The energy cost of goods and services

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First developed for economic analysis, static linear input-output analysis has been adapted to deal with energy. This paper uses as a data-base the 1967 results of the input-output analysis of the US economy carried out every five years by the US Department of Commerce. In the 357 sector breakdown of the US economy there are five energy sectors, coal, crude oil and gas wells, refined petroleum, electricity and gas utilities. The model is used to determine the primary energy inputs to all sectors, taking account of the fact that energy is sold at different prices to different customers. Possible uncertainties in the model and updating methods are discussed.

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When you consume anything, you are consuming energy. The emerging art of 'energy analysis' seeks to determine *how much* energy is required to provide goods and services. Here we describe a method based in part on static input-output economic analysis which we have applied it to the United States economy (357 sectors) for 1967. The method allows explicit treatment of the flow of energy involved in the flow of goods across regional boundaries, which has key significance for the question of energy self sufficiency.

There are many reasons for wanting to quantify the energy cost of goods and services. Initially we were motivated by an interest in energy conservation and the potential for saving energy through substitution of products and services. Chapman[1] has pointed out that observation of energy costs of natural resources may provide a firm basis for estimating recoverable reserves, taking full account of the Second Law of thermodynamics, and accounting for the absolute scarcity of free energy reserves. Taking the concept one step farther, Wright[2] has calculated the natural resource requirements for a number of consumer goods.

In a simultaneous, but independent study, Wright[3] estimated energy costs of goods and services, using a technique similar to ours, based on input-output data for 1963. His results, however, differ substantially from ours due to two simplifying assumptions. The methodological differences will be noted below, and the effect of these assumptions on numerical results are discussed later.

General discussion of method

The basis is the idea of 'conservation of embodied energy'. This says that the energy burned or dissipated by a sector of the economy (say a steel mill) is passed on, embodied in the product.[4] Applying this to every sector yields the following picture: primary energy is extracted from the earth, is processed by the economy, and ultimately gravitates to final demand (ie, personal and government consumption and exports). The method also yields the energy intensity, that is, the embodied energy per unit of output, for each economic sector.

Before proceeding, we must add a caveat. This approach covers the whole spectrum of consumer goods and services. In return for the gift of a large body of data from economics, we as energy analysts have had to make several simplifying assumptions, as well as using data that are eight years old. We thus obtain results which are exhaustive, and which are applicable to large scale questions, but which are less useful for very detailed, micro questions (for example, the energy cost

[1] P. Chapman, 'No overdrafts in the energy economy,' *New Scientist*, May 17, 1973, pp 408-410.
[2] D. Wright, 'The natural resource requirements of commodities,' *Applied Economics*, v 7, 1975, pp 31-39.
[3] D. Wright, 'Goods and services: an input-output analysis,' *Energy Policy*, vol 2, No 4, Dec. 1974.
[4] This is in addition to energy from the earth (for a primary energy sector) or in the form of feedstocks.

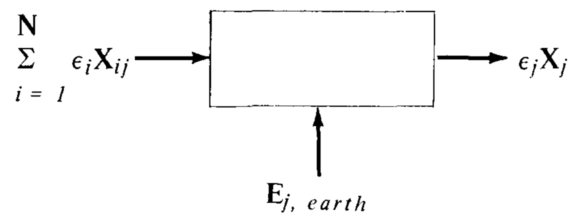

Figure 1: Conservation of embodied energy for an economic sector.

of different building materials). For the latter specific process analyses should be more accurate.[5 6 7 8]

In Figure 1, we apply 'energy balance' to an economic sector.

X_{ij} is the transaction from sector i to sector j

X_j is the total output of sector j

ϵ_j is the embodied energy intensity per unit of X_j

$E_{j,\ earth}$ is that energy extracted from the earth by sector j, and is non-zero only for primary energy sectors. (All quantities are measured for a standard time period.)

We assume that the energy embodied in inputs to sector j, plus the energy burned in that sector, is passed on as part of j's output. This 'energy balance' yields one equation for each of the N sectors; we then solve for the ϵ_j.

So far we have not specified the units of the transactions X_{ij}; the validity of the energy intensities depends on the choice. Ideally, we would like to use physical units (tons of steel, cubic yards of concrete, etc), since these would presumably serve as good linear allocators. Adequate physical data do not exist at the 357-level of detail, so instead we rely mainly on dollar transactions data from Reference 9. This is the data base of an input-output analysis (I-O) of the US economy carried out every 5 years by the US Dept of Commerce.

