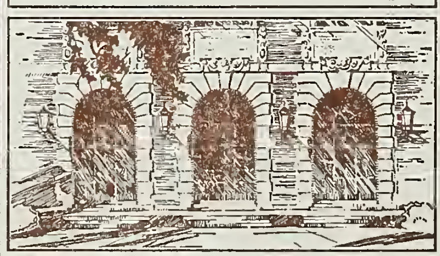

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ENERGY IMPACT OF CONSUMPTION DECESIONS

By

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October, 1974

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ABSTRACT

The energy cost of goods and services is computed, and applications are discussed. The method utilizes the data base of input-output economics, but entails additional analysis. Applications range over consumption options for individuals, business, industry, and government; from the total energy cost of bus vs. auto travel to the national import-export balance.

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1. INTRODUCTION

When anyone consumes anything, he consumes energy. Since energy reserves appear to be finite, and since every type of energy implies some kind of environmental impact, it is of interest to know the "energy cost" of the whole spectrum of goods and services produced by the U. S. economy. By energy cost we mean the total amount required to support all activities necessary for delivery of the product --from mining to final fabrication. In this paper we describe a method for computing energy costs, based mainly on the data from input-output analysis but with additional analysis. In an appendix we discuss a similar method for computing "labor cost", the total man-hours required to produce a product.

One motivation for determining total energy cost lies in the magnitude of "direct" and "indirect" energy requirements. For example, only about 30% of America's energy is used in the private sector, that is, in homes and private transportation. An additional 40% is supplied to commerce and industry to be demanded by consumers through the purchase of non-energy products. The remainder is utilized for governmental activities and exports.

Indirect energy requirements are thus extremely important. Consider an example from manufacturing: less than 10% of the energy needed to make an automobile is consumed directly by the manufacturer. Over 90% is required to produce the steel, glass, rubber and other necessary inputs. We seek a method that accounts for these inputs explicitly.

To determine energy cost, we must model the physical flow of materials and energy through a system: the U. S. economic system. Data collection for this large, complex system is extremely costly and time consuming; therefore limited. This lack of data is the binding constraint, since in modeling physical systems the state of the art is quite advanced. In this paper we have chosen not to start with a general theoretical development and simplify to accommodate data constraints. Instead, we begin with this constraint and basic physical principles and develop a model of increasing complexity. Since this approach maximizes use of existing data and provides immediate answers to a subset of policy questions, we believe it provides a useful framework for convincing government of the marginal utility of additional data required for more sophisticated models. The interested reader may refer to a set of papers outlining general theoretical approaches to problems such as this [1, 2, 3, 4], and will note several conceptual similarities shared with the method developed in this paper. In particular, Krenz [4] has used an approach somewhat similar to ours. However, he assumed that energy is sold to all customers at the same price, which we have found leads to errors of at least a factor of two.

Our methods of analysis are described in Section 2. In Section 3 we discuss attempts, empirical and theoretical, to verify the accuracy of the approach. Section 4 contains applications which cover such diverse subjects as the energy cost of an electric mixer and the energy impact of federal public works projects.

2. COMPUTING ENERGY COST

To determine the energy cost of a specific product, a detailed study of its manufacture, "vertical analysis", is often useful. Performing vertical analyses for a whole spectrum of products becomes too large a project to handle, so we sought a more all-encompassing approach which would probably sacrifice some accuracy. In Section 2.1, after giving a brief description of vertical analysis, we present connections between the two techniques and discuss possible complications.

2.1 Vertical Analysis

Vertical analysis is best described by example. Suppose you want to know the energy cost of producing a car. First you would obtain the energy bill of the car manufacturer, which you would allocate on a per-car basis. In addition, you would need to know the non-energy inputs to the car manufacturer, which you could also allocate on a per-car basis. Next, you would obtain the energy bill of the manufacturer of each of these inputs (steel, glass, tires, etc.), allocating those on a per unit basis (ton, gallon, etc.). It would also be necessary to determine their manufacturing inputs (iron ore, sand, etc). There are many stages through which the original product must be traced. Theoretically this process could go on for an infinite number of steps. Practically speaking, however, the series can be truncated after several steps, but with some loss of accuracy. The error would be difficult to evaluate.

Vertical analysis can be used to treat very specific products. The actual physical quantity used to allocate energy can be selected as appropriate to the particular step in manufacture. These two advantages must be weighed against the problem of truncation along with the fact that vertical analyses are tedious and time-consuming.

2.2 Energy Intensity of Goods and Services

Rather than laboriously performing a vertical analysis for each individual product, we will use a method for simultaneously treating all goods and services in the economy. It will be seen that the data base required is no different (with certain assumptions) from that required for vertical analyses, and the method is more tractable.

Consider an economic system composed of N sectors, each producing a unique output. We assume there is an energy intensity ε_j, measured in Btu/unit output, associated with the output of each sector j.

Our data base is an N x N matrix of interindustry transactions $\underline{\underline{T}}$, a vector of total outputs $\underline{X}$, and a vector of energy extraction (mining) data $\underline{E}$. An element T_{ij} of the transactions matrix represents the amount of product i sold to sector j during a given time period (typically one year). The total output X_j of a sector is the sum of its sales to other sectors plus its sales for final consumption, Y_j.

$$X_j = \sum_{k=1}^{N} T_{jk} + Y_j \tag{2-1}$$

With these data, we can now construct an energy balance diagram for each sector. Shown in Fig. 1, it simply states that the energy embodied in a sector's output is equal to that embodied in its inputs, plus energy extracted from the earth by that sector.

Based on Fig. 1, we can write a set of N energy balance equations.

$$\sum_{i=1}^{N} \varepsilon_i T_{ij} + E_j = \varepsilon_j X_j \tag{2-2}$$

Converting to matrix notation and solving, we have

$$\underline{\varepsilon} = \underline{E} \, (\hat{\underline{\underline{X}}} - \underline{\underline{T}})^{-1} \tag{2-3}$$

where $\hat{\underline{\underline{X}}}$ denotes a diagonal matrix with the elements of the vector $\underline{X}$ along the diagonal. Hereafter, the symbol ^ over a matrix will indicate such diagonalization of a vector.

2.2.1 Relation to input-output theory

It is sometimes convenient to define a new matrix $\underline{\underline{A}}$:

$$A_{ij} = \frac{T_{ij}}{X_j} \tag{2-4}$$

Eq. 2.3 now takes the form

$$\underline{\varepsilon} = \underline{E} \, \hat{\underline{\underline{X}}}^{-1} \, (\underline{\underline{I}} - \underline{\underline{A}})^{-1} \tag{2-5}$$

The elements of a column of $\underline{\underline{A}}$ are said to specify the "technology" of sector j. Each coefficient A_{ij} represents the amount of i purchased by sector j per unit output of j produced. In economics, a sector's production function is sometimes specified in terms of these fixed technological coefficients, A_{ij}, and called an input-output production function. Under the rather restrictive assumption that the matrix $\underline{\underline{A}}$ is constant, independent of scale and time (the fundamentals of static input-output theory), an element $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}_{ij}$ represents the amount of i required directly and indirectly per unit of j delivered for final consumption [1].

