Wright, Brian D.

Working Paper

The Cost of Aggregate Energy Conservation

Center Discussion Paper, No. 327

Provided in Cooperation with:
Yale University, Economic Growth Center (EGC)

Suggested Citation: Wright, Brian D. (1979) : The Cost of Aggregate Energy Conservation, Center Discussion Paper, No. 327, Yale University, Economic Growth Center, New Haven, CT

This Version is available at:
https://hdl.handle.net/10419/160254

ECONOMIC GROWTH CENTER

YALE UNIVERSITY

Box 1987, Yale Station
New Haven, Connecticut

CENTER DISCUSSION PAPER NO. 327

THE COST OF AGGREGATE ENERGY CONSERVATION

Brian D. Wright

November 1979

ABSTRACT

This paper considers the cost to society of long-run reductions of aggregate energy input from its equilibrium level. A heuristic partial equilibrium model reveals the economics behind the results obtained from partial equilibrium simulation models. This partial equilibrium approach provides a previously unrecognized upper bound on the social cost of conservation in an otherwise undistorted economy. The net social cost attributable directly to conservation, rather than to the aggravation of existing distortions such as a non-optimal tax structure, is likely to be much less than the cost of the energy saved.

THE COST OF AGGREGATE ENERGY CONSERVATION

Brian D. Wright
Yale University

Within the past decade there has been a dramatic increase of interest in proposals to reduce aggregate energy consumption below the level implied by an unrestricted domestic market. Recent destabilizing events in the Middle East have made these proposals more urgent. If they are to be intelligently evaluated, it is essential that their costs and benefits to society be appropriately estimated and interpreted.

The benefits of conservation include improved national security through greater energy independence.[1] In this paper I take these benefits as given, and evaluate the cost to society of aggregate energy conservation, defined as the reduction of national energy use below its equilibrium level at the overseas-determined import price, by means of taxes, quantitative measures, and/or moral suasion. The import price is assumed constant; as is emphasised below, the domestic social cost of an OPEC price increase is much greater than the cost of an equivalent domestic tax. Further, conservation is envisaged here as a long-run, gradual process; embargoes and other short-run disturbances are not considered.

This question has already been addressed by a number of energy modeling studies. Those that allow for the crucial substitution responses which economists expect to occur all agree that conceivable long-run reductions of energy inputs will have a much less than proportional affect on GNP. In this paper I show that a very simple heuristic model can adequately reproduce the estimate of the cost of aggregate energy conservation produced by more complex models, as long as the overall capital-

energy substitution elasticity implicit in the latter is known. This simple model clarifies the economic relationships which underlie the partial equilibrium response.

A large segment of the population, including many well-informed members of the business community, apparently is afraid that conservation will be much more costly than predicted in these models. One reason why the modeling results are not more widely accepted is that energy modelers and model analysts have themselves raised several serious questions concerning their validity as a guide to real-world decisions.

Almost all the energy models take a partial equilibrium approach, and several evaluative and interpretive studies have expressed concern that the relatively small impact of energy conservation on GNP derived from partial equilibrium models might not be a good indicator of the cost of the full general equilibrium response (Hogan and Manne, 1977; Modeling Resource Group, 1978: Hogan, 1977). The common belief that this question hinges on the substitutability or complementarity of capital and energy is little comfort, since the latter is also the subject of vigorous debate. (See Berndt and Wood, 1979). Others have also argued that real-world market distortions, such as taxes, might greatly increase the general equilibrium cost of energy conservation (Sweeney, 1978).

To address these problems, I present a general equilibrium extension of the heuristic partial equilibrium analysis, and show that the partial equilibrium response to conservation can be interpreted as a constrained general equilibrium response. Thus the partial equilibrium cost estimate is an outer bound on the general equilibrium social cost, if the economy is otherwise undistorted. Any claim that partial-equilibrium models of this type

understate the real costs of restricting energy consumption must be based on the argument that energy-price increases aggravate existing distortions such as non-optimal factor taxes.

The paper is organized as follows. In Section 1 the heuristic partial equilibrium analysis is developed to show how the qualitative results of modern partial equilibrium simulation models can be interpreted in terms of simple and familiar aggregate economic responses. As a prelude to the analysis of the general equilibrium implications of the partial equilibrium results, Section 2 contains a critical discussion of the criteria which must be met if a model is to be capable of predicting the full general equilibrium implications of an aggregate energy reduction.

In Section 3 the general equilibrium effect of energy conservation on natural product is compared with its partial equilibrium counterpart. Previous attempts to derive simple bounds on or predict the direction of the general equilibrium response, based on the characteristics of the production function, are shown to represent at best special (and rather unlikely) cases. Thus the issue of capital-energy complementarity is placed in proper perspective. The general equilibrium welfare cost in an undistorted economy is considered in Section 4, and the implications of other economic distortions are considered in Section 5. The conclusions are summarized in the closing section.

1. The Cost of Aggregate Energy Conservation in Partial Equilibrium

In analyzing the effects of energy taxation or regulation, a common approach is to concentrate on modeling the energy sector in considerable detail, using energy demand and input supply relations to represent the connections between this sector and the rest of the economy. This partial equilibrium approach assumes that these relations are independent of the changes in policy under consideration.

Interpretation of the results of such models is hindered by two serious difficulties. The first is that since each model incorporates a great number of technical and economic assumptions, it is not always possible for those not intimately familiar with the models to know whether differences in outputs are due to differences in assumptions and exogenous inputs, or to differences in internal structure. Great progress has been made in attacking this problem in a recent research project for the Modeling Resource Group, chaired by Tjalling Koopmans, of the National Academy of Sciences CONAES study (MRG 1978) which used input from experts to define a standard set of key assumptions which were then adopted in simulations of the DESOM model of Brookhaven National Laboratories (Marcuse et al., 1975), the Nordhaus model (Nordhaus, 1973, 1976), and the ETA model (Manne, 1976). This approach has been extended by the Energy Modeling Forum at Stanford to study a wider set of partial and general equilibrium models, as discussed further below.[2]

These standardized simulations have helped in identifying the parameters which are most important in determining the cost of conservation (MRG, 1978, pp. 46, 106-115; EMF, 1977, Vol. 1, pp. 19-26, Vol. 2, Appendix D). Working with a simpler heuristic model Hogan and Manne (1977) have confirmed the insight that the elasticity of substitution

and the extent of change in energy use are the major determinants of the economic cost of aggregate energy conservation in these partial equilibrium models. All the above studies agree that the relationship is nonlinear, small cutbacks being associated with disproportionately low economic cost. Figure 1 is a typical illustration of this relationship.

In each of the above works this relationship is derived from the numerical results of model simulations. The underlying economic relationships are neither identified nor explained. Thus a second major problem, the lack of attention to the analytical relationships involved, remains. It is reflected in recent evaluations of the conditions under which partial equilibrium results are valid or even useful indicators of the general equilibrium response, as is shown below.

To demonstrate the simple and basically familiar economic relationships which determine the cost of modifying aggregate energy use, I will now outline a heuristic partial equilibrium approach which adequately (for our purposes) reproduces the cost of aggregate conservation derived from more ambitious partial equilibrium simulation models. This approach is based on the following model which will later be used to show the relationship between partial equilibrium and general equilibrium estimates of this cost.

Consider an economy where the final output is a single good Y which is produced by the only domestic primary resource and by energy. The total domestic primary resource endowment is normalized to unity. Of this a fraction N (for non-energy resource) is used as an input to the production of Y. Though primary domestic resources include in practice at least capital and labor, for simplicity only one domestic primary resource is considered here. Energy E is initially assumed to be

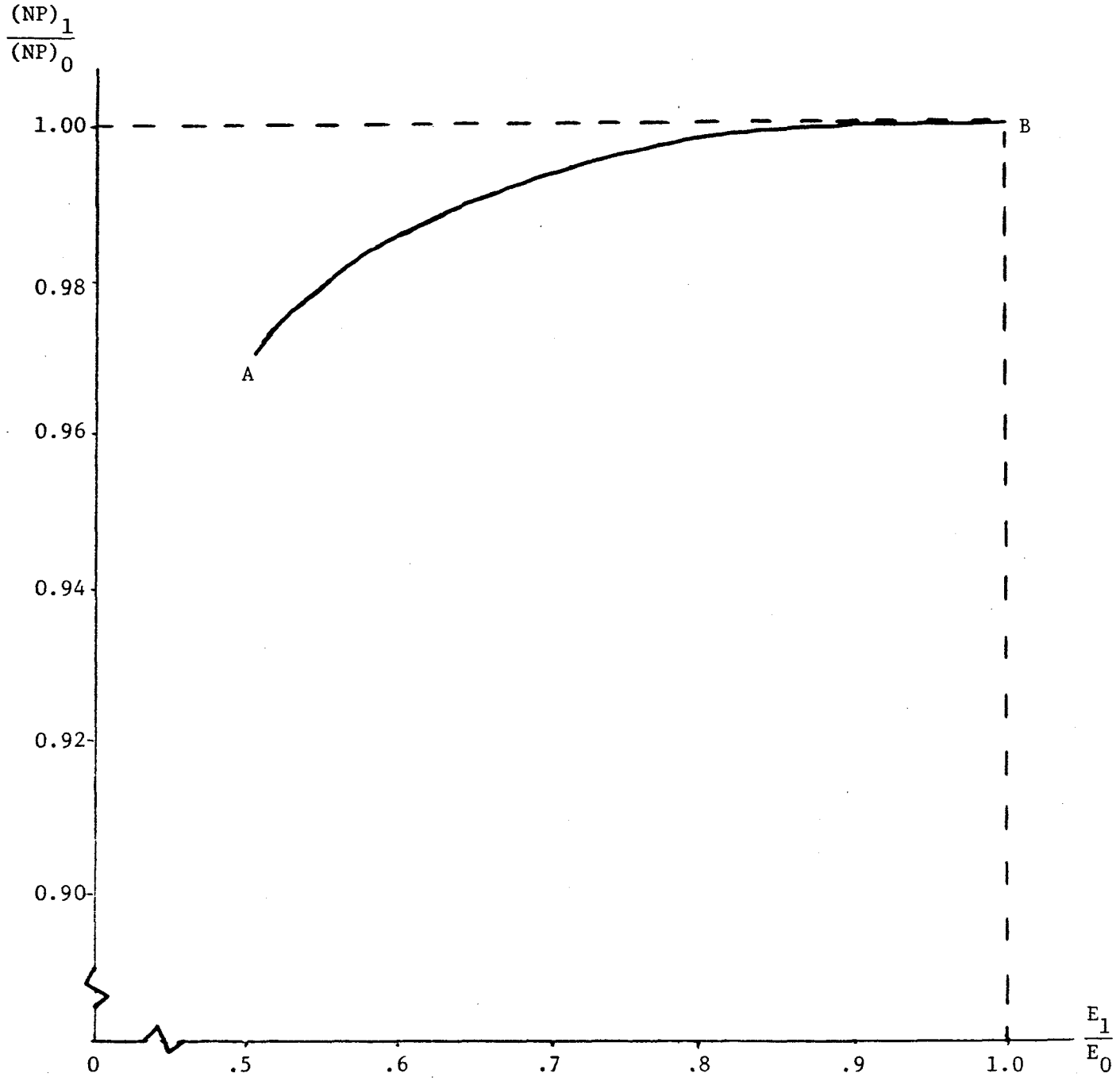

FIGURE 1

The Relation between Energy Use and National Product

Source: Curve AB illustrates the results of simulation of the Nordhaus model under increasingly severe constraints on aggregate energy use. These results are also presented in Table 2 below.

entirely purchased from a stock held by foreign oil producers ("OPEC") in exchange for Y. The economy is a price-taker with regard to E. More specifically, any amount is available at a constant price P_0^E, denominated in units of Y, which is the numeraire.