Dollar data are inferior to physical, being more subject to economies of scale. Reliance on monetary data for energy transactions effectively assumes energy is sold at the same price to all users. Since this assumption is most questionable for the USA, we use physical data (Joules)[10] exclusively. The transactions table X_{ij} is thus in mixed units. This method differs from that of Reference 3 which assumed that energy was sold at the same price to different users.

Attention must be paid to imports. Ideally, we would like to remove them from the energy flow diagram in order to calculate energy intensities for domestic technology, and then reintroduce them to account for their embodied energy flow into the country. This is complicated by the existence of two kinds of imports in the economic data we use.[9] First, transferred – also known as competitive – imports which have domestic counterparts, such as steel. Second, directly allocated – non-competitive – imports, which do not, such as bananas. Transferred imports of steel are added to the output of the domestic steel sector. Since the inputs needed to produce that steel are not counted, we remove transferred imports from the output as shown

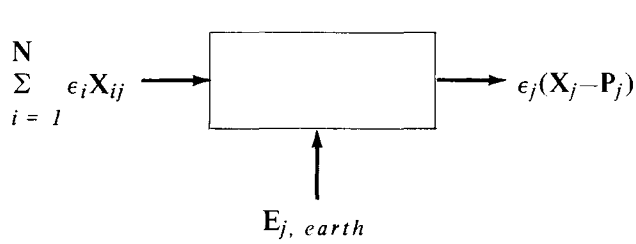

Figure 2: Energy balance for a domestic sector. P_j is transferred imports.

[5] R. Berry and M. Fels, 'The production and consumption of automobiles, Report to the Illinois Institute for Environmental Quality, July 1972.

[6] B. Hannon, 'System energy and recycling: A study of the beverage industry,' CAC Doc No 23, Center for Advanced Computation, University of Illinois, March, 1973.

[7] B. Commoner, M. Gertler, R. Klepper, and W. Lockeretz, 'The effect of recent energy price increases on field crop production costs,' Report, Center for the Biology of Natural Systems, Washington University, St Louis, Missouri, December, 1974.

[8] A. Makhijani and A. Lichtenberg, 'Energy and wellbeing,' *Environment*, vol 14, No 5, June, 1972, pp 10-18.

[9] *Input-Output Structure of the US Economy: 1967*, vols. I-III, US Department of Commerce, 1974. Published by the US Government Printing Office. The data are available on tape from Bureau of Economic Analysis, US Department of Commerce. Additional explanation is found in the February, 1974, *Survey of Current Business*, and in *Definitions and Conventions of the 1967 Input-Output Study*, unpublished but available from the Bureau of Economic Analysis.

[10] *1967 Census of Manufacturers, 1967 Census of Mineral Industries*, US Department of Commerce, were basic documents. A complete explanation is D. Simpson and D. Smith, *1967 Direct Energy Transactions*, Technical Memorandum No 39, Center for Advanced Computation, University of Illinois.

in Figure 2. Here again our method is different from that of Reference 3 which did not reduce gross outputs by the amount of imports.

No similar correction is possible for those directly allocated imports which are inputs to domestic sectors. (We simply do not know the energy intensity of jade, teak, or bananas.) Fortunately, these imports are relatively small; in 1967 directly allocated imports sold to producing sectors were worth \$3·8 billion* against transferred imports of \$22·6 billion.[11] We therefore neglect them in calculating energy intensities. For a nation with larger imports this would introduce significant error.

Once the energy intensities are obtained, we can treat transferred imports as if they embody the same energy as their domestic counterparts. (One way to justify this is to note that they would require this much energy if they were manufactured here.) Directly allocated imports must be assigned an approximate energy intensity.

The US economy, or that of any nation, may be viewed as receiving energy in three ways:

1. Primary energy (coal, crude, gas, hydro, nuclear) from the American (or nation's own) earth.
2. Imported energy (for the USA, almost exclusively petroleum), with an associated embodied energy penalty due to losses in extraction, refining, etc, carried out abroad.
3. The energy embodied in imported non-energy goods.

Computational details

For the present we assume that only one kind of energy is extracted from the earth. The approach can be extended to several kinds of energy as well.

We assume that each sector is in energy balance, from Figure 2:

$$\sum_{i=1}^{N} \epsilon_i X_{ij} + E_{j\ earth} = \epsilon_j (X_j - P_j) \tag{1}$$

In matrix notation we have

$$\epsilon = \mathbf{E}_{earth} (\hat{X} - \hat{P} - X)^{-1} \tag{2}$$

where

ϵ is the row vector of energy intensity coefficients

$\hat{X}$ is a diagonal matrix with gross outputs, $\mathbf{X}_j$ on the diagonal
$\hat{P}$ is a diagonal matrix with transferred imports, $\mathbf{P}_j$ on the diagonal
$\mathbf{X}$ is the transactions matrix
$\mathbf{E}_{earth}$ is a row vector with one non-zero term (corresponding to the one assumed primary energy sector).