The similarities with input-output (I/O) theory are apparent, but there are several key differences. First, the units of A_{ij} in most applications of I/O theory are expressed in the units: dollars worth of i per dollar's worth of j. In our work we defined a set of N energy intensities, $\underline{\varepsilon}$ (one for each sector) and in Fig. 1 allocated these energies proportional to transactions $\underline{\underline{T}}$ and outputs $\underline{X}$. Thus we are free to define energy intensities in terms of physical units (e.g. Btu per ton of steel, cubic yards of concrete, etc.) or any other units expected to be the best allocators of embodied energy.

The second major difference is the severity of assumptions made. In I/O problems, one is usually interested in obtaining N^2 results, the elements of $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}$. It is therefore necessary to assume the entire matrix $\underline{\underline{A}}$ to be constant, independent of scale and time. Such a restrictive assumption is merely sufficient, not necessary, to obtain the vector $\underline{\varepsilon}$ from eqs. (2-3) or (2-5). In our problem, we need only assume that vector $\underline{\varepsilon}$ obtained for the base year is independent of scale and time. That is, we require that a product has the same total energy intensity from one year to the next; not that all aspects of every production process remain identical.

Actually, the first calculation of energy intensities for 360 sectors of the U. S. economy was based on I/O theory [5], utilizing the published dollar-based inverse matrix [6]. Subsequent enhancements have removed difficulties associated with using redundant (physical and monetary) energy allocation data; Btu units have replaced dollars in the energy sector rows of $\underline{\underline{T}}$. We proceed with a review of these and other enhancements, continuing from Fig. 1 and Eq. (2-5).

2.2.2 Extension to several types of energy

Up to this point, we have spoken in terms of total energy intensity:

the amount of energy that must be extracted from the earth per unit of product j delivered for final consumption. If we define "coal intensity" in an exactly analogous way, Fig. 1 and the energy balance equations still apply--coal inputs to each sector equal coal outputs. Thus, the solution generalizes to

$$\underline{\underline{\varepsilon}} = \underline{\underline{E}}\,\hat{\underline{\underline{X}}}^{-1}\,(\underline{\underline{I}} - \underline{\underline{A}})^{-1} \tag{2-6}$$

where an element ε_{kj} of $\underline{\underline{E}}$ now represents the "energy of type k intensity of a unit of j". Similarly, the extraction data E_{ki} represent the (primary) energy of type k extracted from the earth by sector i. This is nonzero only for i = k, and its magnitude is equal to X_i, the total output (Btu) of sector i. Therefore, the product

$$\left(\underline{\underline{E}}\,\hat{\underline{\underline{X}}}^{-1}\right)_{ij} = \begin{cases} 1, & i = j = \text{primary energy sector} \\ 0, & \text{otherwise} \end{cases} \tag{2-7}$$

The multiplication in eq. (2-6), therefore, extracts the energy sector rows from the inverse matrix, and identifies them as energy intensities $\underline{\underline{\varepsilon}}$.

In reality, some energy sectors process various types of energy into another form, such as electricity. Such "secondary" energy sectors do not extract input energy from the earth but receive it embodied in their purchases from the primary energy sectors. To determine the "electricity intensity" of goods and services, we simply extract the electric sector row of $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}$. Mathematically this is equivalent to imagining an artificial extraction of electricity directly from the earth by the electric sector.

Obviously, primary and secondary energy intensities cannot be summed directly to obtain total primary energy intensities; coal used to make electricity would be double-counted. The model contains 5 energy sectors: coal, crude oil and gas wells, refined petroleum, electricity, and utility gas. The first two are primary sectors; but electricity is mixed because it includes hydropower and nuclear, which are considered primary energy resources. We calculate the total primary energy intensities $\underline{\varepsilon}$ from the matrix $\underline{\underline{\varepsilon}}$ using the formula

$$\varepsilon_j = \varepsilon_{1j} + \varepsilon_{2j} + \frac{f}{\eta}\varepsilon_{4j} \qquad (2\text{-}8)$$

where f is the fraction of electricity produced from hydro and nuclear sources, and η is the efficiency of converting fossil fuels to electricity. This follows the established convention of defining the primary energy content of nuclear and hydro electricity as their fossil fuel equivalents.

2.2.3 Relation to vertical analysis

To understand the relation between the energy intensities obtained by vertical analysis and those found through matrix inversion, consider the series expansion:

$$(\underline{\underline{I}} - \underline{\underline{A}})^{-1} = \underline{\underline{I}} + \underline{\underline{A}} + \underline{\underline{A}}^2 + \underline{\underline{A}}^3 + \ldots \qquad (2\text{-}9)$$

For this expansion to be valid the spectral radius (the maximum of the absolute values of the eigenvalues) of $\underline{\underline{A}}$ must be strictly less than unity [7]. This condition is satisfied in our model. (Our $\underline{\underline{A}}$ does not possess a column norm ≤ 1 with at least one column sum < 1; this condition is sufficient, but not necessary.)

Terms on the right hand side of Eq. 2-9 can be seen to represent successive terms in a vertical analysis. As a simple example, suppose

Sector 1 is coal mining and Sector 2 is auto manufacturing. Then the second element of the first row of the inverse matrix will be the coal intensity of autos. Now consider each term on the right hand side contributing to this total. The first term is zero; the second term is the coal consumed directly by the auto sector per car produced; the third term represents coal used directly by the auto sector's suppliers to produce non-energy inputs (steel, glass, tires, etc.); the fourth term adds the coal used to produce each of their inputs, etc.

In practice we often desire more detail than this affords - for example, differentiating a specific auto manufacturing line from the larger aggregated sector, "motor vehicles and parts". A "hybrid" analysis is used, replacing the first few stages of the expansion with more detailed problem-specific data, and using our average coefficients for the remainder. Thus, from the identity

$$(\underline{\underline{I}} - \underline{\underline{A}})^{-1} = \underline{\underline{I}} + \underline{\underline{A}} + \underline{\underline{A}}^2 + \ldots + \underline{\underline{A}}^{n-1} + (\underline{\underline{I}} - \underline{\underline{A}})^{-1} \underline{A}^n \qquad (2\text{-}10)$$

we calculate

$$\underline{\underline{\varepsilon}}' = \underline{\underline{E}}\, \hat{\underline{\underline{X}}}^{-1} [\underline{\underline{I}} + \underline{\underline{A}}' + (\underline{\underline{A}}')^2 + \ldots + (\underline{\underline{A}}')^{n-1} + (\underline{\underline{I}} - \underline{\underline{A}})^{-1} (\underline{A}')^n] \qquad (2\text{-}11)$$

where the primes denote problem-specific data which may be expressed in physical units, or in dollars. Accuracy will depend on the choice of n.

2.3 Treatment of Imports and Exports

When we export goods, we export energy embodied within them. Imported goods on the other hand can be viewed as implied energy imports, displacing the need to consume energy domestically. We wish to construct our model in such a way that we obtain "domestic" energy intensities. This will permit us to apply the results to a variety of foreign policy issues and "the energy balance of trade".

