981 survey significantly underestimated the range of uncertainty for fossil fuel prices in the fairly near future. A graphical representation of uncertainty surrounding the most likely trajectory for energy consumption is provided in fig. 1; the mean path is, therein, surrounded by trajectories deviating from the mean by one and two standard deviations.

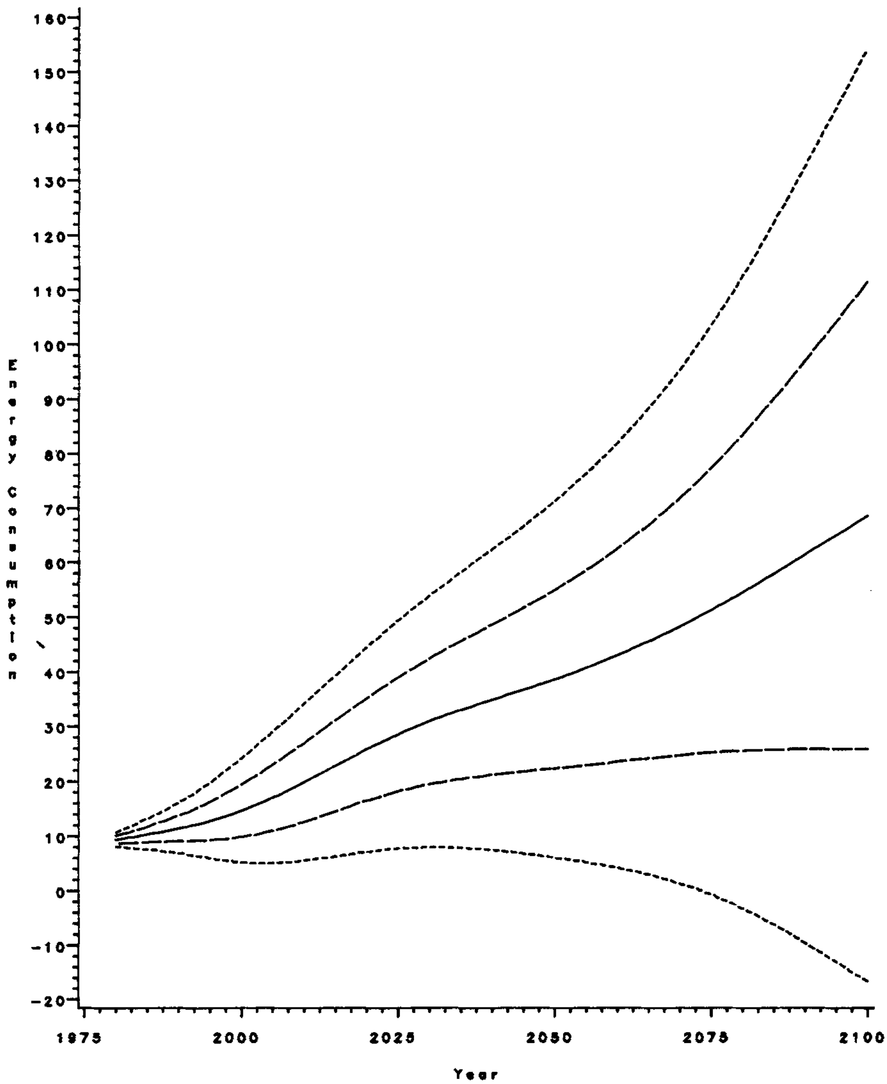

Fig. 1. Energy consumption in billions of metric tons of coal equivalent (1981 survey).

Table 3
Results based on the 1981 survey.

	1980	1990	2000	2025	2050	2075	2100
Means (1981 survey)							
Energy consumption	9.38	11.46	14.68	28.59	38.64	51.35	68.72
Price of fossil fuel	0.071	0.093	0.118	0.131	0.149	0.185	0.284
Price of non-fossil fuel	0.262	0.279	0.299	0.305	0.311	0.319	0.329
Fossil fuel consumption	8.41	9.53	11.14	20.49	25.31	29.11	30.49
Non-fossil fuel consumption	0.99	1.93	3.55	8.11	13.33	22.23	38.24
World GNP	7.89	12.16	18.73	39.26	58.28	87.13	131.25
Standard deviations (1981 survey)							
Energy consumption	0.69	2.34	4.78	10.42	16.35	26.90	42.79
Price of fossil fuel	0.004	0.012	0.024	0.031	0.044	0.082	0.256
Price of non-fossil fuel	0.009	0.033	0.061	0.076	0.093	0.111	0.132
Fossil fuel consumption	0.76	2.46	4.75	9.59	13.51	17.81	24.31
Non-fossil fuel consumption	0.18	0.88	2.19	5.61	10.43	19.61	36.54
World GNP	0.37	1.71	4.26	11.27	21.03	38.11	68.55