It is helpful to normalize with respect to domestic output

$$\epsilon = \mathrm{E}_{earth} (\hat{X} - \hat{P})^{-1} (I - X(\hat{X} - \hat{P})^{-1})^{-1} \tag{3}$$

and to define a matrix A of domestic technological coefficients:

$$A = X(\hat{X} - \hat{P})^{-1} \tag{4}$$

Then Equation (3) can be rewritten

$$\epsilon = e(I - A)^{-1} \tag{5}$$

* 1 billion = 1000 million

[11] By definition, all transferred imports are inputs to producing sectors. In contrast, most directly allocated imports are sold directly to final demand (\$14·43 billion in 1967). The latter have no bearing on the calculation of energy intensities.

where e is a vector whose elements are zero except for the energy sector; that element is unity.

To arive at Equation (5), we have assumed only that there exists a vector ϵ which results from applying Equation (2) to the base period data. Our intent is to make ϵ more useful by requiring that it apply, in the stated linear fashion, Equation (1), to *any* set of transactions that might occur. For example, if twice as much of commodity j is produced, twice as much embodied energy is implied. This linearity assumption, which equates average and marginal energy intensity, is a weakness of the method. There are two approaches to this problem:

The first is to apply a sufficient condition: let $\mathbf{A}$ be constant, independent of scale and time. This is the assumption of standard input-output (I-O) analysis.

The second is to apply only a necessary condition, that ϵ is constant. This leads to a large set of equations relating the X_{ij}.

The first approach requires the specification of more information than the second; for the purpose of obtaining only ϵ it is too strong. Hence at this point it is *not* necessary to apply the usual I-O assumption.

For the case of the transactions table X_{ij} expressed in both energy and dollar flows, the units of ϵ are Joules/Joule for energy sectors, and Joules/dollar for non-energy sectors. This is illustrated for an example three-sector economy in Appendix A.

We have identified the energy intensity ϵ_j as the energy embodied in – needed to produce, directly and indirectly – a unit of product j. This interpretation implies some double counting if we sum the energy embodied in the output of all sectors (for the same reason that adding sector dollar outputs exceeds the gross national product). It is easily shown, however, that ϵ_j is also the energy needed to produce a unit of product j delivered to final demand. Summing the energies necessary to produce all final demands yields just the energy inputs to the economy. This justifies the concept of final demand as the final sink for all energy. (See Appendix B.)

The ϵs obtained above may be used to compute the energy impact of an arbitrary final demand.

Extension to several kinds of energy

In the 357-sector breakdown of the US economy, there are five energy sectors (coal, crude oil and gas wells, refined petroleum, electricity, and gas utilities). One might wish to obtain either energy intensities for a certain energy type, or the total primary energy required (ie, the sum of the coal, crude oil and gas, and hydro and nuclear power).

For the first purpose one can treat the energy sector in question as if it receives its domestic output from the American earth, even if it is a secondary energy producer like electricity. One therefore solves Equation (3) with a non-zero entry for $\mathbf{E}_{earth}$ only in the relevant energy sector. Doing this for all five energy sectors effectively converts $\mathbf{E}_{earth}$ into a matrix (5 x 357, with 5 non-zero entries), and now ϵ becomes ϵ (5 x 357)

$$\epsilon = \mathrm{E}_{earth}\ (\hat{\mathbf{X}}-\hat{\mathbf{P}}-\mathbf{X})^{-1}$$

This is also illustrated in Appendix A.

The total primary energy coefficient is a linear combination of the respective single primary energy coefficients. Thus

$$\epsilon_{total\ primary,j} = \epsilon_{coal,j} + \epsilon_{crude + gas,\ j} + \alpha\,\epsilon_{electricity,j}$$

α is a factor to account for the electricity produced from hydro and nuclear sources. Refined petroleum and fossil electricity are secondary energy types and are omitted to avoid double-counting. The actual value of α depends on the convention one uses for energy 'costing' of these sources. In this paper we use $\alpha = 0{\cdot}6165$, based on a heat rate of 11 133 Btu/kWh and the fact that in 1967, 18·9% of US electricity was from hydro or nuclear sources. This follows the prevailing US convention of costing them according to the fossil fuel technology they replace. Very likely a different convention is appropriate for a nation with a high percentage of hydroelectricity.

