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EMBODIED ENERGY AND ECONOMIC VALUE IN THE UNITED STATES ECONOMY: 1963, 1967 and 1972

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An economy can be said to operate on an energy theory of value if economic value can be shown to be proportional to an appropriate energy indicator. We have investigated this hypothesis for an 87 sector breakdown of the U.S. economy for the years 1963, 1967 and 1972. Input–output (I–O) models of the economy, modified to include households and government as endogenous sectors, were used to calculate each sector's direct plus indirect (embodied) energy consumption based on various estimates of the distribution of direct energy inputs to the sectors. Dollar value of sector output is highly correlated with this energy indicator (though not with direct energy consumption or with embodied energy calculated excluding labor and government energy costs). We also test explicitly the criticism that this result is merely a mathematical artifact of incorporating household and government sectors, thus making the system more 'closed'. Application of these tests to a 4-sector example implies that the mathematical artifact argument is not valid (except for a specific, limited case). Application of the tests to the full 87 sector model also indicates that the mathematical artifact argument is not valid. We conclude that embodied energy, calculated in the way we suggest, is a good predictor of economic value, at least for the relatively large aggregates of marketed goods and services that appear in I–O tables.

1. Introduction

An economy can be said to operate on an energy theory of value if economic value can be shown to be proportional to an appropriate energy indicator. One of us previously found evidence of such proportionality [Costanza (1980)], while the other challenged that result [Herendeen (1981)]. This paper represents a partial resolution of our differences.

We present further analysis of the type used in Costanza (1980), and address specifically the major remaining technical criticism raised in Herendeen (1981): that the observed proportionality is merely a mathematical artifact of the manipulation of the data. The other major technical criticism, having to do with double counting [Huettner (1982)], has already

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been disposed of [Costanza (1982)]. We find that the 'mathematical artifact argument', while holding in one limited situation, is in general invalid. This conclusion is based on empirical calculations. We have not been successful at finding a closed form proof.

The basic idea behind the analysis is: if proportionality is found to result from acceptable manipulations and computations with acceptable data, then it is a valid 'revealed' result. The major issue is that of data manipulation.

Our energy indicator is embodied energy, calculated using the energy input–output (I–O) method developed by Bullard and Herendeen (1975). This method uses the standard assumptions [linearity, constant coefficients, etc., cf. Carter and Brody (1970)] of I–O analysis, and is applied to an 87-sector breakdown of the U.S. economy for the years 1963, 1967 and 1972.

Features of this analysis are: (1) the energy costs of labor and government services are included by considering households and government to be endogenous sectors [Costanza (1980, 1982)]; (2) analysis of the mathematical artifact argument; and (3) use of two alternative measures of the distribution of direct energy inputs to the system. The first measure follows previous practice and assumes energy enters the economy only through the 'energy sectors'. The second measure assumes direct energy input occurs at the point of consumption, not the point of physical entry. The second method is more consistent with the treatment of transportation sectors in I–O analysis.

Embodied energy costs are calculated for each year and compared with the corresponding dollar value of output of the sectors. The accuracy of embodied energy as a predictor of sector dollar output is investigated. The differences between the results based on the two measures of direct energy input are interpreted, both from an empirical and a theoretical perspective.

2. Input–output methods

Any economic or ecological system can be divided into a number of interacting components or processes that consume, produce and exchange energy, organized material, information and services (or 'commodities' for

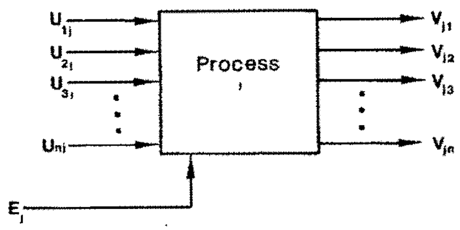

Fig. 1. Process j consumption and production relations for a specified time interval. U_{ij} is the consumption or 'use' of internally produced commodity i by process j. E_j is the use of externally produced commodities by process j. V_{ji} is the production or 'make' of commodity i by process j. 'Sector' and 'process' are synonyms.