Data from Ref. 6 include transactions and outputs of imported goods, as well as those domestically produced. We correct the data by subtracting imports from total outputs so each sector's energy use is allocated only to domestic outputs. Solving the equation implied by Fig. 2 gives

$$\underline{\underline{\varepsilon}} = \underline{\underline{E}} \, (\hat{\underline{\underline{X}}} - \hat{\underline{\underline{Q}}} - \underline{\underline{T}})^{-1} \qquad (2\text{-}12)$$

where $\hat{\underline{\underline{Q}}}$ represents that portion of $\hat{\underline{\underline{X}}}$ composed of imported goods. The energy intensities $\underline{\underline{\varepsilon}}$ now reflect the true energy intensity of products made exclusively from domestically produced inputs.

Some practical problems arise here because there are two classes of imported goods. Competitive imports are defined as those goods for which there are domestic counterparts, and are counted as part of the total output of the corresponding domestic sector. For example, in Ref. 6, the total output of the auto manufacturing sector, X_{cars}, includes Volkswagens as well as Chevrolets. Fortunately, the vector $\underline{Q}$ is also recorded so the two types of outputs are distinguishable and eq. (2-12) can be solved.

The other category of imports, noncompetitive, is defined as that for which no domestic counterpart exists. Examples include diamonds, bananas, and coffee. In Ref. 6 these products are not identified by type. Since they comprise only 20% of all imports, and only 1% of GNP, we ignore them in our analysis.

Exports are treated as part of final consumption, along with personal and government expenditures. The energy intensities of exported goods are likewise given by eq. (2-12).

We can now construct a complete picture of energy flow through the U. S. economy. We assign to competitive imports the energy content of their domestic counterparts; this is equivalent to assuming that if we didn't import them, we'd produce them here at that energy cost. Figure 3 shows the energy balance under this assumption.

The U. S. economy receives energy in three ways:

1. Primary energy (coal, crude, hydro, nuclear) extracted domestically.
2. Imported energy (almost exclusively petroleum) with the associated embodied energy penalty due to losses in extracting, refining, etc. carried out abroad.
3. Energy embodied in other competitive imports.

Taking the product of energy intensities with total final demands, we obtain the total energy required to sustain that level of consumption,

$$\underline{\varepsilon}\ \underline{Y} = \underline{e} \tag{2-13}$$

where $\underline{e}$ is a vector of total requirements for each fuel type. This total can be decomposed into its components, domestic extraction and energy embodied in imports (including energy imports):

$$\sum_{j=1}^{n} \varepsilon_{kj}\, Y_j = e_k = \sum_{j=i}^{n} E_{kj} + \sum_{j=i}^{n} \varepsilon_{kj}\, Q_j \tag{2-14}$$

where the subscript k indicates fuel type and Q_j are competitive imports. Remember that noncompetitive imports have been neglected in this analysis.

2.4 Secondary Products

All interindustry data described thus far are collected from individual establishments and aggregated to N sectors. We have spoken of sector outputs as homogeneous quantities. In this section we shall discuss the realities of the situation, since outputs are not homogeneous.

If an establishment produces primarily automobiles (its primary product), it is placed in the automobile sector. It may also produce secondary products, items that are the primary outputs of other sectors. Therefore, a unit of output from sector i is not necessarily equivalent to a unit of (primary) product i; the output X_i may represent a heterogeneous mixture of products. This raises serious problems for applications, since we wish to know the energy intensity of goods and services, not sector outputs.

2.4.1 Activity-based analysis

The ideal solution to this problem would be to define a set of activities, one associated with each product. To define these activities, consider an establishment in the automobile sector whose output consists of 90% autos and 10% airplanes. We say that this single establishment engages in two activities: a primary activity (making cars) and a secondary activity (making airplanes). If the establishment's accounting practices do not distinguish between purchases of inputs (say electricity) for making cars and making planes, it is not possible to construct a precise "activity-based" transactions matrix.

2.4.2 Makeup of the transactions matrix

To gain a thorough understanding of the secondary product problem and other aspects of this large and valuable data base, we present a brief outline of the method for assembling the data. Then we return to activity-based analysis.

Actually the transactions matrix of Ref. [6] is obtained by summing four N x N matrices:

$$\underline{\underline{T}} = \underline{\underline{DA}} + \underline{\underline{TF}} + \underline{\underline{MDT}} + \underline{\underline{IM}} \qquad (2\text{-}15)$$

$\underline{\underline{DA}}$ is the direct allocations matrix. Its elements DA_{ij} represent direct sales of primary product i to the purchasing sector j. The sum of elements of the airplane sector row of $\underline{\underline{DA}}$, plus total final demand for airplanes equals the total sales of airplanes, regardless of whether produced by the airplane sector, auto sector, or any other.

$\underline{\underline{TF}}$ is the domestic transfers matrix. Its elements TF_{ij} represent the value of j, a secondary product, produced by sector i. Thus, the value in producers' prices of airplanes produced in the auto sector would appear in the auto row and the airplane column of $\underline{\underline{TF}}$. It is important to note that if one looks only at the $\underline{\underline{T}}$ matrix (eq. 15), the transferred output from the auto sector to the airplane sector is indistinguishable from the Chevys that Lockheed bought as fleet vehicles (the latter is a direct allocation).

$\underline{\underline{MDT}}$ is the matrix of margins on domestic transactions. It has no direct bearing on secondary products, but is explained here to aid in understanding Section 2.6. It contains nonzero elements only in the trade, transportation, and insurance rows. An entry represents the sum of domestic costs of distribution (transport, trade, insurance) associated with all of the inputs purchased by the consuming industry.

It is important to note that the purchase of an airplane ticket for a GM executive appears as an entry in $\underline{\underline{DA}}$, while the sum of all air freight charges on GM's purchased inputs appears in $\underline{\underline{MDT}}$. The two types of purchases are indistinguishable in $\underline{\underline{T}}$, appearing only as a transaction from the air transport sector to the auto sector.

$\underline{\underline{IM}}$ is the transferred (competitive) imports matrix. It contains nonzero entries in one row, indicating the foreign port value of competitive imports. Note that this matrix would be deleted from eq. (2-15) in accordance with the methods outlined in Section 2.3. But in the source data, when $\underline{\underline{IM}}$ is used to calculate $\underline{\underline{T}}$, competitive imports are effectively "transferred" to the corresponding domestic sector in a manner identical to the treatment of domestic transfers. There is one more feature of $\underline{\underline{IM}}$; it also has nonzero entries in the trade, transportation, and insurance rows. These fictitious purchases effectively bring the purchaser's price of imported goods to domestic port value. Summing the columns of $\underline{\underline{IM}}$ yields the $\underline{Q}$ of Section 2.3.

2.4.3 Secondary product adjustments

Utilizing the above data, several approaches have been proposed for determining the energy content of primary products. The first was used by Herendeen [5] to allocate a sector's energy consumption over only its products (primary and secondary), excluding that portion of its output produced as secondary products by other sectors. The advantage of this method was that it permitted use of the already published $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}$ matrix, avoiding costly inversion of an altered matrix. Its main disadvantage was that it did not attempt to allow for secondary products requiring more or fewer energy inputs.

Another method sometimes employed in econometric analyses [8] is based on the assumption that each product is produced with precisely the same technology (input proportions), regardless of the sector in which it is produced. This approach is more complete, since it corrects for transfers out of a sector as well as transfers into a sector. Its main disadvantage is that the assumption is evidently physically unrealistic because it results in numerous negative entries in the total requirements matrix $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}$. Such values are physically impossible and demonstrate that the assumption is too strong.