Energy intensities for the US economy, 1967

From Reference 9, and from independent determination of the energies used by the sectors in the base year,[10] we have obtained enought data to apply Equation (3) to the US economy in 1967. We stress that for most sectors we have explicitly accounted for the fact that energy is sold at different prices to different customers (eg cheap electricity to aluminum smelters.) Results are available for the five kinds of energy and for total primary energy.* For the non-energy sectors, the intensities are in thousands of Joules per dollar, while for energy sectors the units are Joule per Joule. Subject to the conditions mentioned below, they can be applied to a variety of problems. We give a few example applications below, but most have been published elsewhere.

Some of the potential limitations of the results derive from data problems, but others derive from economic conventions used in computing the I-O data base:

- I-O data are subject to inaccuracies from lack of complete coverage of an industry, restriction of information for proprietary reasons, and use of different time periods for data on different sectors. Also, errors in **A** may generate disproportionate errors in $(\mathbf{I}\text{-}\mathbf{A})^{-1}$.
- The use of dollars rather than physical units to express physical dependencies is less than perfect. For example, aggregation can combine in the same sector two processes whose energy intensities differ widely. And, as we mentioned, economies of scale may be implicit in the dollar data, whereas there would be little or no corresponding effect in physical terms.
- There is a problem with secondary products. The definition of an I-O sector is based on the establishment rather than activity. For example, if those establishments which produce primary aluminum also produce aluminum castings (amounting to less than 50% of total sales), the primary aluminum sector is credited with the summed output. The secondary output is transferred to the aluminum castings sector, ie treated as a sale. The corresponding inputs are not transferred. This means that the dollar output corresponding to production of these aluminum castings has been counted twice, but the energy only once. The fraction transferred varies from sector to sector, so that a

* A table of results referring to the 1967 US economy is available from the authors.

correction is required. In Reference 12 an approximate correction was used. There is an exact method,[13] but inadequate data to implement it. The results here incorporate no correction for secondary products.

- A problem arises in capital goods; these are not considered part of the inter-industry transactions but are listed as sales to final demand. Conceptually, we would consider the energy to make a steel forming press owned by an auto manufacturer to be as valid an energy contribution as that used to make the steel in the auto itself, but this is not compatible with the primary data source[9] which defines the system boundary consistent with the definition of GNP. Calculations to incorporate capital flows are also described in Reference 13, but they are not applied to the results here.
- Final demand is measured in producer's, not purchaser's prices. Since two of the I-O sectors are wholesale and retail trade, it is possible to make the conversion, including the energy requirements implied in the markup (as has been done for the automobile, below). For direct purchases by consumers, it is desirable to convert beforehand to purchaser's prices.
- Input-output coefficients change with time, yet we hope to use the results to predict the consequences of hypothetical future consumption patterns. Can one quantify their loss of reliability with time? This is a major point, for which much work is needed. Our feeling is that our results are most sensitive to changes in direct energy use coefficients, which may change faster than others due to fuel substitutability and the potential for energy conservation.
- As mentioned, the assumption of linearity is equivalent to equating marginal and average energy intensity, which is questionable.
- The assumption that foreign technology is as energy intensive as domestic may be wrong and will introduce error into analysis of imports.

Comparison with other results

The results published by Wright[3] are for 1963, so are not directly comparable with those presented here, which are for 1967. We have, however, also done a similar calculation for 1963[14], comparable to Wright's. As a basis for comparison, we used the difference in the two values (for total primary energy) divided by our result. Treating the intensities from each sector as independent and of equal weight, we find Wright's figures average 12% lower than ours, with a mean deviation of 23%.[15] Thirty-four of the intensities differ by more than 50%.

That energy intensities calculated by our domestic base method average higher is due to the fact that Wright's approximation admits imported goods at zero energy cost; ours costs them as if they were produced domestically. Errors are greatest in those sectors where imports are a large fraction of sector output.

The deviation not explained by imports is due to Wright's admitted assumption that energy is sold at a uniform price to all consumers. While this assumption may be valid for some countries, it is certainly not true for the USA where declining block rate structures are

[12] R. Herendeen, 'An energy Input-Output matrix for the United States, 1963: User's Guide,' CAC Doc No 69, Center for Advanced Computation, University of Illinois, March, 1973.

[13] C. Bullard and R. Herendeen, 'Energy impact of consumption decisions', *Proceedings of the IEEE, Special Issue on Social Systems Engineering*, March, 1975.

[14] C. Bullard III and R. Herendeen, 'Energy Cost of Consumer Goods 1963/67,' CAC Doc No 140, Center for Advanced Computation, University of Illinois, November, 1974.