short). Fig. 1 is a diagram of a typical process, J, which uses or consumes internally produced commodities (U_{iJ}) and externally produced commodities (E_J) in order to produce or make its output commodities (V_{Ji}). Various mathematical formulations are possible starting with this picture [cf. Ritz (1979), Carter and Brody (1970), Hannon et al. (1983), Costanza and Neill (1984)]. These approaches all share the assumptions of scale and time independent production functions. Costanza (1980) and Bullard and Herendeen (1975) did not allow for 'joint products', produced when an individual process has more than one output commodity. Our approach allows for joint products. For the purposes of this study the following formulation is employed. An embodied energy balance equation can be written for each process in the form:

$$E_J + \sum_{i=1}^{n} \varepsilon_i U_{iJ} = \sum_{i=1}^{n} \varepsilon_i V_{Ji}, \tag{1}$$

where ε_i represents the embodied energy intensity of each of the n commodities in the system and E_J represents the direct energy input to process J. It is assumed that the energy intensity for a commodity is a single number representing the average over the processes which produce it.

In matrix notation for a system with n commodities and m processes one can write:

$$\boldsymbol{E} + \boldsymbol{\varepsilon U} = \boldsymbol{\varepsilon V}^T, \quad \text{where} \tag{2}$$

$\boldsymbol{E}$ $= m$ dimensional row vector of direct energy inputs,
$\boldsymbol{U}$ $= n \times m$ matrix of the use of commodities by processes,
$\boldsymbol{V}^T = n \times m$ matrix of the production of commodities by processes,
$\boldsymbol{\varepsilon}$ $= n$ dimensional row vector of embodied energy intensities.

Given data on $\boldsymbol{U}$, $\boldsymbol{V}$ and $\boldsymbol{E}$ we wish to solve eq. 2 for the embodied energy intensity vector, $\boldsymbol{\varepsilon}$. If $m=n$ this is possible using standard matrix manipulation techniques:

$$\boldsymbol{\varepsilon} = \boldsymbol{E}(\boldsymbol{V}^T - \boldsymbol{U})^{-1} = \boldsymbol{E V}^{T-1}(\boldsymbol{I} - \boldsymbol{U V}^{T-1})^{-1}. \tag{3}$$

There are potential problems with this formulation, in that it can yield negative energy intensities. We believe (as will be pointed out) that these arise mainly as a result of deficiencies in the data, and are best handled by using preliminary runs to pinpoint problems. For example, preliminary runs on the U.S. economy produced negative intensities for three sectors (out of 88), one of which was Radio and TV broadcasting. On closer inspection it was discovered that this sector consumed all of its own output, according to the Bureau of Economic Analysis I–O data base we used. This was obviously done as an accounting convenience and does not reflect the real situation. This sector was aggregated with communications to eliminate the problem. Similar steps were taken for the other two problem sectors (business services and state and local government enterprises).

Most energy I–O modeling assumes the standard I–O accounting convention that places households and government outside the boundaries of the economic system (they are assumed to be exogenous). This accounting stance can lead to major distortions of energy cost calculations since labor and government provide services to the economy whose energy costs would be ignored. In this study we employed I–O models which included households and government as endogenous sectors (rows and columns in U and V) in order to capture their energy cost contributions. Specific methods for doing this followed Costanza (1980) and will be discussed in detail further on.

Once modified U and V matrices were formed that included households and government as endogenous sectors and 'problem' sectors were rectified, the matrix $(V^T - U)$ was inverted and energy intensities were calculated as a function of various estimates of the direct energy input vector, E. The different E vectors reflected different measures of the distribution of direct energy inputs to the economy. The resulting energy intensities were then evaluated in terms of their relationship to market prices for the sectors. Since U and V are measured in constant 1972 dollars for the economy, and direct energy inputs are in Btu's, the energy intensities have the units Btu/\$. If the energy embodied in a commodity (Btu/physical unit) is proportional to its price (\$/physical unit) then the energy intensities expressed as Btu/\$ should all be constant.

To test for this, the total energy embodied in sector inputs was regressed on dollar value of sector outputs. A high degree of correlation between these variables indicates a relatively constant energy intensity (Btu/\$) and a high correlation between embodied energy and economic value across sectors.