The production function is:

$$(1) \qquad Y = F(N,E),\ F_N \geq 0\ ,\quad F_E \geq 0$$

and unless otherwise stated it is assumed to have constant returns to scale. In this one-period model, saving is ruled out. Therefore consumption of final product in this model equals Net National Product (NNP), which, since depreciation is also assumed away, equals GNP, or simply National Product (NP):

$$(2) \qquad C = NP = Y - P_0^E E\ .$$

Social welfare is measured by the utility of anyone in the population whic is assumed to be composed of identical individuals. Questions of income distribution are thus avoided

$$(3) \qquad U = U(1-N,\ C),\ U_N \leq 0\ ,\quad U_{NN} \leq 0\ ,\quad U_C \geq 0\ ,\quad U_{CC} \leq 0\ ,\ U_{CN} < 0$$

The initial competitive equilibrium is equivalent to that achieved by maximization of the social welfare function U , subject to the constraints (1) and (2). The Lagrangian is:

$$(4) \qquad L = U(1-N,\ C) - \lambda(C - Y + P_0^E E) - \mu(Y - F(N,E))$$

The first order conditions are equations (1), (2) and

(5) $$P_0^E = \frac{\mu}{\lambda} F_E$$

(6) $$\frac{\partial U}{\partial C} \equiv U_C = \lambda$$

(7) $$\frac{\partial U}{\partial N} \equiv U_N = -\mu F_N$$

(8) $$\lambda = \mu \ .$$

Since the importing country is assumed to be a price-taker:

(9) $$dP^E = 0 \ .$$

Now let us examine the partial equilibrium effects of a reduction (dE) of the energy input from its initial equilibrium value. The assumption which identifies this exercise as a partial rather than a general equilibrium approach is that the aggregate input of N is assumed fixed at N_0, the level of N at the initial equilibrium:

(10) $$N = N_0$$

Taking a second-order approximation to (2) about the initial equilibrium, using (1), (9) and (10):

(11) $$dC = F_E dE - P_0^E dE + \frac{1}{2} F_{EE} (dE)^2 \ .$$

From (5) and (8)

(12) $$P_0^E = F_E \ .$$

From (11) and (12):

(13) $$d(NP) \equiv dC = \frac{1}{2} F_{EE} (dE)^2 \ .$$

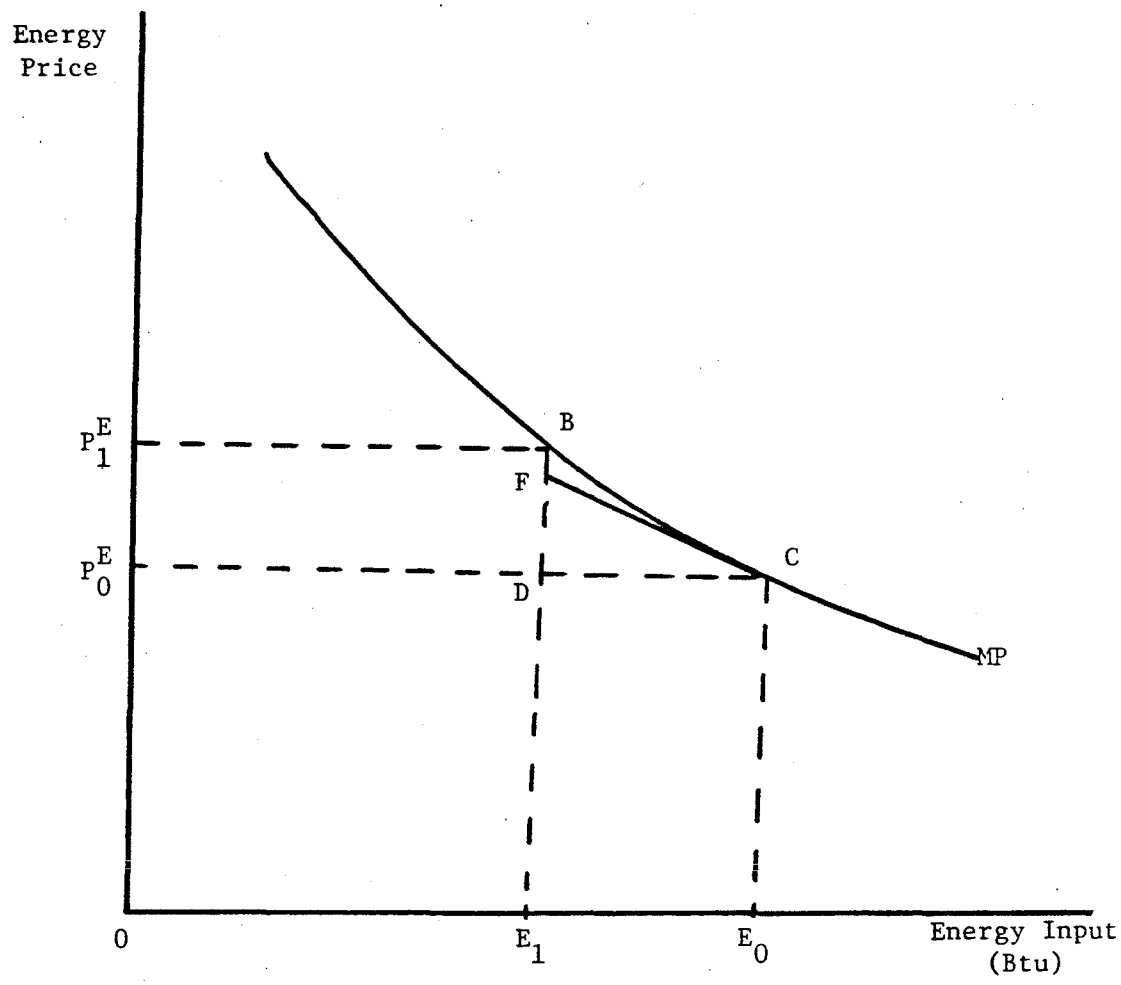

FIGURE 2

The Effects of an Energy Input Reduction

This estimate of the change in national product is illustrated in Figure 2 as the area of the triangle FCD under the marginal product curve, MP , for a reduction of E from E_0 to E_1. The change in Y is given by the area E_1BCE_0. Area E_1DCE_0 represents resources saved by reducing oil purchases at the price P_0^E. The difference, the change in C, is given by the area BCD. If F_{EE} is calculated at N_0, equation (13) approximates area BCD as area FCD.

If the change in energy consumption were a response to an OPEC price rise to P_1^E , then the change in C would also include the increase in the cost of the energy units purchased at the new price, which is represented by area $P_1^EBDP_0^E$. In the case considered here the area represents domestic revenue from the tax on E , which we assume is redistributed as a lump sum payment to consumers so that this area represents no net cost to the economy. Hence the welfare effects of moderate conservation forced on the economy by direct OPEC action are much more serious than the effects of an equivalent curtailment of imports through domestic taxes, as long as the revenues from the latter are put to socially desirable use. To characterize the latter case as a self-imposed embargo, as some prominent economists have done, is to court confusion of the very different welfare implications of the two cases.

Now is the net cost of energy conservation, represented by the area BCD , a large or a small burden for the economy to bear? After the OPEC embargo of 1973, many claims were made, at least partly on the

basis of casual inferences drawn from historical trends, that the cost of a given percentage change in national energy consumption would be a roughly equivalent percentage fall in GNP. In this sense growth in GNP was said to be "coupled" to growth in energy use. This rule of thumb, still current in business circles,[3] can be evaluated using this analytical model. For finite changes in E in the range considered in model simulations the following approximation measures the proportional change in National Product and consumption in response to a change in E:

$$(14)\quad \frac{\Delta(NP)}{(\bar{NP})} = \frac{\Delta C}{\bar{C}} = \frac{1}{2}\bar{\phi}\,\frac{\bar{\bar{E}}\bar{F}_E}{\bar{C}}\left[\frac{\Delta E}{\bar{E}}\right]^2$$

where bar superscripts denote averages of the values before and after conservation. Thus the proportional response of national product is half the product of ϕ, the elasticity of marginal product with respect to the quantity of energy used, the value share of energy in GNP, and the square of the proportial energy input reduction. Readers might wonder why I express this relation in terms of the elasticity of marginal product of energy rather than using the elasticity of derived demand for energy, to which it is inversely related. The reason is that since ϕ is determined solely by the production technology it has a straightforward definition which is consistent with both the partial and the general equilibrium modeling frameworks used in this paper.

The graph of this expression gives a figure like Figure 1 above, which has been derived numerically in other studies. The elasticity of C with respect to energy use is

$$(15)\quad \frac{\Delta C}{\bar{C}}\Big/\frac{\Delta E}{\bar{E}} = \frac{1}{2}\,\bar{\phi}\,\frac{\bar{\bar{E}}\bar{F}_E}{\bar{C}}\cdot\frac{\Delta E}{\bar{E}}$$

Since the mean domestic value share of energy, $\bar{E}\bar{F}/\bar{C}$, is likely to be less than 0.1, this elasticity is very low unless the absolute value of $\bar{\phi}$ and/or of the (positive or negative) energy change from E_0 is large. Clearly the one-to-one "coupling" of proportional changes in energy and GNP is repudiated, for accepted parameter values, by this analysis. In fact the elasticity is generally so low that I propose the following rule of thumb measure of the cost of moderate energy conservation which has greater intuitive appeal. The ratio of the net cost of conservation to the cost of the energy saved is approximately.

$$(16) \quad \frac{dC}{F_E(E_0,N_0)dE} = \frac{1}{2}\,\phi\,(E_0,N_0)\,\frac{dE}{E} \quad .$$

The ratio given by equation (16) is an approximation to the ratio of the area BCD to area DCE_0E_1 in Figure 2. It has unitary elasticity with respect to ϕ and with respect to the proportional change in E (see Figure 3). By this rule of thumb if, for example, $\Delta E/E_0 = -0.1$, $|\phi|$ must exceed 10 before the estimated net economic cost exceeds half the value of the energy input conserved.[4] On the other hand, if $\phi = 2$, an energy tax which produced a ten percent long-run cutback in total energy consumption from an undistorted equilibrium would by this rule have a net cost to the economy equal to about 10 percent of the resource cost of the energy saved.

The isoquant map presented in Figure 4 illustrates the adjustment which prevents a one-to-one coupling of the percentage changes in National Product and in energy use in this model. In Figure 4 N is held at N_0, its original level, as E is reduced from E_0 to F_1, reducing the maximum level of output from Y_0 to Y_1. This reduction is the equivalent of the