Remembering that our earlier calculation of energy intensities of sector outputs was possible under an assumption much less restrictive than that normally employed in input-output theory, we are able to make a similar assumption here: that the energy intensity of each product is independent of the sector in which it is produced. This does not require identical production technologies, only that the energy embodied directly and indirectly in the final product be the same. While this assumption is strong, it is not nearly as restrictive as needed in input-output analyses and it is the weakest possible within existing data constraints. Figure 4 shows the energy balance for a typical sector (a group of establishments) under this assumption.

Solving the energy equation corresponding to Fig. 4, we obtain the energy intensity of products, rather than sector outputs.

$$\underline{\varepsilon} = \underline{E} \, [\hat{\underline{\underline{Y}}} + \hat{\underline{\underline{D}}} - \underline{\underline{DA}} + \hat{\underline{\underline{M}}} - \underline{\underline{MDT}} - \hat{\underline{\underline{TF}}} + \underline{\underline{TF}}^t]^{-1} \qquad (2\text{-}16)$$

where $\hat{\underline{Y}}$ is a diagonal matrix whose elements are domestic final demands, and the elements of diagonal matrices $\hat{\underline{\underline{D}}}$, $\hat{\underline{\underline{M}}}$, and $\hat{\underline{\underline{TF}}}$ are the row sums of $\underline{\underline{DA}}$, the row sums of $\underline{\underline{MDT}}$, and the column sums of $\underline{\underline{TF}}$, respectively.[1] The superscript t denotes transpose.

In the absence of specific data, we cannot verify our assumption that a product's energy intensity is independent of its sector of origin. A sufficient indication that our assumption is in error would be the occurrence of negative values in $\underline{\varepsilon}$, a physical impossibility. In terms of Fig. 4, this can occur if the energy ascribed to secondary products by our assumption exceeds energy embodied in inputs. In preliminary results with a 92 sector model, this happened for only two sectors. For both of these sectors, over 90% of outputs are secondary products, and it is not yet clear whether the source of the difficulty lies in our additional assumption, or slight inaccuracies in those sectors' direct energy input data. Work is currently underway to resolve this question, and alternative assumptions and methods of solution are being evaluated [9]. Accordingly, the numerical results presented here are derived from establishment-based data, pending refinement of the above methods for secondary product adjustments.

2.5 Capital Purchases

Since I/O tables are assembled only once every four or five years, and since their usefulness depends on the stability over time of the

1. The solution (2-16) requires that the NxN matrix be well-behaved. This requires that a unique primary output be associated with each sector. Actually this is not the case, since Ref. [6] contains several "dummy industries" (e.g. office supplies) in which no production occurs; all outputs are transferred in from the primary producing sector (dummy industries result from data acquisition constraints). The result is more equations than unknowns; the energy intensities of dummy sector outputs are linear combinations of other energy intensities. Eliminating such sectors, and adding their outputs to those of the appropriate primary sectors, we obtain a tractable system of simultaneous equations.

technological coefficients $\underline{\underline{A}}$, the transactions matrix is constructed exclusively from current account data. Thus, interindustry transactions exclude flows of capital goods, partly because they could cause erratic annual fluctuations in the $\underline{\underline{A}}$ matrix.

Therefore, capital purchases are normally listed as a component of final demand, not as interindustry purchases. In Fig. 1 the purchase of (say) machinery for manufacturing does not appear on the input side. Intuitively, we should expect it to be there; otherwise the energy to produce it does not contribute to the final product. To correct this problem, we would like to allocate capital purchases, away from final demand, to interindustry purchases. This would require construction of a complete capital flow table, and separation of growth and replacement ("depreciation") components. In section 3.1 we discuss an example calculation.

2.6 Producers' vs. Purchasers' Prices

The energy intensities obtained here are in terms of producers' prices - the price at the end of the assembly line. The actual price paid by a consumer includes margins ("markups") for transportation, insurance, and wholesale and retail trade. Each margin has its associated energy intensity. (For the energy sectors, whose output we measure in Btu, not dollars, we can state it this way: there is an additional energy penalty from marketing.)

In the normal final demand vector, transportation and trade margins are lumped with direct sales (i.e. final demand "buys" some retail trade services). If we want the total energy intensity of a product sold to final demand, we must use independent data to allocate margins on these sales to the appropriate products. Energy intensities in terms of purchaser's prices have been calculated for over 360 types of goods and services [10].

3. APPLICATIONS: CHECKS ON ACCURACY

Questions relating to the accuracy of our approach fall into these classes:

a. Conceptual problems persisting from the use of economic accounting data. Examples: the aggregation and capital problems.

b. Using dollars to allocate embodied energy, or actual errors in dollar data.

c. Technological change over time.

While we have not performed a comprehensive error analysis to answer all these questions, we will discuss these: For class a, we have incorporated a capital flow matrix, described in section 3.1. For classes b and c, two approaches have been used. First we have compared our results for energy cost of certain products with results of independent vertical analyses (section 3.2). Second, work is in progress to determine the sensitivity of energy cost to errors or time variation in the direct coefficients matrix $\underline{\underline{A}}$ (section 3.3).

For empirical checks, we shall sometimes refer to our published results of calculations of energy intensity [5]. This earlier work used a method qualitatively similar to that offered in Section 2, but differing slightly quantitatively. We shall indicate which method is used in each comparison. Example values for energy intensities are listed in Table 1.

3.1 Capital Correction

The philosophy of energy cost implies that capital purchases, at least those for replacement, should be part of the interindustry transactions. The energy to produce them would no longer be viewed as being delivered to final demand, but instead would be part of the products they help produce. From the standard I/O data base we know the sum of all capital sales by selling sector (e.g., all airplanes sold as capital stock). We do not know who bought the planes. However, the Bureau of Economic Analysis of the U. S. Department of Commerce has independently produced a table of interindustry capital flows compatible with its 82 sector table [11]. We have expanded this to 92 sectors, and calculated the effect of including the capital flows.

With capital flows, Fig. 2 is modified as shown in Fig 5. The effect is to increase or leave unchanged, (but not to decrease) the ε_{kj}. C_{ij} is the replacement capital flow, which is some fraction of the C_{ij} given in the capital flow table.

In our calculation [20] we assumed that half of each capital transaction that year was for replacement of obsolete or depreciated equipment. Because capital flow data are less reliable than current account transactions, and the uncertainty over the "typicalness" of 1963 capital flows, we consider this only an exercise in ascertaining an idea of the distribution of errors.

In Table 2 we list the distribution of changes in primary energy intensity resulting from including the capital flows. The dollar value of the replacement flows was about 4.5% of the GNP; this is roughly the expected average increase. The average appears close to this value. Only six of the 92 sectors show changes exceeding 12%. These are agricultural or service sectors.

3.2 Comparison with Results of Vertical Analysis

In Table 3 we compare energy costs computed from vertical analysis with our results. Comparisons are listed as the ratio (other study)/(our study). Performing this comparison is complicated by these factors:

a. Matching the economic sector exactly with the specific product is usually not possible. E.g., metal containers includes paint cans and buckets in addition to beverage cans (this is the aggregation problem).

b. Primary/secondary product ratios are often low, thus casting doubt on the accuracy of establishment-based energy coefficients.

c. Price data (implied or actual) are often unavailable. Prices are needed to bridge the gap between our dollar-based approach and the usual physical basis of vertical analysis

In theory, the ratio above should be ≤ 1, since our approach is analogous to an infinite vertical analysis. (Neither method included a capital correction.) The results for 13 independent verifications yield an average value of 0.92, a spread of from 0.52 to 1.23, with a standard deviation of 0.23.