3. I–O data

Eighty-eight sector U and V matrices were obtained from the Energy Research Group (ERG), University of Illinois, for the years 1963, 1967 and 1972. These data were aggregated and modified from the original I–O data available through the Bureau of Economic Analysis (BEA). Staff at the ERG invested considerable time and effort making the three year's data as compatible as possible, so that valid comparisons between years could be made. As mentioned earlier, three problem sectors remained in the data and these were first eliminated by aggregation to an 85 sector model. Household and Government sectors were then added yielding revised 87 sector matrices for all three years.

Inputs to the Government and Household sectors (columns 86 and 87 of the revised U matrix) were developed from data on government expenditures (GE) and personal consumption expenditures (PCE) available as components of final demand. Inputs of government services to households ($U_{86,87}$) were estimated as personal taxes (PT) and household services to government

Table 1
Government salaries, personal taxes, and household and government gross investment for 1963, 1967 and 1972 ($\times 10^9$ 1972$).

	1963	1967	1972
Government salaries[a]	71.76	92.34	119.40
Personal taxes[a]	68.22	84.26	95.70
Household gross investment[b]	280.82	338.76	471.66
Government gross investment[b]	129.14	151.94	213.58

[a]From U.S. Bureau of the Census (1976).
[b]Values for 1963 and 1967 based on estimates in Kendrick (1976). Values for 1972 based on Eisner et al. (1981) and Kendrick (1976). See table 2.

($U_{87,86}$) as government salaries (*GS*). Values for these components for all three years are listed in table 1. 'Self sales' of households and government ($U_{86,86}$ and $U_{87,87}$) were assumed to be zero, since these values have no effect on the energy intensities. The inputs of government and household services to the other sectors (rows 86 and 87 of the revised U matrix) were estimated as indirect business taxes (*IBT*) and employee compensation (*EC*) respectively, both of which are also available in the I–O data base as components of value added. These modifications leave property type income (*PTI*) as the financial net input and gross capital formation (*GCF*), plus net inventory change (*NIC*), plus net exports (*NE*), plus estimates of household and government capital formation as the net output in financial terms. This net output will be referred to simply as revised net output (*RNO*) henceforth.

In a zero growth economy with no net exports this boundary definition would leave gross capital formation (including human and government capital formation) as the only non-zero components of *RNO*. At steady state, *RNO* is just enough to counteract depreciation, the system's tendency (by the second law of thermodynamics) to evolve toward a higher state of entropy if net energy inputs were cut off. It is worthwhile to note the magnitude of these adjustments to GNP. The ratio of *RNO* to 'normal' GNP was 63.1%, 63.8% and 75.0% in the three years, respectively.

Only two additional entries in the V matrix were required, $V_{86,86}$ and $V_{87,87}$. These represent the total output of the Government and Household sectors, respectively, exclusive of 'self-sales'. These values include estimates of gross household and government investment (capital formation), which were available in Kendrick (1976) and Eisner et al. (1981) (table 2), as well as data on *IBT*, *PT*, *EC*, and *GS*. The estimated total outputs of the government and household sectors are listed in table 3. The complete revised 87 sector U and V matrices in 1972$ for 1963, 1967 and 1972 are available from the first author on request.

Table 2

Total gross investment for 1963, 1967 and 1972 (10^9 1972\$).[a]

	Kendrick				Eisner
Year	Business	Government	Households	Total	Total
1963	115.48	129.14	280.82	525.44	512.95
% of total	21.98	24.58	53.44	—	—
1967	155.05	151.94	338.76	645.75	667.41
% of total	24.01	23.53	52.46	—	—
1972	204.68	213.58	471.66	—	889.93
% of total	23.00	24.00	53.00	—	—

[a]Kendrick (1976) provides business, government, and household components for gross investment, but his series stops at 1969. To extend the series to 1972, data on total gross investment from Eisner et al. (1981) was used. Eisner's totals agree well with Kendrick's for 1963 and 1967, but sector breakdowns were not provided. The average percent of total for each sector from the 1963 and 1967 Kendrick data was therefore used to estimate the breakdown of the Eisner total for 1972.