[15] Not standard deviation, which would be greater. Mean deviation is the average value of the absolute value of the deviation from the mean.

common in regulated energy industries. For example, the primary aluminum industry in the USA paid only 38% of the average industrial price for electricity in 1967.[16] Accordingly, our value for the total primary energy intensity of aluminum exceeds Wright's by a factor of 2·5. Most of this difference is due to his constant-price assumption, but some results from the fact that US aluminium imports amounted to about 10% of domestic production, as already mentioned. A similar situation exists for natural gas, which is also regulated in the USA. In 1963, prices to commercial users were more than twice the average industrial rate, and off-peak industrial users on interruptible service received rates much lower than average.[17]

Sectors most affected by preferential prices are primary metals and large manufacturing sectors, where energy prices deviate most from the national average. Since I-O tables are highly disaggregated in those sectors, they contribute heavily to our (equally weighted) computation of the average difference (12%) between our results and Wright's. The true effect of neglecting energy embodied in imports is less than 5% (on the average) for the relatively closed economy of the USA.[13] For a more open economy, imports could not be neglected and as we have seen here, they should never be neglected when we are concerned with the energy intensities of *individual* commodities.

Example applications

Several applications of this method have already been published.[13 18 19 20 21] These usually identify some group as consumers – households, government, specific industries – and energy-cost their purchases. Here we will briefly discuss four applications: the energy cost of energy; the total energy cost of the automobile; the total energy cost of an electric mixer; the total energy import-export balance of the United States.

1. We first obtain the energy cost of energy for 1967. Energy delivered refers to the point of use and 3·80 Joules of primary energy are required to effect delivery of 1 Joule of electricity as electricity, after allowing for losses in mining, generation and transmission. The reciprocals are the energy delivery efficiency of the system, as listed in Table 1. We would emphasize that these are underestimated due to the exclusion of capital flows from the data base; however, from unpublished calculations we feel that the inclusion of capital purchases will decrease these efficiencies by no more than 2%.
2. The total energy cost of the automobile has been computed twice before,[12 21] but we do so again with our latest values for energy intensity. The idea is to determine all auto-related expenditures and apply each to its appropriate energy intensity. Details are in Table 2. We note that our figure for the energy cost to manufacture the average car in 1967, 148 x 10^9 Joule, is only 11% greater than the result of a detailed process study by Berry and Fels.[5] Final demand expenditures associated with the auto accounted for 19·8% of the nation's energy budget. Only 56% of this was for direct use as fuel.
3. Computing the energy cost of an electric mixer illustrates the relative roles of the energies to manufacture and operate the device. In 1967, an average mixer cost $14 retail.[22] To be exact, we should separate the transportation and trade margins from the manufacturer's price, and apply the appropriate energy intensities.

Table 1. Energy cost of energy: efficiency of the US economy in delivering energy, 1967

Sector, I/O Number	Efficiency (%)
Coal, 7.00	99·3
Refined petroleum, 31.01	82·8
Electricity, 68.01	26·3
Natural gas, 68.02	90·9

Efficiencies measured fob producer (mine or refinery); an additional energy cost would be associated with marketing. For electricity and gas, producer sells directly to consumer.

[16] The average price of electricity to industrial customers in 1967 was 0·9c/kWh ('Statistical Yearbook of the Electric Utility Industry for 1971', Edison Electric Institute, New York, p 53). The average price of electricity sold to the primary aluminum industry was 0·34c/kWh, as computed from data for SIC industry category 3334, primary aluminum, on p 23 of 'Fuels and Electric Energy Consumed,' 1967 Census of Manufacturers, US Department of Commerce Document M667(5)-4. We have found a similar difference for 1963.
[17] *Gas Facts*, American Gas Association Inc, Arlington, Virginia, 1970, pp 99-100.
[18] R. Herendeen, 'Affluence and energy demand', presented at the 94th Winter Annual Meeting of the American Society of Mechanical Engineers, Detroit, November, 1973 (Paper 73-WA/ERER-8). Also reprinted in *Mechanical Engineering*, October, 1974. Also available as Document No 102, Center for Advanced Computation, University of Illinois, July, 1973.
[19] R. Bezdek and B. Hannon, 'Energy, manpower and the highway trust fund,' *Science*, vol. 185, p 669, August, 1974.
[20] E. Hirst, 'Food related energy requirements,' *Science 184*, pp 134-138.
[21] E. Hirst and R. Herendeen, 'Total Energy Demand for Automobiles,' Society of Automotive Engineers paper 730065. Presented at the International Automobile Engineering Congress, Detroit, Michigan, January, 1973.
[22] *Merchandising Week*, Vol 104, No 9, 28 February 1972.