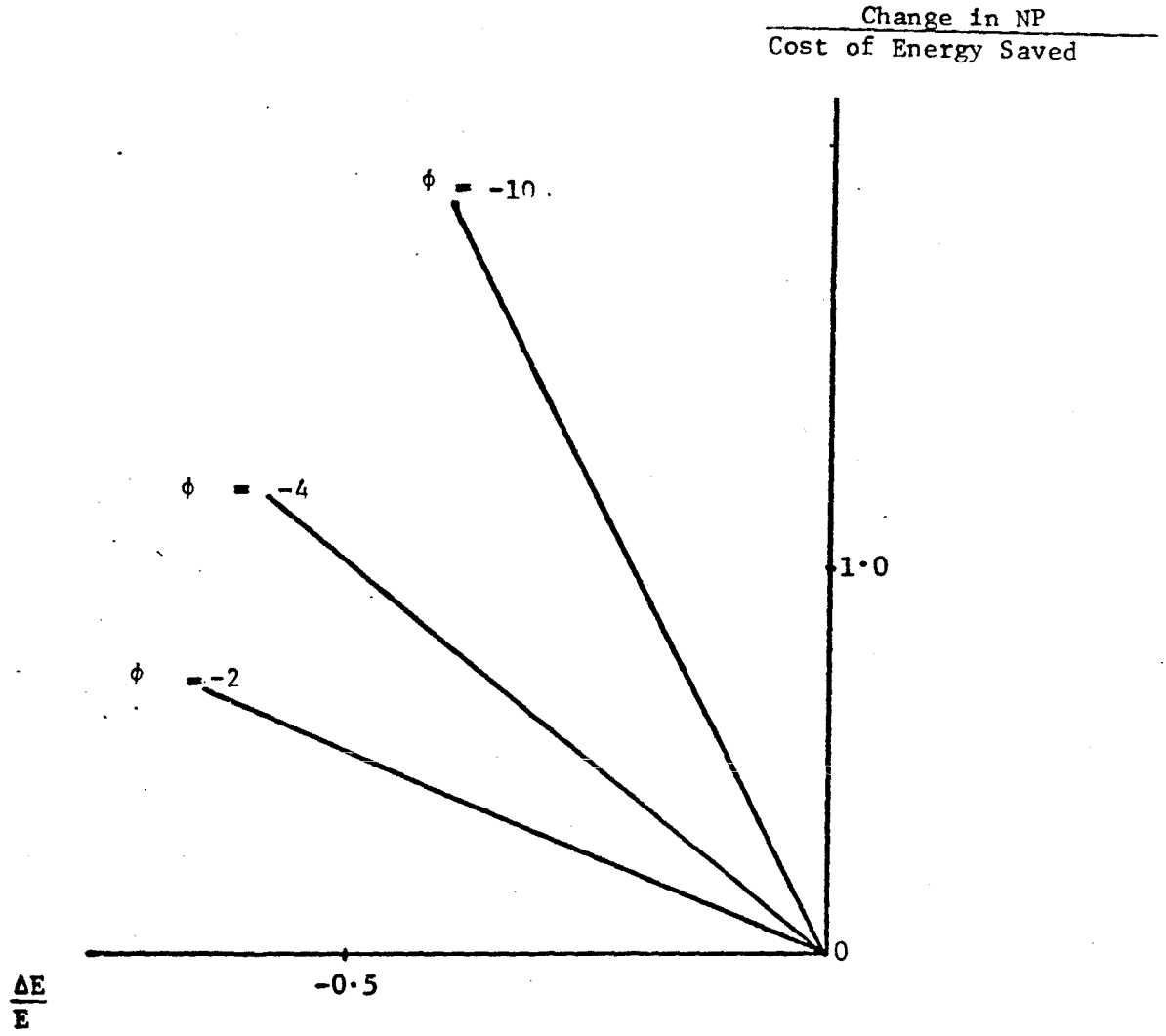

FIGURE 3

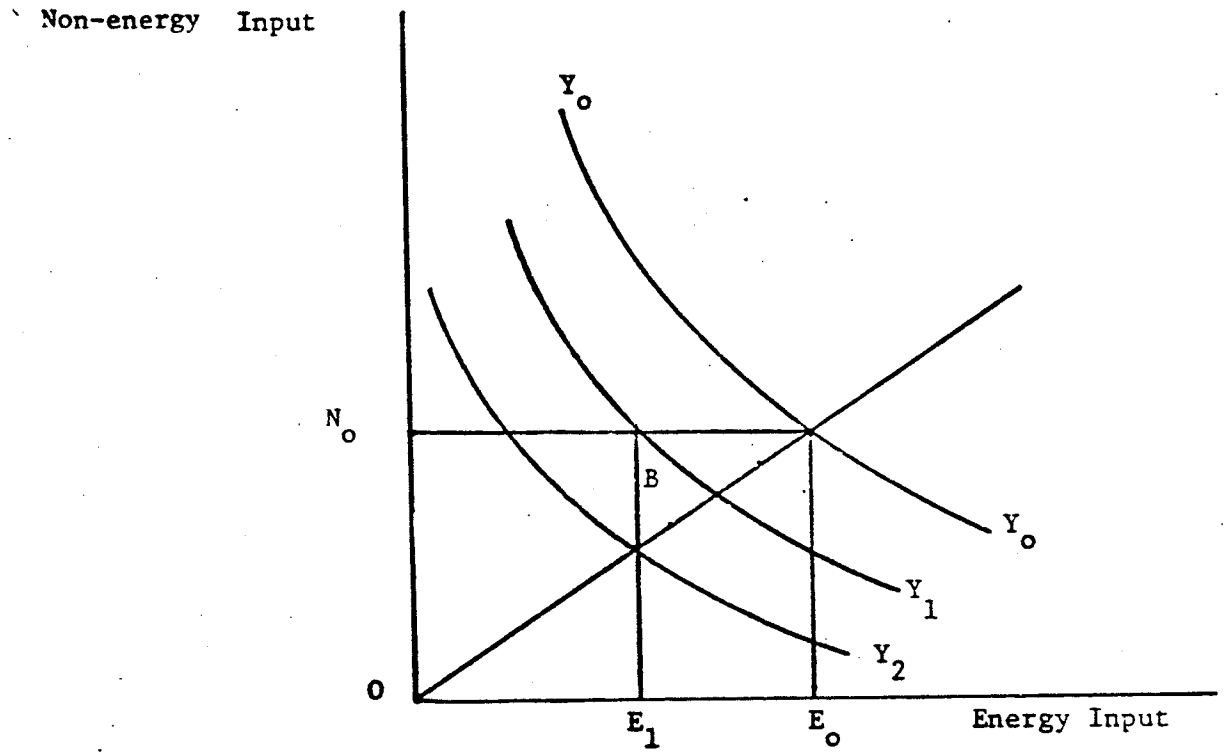

Figure 4

area BCE_0E_1 in Figure 2. The direct effect of a reduction in E (which is a reduction in Y from Y_0 to Y_2) is, in this partial equilibrium model with N held fixed, mitigated by an increase in the ratio of N to E (which increases Y from Y_2 to Y_1), which we might more comfortably call "substitution" of N for E in production if that particular term had not become such a source of confusion in the literature. Only in the limiting case of Leontief technology illustrated in Figure 5 (and reflected in certain energy models such as at least the early versions of the PILOT model (Parikh, 1977)) is this change in factor ratios incapable of reducing the impact of an energy input reduction. Given constant returns to scale, Figure 5 depicts one-to-one coupling of energy and GNP in this partial equilibrium model.

Thus far we have considered only the case where all energy E comes from an overseas supplier, "OPEC." But in most countries a large proportion of energy is produced domestically. We can easily extend the simple model developed above to handle domestic energy if we accept two radical simplifying assumptions:

(1) All energy is a homogeneous product.

(2) Each type of energy production uses as input only Y and perhaps some limited natural resource (such as oil deposits, coal beds, river flow, etc.).

Given these assumptions, and assuming finite amounts of energy are available at constant cost from each source (as in programming models), a partial equilibrium energy market projection for, say, the year 2010 can be illustrated by Figure 6.[5] The solid line AK is the energy supply curve. Segment JC represents imported oil, and segment GH represents nuclear energy. The cost of a cutback in imported oil to reduce total energy from E_0 to E_1 is represented by the area of triangle BCD .

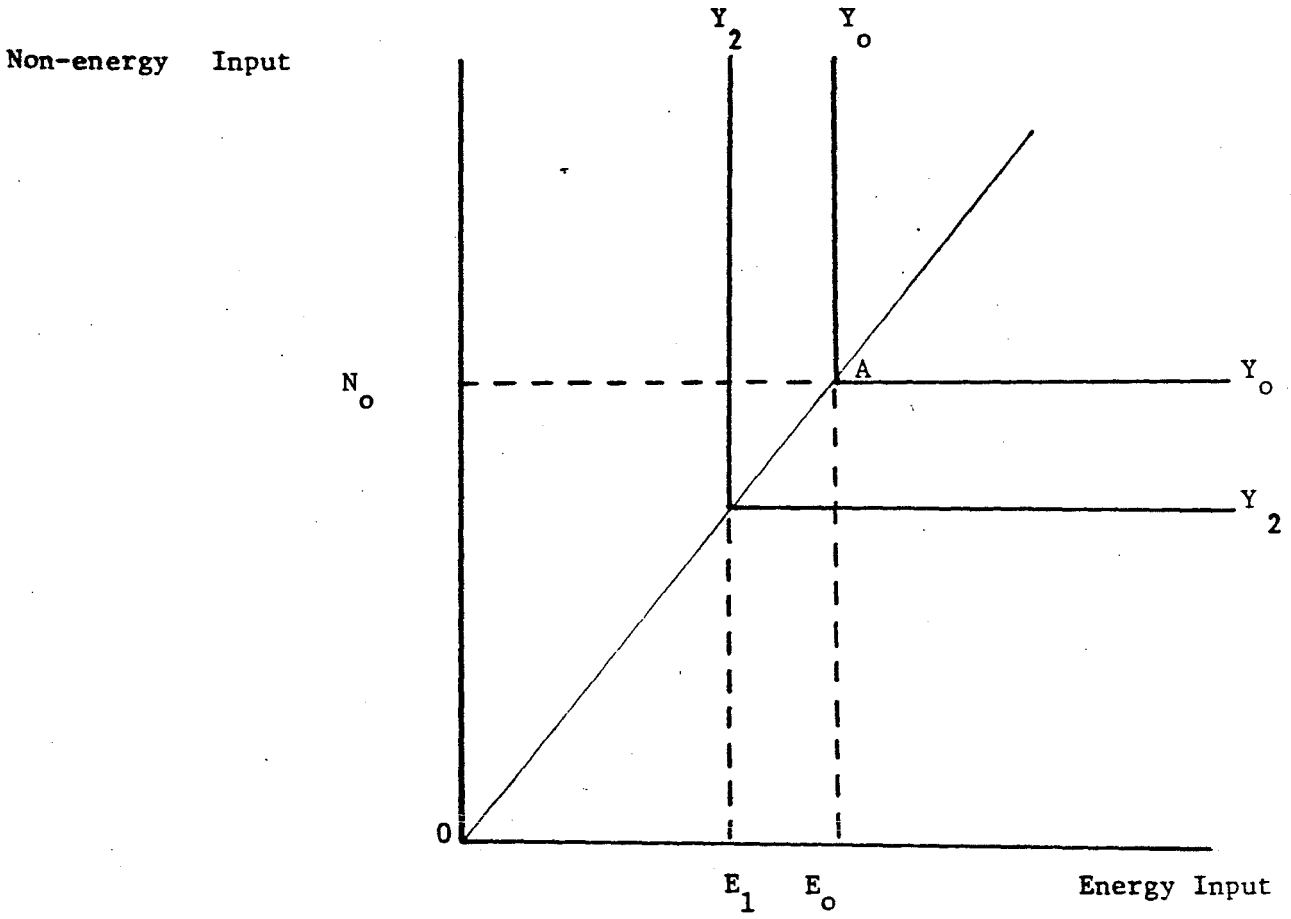

FIGURE 5

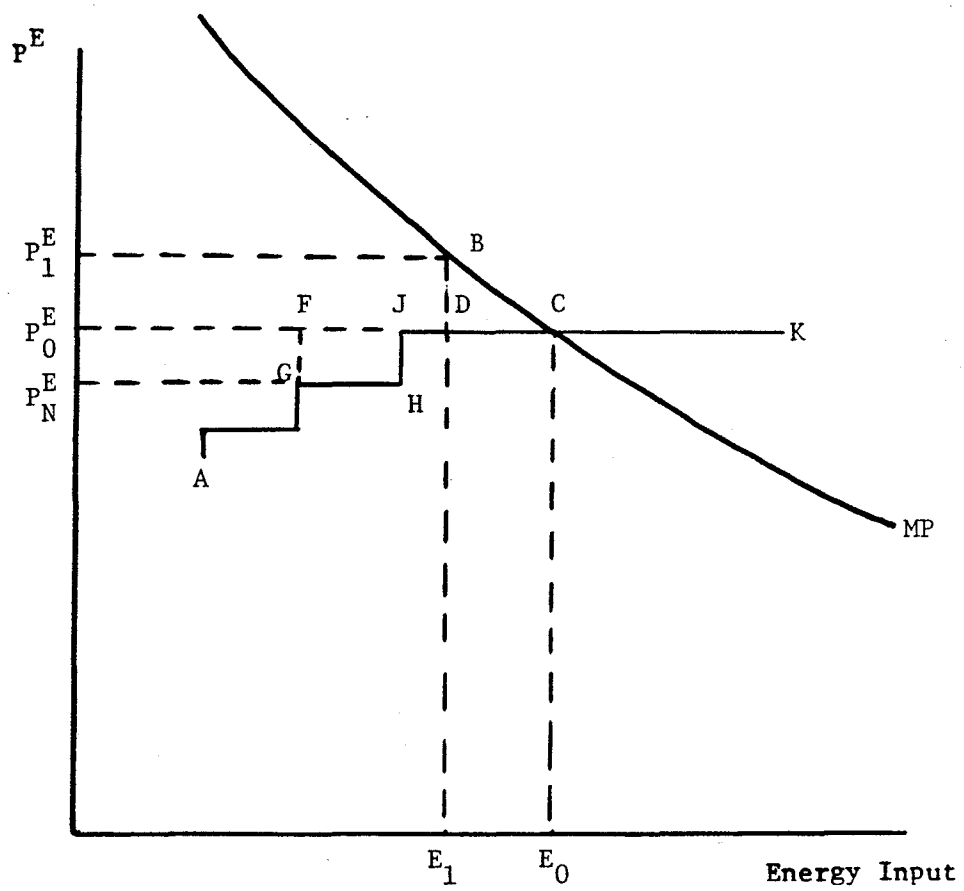

FIGURE 6

If, instead, this cutback represents elimination of nuclear energy, the rectangle FJHG must be added to the total cost. It is the foregone rent on the lost nuclear capacity. The more nearly marginal is nuclear, then (by definition) the smaller is the difference $P_0^E - P_N^E$, and the area FJGH ..