3.3 Sensitivity of Results to Errors in $\underline{\underline{A}}$

Eq. (2-6 represents a nonlinear operation on the matrix $\underline{\underline{A}}$. $\underline{\underline{A}}$ is constructed from empirical data and is subject to error. We ask what errors are thereby implied in $\underline{\underline{\varepsilon}}$.

Attempts to obtain a closed form solution lead only to a a rather weak inequality demonstrating that we cannot be sure that there is less than a factor of 5 (the condition number of the 360-order $\underline{\underline{A}}$ matrix) multiplier on errors in $\underline{\underline{A}}$ [13]. We expect that errors in $\underline{\underline{A}}$ are at least $\pm$ 10%, probably higher; this gives a least upper bound of $\pm$ 50% for errors in ε, which we consider unacceptably high.

Work is now in progress [14] using numerical methods to improve these early estimates; these involve actual inversions of perturbed matrices under two assumptions: first, that the errors in $\underline{\underline{A}}$ act in concert to give the worst possible error in $(\underline{\underline{I}} - \underline{\underline{A}})^{-1}$, and second, that the errors in $\underline{\underline{A}}$ vary stochastically. In addition, the work includes sensitivity analyses to identify important input data. All of these methods can be used to determine the effects of errors in published data [6] and to evaluate effects of expected technological change. Since we are dealing with N^2 technological coefficients (where N may be as large as 360), a systematic updating process must await development of these techniques.

4. APPLICATIONS: SELECTED RESULTS

Almost all of the applications presented here are based on conceptually isolating some group--citizens, an industrial sector, the federal government--as a consumer, and analyzing the energy impact of changes in that group's consumption.

We first illustrate the idea of total energy cost for two family items, the private auto and an electric mixer (to indicate the range of applicability!). We then discuss results of this type of analysis, applied to 1) consumer's choice on urban transportation (bus or car), and overall family spending pattern, and 2) federal government choice of alternative public works projects (highways vs. mass transit). We also use energy costing techniques to analyze an industry's total energy dependence through its inputs of goods as well as energy and apply this notion to the nation's total import-export energy balance. Finally, we calculate the price impact (on all products) resulting from a tax on energy.

4.1 Total Energy Cost of an Automobile and an Electric Mixer

Results for the average automobile are listed in Table 4. Every auto-associated expenditure is converted to energy terms. This requires allocating each expenditure to the appropriate sector and multiplying by the corresponding energy intensity. The net effect is that the actual fuel in the tank accounts for only about 57% of the total. An additional 13% goes to the "energy cost of energy" (refining losses, etc.), which leaves 30% attributable to manufacture of the car, parts, maintenance, road construction, etc. Thus a multiplier of about 1.7 must be applied to the direct gasoline energy to obtain total impact. This same approach must be applied to other transportation modes before a true energy-per-service-mile comparison can be made.

Table 5 shows the total energy cost of an electric mixer. We account for the energy of manufacture and sale, and the expected service lifetime. Assuming that the mixer (125 watts) is used 13 minutes per week, we find that the operational energy must be multiplied by 1.58 to yield total energy impact. This factor varies for different appliances. For the big users of energy such as refrigerators, stoves, etc. the multiplier is less than 1.1.

4.2 Energy Impact of Urban Bus and Auto Transportation

This question has been treated by Hannon and Puleo [15]. National average figures for all cars and buses were not adequate, so the specific urban transportation systems had to be analyzed individually by the hybrid technique. Expenditures and fuel consumption data for 38 urban bus systems were obtained and converted to energy terms as described; likewise for the car, with attention to the relatively poor gasoline economy in city traffic. Additionally, average load factors were used, leading to the results in Table 6.

We mention a problem associated with this comparison: the two options differ in their total expense to the consumer. Therefore, the total energy comparison "should" include the energy impact of spending of the saved money. There are two tacks. One is to try to predict consumer spending, a task we have foregone. The other is to compute the effective energy intensity of the saved money ($\frac{Btu}{\$}$), and present the consumer with a list of spending alternatives rated according to their energy intensities. These are listed in Ref. 15.

4.3 Total Energy Impact of a Family's Expenditures

Herendeen [16] has computed the energy impact of all expenditures by American families as a function of income. Personal consumption expenditure data from the Bureau of Labor Statistics were converted to energy terms. Fig. 6a shows some of the expenditures, illustrating that direct energy consumption such as gasoline seems to level off with increasing income, while purchases of education and transportation other than the car (normally not considered energy purchases) do not.

These have been converted to energy terms in Fig. 6b. The energy impact of energy purchases indeed does level, but that of non-energy purchases does not. For the lowest income group, energy purchases account for 2/3 of the total, while for the highest income group, the fraction has dropped to 1/3. This suggests that estimates of the effects on consumers of energy shortages will be quite misleading if based on direct use only, especially for the more affluent.

These results are averaged over geographical location, age, race, education and size of family. A question which arises here is: are there different spending patterns, resulting in significantly different energy impacts within the same income class? (Remember that even savings or investments have an energy impact--they help build shopping centers.) So far this question is unanswered.

4.4 Energy and Labor Impacts of Government Spending

As we show in the Appendix, we can derive "labor intensity" analogously to energy intensity. Knowledge of the two allows one to search for ways to conserve energy while not causing a decrease in employment. Bezdek and Hannon [17] have analyzed several federal government "public works" programs this way. The problem is to break down the program into expenditures compatible with the model's sectors, and then apply energy and labor intensities. In Table 7 we list their results for the highway trust fund and several programs which have been suggested as alternatives.

There are several programs which reduce energy impact, yet don't decrease (and sometimes increase) employment. Even if money is given back to individual consumers through tax relief, and then is spent by them in an "average way, energy requirements decrease.

4.5 Industrial Energy Dependence

With the concept of energy intensity, an industry's dependence on energy is seen to involve material and service inputs as well as actual energy. An industry may find that the effect of an energy shortage is to interrupt its supply of a critical energy intensive material more drastically than its intrinsic supply of energy. Or, if energy conservation is a goal, greater results may be obtained from a policy of conserving energy intensive materials (e.g. aluminum) than by turning down thermostats.

The method we have described in Section 2 is adaptable to this sort of energy analysis of inputs. Referring to Fig. 2, we write:

$$g_{kij} \equiv \frac{\varepsilon_{ki} \; T_{ij}}{\varepsilon_{kj} \; (X_j - Q_j)} \times 100$$

g_{kij} is defined thus: of the total amount of energy of type k required to produce 1 unit of product j, a percentage g_{kij} entered through j's purchase of i.

$$\sum_{i=1}^{N} g_{kij} + \frac{E_{kj} \times 100}{\varepsilon_{kj} \; (X_j - Q_j)} = 100$$

The g_{kij} are calculated from base year data. It is attractive to treat them as constants, independent of X_j. Since we have already required that the ε_{kj} be constants, this requires that $\frac{T_{ij}}{X_j - Q_j}$ be constant. This is the constant technology assumption of input-output theory. The assumption was not necessary to compute energy intensities ε_{kj}, but it is necessary to attach significance to the g_{kij}. Table 8 presents an energy input analysis of two industries. The input sectors have been aggregated for simplicity, but the receiving sectors are at the 360 sector level of detail. For both receiving sectors (motor vehicles and parts, and seeds and feed grains) we see that energy inputs from energy sectors are sometimes smaller than those from certain materials inputs (e.g., primary metals for cars) [18]. Such an accounting suggests access points for energy conservation, but the actual conservation potential depends on the nature of the industry's dependence on that commodity.