Table 2. Energy impact of the automobile, 1967[a]

	Expenditure (10^9\$)	Sector	Energy Intensity[b] (10^3J/\$)	Energy (10^{15}\$)	% of Total
Gasoline					
production	7·28[c]	31·01	–	7400	55·9
refining	–	31·01	(0·208 J/J)	1540	11·6
retail markup	3·50[d]	69·02	37400	131	1·0
Oil					
production & refining	1·09[f]	31·01	–	53[e]	0·4
retail makeup	0·73[f]	69·02	37400	27	0·2
Auto					
manufacture	17·80[g]	59·03	70400	1250	9·4
retail markup	5·93[h]	69·02	37400	222	1·7
Repairs, maintenance, parts	14·31[i] 14·44[i]	75·00	51800	742	5·6
Parking, garaging	14·44[i]	75·00	51800	748	5·6
Tyres					
manufacture	1·11[f]	32·01	104500	116	0·9
retail markup	0·74[f]	69·02	37400	27	0·2
Insurance	11·32[i]	70·04	22000	249	1·9
Taxes (highway const.)	5·94[d]	11·04	123900	735	5·6
Total	84·2			13240	100·00

a The analysis is described in Reference 16. The numbers here differ somewhat since the calculation in Reference 16 was for 1970.
b From I-O calculation results.
c Statistical abstracts of the USA, 1972.
d Petroleum facts and figures, 1971, API.
e 0·51 gallon oil to 100 gallon gasoline. See d above, p 321.
f Purchased cost from c above, Table 896. Retail markup assumed to be 40% of this.
g There were 7·437 x 10^6 cars worth \$15 653 x 10^6 (wholesale) manufactured domestically in 1967 (See d above,/p 306). Also 1·021 x 10^6 cars were imported (See c above, Table 892). We assume they had the same unit price of \$2104·75 wholesale.
h Retail markup from difference between purchase cost of \$2806 (See c above, Table 896) and wholesale price above.
i See c above, Table 896.

For simplicity we assume that all of the margins are allocable to retail trade (I-O sector 69·02). Electric mixers belong in sector 54·04, electric housewares and fans. Then the energy to manufacture and sell the mixer is

$$[0{\cdot}6\,\epsilon_{54\cdot04} + 0{\cdot}4_{\,69\cdot02}] \times 14$$
$$= [0.6\,(73\,500) + 0.4\,(37\,300)]\ 1.4 \times 10^4\,\mathrm{J}$$
$$= 8.26 \times 10^8\ \mathrm{J}$$

Assuming that the mixer lasts 14 years, with no maintenance or disposal costs, the yearly energy impact of manufacture and sale is $5{\cdot}9 \times 10^7$J. Operational energy is obtained by noting that a typical mixer uses about 10 kWh of electricity per year (125 Watts, 13 minutes per day).[23] Taking into account the inefficiency of electricity generation and delivery (Table 1), this is $1{\cdot}37 \times 10^8$/ J/yr. Then the total yearly energy impact of the mixer is

$$1{\cdot}37 \times 10^8 + 5{\cdot}9 \times 10^7 = 1{\cdot}96 \times 10^8\,(0{\cdot}70 + 0{\cdot}30)\mathrm{J}.$$

70% results from operating the device; 30% from producing it.

4. Figure 3 shows the energy import-export balance for the US in 1967. We recall that there are three ways for energy to enter the economy through imports.

1. Actual energy value of imported energy. For transferred imports, this is $\sum_l P_l$, where the sum is over the energy sectors.
2. Energy penalty associated with energy imports. This is

$$\sum_l (\epsilon_l - 1)P_l$$

3. Energy embodied in imported goods. This is $\sum_{i \neq l} \Sigma_i P_i$

[23] Electric Energy Association, *Annual Energy Requirements of Electric Household Appliances*, EEA 201-73, 1973.

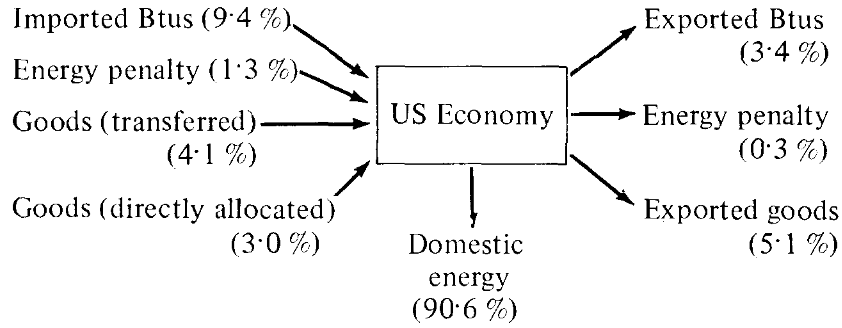

Figure 3: Energy import-export balance for the United Stated, 1967. Figures expressed as percentages of US energy requirement, which is defined here (following the usual convention) as the sum of domestic energy plus raw imported energy, 66·83 x 10^{18} Joule. Directly allocated imports are estimated and correspond to an energy intensity of 116 x 10^{6} J/\$. The correct value is probably a bit smaller.