In general, area BCD plus any change in rents measures the cost of any energy conservation policies. This is the one-sector analogue of the cost estimated by the partial equilibrium models for each year of the forecast interval. As stressed above, this analogy rests on a number of simplifying assumptions. Do these assumptions cause the heuristic model to fail in its task of representing the major economic responses involved in partial equilibrium studies of energy conservation? This question would be difficult to answer in detail in the context of this paper. But it is easy to show that the heuristic model does adequately reproduce the cost of moderate levels of conservation predicted using the Nordhaus model, a complex partial equilibrium programming model which gives estimates of the cost of aggregate energy conservation which are qualitatively similar to those of other major energy models which allow for substitution in production.[6]

The MRG study presents the results for the year 2010 of simulations of the Nordhaus model for increasingly severe constraints on aggregate energy consumption (MRG, 1978, pp. 112-113. The original modeling exercise is reported in Nordhaus, November 1976). The energy demand elasticity reported for the Nordhaus model for year 2010 at base case prices and quantities (MRG, 1978, p. 210, Table C.3) is interpreted in the following exercise as the inverse of the arc elasticity of marginal product ϕ over the range of change.

The results of the heuristic model using this elasticity, are compared with those of the Nordhaus model in Table 1. They are similar up to sub-

TABLE 1

Partial Equilibrium Estimates of the Cost of Conservation in Year 2010

Energy Consumption Changes* $\left(\frac{\Delta E}{E_0}\right)$	Nordhaus Model* $\frac{\Delta(NP)}{(NP)_0}$	Heuristic Model** $\frac{\Delta(NP)}{(NP)_0}$
0.000	0.000	0.000
-0.107	0.000	0.000
-0.249	-0.004	-0.004
-0.369	-0.011	-0.011
-0.469 (zero growth from 1975)	-0.023	-0.023

*The energy consumption changes and the Nordhaus income changes are calculated directly from MRG (1978), Table III.24.

**This column is calculated using equation (14). The arc elasticity $\bar{\phi}$ is approximated by the inverse of the "elasticity of demand" of -0.49 derived from the Nordhaus model for year 2010 base case prices and quantities, as presented in MRG (1978), Table C.3, p. 210. The share of primary energy in GNP in the base case, year 2010, is calculated from information in MRG (1978), p. 70, Table III.10 p. 89, Table III.17, p. 90, Table III.18 and the additional assumption that the price of oil, NGL and gas is the same per Btu. $\bar{E}\bar{F}_E$ is calculated using ϕ, $\Delta E/\bar{E}$ and the base case share of primary energy in GNP discussed immediately above.

stantial reductions in energy use. (Indeed the accuracy of approximation might ordinarily be somewhat lower for other similar exercises.) This comparison is consistent with the propositions that changes in rents are a relatively minor component of the cost of economically rational measures to achieve moderate energy cutbacks, and that once the aggregate estimate of ϕ has been determined the more complex multisectoral structure necessary to answer the detailed questions which these models must address is not essential for estimating the cost of economically rational aggregate energy conservation.[7]

The relative simplicity of this heuristic model makes it a valuable tool in examining the conditions under which the partial equilibrium modeling approach is both valid and useful. In the model evaluation literature there is a common implication that the partial equilibrium approaches are valid only if energy-economy "feedback" is acceptably small. For example, Hogan and Manne (1977, p. 260) state that "If the substitution effects are significant, the feedback effect on the evaluation of the energy system is relatively small. In this case, the energy sector may be analyzed by itself. The changes in energy utilization and economic costs can be represented adequately by the first order effects contained in traditional microeconomic demand curve analyses."[8]

How significant is general equilibrium feedback? Does it render partial equilibrium estimates of the cost of energy alternatives completely useless? Or can the partial equilibrium approach still yield helpful indicators of the social cost of alternative energy policies? These important questions have been studied by energy modelers in recent years.

Unfortunately, the analytical models used in these studies do not apply the necessary general equilibrium constraints, as discussed below. These questions are addressed in the following sections, where the heuristic model is compared to its general equilibrium counterpart. But first it is necessary to consider further what we mean by "general equilibrium" feedback, since the current terminology is imprecise and confusing. In the next section I discuss the links between energy use, primary factor supplies and aggregate demand which transmit the general equilibrium responses which partial equilibrium models must ignore.

2. The Energy-Economy Feedback in General Equilibrium Models

The economic flows in the general equilibrium counterpart of the model we have been considering are illustrated in Figure7 . Households may now alter their supply of factor N (and consumption of $1 - N_0$) in response to changes in energy used in production. Such a "feedback" response will affect output Y and consumption C , which will in turn affect the consumer's allocation of N . If N is labor (capital), the response affects the labor-leisure (consumption-saving) decision. At the new equilibrium, the value of N must equal the value of C to consumers. In partial equilibrium models, one must choose between holding N constant and observing the change in the value of C (the approach taken above), or holding C constant and observing the change in N .

In this paper, the consistency between the value of inputs and the value of marketed output (N and C respectively) is viewed as a necessary feature of a general equilibrium model. Without it, inferences regarding the effects of "general equilibrium feedback" between energy and primary factor inputs can be seriously misguided, as is shown below. Though this point might appear obvious in this stark model depicted in Figure 7, most of the models commonly referred to as general equilibrium energy models do not connect this link.

For example, the original Hudson-Jorgenson, (1974) inter-industry model took the prices of primary inputs (capital and labor), and aggregate demand, from their separate macroeconomic growth model, but there was no feedback link from the inter-industry model to the growth model; the growth path was exogenous. Therefore the simulations of aggregate energy conservation via a Btu tax are analogous to simulations of a multisectoral version of the partial equilibrium model presented above, modified so that domestic energy production is taken into account.[9]

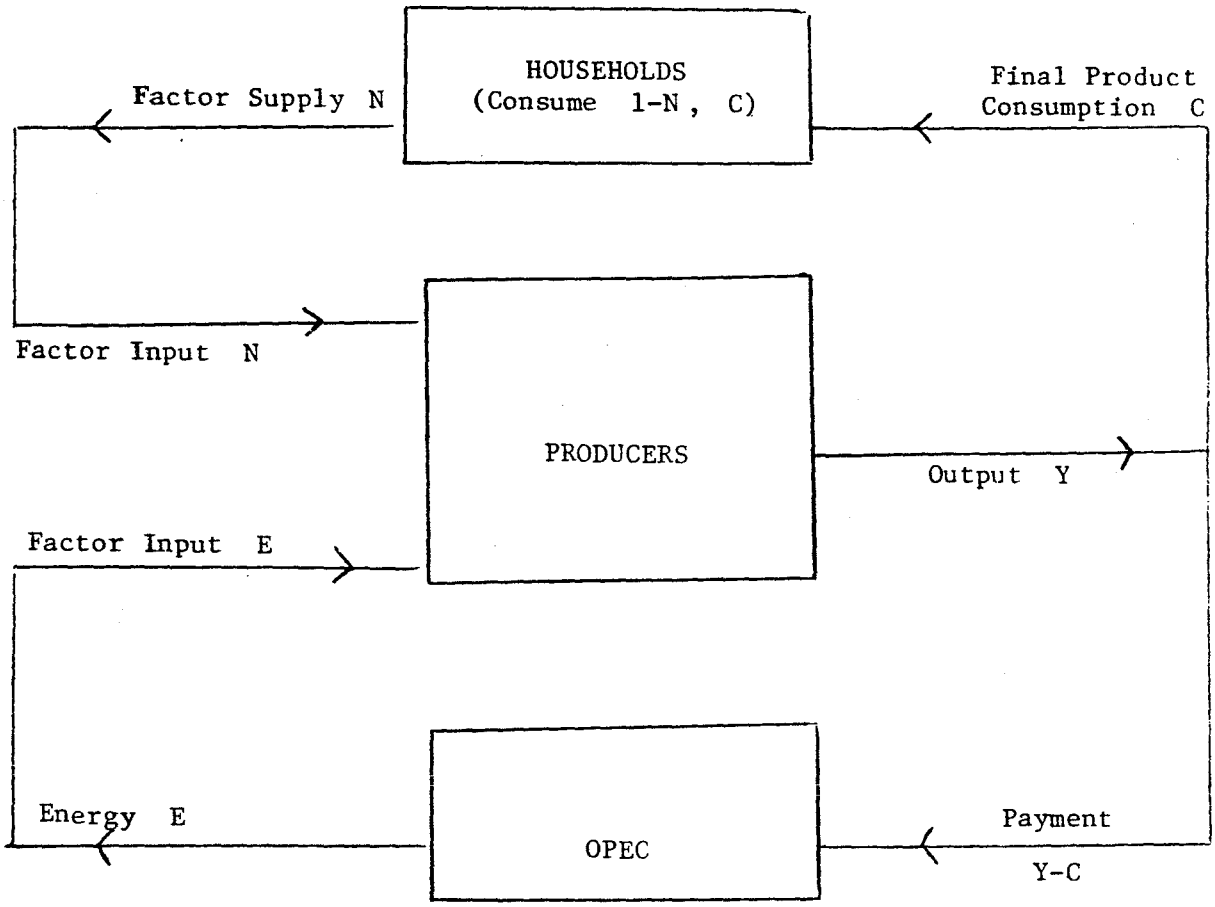

FIGURE 7

Economic Flows in the Simple General Equilibrium Model

Alan Manne's ETA-MACRO is a model "designed to estimate the extent of two-way linkage between the energy sector and the balance of the U.S. economy" (Manne, 1977, p. 1). It is constructed by linking the ETA model (Manne, 1976) with a simple macroeconomic growth model which incorporates an innovative putty-clay distinction between "old" (1970 and prior vintages) and "new" capital stocks. It is difficult to assess this model since the MACRO sub-model is not fully documented in available publications. But the aggregate primary capital and labor resource constraints do not appear to be imposed on the energy model. If this is true, the general equilibrium relationships between energy availablility, aggregate demand, and consumers' allocations of their primary resource endowments, which complete the "two-way linkages between energy and the rest of the economy" (Manne, 1977, p. 1) are mis-specified in the model.[10]

Reister and Edmonds (1977, p. 199) characterize their model as a "two-sector general equilibrium energy demand model," but in their view "general equilibrium means that there are strong interactions between the two sectors of the model." Since their model treats the price of capital, the price of labor and the supply of labor as exogenous (p. 212) it cannot be used to study the general equilibrium energy-economy relationships in which we are interested.