6. Results using the 1983 survey

The runs of the previous exercise were subsequently altered to reflect the lower means and the wider variances of the 1983 survey for crude oil prices in both 1990 and 2000. This alteration was accomplished by adjusting the supply equation for fossil fuel, eq. (4) according to

$$\begin{aligned} P^c(t) &= P^c_d + [g_0 + g_1[(R(t)/(\bar{R} - R(t))]\exp(h_1(t)t)]k + tQ/625, \qquad 1 \leqq t < 24, \\ &= P + [g_0 + g_1[(R(t)/(\bar{R} - R(t))]\exp(h_1(t)t)]k + Q, \qquad t \geqq 25, \end{aligned} \tag{6}$$

with k being specified to produce the appropriate mean index and Q being a random variable added to produce the appropriate variance in the year 2000. For our purposes, k is set equal to 0.74 and Q surrounds a zero mean with $+0.05$ and -0.05 values at the 25% extremes.

Two points need to be made about this methodology before the results of this exercise are recorded. First of all, the reader may have questioned whether or not this procedure might not effect the initial conditions of the model and thereby distort the results by imposing different starting points upon each run. This is not a concern, though, because of the averaging process that was built into the model to accommodate the rapid price increases of the late 1970's. The effective price for fossil fuel, $P^c_e(t)$ fed into the derived demand equations during the first 25 years of each run is the following convex combination of the 1975 price and the price $P^c(t)$

represented in above:

$$P_e^c(t) = [(25-t)/25]P^c(1975) + [t/25]P^c(t).$$

The rationale for that weighting is found in the need to deal with the putty–putty nature of the model outlined in section 3. That model, and most models like it, allow instantaneous responses to changes in relative prices, and that type of response cannot be expected from the energy intensive industrial infrastructure of the 1970's. To exclude the potential anomaly of allowing this type of rapid substitution, the dramatic fossil fuel price increases of the late 1970's were incorporated gradually over the 25 years between 1975 and 2000. The adjustment to the fossil fuel supply equation recorded in eq. (6) does not effect the model's initial price of fossil fuel; the initial price of fossil fuel remains $P^c(1975)$ regardless of the values assumed by k and Q.

Secondly, concern may be expressed that the inclusion of the variables k and Q might distort the price trajectories during the outyears in a way that would be inconsistent with the long-range forecasts of previous work. This concern, too, can be discounted by examining the workings of the model. The price of fossil fuel will be observed to grow over time at a rate that will quickly dwarf the impact of the extreme values of Q; the added variance is, in other words, only significant through the first few decades of the projections where, according to the 1983 survey, it should be observed. The effect of the multiplicative factor k is similarly diminished because, ceteris paribus, lower in-year prices cause larger consumption levels early in each path than would otherwise be the case. More significant early depletion therefore results in appropriately higher prices later despite the workings of the k parameter. The tracks of the prices produced by these amended runs do, in fact, pass through the projected range for the years 2025–2030 upon which the specification of the depletion factor g_1 is based.

A second adjustment is also required to respond to an observation made by Alan Manne about a previous draft of this paper. The 1983 survey produced not only a lower expected trajectory for energy prices, but also a lower expected trajectory for energy consumption. The median estimate for the OECD countries now predicts an energy consumption index of 134 for the year 2000; the previous estimate produced an index of 139. Since this decline is inconsistent with lower prices and the same derived demand schedule, it must be the case that forecasters now foresee lower growth in demand for energy at every price. This expectation is reflected in the new runs by including lower estimates of productivity growth through the year 2000.

Table 4 records the results of the second set of runs based upon this adjustment in eq. (4). The index means emerge equal to 120.2 and 146.4 for 1990 and 2000, respectively. Fig. 2 repeats the exercise of fig. 1, surrounding