Analogous terms apply for exports. Analogous terms would also apply for directly allocated imports if their energy costs were known.

These terms are evaluated in Figure 3. Imports and exports are expressed as a percentage of the total US energy budget, which we define as the sum of domestic and all imported actual energy.[24]

The energy content of directly allocated imports is estimated at between 2% and 3% of domestic energy use. In terms of actual energy, the USA was a net energy importer (9·4 - 3·4 = 6·0%). In terms of total energy, the US was even more of a net importer [14·8 + approx 3 (for directly allocated imports) - 8·8] = 9·0%.

Updating results

Energy intensities presented here are based on 1967 economic and energy data: ie, on '1967 technology.' How good are they now? Strictly speaking, we don't know. However, since we have results for 1963[23] and 1967 (this report), we can discuss empirical checks of approximate techniques one might use for updating.[25] The problem is data availability. In the USA price indices, GNP, and overall energy use are tabulated annually. We therefore define the following 'options' for updating:

Option O: Use the old intensities unchanged.
Option 1: Use price indices to correct for inflation (this assumes no technology change).
Option 2: In addition to Option 1, include an overall average change to account for a change in the energy/GNP ratio. Option 2 is what we have used in our past work.

Beyond Option 2 actual technology changes are needed. The most likely place to start is in the technology of energy use: the energy rows of the transactions matrix **X**. We define:
Option 3: Option 1 plus specific changes in the use of energy.

We have applied Options 1, 2 and 3 to the 1963 results in an attempt to update them to 1967 (aggregation to 90-order economy was necessary because of limited data on price indices). For Option 3, we used the actual 1967 energy rows. To compare the projected intensities with the actual 1967 values, we computed

$$\delta_j(\cdot) = \frac{\epsilon_{6,j}(1967) - \epsilon_{6,j}(\cdot)}{\epsilon_{6,j}(1967)}$$

where $(\cdot)$ denotes the option used. We treated the δ_j as independent and of equal weight,[26] and calculated mean and mean deviation, thus

[24] Reflecting the flavor of the approach used in this paper, we should more properly add to this the energy penalty and the energy embodied in imported goods. However, we retain the conventional definition of a country's energy requirements: domestic extraction plus raw energy imports.

[25] R. Herendeen and K. Shiu, 'Comparison of Methods for Projecting Energy Coefficients,' Technical Memo No 47, Center for Advanced Computation, University of Illinois, February 1975.

[26] We use equal weighting because in our work we often use the coefficients singly (eg, how much energy to make steel). Other weightings are appropriate for other purposes (eg, weighting according to final demand expenditures to obtain the energy cost of the whole GNP).

Table 3. Empirical check if techniques to update energy intensity 1963-1967[a]

Option		Mean[b] of δ	Mean deviation[b,c] of δ
0	No update	−0·20	0·20
1	Price indices introduced	−0·16	0·22
2	Option 1 plus overall energy/ GNP factor	−0·16	0·22
3	Option 1 and specific updates on energy use in each sector	−0·02	0·07

a Source: Reference 25
b Computed for total primary energy 90 level economy; mean and mean deviation (md) computed for the 85 non-energy sectors only.
c $$\text{md} = \frac{\sum_{I=6}^{90} \delta\,(I) - \text{Mean}}{85}$$

asking how well the options reduce the average 'error' and scatter of the co-efficients. Results are in Table 3.

We see that Option 2, ie, use of price indices and an overall energy/GNP factor was a very poor updating method for 1963-67. In fact, it was very little better than doing nothing at all. On the other hand, Option 3, ie, use of actual 1967 energy-use technology as well as price indices, was quite successful, reducing the average error to 2% and the mean deviation to 7%.

Appendix A

We perform the computations described in Equations (1)-(5) in the section on computational details for a 3-sector economy.