In fact the only energy models currently available to this author which clearly meet the criteria necessary to characterize them as complete general equilibrium models are the Hudson-Jorgenson LITM (Hudson and Jorgenson, 1977) and models derived from or otherwise closely related to it.

(e.g. Hnyilicza, 1976). The relationship between energy cost estimates produced by such general equilibrium models and the results of partial equilibrium models is examined in the next section, by comparing the solution using the heuristic partial equilibrium model with its general equilibrium counterpart.

3. The Effect of Conservation on Economic Activity in General Equilibrium

Using the definition of general equilibrium applied above, the general equilibrium counterpart of the partial equilibrium cost of conservation in the heuristic model developed in this paper emerges when the constraint given by (1C is relaxed. For small changes in E, the change in consumption is approximated by substituting (1) in (2) and totally differentiating:

(17) $dC = F_E dE + F_N dN - P_0^E dE$

Using (12),

(18) $dC = F_N dN$

The change in C is directly related to the change in N. The sign of (18) is the sign of dN, which is obtained from differentiation of (12):

$$(19) \quad dN = -\frac{F_{EE}}{F_{NE}} dE$$

For small reductions in E the sign of dN and dC is opposite to the sign of F_{NE}. If F is linear homogeneous F_{NE} is positive and a small amount of conservation reduces C indirectly through (18) by inducing a reduction in the supply of N.

Second-order effects are ignored in (17), (18) and (19). Since they were crucial in the partial equilibrium result, I now extend the model to include them. Taking a second-order approximation to (2), using (1) and (9),

$$(20) \quad dC = F_E dE + F_N dN - P_0^E dE + \tfrac{1}{2}F_{EE}(dE)^2 + \tfrac{1}{2}F_{NN}(dN)^2 + F_{NE} dN dE.$$

If the second-order terms are non-negligible, the signs of the changes in C and N are indeterminate in the absence of further restrictions

on the model, even if F_{NE} is known. Two alternative cases are illustrated in Figures 8 and 9. In both figures U^0 is the initial social indifference curve before conservation. $TP(N, E_0)$ is the total product curve for input of N (increasing from right to left) given the original input of E, E_0. Total product at an input of N_0 (and consumption $1 - N_0$ increasing from left to right) is $(C_0 + P_0^E E)$ units of Y. The slope of the radius OR_0 is the price of N in units of C. Consumption of final product, C_0, equals the earnings of N_0 units of domestic primary resource used in production. When E is reduced to E_1, the total product curve falls to $TP(N, E_1)$. If N is held constant at N_0, consumption of final product, C, decreases by the fall in output Y net of the saving in expenditures on E. This fall in consumption, $C_0 - C_2$, measures the cost of the energy cutback which is approximated in equation (13).

If the two-factor production function has constant returns to scale, $F_{NE} \geq 0$, so that the marginal product $F_N(N_0, E_1)$ is lower than $F_N(N_0, E_0)$. This negative effect on the marginal value of N_0 as an input in production would, ceteris paribus, increase consumption by households of this domestic primary resource $(1 - N_0)$, and reduce its use in production. But if N is a normal good, this effect will be opposed by the income effect of energy conservation, which increases the supply of N offered in the market. The general equilibrium response is the net result of these two effects.

In Figure 8, where the income effect on the supply of N is outweighed by the decline in marginal productivity, the new equilibrium point F is associated with a decrease in the absolute value of N (an increase in consumption of the primary resource from $(1 - N_0)$ to $(1 - N_1)$) and

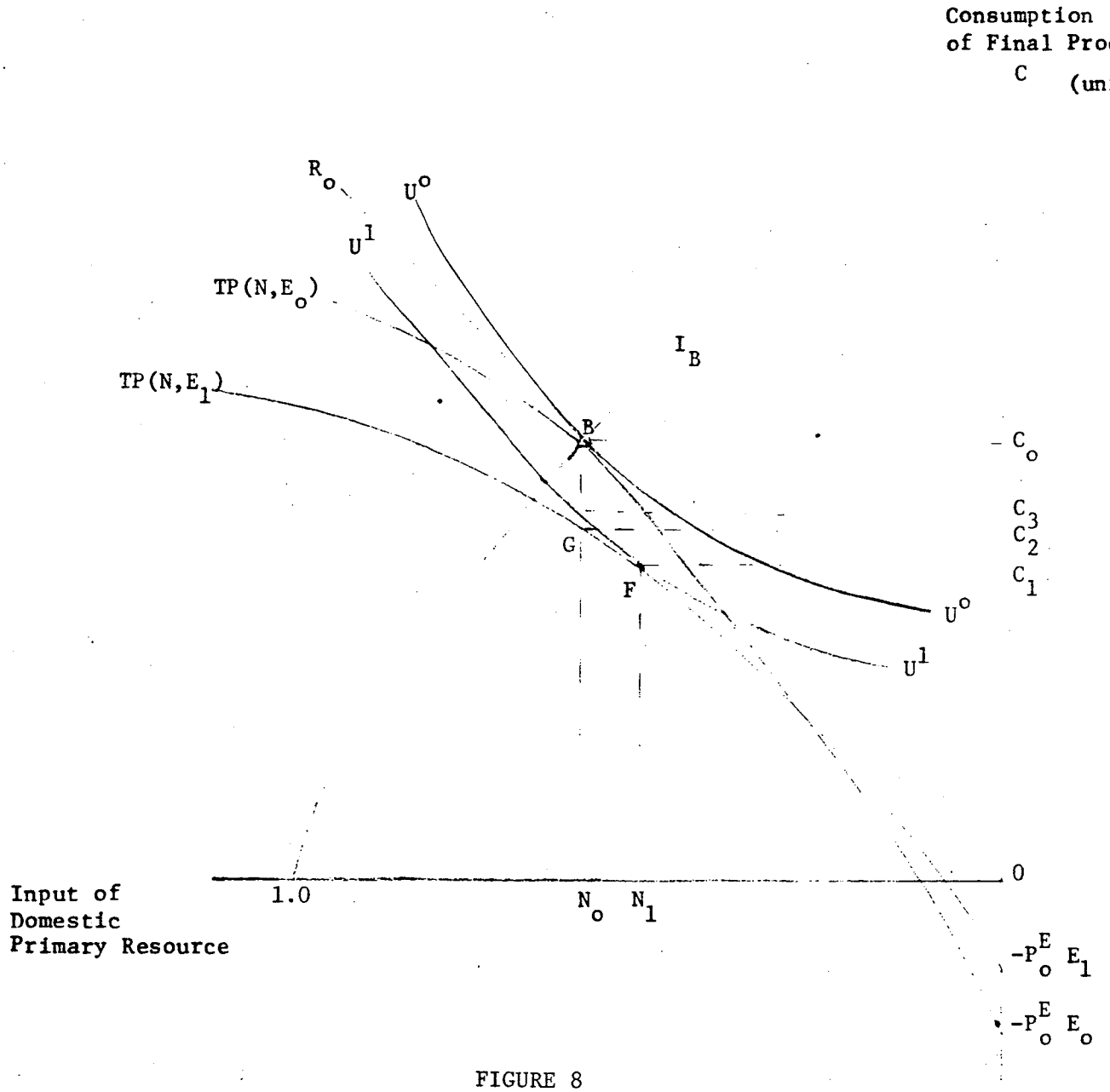
Consumption
of Final Product
C
(units o
R
o
U
o
U
1
TP(N,E
o
)
TP(N,E
1
)
I
B
B
G
F
C
o
C
3
C
2
C
1
U
o
U
1
0
1.0
N
o
N
1
Input of
Domestic
Primary Resource
-P
E
o
E
1
-P
E
o
E
o

FIGURE 8

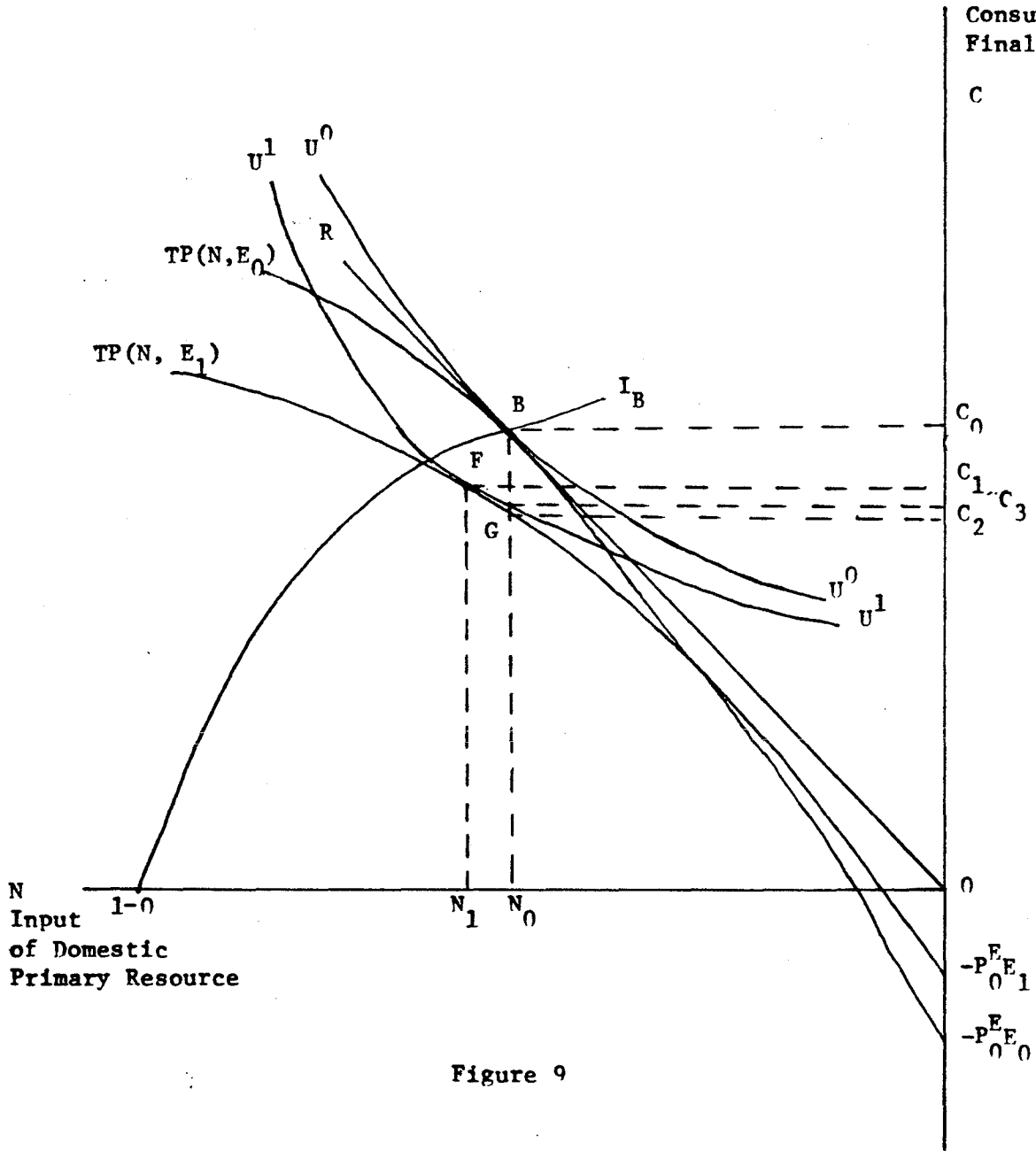
Consumption o
Final Product
C
U^1 U^0
R
$TP(N,E_0)$
$TP(N, E_1)$
I_B
B
C_0
F
C_1
C_3
C_2
G
U^0
U^1
N
Input
of Domestic
Primary Resource
1-0
N_1
N_0
0
$-P^E_0E_1$
$-P^E_0E_0$

Figure 9

a decrease in C to C_1. But in Figure 9, the income effect outweighs the decline in marginal productivity. At the new equilibrium F, N has increased to N_1. If $F_{NE} > 0$, and N is a normal good, the new equilibrium must lie to theright of the income consumption curve through B, I_B. In this case if C is inferior in the relevant range, the new equilibrium could be associated with an increase in C; otherwise C falls as in Figures 8 and 9. If $F_{NE} > 0$ and N is inferior in the relevant range, it is easy to confirm that C and N both fall. (See Figure 11 below). If $F_{NE} < 0$, the sign of the change in N is ambiguous regardless of the income elasticities. The above cases indicate that a wide variety of responses to energy conservation is possible even in a two-factor model.