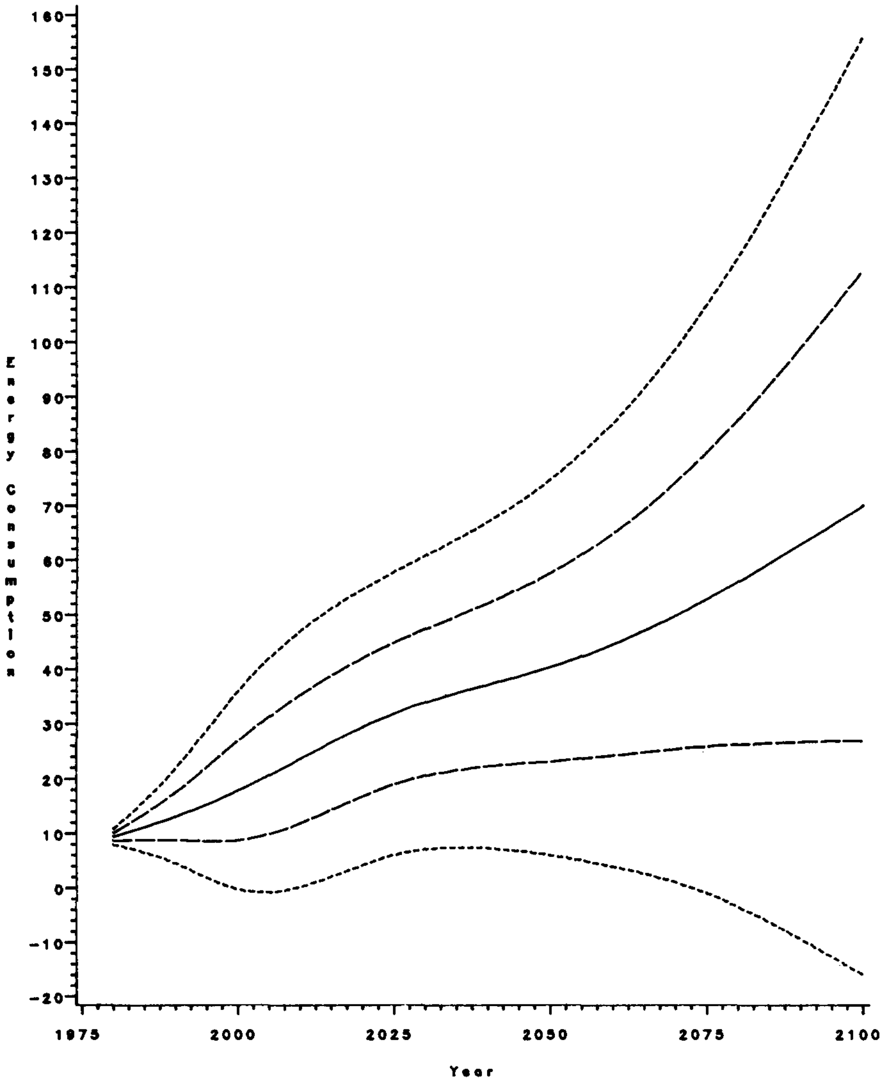

Fig. 2. Energy consumption in billions of metric tons of coal equivalent (1983 survey).

Table 4
Results based on the 1983 survey.

	1980	1990	2000	2025	2050	2075	2100
Means (1983 survey)							
Energy consumption	9.41	10.64	14.45	26.19	34.35	45.56	64.46
Price of fossil fuel	0.069	0.083	0.101	0.116	0.131	0.164	0.238
Price of non-fossil fuel	0.262	0.279	0.299	0.305	0.311	0.319	0.329
Fossil fuel consumption	8.54	9.18	10.85	19.94	23.69	27.53	29.80
Non-fossil fuel consumption	0.96	1.46	3.63	6.25	10.66	19.08	34.66
World GNP	7.91	8.57	13.40	27.98	41.40	61.76	94.43
Standard deviations (1983 survey)							
Energy consumption	0.75	3.54	7.45	11.01	15.20	23.77	39.66
Price of fossil fuel	0.005	0.021	0.033	0.032	0.039	0.111	0.210
Price of non-fossil fuel	0.009	0.033	0.061	0.076	0.093	0.111	0.132
Fossil fuel consumption	0.86	3.53	7.70	10.57	12.84	17.29	23.83
Non-fossil fuel consumption	0.21	0.71	1.87	5.37	8.59	18.71	33.67
World GNP	0.37	1.27	3.06	8.41	15.28	29.11	47.33

the mean trajectory of energy consumption with boundary paths of one and two standard deviations.

7. Comparison of the results

Comparison of the results of the two sets of runs can now be accomplished. Table 5 records the differences between the values of indicated variables produced according to the 1983 survey and the values produced according to the 1981 survey. Positive numbers, in this table, indicate that the value based upon the 1983 survey is larger. Notice that world GNP, world energy consumption, and world consumption of fossil fuel are all lower for the 1983 results throughout the projection period. In every case, though, growth in this difference begins to decline around the year 2025.