Let the economy be represented by its dollar and energy flows:

$$\mathbf{X} = \begin{bmatrix} 10 & 40 & 0 \\ 5 & 5 & 10 \\ 5 & 0 & 5 \end{bmatrix} \begin{matrix} \text{Btu} \\ \text{Btu} \\ \$ \end{matrix}$$

$$\hat{\mathbf{X}} = \begin{bmatrix} 50 & 0 & 0 \\ 0 & 50 & 0 \\ 0 & 0 & 30 \end{bmatrix} \begin{matrix} \text{Btu} \\ \text{Btu} \\ \$ \end{matrix}$$

$$\hat{\mathbf{P}} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 10 & 0 \\ 0 & 0 & 10 \end{bmatrix} \begin{matrix} \text{Btu} \\ \text{Btu} \\ \$ \end{matrix}$$

$$\mathbf{Y} = \begin{matrix} \text{Btu} \\ \text{Btu} \\ \$ \end{matrix} \begin{bmatrix} 0 \\ 30 \\ 20 \end{bmatrix}$$

$$E_{earth} = \underset{\text{Btu}}{(50} \quad \underset{\text{Btu}}{0} \quad \underset{\$}{0)}$$

For computation it's a bit easier to work with Equation (4).

$$\mathbf{A} = \mathbf{X}(\mathbf{X}-\mathbf{P})^{-1} = \begin{bmatrix} \frac{1}{5} & 1 & 0 \\ \frac{1}{10} & \frac{1}{8} & \frac{1}{2} \\ \frac{1}{10} & 0 & \frac{1}{4} \end{bmatrix}$$

Note that the units of A are:

$$\begin{bmatrix} \frac{\text{Btu}}{\text{Btu}} & \frac{\text{Btu}}{\text{Btu}} & \frac{\text{Btu}}{\$} \\ \frac{\text{Btu}}{\text{Btu}} & \frac{\text{Btu}}{\text{Btu}} & \frac{\text{Btu}}{\$} \\ \frac{\$}{\text{Btu}} & \frac{\$}{\text{Btu}} & \frac{\$}{\$} \end{bmatrix}$$

We first concentrate on crude oil; ie, one type of energy.

$$\epsilon = (100) \begin{bmatrix} \frac{105}{64} & \frac{15}{8} & \frac{5}{4} \\ \frac{5}{16} & \frac{3}{2} & 1 \\ \frac{5}{32} & \frac{1}{4} & \frac{3}{2} \end{bmatrix}$$

$$= \left(\underset{\text{Btu/Btu}}{\frac{105}{64}} \quad \underset{\text{Btu/Btu}}{\frac{15}{8}} \quad \underset{\text{Btu/\$}}{\frac{5}{4}} \right)$$

Now we worry about crude and refined as separate energy types. As before, we use Equation (3) for the actual computation:

$$E_{earth} = \begin{bmatrix} 50 & 0 & 0 \\ 0 & 40 & 0 \end{bmatrix}$$

Note that we use the *domestic* refined petroleum figure for E_{earth}.

$$E_{earth}\,(\mathbf{X}-\mathbf{P})^{-1} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$\text{and } \epsilon = \begin{bmatrix} \frac{105}{64} & \frac{15}{8} & \frac{5}{4} \\ \frac{5}{16} & \frac{3}{2} & 1 \\ \frac{\text{Btu}}{\text{Btu}} & \frac{\text{Btu}}{\text{Btu}} & \frac{\text{Btu}}{\$} \end{bmatrix}$$

Appendix B

Final demand as the ultimate energy sink

We wish to show that the sum of the domestic and total imported energy (actual fuels and embodied energy) is equal to that energy (actual and embodied) delivered to final demand. We illustrate for the case of one energy type. Rewrite Equation (1):

$$E_{earth} = \epsilon(\hat{\mathbf{X}}-\hat{\mathbf{P}}-\mathbf{X}) = \sum_{i=1}^{N} \epsilon_i(\hat{\mathbf{X}}-\hat{\mathbf{P}}-\mathbf{X})_{ij}$$

$$E_{earth} = \sum_{j=1}^{N} (E_{earth})_j$$

$$= \sum_{j=1}^{N} \sum_{i=1}^{N} \epsilon_i(\hat{\mathbf{X}}-\hat{\mathbf{P}}-\mathbf{X})_{ij}$$

But $\sum_{j=1}^{N} (\hat{\mathbf{X}}-\hat{\mathbf{P}}-\mathbf{X})_{ij} = \mathbf{Y}_i - \mathbf{P}_i$, where $\mathbf{Y}_i$ is the final demand for sector i's output, and

$$E_{earth} + \sum_{i=1}^{N} \epsilon_i \mathbf{P}_i = \sum_{i=1}^{N} \epsilon_i \mathbf{Y}_i \quad (\mathbf{B}\text{–}1)$$

This also shows that the energy intensity of a unit of product i sold to final demand is just ϵ_i. Extension to several kinds of energy follows easily.

This proof has ignored directly allocated imports (P_j refers only to transferred imports). To account for them, we would have to add their embodied energy to both sides of Equation (B-1).