Four of the possible general equilibrium responses of input N and output Y to an energy input curtailment are illustrated in factor-factor space in Figure 10 by points A, B, C and D. The partial equilibrium response is represented by point P. Even if both N and C are normal goods and F_{NE} is positive, only point A is ruled out as an equilibrium response.

The conclusion that the general equilibrium response of national product to energy conservation can differ greatly from the partial equilibrium response in either a positive or negative direction is none too comforting for partial equilibrium modelers. Several studies attempting to reduce this ambiguity have proposed simple rules which attempt to relate the sign of the difference between the partial and general equilibrium effects on national product to a single specific parameter of the model, or calculate bounds on the general equilibrium response using partial equilibrium approaches. The heuristic model developed and illustrated above is useful in evaluating these rules, which include the following:

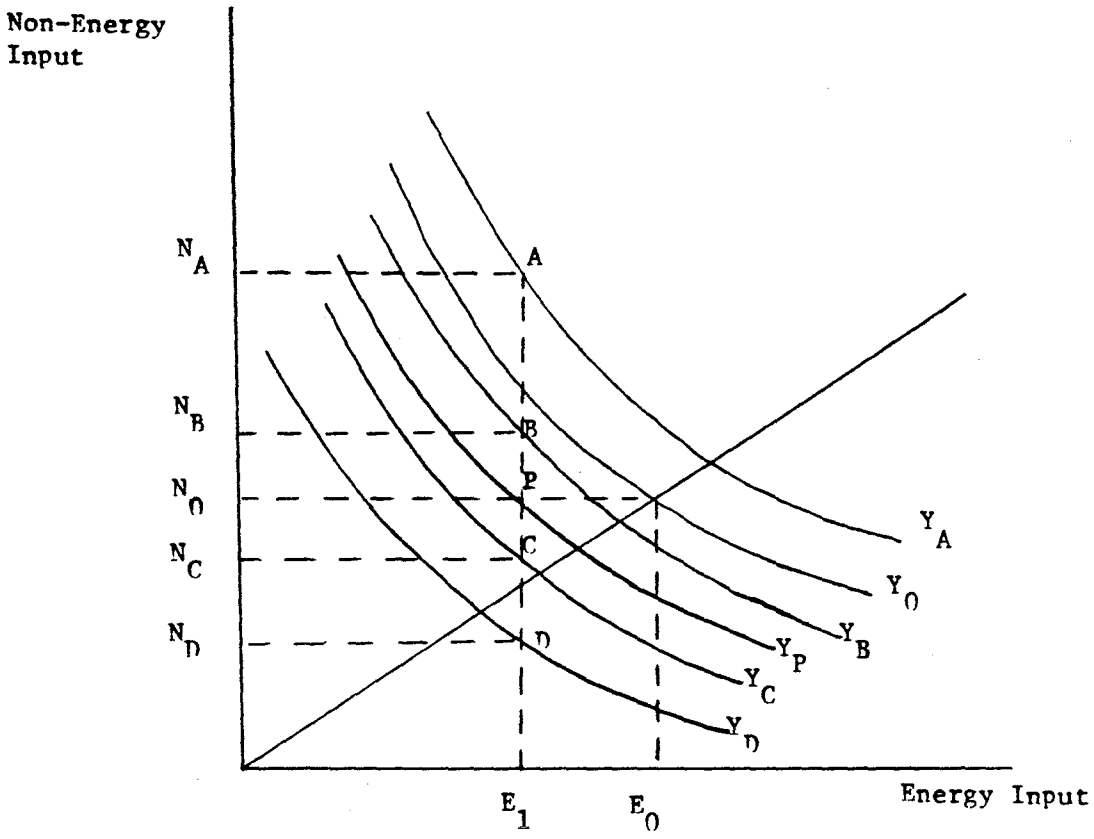
Non-Energy Input
N_A
N_B
N_0
N_C
N_D
A
B
P
C
D
Y_A
Y_0
Y_B
Y_P
Y_C
Y_D
E_1
E_0
Energy Input

Figure 10

1) Until recently, a prevalent view was that the substitutability or complementarity of energy with labor or capital in production, measured by the sign of the Allen partial elasticity of substitution in production, determined the direction of change of equilibrium primary inputs in response to a change in energy use.[11] But in the simple two-factor model with negative elasticity of substitution in production, I have shown that conservation might induce an increase or a decrease in the use of the domestic primary resource, depending upon the characteristics of the complete model.[12]

2) Hogan and Manne (1977, p. 273) have posited that in a three factor model with two primary domestic resources (K and L) if L is held constant at its initial level the response which maintains the marginal product of K represents a lower bound on the input of that resource and an upper bound on the effect of a change in energy supply on output.

This general proposition can be examined in the model used here. The model with fixed labor is equivalent to the two factor model used here, where the production function F has decreasing returns, and N is understood to represent the capital input. It is then possible that $F_{NE} < 0$, and that $F_N(E_1,N_0) > F_N(E_0,N_0)$ where $E_0 > E_1$.[13] In this case, if the response to conservation is to maintain the marginal product of N, it must involve an increase in N which moderates the fall in E. Output would be <u>higher</u> in this case than if N were held fixed an N_0, given E_1. Thus the case where the marginal product of the variable factor is constant clearly does not give a general <u>lower</u> bound on the change in primary resource input or in output, in response to a change in E_1. If as is in general more likely $F_{NE} > 0$, then capital must be an inferior good if its marginal product is to remain constant,

as is shown below. Even if this is true, the conditions do not constitute a bound on the response of capital or national product.

3) In a re-examination of this issue, Hogan (1977) argues that "the likely relationship between capital and energy is one of aggregate complementarity. Restrictions on energy use should induce reductions in the demand for capital and, therefore, exacerbate the economic impacts of energy policy" (p. 24). This general conclusion is based on the same assumptions as the earlier Hogan-Manne conclusions, namely constant marginal productivity of capital which is justified as "most plausible" by a rather circular rationale,[14] and exogenous labor supply. Under these assumptions Hogan (p. 21) claims that the necessary and sufficient condition for a reduction in energy to cause a negative response in capital (complementarity) is, in the notation used here, $F_{NE} > 0$.

In the heuristic model developed here, the condition of constant F_N, means that the new equilibrium point must lie on the income consumption curve I_B through the initial equilibrium point B in Figures 8, 9, and 11. In Figures 8 and 9 the new equilibrium point F does not lie on I_B. In fact if $F_{NE} > 0$ F can lie on I_B only if the income elasticity of consumption of the domestic primary resource, (1-N), is negative in the relevant range, that is, the domestic primary resource is an inferior good as illustrated in Figure 11. This is hardly the most plausible situation. It is true that if we consider only first-order effects of conservation, equations (18) and (19) above confirm Hogan's insight that the capital response to conservation has the sign of $(-F_{NE})$. But, as is shown below, this assumption is equivalent to assuming that energy conservation has no effect on welfare, and hence no income effect.

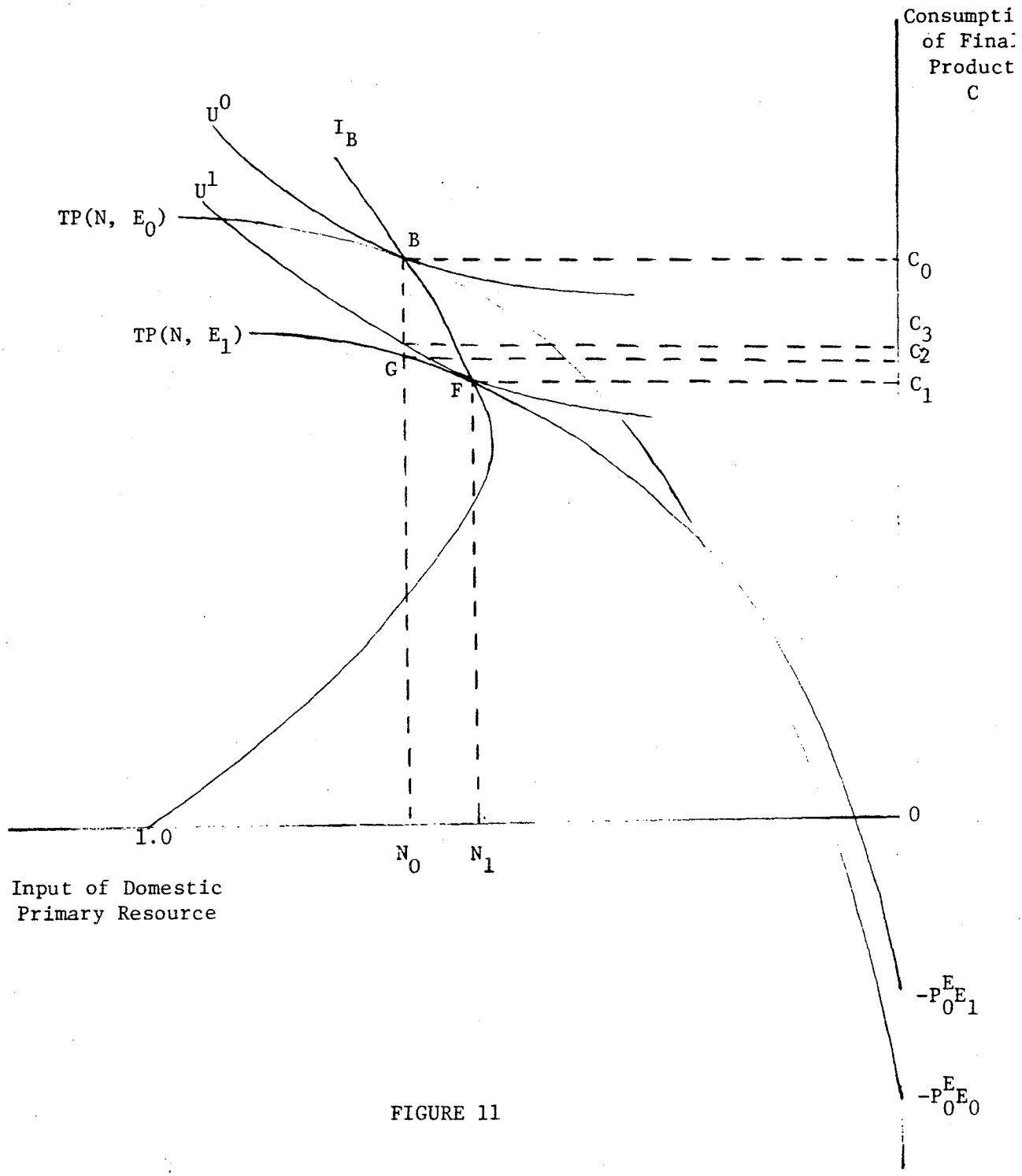
Consumpti
of Fina
Product
C
U^0
I_B
U^1
$TP(N, E_0)$
B
C_0
$TP(N, E_1)$
C_3
C_2
G
F
C_1
0
1.0
N_0
N_1
Input of Domestic
Primary Resource
$-P_0^E E_1$
$-P_0^E E_0$

FIGURE 11

It is possible to consider the effects of energy conservation in an intertemporal context by reinterpreting Figures 8, 9 and 11 as representing a simple two-period Fisherian model. Capital is assumed to be putty-putty--for our purposes this is a non-crucial simplification. N units of capital are committed in period 1 to production in period 2, reducing consumption in period 1 from its maximum level of unity, which is the endowment given by the sum of current income plus past net accumulation, to $(1-N_0)$. The price of "OPEC" energy remains exogenous. If labor supply is fixed, consumption C in period 2 is given by equation (2). Under this redefinition of the variables, $TP(N, E_0)$ represents the intertemporal opportunity locus given that E is held at its free market level E_0. If energy input is reduced to E_1 by, for example, a redistributed tax, then the locus becomes $TP(N, E_1)$.