Table 5
Differences in the maximum likelihood estimates.[a]

Differences in the means	1980	1990	2000	2025	2050	2075	2100
Energy consumption	0.03	−0.82	−0.23	−2.40	−4.29	−4.79	−4.26
Price of fossil fuel	0.002	−0.010	−0.017	−0.015	−0.018	−0.021	−0.046
Price of non-fossil fuel	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fossil fuel consumption	0.13	−0.35	−0.32	−0.55	−1.61	−1.58	−0.69
Non-fossil fuel consumption	−0.03	−0.47	0.09	−1.86	−2.67	−3.2	−3.58
World GNP	0.02	−3.59	−5.33	−11.28	−16.88	−25.37	−36.82

[a]1983 survey values minus 1981 survey values.

From 2050 through 2100, in fact, the rates of growth for these major variables are almost identical for the two surveys. The reason for this trend becomes clear when the price of fossil fuel and the consumption of non-fossil fuel are traced over the same periods. Up through 2050, the initial lower tracking of the price of fossil fuel mandated by the 1983 survey holds firm but combines with the lower early rates of productivity growth to retard economic activity. The cost of low initial productivity growth is, however, finally paid by 2050 and overall growth finally assumes the pace dictated by the outyear variables. The absolute divergence in GNP levels expands, to be sure, but only because the 1983 survey mandates that growth starts from a lower 2050 benchmark.

There is, moreover, a second major difference in the outyears that deserves some mention. Notice that lower fossil fuel prices depress the derived demand for non-fossil fuel throughout the 125 year projection period. With less pressure on the price of fossil fuel, though, this is to be expected. Less price pressure on the fossil fuel side of the market simply delays the need for substitution out of that type of fuel. This effect will be critical when the results are applied to comparisons of carbon dioxide emissions and concentrations in the next section.

Differences in the ranges of uncertainty surrounding the mean trajectories turned out to be small. Measured in terms of their 't-statistics', in fact, the two surveys produced variations in the long term that were very nearly identical.

8. Carbon emissions and atmospheric concentrations

The effects of the differences between the two surveys on the long-term trajectories of carbon emissions and atmospheric concentrations of carbon dioxide can also be explored. All that is required is a short extension of the model to link fossil fuel consumption to carbon emissions and carbon emissions to atmospheric concentrations. The former link is easily defined by letting

$$C(t) = Z_0 E^c(t) \exp(z(t)t),$$

where

$C(t)$ = emissions of carbon in gigatons per year,
Z_0 = the initial emissions factor (the initial ratio of carbon emissions to fossil fuel consumption based on 1975 consumption patterns), and
$z(t)$ = the rate of growth of the emissions factor.

The last two variables are, of course, exogenous, with the $z(t)$ variable being incorporated as a ninth random variable. It is, in particular, the product of another straightforward aggregation procedure, and its trajectory over time depends critically upon the mix of fossil fuel actually consumed.[2]

The link between emissions and concentrations is more problematical because of uncertainty about the contribution of the biosphere to atmospheric levels of carbon dioxide. For our purposes,

$$M(t)=M(t-1)+AF(s)[0.471C(t)]-sM(t-1)$$

is employed to formalize that link, with

$M(t)$ = carbon mass in the atmosphere in period t measured in parts per million,
s = a seepage factor reflecting the slow mixing of airborne carbon dioxide into the deep oceans, and
$AF(s)$ = the marginal airborne fraction of carbon dioxide.

This representation is a fairly standard simplification of the complex workings of the carbon cycle. The coefficient 0.471 preceding $C(t)$ simply converts gigatons of carbon into the appropriate atmospheric units of parts per million; it is based upon the molecular weight of carbon dioxide. The seepage factor is taken to be 0.001 in our work, but the marginal airborne fraction can be seen to be quite sensitive to that specification; thus, the notation $AF(s)$. The airborne fraction employed is, moreover, the final random variable setting extreme values of 0.38 and 0.59 around a mean of 0.47.[3] Table 6 records the results of tacking this additional structure onto the model that produced the runs for the two different surveys. Given the lower energy consumption paths of the 1983 survey, it should have perhaps been expected that significant differences would be evident in the emissions and concentrations trajectories. That is not, however, the case and a careful examination of the energy mixes recorded above can uncover why. Recall that the lower energy consumption of the 1983 survey puts less pressure on the price of fossil fuel and thus produces less substitution into the non-fossil alternative. It is, consequently, midway into the next century before the 1983 based projections generate any substantial reduction in fossil fuel consumption. Since carbon emissions depend upon fossil fuel consumption and not energy consumption in the aggregate, little effect is noted before the year 2050 in either emissions or concentrations. The relative decline in fossil fuel is, moreover, a temporary phenomenon, and fossil fuel consumption in

[2]A complete description of the genesis of the $z(t)$ parameter can be found in Nordhaus and Yohe (1983).