In Table 8 we see that a large energy input appears to come from "self-sales". This is a consequence of aggregation. It may represent an actual "self-use", but more likely it results from the sales between dissimilar firms (preliminary and final assembly plants, for example) grouped in the same sector. This large self-energy is not that troublesome, however. First, it is somewhat arbitrary; the actual value of self-sales does not affect the value of $\underline{\varepsilon}$. Second, the relative values of energy inputs from all other sectors (except self-sales) are not affected.

4.6 National Import-Export Energy Balance

Once we have obtained the energy intensities for all sectors we can quantify the import-export energy balance. Recalling Fig. 3, we note that there are 3 ways for energy to enter the economy through imports.

1) Btu content of imported energy. This is just $\sum_{\ell} Q_{\ell}$, where ℓ runs over the energy sectors.

2) Implied primary energy penalty on this imported energy. This is $\sum_{\ell} (\varepsilon_{\ell}-1)Q_{\ell}$.

3) Embodied primary energy in imported goods. This is $\sum_{i \neq \ell} \varepsilon_i Q_i$.

Analogous terms apply to exports. All quantities are known, leading to Fig. 7. Imports and exports are expressed as a percentage of the total U. S. energy budget, which we define consistent with the approach here, as the sum of domestic and all imported energy, actual and embodied.

We see that while the U. S. was a net importer of actual energy, it was a net exporter of energy embodied in goods. The combined effect is that the U. S. was still a net energy importer.

This suggests an interesting way to look at foreign trade policies. If energy embodied in exports exceeds that of imports, domestic energy supplies are being depeleted by trade. As our economy becomes more open, the energy flux associated with trade will grow. A framework which explicitly recognizes this flow will be necessary for evaluating policies directed toward energy self-sufficiency.

4.7 An Energy Conservation Tax

It has been suggested that a tax be levied on energy use, to encourage conservation and to raise the revenue needed to solve energy-related problems [19]. Under the assumption that all taxes are passed through 100% in the form of consumer price increases, it was found that an energy tax (20¢/million Btu) could raise very large amounts of revenue (about $15 billion) and would result in only slight price increases for most goods and services. However, tax impacts would be distributed in such a way that prices of some energy intensive products would rise substantially compared to their less energy intensive competitors.

It was determined that a "per Btu" tax would be substantially less regressive than an *ad valorem* tax, which would reflect inequities in utility rate structures. Revenues would be adequate to provide per capita income tax credits in an amount equivalent to a subsistence energy use level, thus transferring the burden of the tax to heavy energy users.

The method was based on results of Ref. 5, and the "per Btu" tax was taken to be directly proportional to energy content of goods and services. In an analogous manner, monetary data on energy use from Ref. 6 were used to calculate the "energy value content" of goods and services for determining the impact of the *ad valorem* tax, assuming that each sector passes on its increased dollar costs. During the computation, those elements of the matrix product corresponding to flows of secondary (already taxed) energy were taxed only on their "energy value added" (e.g. energy burned in refineries) to avoid double counting. Estimated price increases on some goods and services under the two taxing schemes are presented in Table 9. The 20¢/million Btu tax was compared to an 18% *ad valorem* tax because it could raise equal revenue.

APPENDIX: LABOR INTENSITY

In Section 4, we mentioned labor intensity of goods and services. The concept is analogous to energy cost ε_j; energy enters the economic system as it is extracted from the earth, while labor enters directly from the domestic labor force. The "labor balance" of a sector is shown in Fig. 8. Here λ_j is the labor intensity (total man-years, direct and indirect), per unit of X_j. L_j is the man-years used directly in industry j. Embodied labor is thus allocated by transactions of X_j as before. There is a question whether dollars or Btu's are better allocators of embodied labor for the energy sectors (perhaps the high price of residential electricity reflects more labor intensive sales, promotions, and service). In the example quoted [17], dollars were used for all T_{ij} although it is not necessary.

Solving the equation implied by Fig. 8 gives:

$$\underline{\lambda} = \underline{L} \cdot (\hat{\underline{\underline{X}}} - \hat{\underline{\underline{Q}}} - \underline{\underline{T}})^{-1} \qquad \text{(A-1)}$$

Eq. A-1 resembles eq. (2-12). The main difference is that while the matrix $\underline{\underline{E}}$ has only a few non-zero entries (primary energy out of the earth), the vector $\underline{L}$ has non-zero entries for almost every sector; every industry receives output from the labor force, which is a part of final demand and not one of the N industrial sectors.

Secondary product and capital corrections can be included in the labor intensity calculation; the methods are analogous to those for energy.

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TABLE 1

Example Energy Intensities (10^3 Btu/$)

Source: Ref. 5. 360 Sector Model

Primary Aluminum	380
Fertilizers	180
Airlines	152
Glass	101
Motor Vehicles	70
Cheese	62
Apparel	46
Hospitals	38
Computing Machinery	27
Banking	19
U. S. Average	82

TABLE 2

Effect on Energy Intensities of Including Capital Flows

Source: Ref. 20. 92 Sector Model

Percent Change of ε	Number of Sectors
0 - 3	18
3 - 6	49
6 - 12	19
12 - 18	5
18 - 24	1
> 24	0
	92

TABLE 3

Comparison of Energy Cost Computed by Our Technique and by Independent Vertical Analysis

Source: Ref. 12. 360 Sector Model

Subject	Ratio (Other Result/Our Result)
1. Auto (manuf.)	.81
2. Finished steel	{ .89 1.00
3. Primary copper	.52
4. Primary aluminum	1.11
5. Rolled & drawn aluminum	{ 1.21 1.23
6. Aluminum castings	.95
7. Bread	1.09
8. Glass containers	.67
9. Raw paper	.63
10. Newspapers	.72
11. Metal containers	1.13

Mean = 0.92, standard deviation $= \sqrt{\frac{\sum_{i=1}^{N} (X_i - \bar{X})^2}{N-1}} = 0.23$

TABLE 4

Energy Cost of the Average Private Car, 1963

Source: Ref. 5

Category	% of Total Energy
Fuel	
Content	57.2
Refining, etc.	11.9
Retail	1.3
Oil	
Content	0.5
Retail	0.2
Car	
Manufacture	9.9
Retail	3.4
Repairs, parts, maintenance	3.3
Parking	8.8
Tires	
Manufacture	0.8
Retail	0.2
Insurance	2.7
Highway construction (taxes)	4.8
	100.0

TABLE 5

<u>Energy Cost of an Electric Mixer</u>

Based on 360 sector model

$E_{tot} = E_{op} + E_{mfg}/\tau$

where

E_{tot} = total primary energy for year

E_{op} = total primary energy to operate per year

E_{mfg} = total primary energy to manufacture and sell

τ = lifetime in years

(Maintenance and disposal energies are assumed negligible)

E_{op} is obtained from industry data (125 watts, 10 KW hr./yr. [21]). It is converted to primary terms by dividing by the energy efficiency of electricity generation [5]. E_{mfg} is obtained by multiplying purchase price ($20 [22]) by the energy intensity for appliances, converted to purchasers' price [10].