Table 3

Total government and household output, 1963, 1967 and 1972 (10^9 1972\$).[a]

	1963	1967	1972
Government			
Indirect business taxes (IBT)	69.32	89.14	106.94
Personal taxes (PT)	68.22	84.26	95.70
Gov't gross investment (GGI)	129.14	151.94	213.58
Government total	266.67	325.06	416.22
Households			
Employee compensation (EC)	433.40	494.21	692.35
Government salaries (GS)	71.76	92.34	119.40
H'hold gross investment (HGI)	280.82	338.76	471.66
Household total	785.98	925.31	1283.41

[a]*Source:* See tables 1 and 2.

The remaining data necessary to complete the analysis were estimates of the direct energy input from nature to the 87 sectors (*E* vectors) for each of the three years. There is considerable debate on the appropriate *E* vector for this analysis. In this analysis we used *E* vectors containing only fossil fuel, hydro and nuclear energy inputs, ignoring direct environmental energy inputs. The alternate *E* vectors used in this study for all three years are listed in table 4, along with the revised sector definitions in terms of their BEA I–O codes. Alternative 1 (DIRECT) consisted of fossil, nuclear and hydro energy

Table 4

Alternative direct energy input vectors used in this study. DIRECT assumes direct energy input at the point of physical entry into sectors, while DEC assumes direct energy consumption as the point of entry into sectors. Units are Btu per year.

No.	I–O Code	Sector name	1963 DIRECT	1963 DEC	1967 DIRECT	1967 DEC	1972 DIRECT	1972 DEC
(1)	700	Coal mining	0.12476E+17	0.11557E+14	0.14794E+17	0.12398E+14	0.14172E+17	0.19053E+14
(2)	800	Crude petro gas	0.30384E+17	0.20272E+14	0.37459E+17	0.35012E+14	0.42336E+17	0.46075E+14
(3)	3101	Petro refin. prod.	0.10654E+16	0.14101E+15	0.12523E+16	0.16994E+15	0.17309E+16	0.23470E+15
(4)	6801	Electric utilities	0.16987E+16	0.32782E+15	0.23902E+16	0.45569E+15	0.34343E+16	0.83297E+15
(5)	6802	Gas utilities	0.71640E+15	0.70079E+14	0.11730E+16	0.99366E+14	0.14512E+16	0.13315E+15
(6)	100	Livestock		0.43954E+15		0.53604E+15		0.34777E+15
(7)	200	Misc. ag. products		0.67037E+15		0.71976E+15		0.12962E+16
(8)	300	Forest, fish products		0.31733E+14		0.49352E+14		0.11743E+15
(9)	400	Ag., for., fish services		0.94095E+13		0.11610E+14		0.60442E+14
(10)	500	Iron ore mining		0.85677E+14		0.93147E+14		0.15258E+15
(11)	600	Nonferr. mining		0.86759E+14		0.80027E+14		0.14255E+15
(12)	900	Stone clay mining		0.12601E+15		0.14442E+15		0.22576E+15
(13)	1000	Chem. mineral mining		0.11624E+15		0.15588E+15		0.19545E+15
(14)	1100	New construction		0.77198E+15		0.11946E+16		0.17365E+16
(15)	1200	Maint. rep. const.		0.48258E+15		0.26876E+15		0.79916E+15
(16)	1300	Ordnance		0.49506E+14		0.11523E+15		0.86169E+14
(17)	1400	Food		0.11292E+16		0.12699E+16		0.14582E+16
(18)	1500	Tobacco		0.21757E+14		0.26066E+14		0.29803E+14
(19)	1600	Fabric and mills		0.33952E+15		0.39455E+15		0.46058E+15
(20)	1700	Textile goods		0.41723E+14		0.63472E+14		0.10627E+15
(21)	1800	Apparel		0.93899E+14		0.11505E+15		0.22885E+15
(22)	1900	Fab. textile prod.		0.10792E+14		0.29194E+14		0.33303E+14
(23)	2000	Wood products		0.15084E+15		0.27445E+15		0.44330E+15
(24)	2100	Wood containers		0.36555E+13		0.62667E+13		0.82064E+13
(25)	2200	H'hold furniture		0.37908E+14		0.39658E+14		0.63837E+14
(26)	2300	Furn., fixtures		0.19212E+14		0.24641E+14		0.46659E+14
(27)	2400	Paper products		0.12520E+16		0.14284E+16		0.17869E+16
(28)	2500	Paperboard cont.		0.48485E+14		0.78269E+14		0.11506E+15
(29)	2600	Printing, publishing		0.10252E+15		0.13806E+15		0.21809E+15