[3]The range of the airborne fraction estimates are the product of an errors in variables econometric analysis of the available data. See the biometric paper by Nordhaus and Yohe (1983) for details.

Table 6
Carbon dioxide emissions and concentrations.

	1980	1990	2000	2025	2050	2075	2100
Means (1981 survey)							
Carbon dioxide emissions	4.88	5.57	7.54	12.25	16.98	21.56	22.61
Atmosphere concentrations	344.26	357.04	371.81	442.16	551.81	701.78	879.03
Standard deviations (1981 survey)							
Carbon dioxide emissions	0.44	1.44	2.79	5.75	9.65	13.79	18.55
Atmospheric concentrations	1.16	4.76	11.13	43.25	104.75	203.06	336.34
Means (1983 survey)							
Carbon dioxide emissions	4.98	5.37	7.02	11.91	15.83	20.34	22.28
Atmospheric concentrations	344.43	357.16	372.31	442.90	546.92	687.62	859.15
Standard deviation (1983 survey)							
Carbon dioxide emissions	0.47	2.21	4.52	6.32	0.06	13.30	18.10
Atmospheric concentrations	1.21	5.82	15.34	55.69	113.53	203.79	331.62
Difference in the means							
Carbon dioxide emissions	0.1	−0.20	−0.52	−0.34	−1.15	−1.22	−0.33
Atmospheric concentrations	0.17	0.12	0.50	0.74	−4.89	−14.16	−19.88

the 1983 projections begins to rise relative to the 1981 survey results by 2075. The economy's momentum, as measured by its consumption of fossil fuel, is thus expected to be larger given the 1983 survey results.

9. Concluding remarks

Two different distributions of possible trajectories through the year 2100 for total world energy consumption, world fossil fuel consumption, and world GNP have been generated. They differ by design to reflect two different short-term projections of fossil fuel prices through the year 2000 gleaned from the results of surveys conducted at two meetings of the International Energy Workshop — the first held at Stanford in June of 1981 and the second, a followup meeting, held in Vienna in June of 1983. The more recent survey predicts both lower oil prices and lower energy consumption through the year 2000. Incorporating these recently expressed expectations into the foundations of long term forecasts produced a marked effect. Lower economic activity is predicted from the 1983 survey well into the next century with lower energy demand and lower GNP charting the course. The resulting reduction in the rate of growth in the price of fossil fuel through the depletion effect retards substitution into alternative non-fossil energy sources. Carbon emissions based on the recent survey are therefore not expected to fall until 2050, and then only for a few decades. By 2075, the underlying, contemporary engines of economic growth dominate any near-term differences, and the rates of growth of all variables predicted by either survey converge.

The prediction is, therefore, that the stagnation of the 1980's and its antecedent slowdown through the year 2000 will have no effect on the likelihood that the greenhouse effect will become troublesome in the next century. The expected time of doubling is, using either survey as a basis, the same 2065–2070 period predicted by the recent report of the Carbon Dioxide Assessment Committee of the National Academy of Sciences.

Finally, beyond the results of the comparison of the two sets of runs, there are a few lessons about the versatility of the general methodology of probability scenario analysis to be gleaned from this exercise. The model employed here was developed as an aggregate representation of the world economy that worked through the derived world demand and supply of energy and other inputs. It recognized ten sources of uncertainty and explicitly incorporated the best current subjective view of how each is distributed. Despite the fact that the projected price of fossil fuel in neither 1990 nor 2000 was employed in the original design of the model to quantify any source of uncertainty, the model was easily adapted to fit those projections. And the result of that adoption is not only a best guess about the trajectories of a few variables into the distant future, but also distribution of the uncertainty with which we can advance those trajectories as predictions. Both the guesses and the distributions therefore reflect not only the underlying subjective views of ten sources of uncertainty, but also the effects of constraining the trajectories of fossil fuel prices to pass through the near-term ranges produced by the two surveys.

Passing from the first to the second survey produced little effect on the long-term distributions in this study, but that need not have been the case. Had, for example, the lower energy prices of the 1983 survey not been accompanied by lower energy consumption, the exercise would have produced a 28% chance of doubling by the year 2035 (550 ppm used as a doubling benchmark). The 1981 survey gives that potentiality slightly more than one chance in ten. The National Academy study recommended waiting and studying for a decade or two in response to the greenhouse threat, but that was a recommendation based in part on the one in ten chance of early difficulty. Being forced to take the same wager on a four sided die for the year 2035 might have made the Assessment Committee more reluctant to postpone action.

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