Thus:

$E_{op} = 10$ KW hrs. x 3412 Btu/KW hrs. x 1/.256 = 1.33×10^5 Btu/yr.

$E_{mfg} = 1.08 \times 10^6$ Btu

We assume $\tau = 14$ years; hence $E_{mfg}/\tau = 7.71 \times 10^4$ Btu/yr.

$E_{tot} = 1.33 \times 10^5 + 7.71 \times 10^4$

$= 1.33 \times 10^5 (1 + 0.58)$ Btu/yr.

TABLE 6

Energy Impact of Urban Car vs. Urban Bus

Source: Ref. 15

Energy Intensity (Btu/pass. mile)	Car	Bus
Direct fuel	5500	2600
Total energy	8900	5300
Trip length (av.)	8.3 mi.	3.8 mi.
Passengers (av.)	1.9 (incl. driver)	12

TABLE 7

Energy and Employment Impact
of Several Federal Spending Options

Data normalized to unity for highway construction
Source: Ref. 17

Program	Energy per $(1963)	Jobs per $(1963)
Highway Construction	1.00	1.00
Rail & Mass Transit	0.38	1.03
Waste Treatment Construction	0.58	1.01
National Health Insurance	0.36	1.65
Tax Relief	0.77	1.07

TABLE 8

Energy Input Analysis of Two Sectors

Source: Ref. 18. 360 Sector Model

Feed Grains

Input Sector	g_{ij} (%)
Refined petroleum	51
Electric utilities	3
Agriculture	11
Construction	1
Chemicals, paints	20
Heavy machinery	1
Finance, insurance	5
Other	8
	100

Motor Vehicles

Input Sector	g_{ij} (%)
Coal mining	3
Electric utilities	4
Gas utilities	2
Chemicals, paints	5
Stone, clay, glass	2
Primary metals	28
Fabricated metal products	9
Heavy machinery	4
Motor vehicles	34
Other	9
	100

TABLE 9

Potential Price Impacts of Energy Tax Schemes
(Cents Per Dollar Delivered for Final Consumption, 1963 Producers' Prices)

Source: Ref. 19

	Btu Tax	Ad Valorem Tax
Electricity	11.5	23.7
Plastics	4.5	2.5
Air Transport	3.1	2.3
Metal Cans	2.8	1.4
Motor Vehicles & Parts	1.4	1.1
Hospitals	.8	1.0
Doctors, Dentists	.3	.4

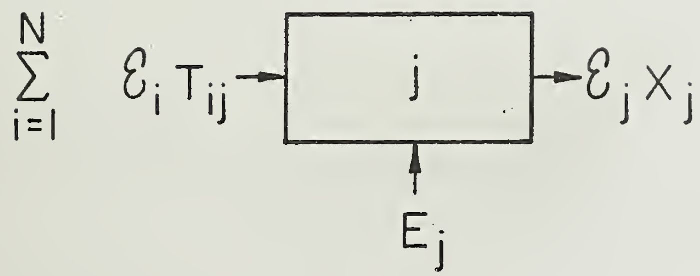

Figure 1. The simplest energy balance diagram.

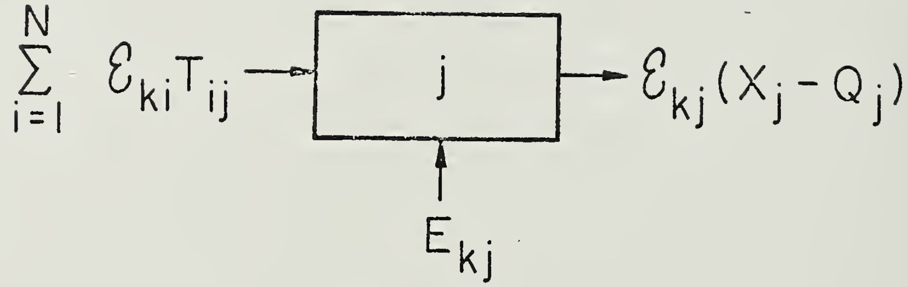

Figure 2. Energy balance for a domestic sector.

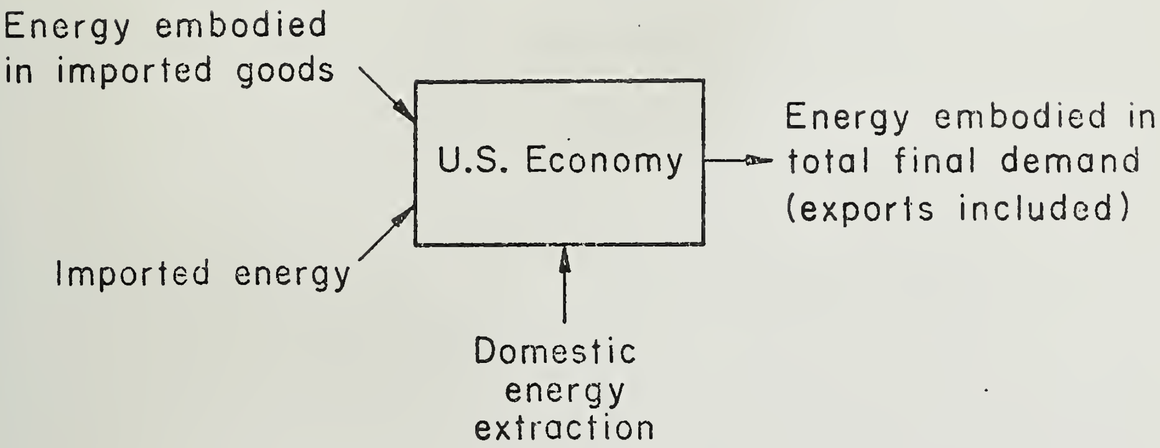

Figure 3. Energy flow through the U. S. economy.

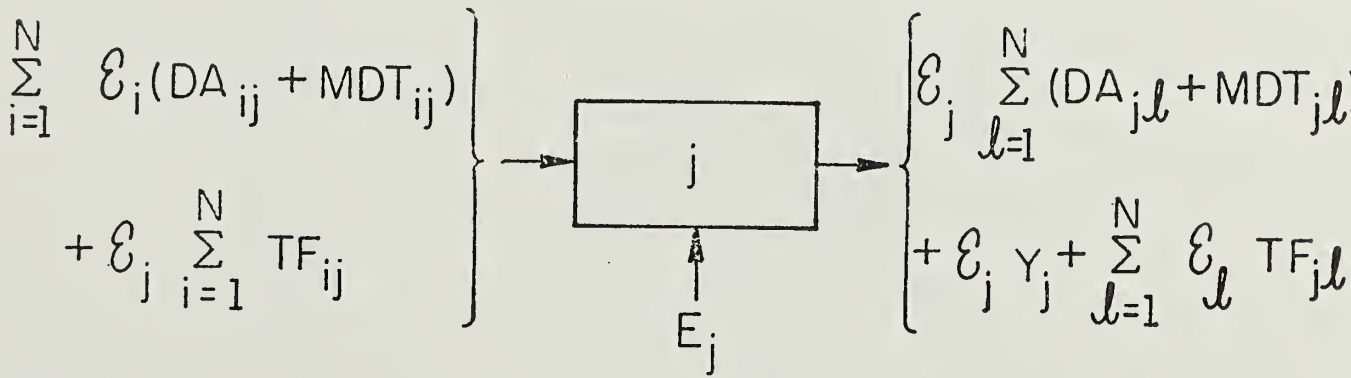

Figure 4. Energy balance with secondary products.