Table 4 (continued)

No.	I–O Code	Sector name	1963 DIRECT	1963 DEC	1967 DIRECT	1967 DEC	1972 DIRECT	1972 DEC
(30)	2700	Chem. products		0.37821E+16		0.38254E+16		0.43613E+16
(31)	2800	Plastics		0.46940E+15		0.68742E+15		0.94899E+15
(32)	2900	Drugs, toil. prep.		0.27175E+15		0.12015E+15		0.18503E+15
(33)	3000	Paints		0.79557E+14		0.51586E+14		0.65851E+14
(34)	3102	Paving		0.21103E+15		0.28791E+15		0.39162E+15
(35)	3103	Asphalt		0.22213E+15		0.23050E+15		0.35914E+15
(36)	3200	Rubber products		0.22514E+15		0.29330E+15		0.45013E+15
(37)	3300	Leather products		0.28141E+14		0.21437E+14		0.22528E+14
(38)	3400	Footwear		0.15926E+14		0.24162E+14		0.30726E+14
(39)	3500	Glass products		0.28714E+15		0.31809E+15		0.41369E+15
(40)	3600	Stone clay products		0.10039E+16		0.12178E+16		0.13650E+16
(41)	3700	Prim. ir., stl. manufact.		0.42033E+16		0.44632E+16		0.43979E+16
(42)	3800	Prim. nonferr. metals		0.10206E+16		0.12944E+16		0.15481E+16
(43)	3900	Metal containers		0.20246E+14		0.38784E+14		0.58753E+14
(44)	4000	Heating, plumbing		0.11421E+15		0.14649E+15		0.18674E+15
(45)	4100	Screw mach. products		0.65586E+14		0.11460E+15		0.15158E+15
(46)	4200	Fab. metal. products		0.13279E+15		0.17981E+15		0.23877E+15
(47)	4300	Engines, turbines		0.45802E+14		0.43359E+14		0.49350E+14
(48)	4400	Farm machinery		0.44383E+14		0.52192E+14		0.64680E+14
(49)	4500	Const., mining eq.		0.54005E+14		0.75505E+14		0.94025E+14
(50)	4600	Mat. handling eq.		0.10751E+14		0.15047E+14		0.24343E+14
(51)	4700	Metalworking eq.		0.50082E+14		0.73236E+14		0.91708E+14
(52)	4800	Spec. ind. mach.		0.29132E+14		0.41292E+14		0.60529E+14
(53)	4900	Gen. ind. mach.		0.67760E+14		0.79103E+14		0.10558E+15
(54)	5000	Mach. shop products		0.23945E+14		0.50987E+14		0.60141E+14
(55)	5100	Ofc. comput. mach.		0.24032E+14		0.30755E+14		0.55097E+14
(56)	5200	Service ind. mach.		0.15349E+14		0.34577E+14		0.84507E+14
(57)	5300	Elec. ind. apparat.		0.80819E+14		0.10948E+15		0.14726E+15
(58)	5400	H'hold appliance		0.53164E+14		0.63704E+14		0.73778E+14
(59)	5500	Elec. light eq.		0.27975E+14		0.43128E+14		0.62908E+14
(60)	5600	R–TV commun. eq.		0.84589E+14		0.95244E+14		0.12282E+15