Table 2 summarizes the implications of energy conservation by showing the effects of the general equilibrium primary resource input response in this simple Fisherian model, for cases representing six possible combinations of parameters. In case 1, which is the most plausible, and in two others, the sign of the general equilibrium response of the domestic primary resource N, and its effect on National Product, is indeterminate. In case 1, if it is positive, it is less than the negative direct effect of the energy reduction. Case 5 is the only case which is consistent with the conclusions of Hogan (1977).[15]

Though Table 2 shows that the difference between the general equilibrium and partial equilibrium effects of energy conservation on National Product is in general indeterminate, the same is not true for the effects on social welfare in an otherwise undistorted economy, as is shown in the next section.

TABLE 2

The Response to Energy Input Conservation in the Two-Period Fisherian Model

Case	Income Elasticity of Demand for		F_{NE}	Change in Investment	Change in National Product	Effect of General Equilibrium Investment Response on		Net Change in Social Welfare *
	Current Consumption (1 - N)	Future Consumption C		$N_1 - N_0$	$C_1 - C_0$	National Product*	Social Welfare	
1	> 0	> 0	> 0	?	-	?	+	-
2	> 0	> 0	< 0	+	?	+	+	-
3	> 0	< 0	> 0	?	?	?	+	-
4	> 0	< 0	< 0	+	?	+	+	-
5	< 0	> 0	> 0	-	-	-	+	-
6	< 0	> 0	< 0	?	?	?	+	-

*It is assumed that at the initial equilibrium there are no market distortions.

4. The Welfare Cost of Conservation: General Equilibrium vs. Partial Equilibrium

The general equilibrium effects of energy conservation include not only the change in National Product, as in the partial equilibrium model, but also the induced change in allocation of the domestic primary resource endowment. In general equilibrium we can no longer use the change in National Product, C , as the sole indicator of the change in welfare. Take a second order approximation to (3) at the initial equilibrium:

$$(21) \quad dU = U_N dN + U_C dC + \tfrac{1}{2}U_{NN}(dN)^2 + \tfrac{1}{2}U_{CC}(dC)^2 + U_{CN}dCdN \ .$$

From (6), (7) and (8):

$$(22) \quad U_N + U_C F_N = 0$$

Differentiating (22) and solving for U_{NN}:

$$(23) \quad U_{NN} = - U_{CC}F_N \frac{dC}{dN} - U_{CN}\frac{dC}{dN} - U_{CN}F_N - U_C F_{NN} - U_C F_{NE}\frac{dE}{dN}$$

Substituting in turn (23), (20) and (6) in (21) eliminating higher-order terms,

$$(24) \quad dU = \lambda\left[\frac{1}{2}F_{EE}(dE)^2 + \frac{1}{2}F_{NE}dNdE\right] = \frac{\lambda}{2}dF_E dE$$

The general equilibrium "welfare triangle", like the partial equilibrium cost measure given in (13) above, contains no first-order terms. The first-order approximations (18) and (19) above involve no net welfare cost, since the change in C is compensated by a change in the allocation of N.

Now, is the welfare cost represented in (24) greater or less than its partial equilibrium counterpart, $\frac{1}{2}\lambda F_{EE}(dE)^2$? One easy way to answer this question is to point out that after the energy cutback, assuming no other market distortions, the partial equilibrium solution can be derived from the Lagrangian

(25) $L = U(1-N, C) - \lambda(C - Y+P_0^E E) - \mu(Y - F(N, E)) - \pi(N - N_0) - \gamma(E_1 - E_0)$.

The relaxation of the restriction on N given by equation (10)must lead to a non-negative welfare change in this perfectly competitive economy, though the net welfare effect of conservation clearly remains negative.

These effects, which are reported in Table 2, can be illustrated using Figure 8, in which the input of N decreases. At the unconstrained equilibrium point F, the fall in national product $(C_0 - C_1)$ is greater than predicted in the partial equilibrium case $(C_0 - C_2)$, but the effect on welfare is mitigated by an increase in consumption of the domestic resource.[16] The net general equilibrium welfare change is $U^0 - U^1$. (For convenience we measure the changes positively here.) This change can be represented in consumption units by aggregate-economy equivalents of familiar partial equilibrium surplus measures (Hicks, 1944), which can be illustrated using Figures 8, 9 and/or 11. The Marshallian surplus measure for the change in welfare due to conservation holding N at N_0 is $(C_0 - C_3)$. This is a lower bound on the Hicksian equivalent variation, the vertical displacement of $TP(N, E_0)$ necessary to allow it to touch U^1. The Hicksian compensating variation, the minimum offsetting change in C needed to justify energy conservation, is the vertical displacement of $TP(N, E_1)$ necessary to allow it to touch U^0. $(C_0 - C_2)$ is obviously an upper bound on this compensating measure. Hence the absolute value of the partial equilibrium change in C, $(C_0 - C_2)$, is an upper bound on the Marshallian surplus, and also on the compensating variation, which is an appropriate welfare cost measure in this case.[17] The general equilibrium response reduces the social cost of conservation, as shown in Table 2.

This useful interpretation of the partial equilibrium results as an upper bound on the welfare cost of conservation in an otherwise undistorted competitive economy clearly extends to the multi-factor case. It has not been recognized in the energy modeling literature.

5. The Implications of Pre-Existing Market Distortions

The conclusions of Section 4 were derived assuming that the economy is subject to no market distortions other than the energy conservation measures themselves. If other distortions exist, do they affect the conclusion that the partial equilibrium cost is an upper bound on the welfare cost of conservation, measured by the compensating variation? The answer is that they do. If, for example, there is a positive distortionary tax on T on N, which is redistributed to the consumer, equation (22) becomes

$$(26) \quad U_N + U_C(F_N - T) = 0$$

Differentiating (26) and solving for U_{NN}

$$(27) \quad U_{NN} = - U_{CC}F_N \frac{dC}{dN} - U_{CN} \frac{dC}{dN} - U_{CN}F_N - U_C F_{NN} - U_C F_{NE} \frac{dE}{dN} + U_{CC}T \frac{dC}{dN} + U_{CN}T$$

Substituting in turn (27), (20), and (6) in (21), and eliminating higher-order terms,

$$(28) \quad dU = \lambda \left[TdN + \frac{1}{2} F_{EE}(dE)^2 + \frac{1}{2} F_{NE} dN dE \right] + \frac{1}{2} U_{CC}TF_N dN^2 + \frac{1}{2} U_{CN}TdN^2$$

Since the last two terms are negative, the existing distortion increases the welfare cost relative to the cost in (24) above, if dN is negative. In this case the partial equilibrium estimate of the welfare cost is not unequivocally an upper bound on the general equilibrium estimate. (Since the supply of N (consumption of 1-N) is already distorted by the tax, the restriction $N = N_0$ imposed by the partial equilibrium approach does not necessarily reduce welfare, as was argued above for the case of an initially undistorted market.) More generally, if conservation aggravates an existing distortion, the welfare loss is greater, but if it reduces an existing distortion of N (i.e. moves N toward its undistorted level) the cost is lower.

The principal market distortion recognized in the modeling literature is the tax-induced divergence of the private from the social rate of return on capital (MRG, 1978, p. 27; Manne, 1977, pp. 18-19; EMF, 1977, Vol. 2, p. F-7; Sweeney, 1978, p. 37). But the mere existence of such a divergence does not imply that the welfare measure (13) is no longer valid. In an intertemporal framework an optimal tax structure under a revenue constraint might include taxes on both capital and labor, depending on the specification of the intertemporal utility function.[18] If the tax on capital is one element of a set of optimal taxes, it can be shown that the second order effects in formula (24) comprise the appropriate estimate of the welfare change, if conservation is achieved by measures that produce zero net revenue. If conservation produces tax revenue, the cost will actually be even lower assuming the rest of the tax structure is optimized.

Even if the tax structure is non-optimal, would it be desirable to recognize this fact in a general equilibrium calculation of the cost of energy conservation? The answer depends upon one's view of the rigidity of the constraints on other means of tax reform. Certainly if the cost of conservation attributable to the non-optimality of the fiscal structure is included in calculating the costs of energy conservation, then to the extent that this tax structure effect is important the energy problem is a fiscal problem rather than a technological and behavioral problem. For this effect represents "the additional costs of maintaining a sub-optimal tax structure subsequent to conserving energy" rather than "costs of energy conservation." If the initial equilibrium is modeled to include optimal taxes, partial equilibrium estimates place a useful upper bound on this latter cost. If the (distorted) general equilibrium cost estimate is higher, some of the attention given to the energy problem should be diverted to the problem of general tax reform.[19]

Conclusions

The net welfare cost of long-run reductions in aggregate energy input of up to one half of its equilibrium level is likely to be less (and perhaps much less) than the cost of the energy input foregone.[20] This rule of thumb, which is consistent with the results of a number of large-scale energy models, is derived from a simple heuristic partial equilibrium model that illustrates the major economic relationships preventing the one-to-one "coupling" of percentage reductions in energy and national product. If the elasticity of marginal product of energy is known, the more accurate measure of the cost of conservation given by equation (14) above adequately duplicates the results of more complex partial equilibrium energy models.

Up to now, questions about the general equilibrium implications of such partial equilibrium results have limited their credibility. These misgivings are largely attributable to confusion over the definition of full general equilibrium linkages, which is also reflected in the structure of some "general equilibrium" energy models.

A general equilibrium extension of the heuristic partial equilibrium model shows that, if the economy is initially undistorted, the partial equilibrium cost estimate is an upper bound to the general equilibrium welfare cost. On the other hand, the general equilibrium effect of energy conservation on national product is more difficult to determine from the results of partial equilibrium analysis. Rules proposed on the recent literature to predict the direction of, or place bounds on, the general equilibrium response of national product, using measures of the substitutability or complementarity of energy with capital such as the Allen elasticities or the second partial derivatives of the production function,

are at best valid only in (rather unlikely) special cases.

If other economic distortions are present, then the welfare implications of the partial equilibrium analysis are less straightforward. But to avoid overstating this difficulty, two points must be emphasized. First, taxes should be considered distortionary only to the extent that they deviate from their optimal levels. Second, the effect of these distortions on the welfare cost of energy conservation should be interpreted as an indicator of the extent to which tax reform might help us solve the energy problem.

These conclusions have been derived in an idealized model with only two primary factors and one final product. Thus we have ignored substitution between different energy products in production and consumption, and between energy and non-energy products in consumption, in discussing the economic cost of energy conservation. However, the extension of the competitive model to a more realistic intertemporal world with interindustry transactions and multiple energy products should confirm the most general implication of this paper. It is that if we can control other economic distortions, the cost of aggregate energy conservation estimated by partial equilibrium energy models is an upper bound on the true social cost, if the model parameters are accurately estimated. Energy modelers can in this sense afford to be more confident that the social cost of long-run energy conservation is at least as low as most of their models make it appear to be.

ACKNOWLEDGMENT

Initial research on this topic was presented at the Engineering Foundation Conference on the Economic Impact of Energy Conservation, New England College, Henniker, New Hampshire, July 23, 1978. Further work was encouraged by Tjalling Koopmans, Paul Nordine and other members of the Yale University Workshop on Economic Models of Energy and Natural Resources. At various stages of this work I benefited from conversations with Ed Hudson, Dale Jorgenson, Mark Rosensweig, John Weyant, David Wood, and Marguerite Alejandro-Wright. Alvin Klevorick, Oliver Williamson and an anonymous referee provided valuable comments on a previous draft. I would like to thank, with the usual caveat, all of the above.

FOOTNOTES

[1]Note that if energy consumers bore the full cost of their marginal contribution to insecurity, this rationale for public intervention would not exist. Another benefit of conservation might be a dampening effect on OPEC price increases. However the argument below assumes that energy import price is exogenous.