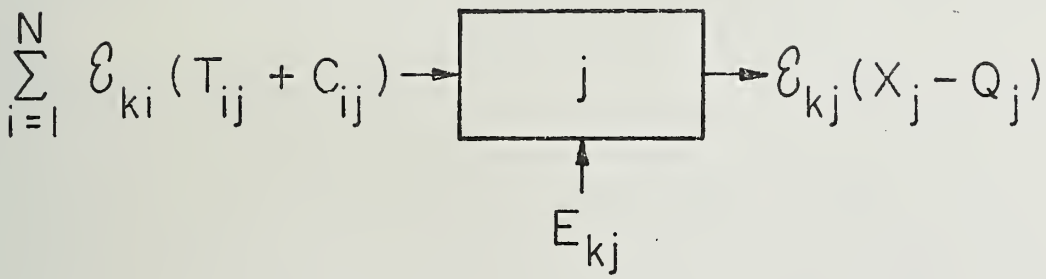

Figure 5. Energy balance with capital flows.

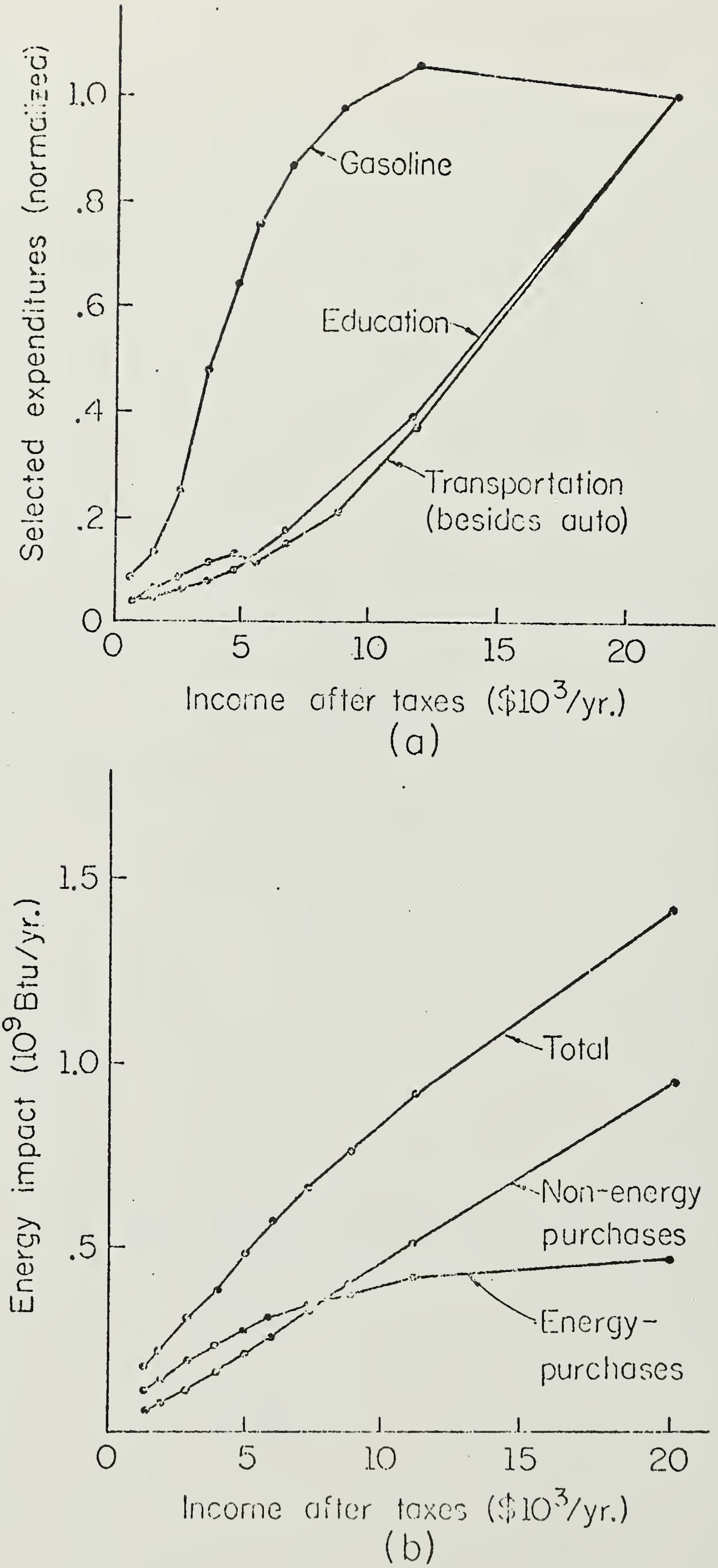

Figure 6. Family energy impact vs. income.

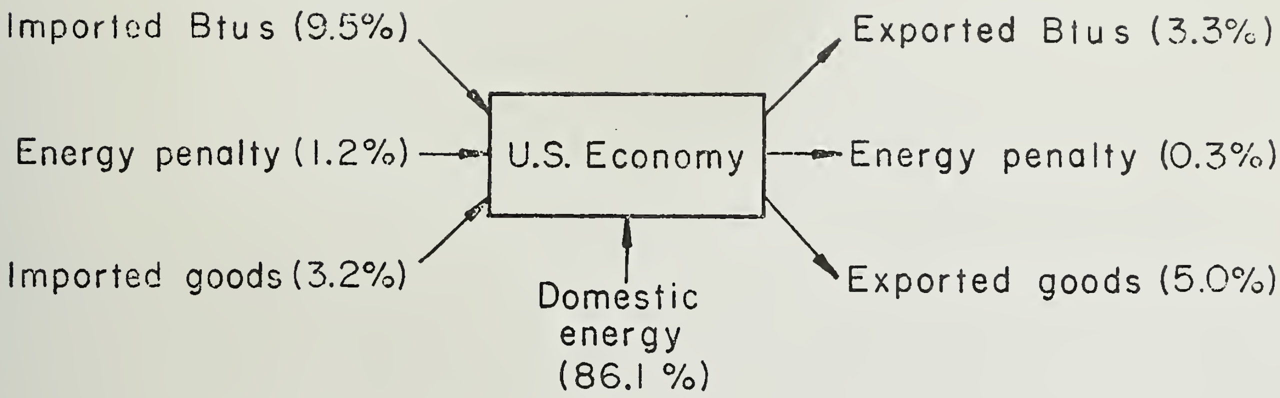

Figure 7. U. S. import-export energy balance, 1963.