(61)	5700	Electronic comp.	0.55087E+14	0.83169E+14	0.11751E+15
(62)	5800	Electrical equipment	0.21783E+14	0.31764E+14	0.46196E+14
(63)	5900	Motor veh. and eq.	0.32010E+15	0.35971E+15	0.45230E+15
(64)	6000	Aircraft and parts	0.13051E+15	0.17568E+15	0.16596E+15
(65)	6100	Transport equipment	0.53549E+14	0.66796E+14	0.99986E+14
(66)	6200	Prof. scient. supplies	0.23448E+14	0.35886E+14	0.57473E+14
(67)	6300	Optical supplies	0.37645E+14	0.28433E+14	0.61267E+14
(68)	6400	Misc. manufact.	0.66204E+14	0.60653E+14	0.12028E+15
(69)	6501	Railroad	0.74905E+15	0.68421E+15	0.81490E+15
(70)	6502	Local transport	0.30822E+15	0.23872E+15	0.23257E+15
(71)	6503	Motor fgt. transport	0.56182E+15	0.51467E+15	0.86260E+15
(72)	6504	Water transport	0.67356E+15	0.70659E+15	0.91699E+15
(73)	6505	Air transport	0.67056E+15	0.12717E+16	0.16780E+16
(74)	6506	Pipe line transport	0.14064E+15	0.14865E+15	0.16362E+15
(75)	6507+73	Tran. busnss. serv.	0.42100E+15	0.38006E+15	0.37657E+15
(76)	66+67	Communications	0.21318E+15	0.22361E+15	0.22758E+15
(77)	6803	Water sanit. serv.	0.16664E+15	0.10875E+15	0.61226E+14
(78)	6900	Whole, retail trade	0.26494E+16	0.34762E+16	0.45105E+16
(79)	7000	Finance, insurance	0.47596E+15	0.37788E+15	0.57143E+15
(80)	7100	Real estate	0.11789E+15	0.29615E+15	0.63482E+15
(81)	7200	Hotels, pers. serv.	0.29341E+15	0.61436E+15	0.62392E+15
(82)	7500	Auto repair	0.10802E+15	0.29491E+15	0.15420E+15
(83)	7600	Amusements	0.69586E+14	0.84822E+14	0.13009E+15
(84)	7700	Med., educ. services	0.81560E+15	0.13727E+16	0.15619E+16
(85)	78+79	Govt. enterprises	0.19701E+15	0.35080E+15	0.31099E+15
(86)	—	Government	0.23369E+16	0.39163E+16	0.43813E+16
(87)	—	Households	0.18993E+17	0.22037E+17	0.27140E+17

Table 5

Domestic primary fossil fuel, hydro and nuclear energy use (10^{15} Btu/yr). Prod. is gross output by sector, primary is total primary energy use based on w, which is a factor that prevents double counting, e.g., when adding crude and refined petroleum. Primary is production times w.[a]

	1963			1967			1972		
Sector	Prod.	w	Primary	Prod.	w.	Primary	Prod.	w.	Primary
(1) Coal mining	12.48	1	12.48	14.79	1	14.79	14.17	1	14.17
(2) Crude petro, gas	30.38	1	30.38	37.75	1	37.75	42.34	1	42.34
(3) Refined petro	19.86	0.054	1.07	23.19	0.054	1.25	27.56	0.063	1.73
(4) Electric util.	3.13	0.543	1.70	4.16	0.575	2.39	5.99	0.573	3.43
(5) Gas utilities	13.19	0.054	0.72	17.35	0.064	1.12	20.85	0.070	1.45
Total			46.34			57.30			63.12

[a]*Sources:* Production: Hannon and Casler (1981). w: Hannon et al. (1983).

Table 6

Weighting factors for energy types for 1963, 1967 and 1972 (Btu primary/Btu energy type delivered for use).[a]

Sector	1963	1967	1972
(1) Coal mining	1.0141	1.0116	1.0227
(2) Crude petro, gas	1.0578	1.0564	1.0601
(3) Refined petro	1.1497	1.1192	1.1487
(4) Electric util.	3.8181	3.7542	3.7714
(5) Gas utilities	1.1684	1.1515	1.1496

[a]*Source:* Hannon and Casler (1981).

into the 'primary' energy sectors (sectors 1–5). No other sectors receive energy input from nature under this alternative. Estimates for total primary energy use for the three years are derived in table 5. The weighting factor w is necessary in table 5 to avoid double counting, since most refined petroleum and natural gas utilities output is made from crude, and a large part of electricity is made from coal or crude (see Bullard and Herendeen (1975)]. Alternative 2 (DEC) uses estimates of direct fossil fuel, hydro and nuclear consumed (burned) by sector. All sectors use such energy, and the total use by sector is a weighted sum of the five fuel types used in this model. The weighting factors used were calculated previously by Hannon and Casler (1981). They reflect, for example, the primary (i.e., coal or crude) fossil energy required to produce a unit of refined petroleum (about 1.15 Btu/Btu in 1972). The weighting factors for each of the three years are given in table 6.