[2]Volume 1 of the 1977 Energy Modeling Forum study and otherwise unpublished parts of Volume 2, will be referred to as EMF, 1977. The papers contained in Volume 2 which are published in more accessible form elsewhere, will be referred to by author in this paper, and page numbers will refer to the more accessible version, cited in the bibliography.

[3]For example: "We all know that the higher cost of energy raises special problems for every company and curbs overall growth prospects for Western industrial nations. (Rule of thumb: Every 1% drop in energy supply reduces overall economic output by the same 1%.)" (Boardroom Reports, Vol. 8, No. 7, April 15, 1979, p. 5, "Energy and Business: Specialist's View.")

[4]This rule of thumb is not very accurate for large changes in energy use, but it does indicate the order of magnitude of the cost incurred for the moderate levels of conservation proposed in most policy discussions. For greater accuracy, use equation (14).

[5]The ranking of cost of the different energy sources is of course purely illustrative.

[6]The cost of aggregate energy conservation in the Nordhaus model is comparable to the cost of conservation scenarios in the ETA model shown in MRG (1978, Figures III-11 and III-12, pp. 107 and 109). Qualitatively similar results were obtained for other models in EMF (1977, Volume 2, Appendix D).

[7]The cost of inefficient conservation plans, or plans subject to additional environmental or other constraints, might of course be much higher. The multi-sectoral models are indispensible for evaluation of different detailed conservation scenarios when additional sectoral constraints are important. An interesting comparison of an optimal conservation strategy derived by imposing an aggregate energy constraint on the Nordhaus model with a priori conservation scenarios subject to additional constraints, is discussed in MRG (1978, p. 112).

[8]A very similar statement appears in EMF (1977, p. 26). MRG (1978, p. 44) shows the same line of thinking: "[W]e have estimated the effects of policies that curtail energy supply below what it would otherwise have been...[D]oes not the diminished F.N. use of energy also reduce GNP below what it would have otherwise been?...Virtually everyone will agree that such a reverse effect exists. For our present purpose, however, the real question is how large or small it is...."

It is ironical that the simulation with fixed capital and labor performed by Hogan and Manne (1977, pp. 268-272) to derive conditions under which "traditional demand curve analysis" is a valid method of estimating economic costs is itself actually a calculation of the excess burden under the marginal product curve, which is approximated by the welfare triangle of equation (13). The difference in accuracy between their calculation and the area of the triangle depends solely on the accuracy of the linear approximation to the demand curve over the range of variation in energy input.

[9] This early Hudson-Jorgenson model should not be confused (as it commonly is) with the Long Term Inter-Industry Transactions Model (LITM) which they developed by in effect replacing the production module of their macroeconomic growth model with their inter-industry model. This integration to form a full general equilibrium model is carefully explained in Hudson and Jorgenson (1977, Section D, pp. 84-90).

[10] The only input link described in Manne (1977) between the MACRO and ETA models is the flow of energy costs represented by the variable COSTEN (see Mann, 1977, Figure 1, p. 6, and p. 39). COSTEN apparently includes both labor and capital services.

[11] For example: "If energy and capital are substitutable, ceteris paribus, then higher priced energy will increase the demand for new capital goods. If energy and capital are complements, then ceteris paribus, higher prices of energy will dampen the demand for energy and the demand for new plant and equipment." (Berndt and Wood, 1975, p. 259)

[12] For illuminating discussions of the interpretation of Allen partial elasticities of substitution under constant output see Berndt and Wood (1979) or Hogan (1977).

[13] Consider, for example, the underlying production function

$$Y = H(N, E, L)$$
$$= G(N, E)^{\mu} L^{1-\mu}$$

where the weakly separable subfunction G(N, E) has a constant elasticity of substitution specification. If L is fixed at L_0 the relevant production function can be written

$$Y = F(N, E) = \left[a N^{\frac{\sigma-1}{\sigma}} + b E^{\frac{\sigma-1}{\sigma}}\right]^{\frac{\sigma\mu}{\sigma-1}}$$

where $a, b > 0$, $0 < \sigma < \infty$, $\sigma\mu < \sigma-1$, $0 < \mu < 1$. Then:

$$F_{NE} = \left\{\mu - 1 + \frac{1}{\sigma}\right\}\{\mu a b G^{\mu-2}\}\left\{\frac{G^2}{EN}\right\}^{\frac{1}{\sigma}} < 0 .$$

[14] "An assumption of a constant savings rate would imply a complementary relationship between capital and energy but a very weak one with little aggregate effect on the equilibrium solution. This is inconsistent with the argument above that the link between capital and energy may be the most important component of energy scarcity. The most plausible approximation, therefore, is a continuation of the assumption implicit in the analysis of the individual firm, a perfectly elastic supply of capital at the equilibrium price of capital" (Hogan, 1977, p. 18).

[15] If a substantial domestic energy production sector were included in the model, the effect of conservation on input use would of course also reflect the response of this sector and its relative factor intensity. But the qualitative welfare conclusions reported below would still stand.

[16] This effect contrasts with the conclusions of Sweeney (1978) that "In an efficient world, induced changes in labor or capital input do not change welfare even though they do change NNP" (p. 36) and that in such a world "Whether energy is complementary or supplementary with capital or labor is totally irrelevant" for welfare analysis of changes in energy use (p. 37). Sweeney's analysis (see his "fundamental" equation 7, p. 8) fails to recognize that, apart from rent transfers, both the direct welfare effects of a change in energy use from an initially undistorted situation, and the indirect effects through induced changes in primary factor supplies, are second (and higher) order effects, as shown in (23) above, and as confirmed by Sweeney's own numerical results for conservation in an otherwise undistorted economy. (See Sweeney, 1978, Table 2 and Figures 3 and 4).

[17] Use of the compensating variation assumes that the benefits of conservation can be treated as a lump-sum "reward" of units of Y. (This assumption is somewhat analogous to the common practice of calculating a set of optimal taxes taking the revenue constraint as given.) A more satisfactory approach to this question involves incorporating the reason for conservation in the analysis, as outlined in footnote 17 below.

[18] For a lucid discussion see Feldstein (1976).

[19] Ideally the optimal level of government-induced energy conservation could be derived from calculation of the optimal fiscal structure. The tax on energy use would reflect both the revenue constraint and the failure of the market to place the appropriate "social insurance premium" on energy consumption. Such a premium would adjust the energy price to reflect the marginal effects of energy consumption on national security, international relations, the cost of oil imports, environmental quality, income distribution, and/or other items of public concern.

[20] To avoid confusion, note that the net cost includes the value of the energy saved.

REFERENCES

Behling, D.J., R. Dullien and E. Hudson, "The Relationship of Energy Growth to Economic Growth under Alternative Energy Policies," Report BNL 50500, Brookhaven National Laboratory, Upton, N.Y., March 1976.

Berndt, E.R., "Technology, Prices, and the Derived Demand for Energy," Review of Economics and Statistics, Vol. 57, (August 1975), pp. 259-268.

Berndt, E.R. and D.O. Wood, "Engineering and Econometric Interpretations of Capital-Energy Complementarity", American Economic Review, 69, No. 3, June 1979, pp. 342-354.

Dantzig, G.B. and S.C. Parikh, "On a PILOT Linear Programming Model for Assessing Physical Impact on the Economy of a Changing Energy Picture," in F.S. Roberts (ed.), Energy: Mathematics and Models. Proceedings of SIMS Conference on Energy, July 1975, Alta, Utah, SIAM, Philadelphia, Pa., 1976, pp. 1-23.

Energy Modeling Forum, Energy and the Economy, EMF Report 1, Volumes 1 and 2, Stanford, Calif., Institute for Energy Studies, September 1977.

Feldstein, M.S., "The Welfare Cost of Capital Income Taxation", Journal of Political Economy, 86, No. 2, Part 2, April 1978, pp. S29-S51.

Griffin, J.M. and P.R. Gregory, "An Intercountry Translog Model of Energy Substitution Responses," American Economic Review, Vol. 66, No. 5 (December 1976).

Hicks, J.R., "The Four Consumers' Surpluses," Review of Economic Studies, (1944).

Hitch, Charles J., ed., Modeling Energy-Economy Interactions: Five Approaches. Washington, D.C.: Resources for the Future, 1977.

Hnyilicza, E., "Optimal Economic Growth and Energy Policy," Ph.D Dissertation, Massachusetts Institute of Technology, September 1976.

Hogan, William W., "Capital Energy Complementarity in Aggregate Energy-Economic Analysis," Appendix C in Volume 2 of Energy Modeling Forum, Energy and the Economy.

_____, and Alan S. Manne, "Energy-Economy Interactions: The Fable of the Elephant and the Rabbit," Appendix B of Volume 2 in Energy Modeling Forum, Energy and the Economy, and reprinted in C.R. Hitch (ed.), Modeling Energy-Economy Interactions: Five Approaches. Washington, D.C.: Resources for the Future, 1977.

Hudson, E.A. and D.W. Jorgenson, "U.S. Energy Policy and Economic Growth, 1975-2000," Bell Journal of Economics and Management Science, Vol. 5, No. 7 (Autumn 1974), pp. 461-514.

_____,"The Long Term Interindustry Transactions Model: A Simulation Model for Energy and Economic Analysis," Data Resources Incorporated, 1977.

_____, "Energy Policy and U.S. Economic Growth," American Economic Review Papers and Proceedings, (May 1978), pp. 118-123.

Kennedy, M. and E.V. Niemeyer, "Energy Supply and Economic Growth," Discussion Paper 4-76, Department of Economics, University of Texas, Austin, Texas, 1976.

Klein, L.R. and W.F. Finan, "The Structure of the Wharton Annual Energy Model," paper prepared for the Energy Modeling Forum Meeting, Washington, D.C., October 1976. Wharton EFA. Philadelphia, Pa., 1976.

Manne, Alan S., "ETA: A Model for Energy Technology Assessment," Bell Journal of Economics (Autumn 1976).

_____, "ETA-MACRO: A Model of Energy-Economy Interactions," in C.R. Hitch (ed.), Modeling Energy-Economy Interactions: Five Approaches. Washington, D.C.: Resources for the Future, 1977.

Marcuse, W., L. Bodin, E. Cherniavsky, and Y. Sanborn, "A Dynamic Time Dependent Model for the Analysis of Alternative Energy Policies", in K.B. Haley (ed.), Operational Research 75. Proceedings of the Seventh IFORS International Conference on Operation Research.

Modeling Resource Group Synthesis Panel of the Committee on Nuclear and Alternative Energy Systems, Energy Modeling for an Uncertain Future. Washington, D.C.: National Academy of Sciences, 1978.

Nordhaus, William D., "The Allocation of Energy Resources," Brookings Papers on Economic Activity, 1973.

_____, "A Simulation Model for the Allocation of Energy Resources and Technology," mimeo, April 1976.

Nordhaus, William D. "What Is the 'Tradeoff' Between Energy Consumption and Real Income?" (mimeo) November 1, 1976.

Parikh, S.C., "Progress Report on the PILOT Energy Modeling Project," Proceedings of an IIASA Workshop on Energy Strategies, Conception and Embedding, Laxenburg, Austria.

Reister, David B. and James A. Edmonds, "A General Equilibrium Two-Sector Energy Demand Model," in C. R. Hitch (ed.), Modeling Energy-Economy Interactions: Five Approaches. Washington, D.C.: Resources for the Future, 1977.

Samuelson, P. A., "Complementarity--An Essay on the 40th Anniversary of the Hicks Allen Revolution in Demand Theory," Journal of Economic Literature, Vol. 12 (December 1974).

Sweeney, J.L., "Energy and Economic Growth: A Conceptual Framework" Paper presented at the Second International Scientific Forum on an Acceptable World Energy Future, Coral Gables, Florida, November 27-December 1, 1978.

Willig, R. D., "Consumer's Surplus without Apology," American Economic Review, Vol. 66, No. 4 (September 1976), pp. 589-597.