4. Results of I–O analysis

One question to answer at the outset is: what is a proper index of proportionality in this case? There are several possible measures of dispersion of the energy intensities that could be used to measure the 'constancy' of energy intensities across sectors, and there are several ways of regressing total dollar output on total embodied energy input across sectors to test for 'proportionality'. In the results given below, we calculate and discuss both the coefficient of variation (*COV*, equal to the standard deviation divided by the mean) of the equally-weighted entries of the energy intensity vector, and a simple linear regression (including an intercept term) of total dollar output on embodied energy input. We manipulate the regressions to determine the effects of the high magnitudes of some observations on the results.

Tables 7, 8 and 9 list the results of the I–O energy analysis for 1963, 1967 and 1972, respectively for the alternative E vectors listed in table 4. Each table lists the calculated energy intensity vector (in Btu/1972$), the total energy embodied in sector inputs (in Btu, calculated by multiplying the calculated energy intensity by total dollar input), and the dollar output from the sector (in 1972$) for each of the three years. The total dollar output was regressed on total embodied energy input both including and excluding the primary energy sectors (sectors 1–5), and the household and government sectors (sectors 86–87). The results are plotted in fig. 2, and are summarized in table 10, which lists the R^2 statistic for each alternative along with the coefficient of variation for the energy intensity vector. All regressions were significant at the 0.001 level. Fig. 2 is a log–log plot because the range of values for dollar output and embodied energy input spanned over four orders of magnitude (the regressions were run on the untransformed data). The R^2 statistic is reported both including and excluding the government and household sectors (86–87) in the regression, since these sectors are much larger than the other sectors and could unduly weight the R^2 values. R^2 values excluding these sectors are also more directly comparable with previously calculated R^2 values based on an I–O model with exogenous household and government sectors.

The results of the present analysis confirm and expand previous studies [Costanza (1980)] and generally provide evidence supportive of a strong cross-sectional relationship between embodied energy and dollar value, especially if the DEC energy input vector is used. A precondition for this conclusion is the accounting for government and household energy costs by making them endogenous sectors. Exclusion of the household and government sectors from calculation of energy intensities [the treatment used by Bullard and Herendeen (1975) and others] yields much poorer values for R^2 and *COV*, both here and in the previous study [Costanza (1980)]. While the use of endogenous household and government sectors has been criticized [Herendeen (1981), Huettner (1982)], we now feel that the criticisms are less valid based on previously published arguments [Costanza (1982)], and the tests presented in a following section.

Table 7

I–O energy analysis results for 1963. I–O code refers to the BEA sector definitions included in our 87 order sectors. Results for both direct energy input vectors listed in table 4 are given.

No.	I–O Code	Sector name	Dollar output ($1972)	DIRECT: Emb. energy intensity (Btu/$)	DIRECT: Emb. energy input (Btu)	DEC: Emb. energy intensity (Btu/$)	DEC: Emb. energy input (Btu)
(1)	700	Coal mining	0.45192E+10	0.33482E+07	0.26358E+16	0.63087E+05	0.27396E+15
(2)	800	Crude Petro, Gas	0.12704E+11	0.25680E+07	0.15021E+16	0.39437E+05	0.49192E+15
(3)	3101	Petro refin. prod.	0.21345E+11	0.15907E+07	0.31180E+17	0.57309E+05	0.14857E+16
(4)	6801	Electric utilities	0.18119E+11	0.46095E+06	0.66390E+16	0.63177E+05	0.82548E+15
(5)	6802	Gas utilities	0.12830E+11	0.80180E+06	0.95969E+16	0.48425E+05	0.56882E+15
(6)	100	Livestock	0.39909E+11	0.70934E+05	0.27976E+16	0.68612E+05	0.22717E+16
(7)	200	Misc ag. products	0.29978E+11	0.10849E+06	0.30880E+16	0.86713E+05	0.18217E+16
(8)	300	Forest, fish prod.	0.32475E+10	0.40713E+05	0.13222E+15	0.34161E+05	0.79205E+14
(9)	400	Ag., for., fish serv.	0.18513E+10	0.72427E+05	0.13371E+15	0.78750E+05	0.13588E+15
(10)	500	Iron ore mining	0.95751E+09	0.12146E+06	0.11654E+15	0.16260E+06	0.68676E+14
(11)	600	Nonferr. mining	0.17408E+10	0.87019E+05	0.15426E+15	0.13715E+06	0.15344E+15
(12)	900	Stone clay mining	0.21678E+10	0.10239E+06	0.23301E+15	0.12294E+06	0.14900E+15
(13)	1000	Chem. mineral min.	0.53601E+09	0.11531E+06	0.67799E+14	0.24915E+06	0.44278E+14
(14)	1100	New construction	0.99193E+11	0.95084E+05	0.94317E+16	0.99810E+05	0.91285E+16
(15)	1200	Maint., rep. const.	0.31773E+11	0.84607E+05	0.26882E+16	0.98678E+05	0.26527E+16
(16)	1300	Ordnance	0.62571E+10	0.82085E+05	0.51798E+15	0.92019E+05	0.53170E+15
(17)	1400	Food	0.93125E+11	0.86350E+05	0.80363E+16	0.91963E+05	0.74567E+16
(18)	1500	Tobacco	0.94895E+10	0.63627E+05	0.60399E+15	0.64834E+05	0.59328E+15
(19)	1600	Fabric and mills	0.14634E+11	0.10230E+06	0.14946E+16	0.14885E+06	0.18195E+16
(20)	1700	Textile goods	0.29788E+10	0.11397E+06	0.33650E+15	0.16321E+06	0.43986E+15
(21)	1800	Apparel	0.21328E+11	0.84969E+05	0.18113E+16	0.10629E+06	0.21695E+16
(22)	1900	Fab. textile prod.	0.26834E+10	0.98741E+05	0.26509E+15	0.12543E+06	0.32698E+15
(23)	2000	Wood products	0.15498E+11	0.70161E+05	0.10951E+16	0.74446E+05	0.10128E+16
(24)	2100	Wood containers	0.50771E+09	0.97659E+05	0.48474E+14	0.10588E+06	0.48877E+14
(25)	2200	H'hold furniture	0.50171E+10	0.88545E+05	0.44433E+15	0.10252E+06	0.47719E+15
(26)	2300	Furn., fixtures	0.22884E+10	0.98974E+05	0.22470E+15	0.11358E+06	0.23889E+15
(27)	2400	Paper products	0.13932E+11	0.13647E+06	0.18848E+16	0.20013E+06	0.15097E+16

(28)	2500	Paperboard cont.	0.53877E+10	0.11229E+06	0.60401E+15	0.13965E+06	0.70393E+15
(29)	2600	Printing, publ.	0.22277E+11	0.72120E+05	0.14813E+16	0.99252E+05	0.17472E+16
(30)	2700	Chem. products	0.15070E+11	0.14927E+06	0.22644E+16	0.41587E+06	0.21898E+16
(31)	2800	Plastics	0.48515E+10	0.15337E+06	0.72501E+15	0.32036E+06	0.10519E+16
(32)	2900	Drugs, toil, prep.	0.92067E+10	0.80633E+05	0.77944E+15	0.12806E+06	0.95747E+15
(33)	3000	Paints	0.29374E+10	0.14512E+06	0.42782E+15	0.16193E+06	0.41728E+15
(34)	3102	Paving	0.47990E+09	0.53258E+06	0.24151E+15	0.55917E+06	0.42066E+14
(35)	3103	Asphalt	0.67291E+09	0.33115E+06	0.21305E+15	0.45168E+06	0.64656E+14
(36)	3200	Rubber products	0.10258E+11	0.92649E+05	0.96175E+15	0.14142E+06	0.12365E+16
(37)	3300	Leather products	0.13717E+10	0.87659E+05	0.12010E+15	0.10520E+06	0.11607E+15
(38)	3400	Footwear	0.45717E+10	0.78989E+05	0.36151E+15	0.91168E+05	0.40189E+15
(39)	3500	Glass products	0.39034E+10	0.95633E+05	0.37249E+15	0.15867E+06	0.32766E+15
(40)	3600	Stone clay prod.	0.11844E+11	0.14695E+06	0.17163E+16	0.17774E+06	0.10711E+16
(41)	3700	Prim. ir., stl. manu.	0.31470E+11	0.20178E+06	0.62055E+16	0.25113E+06	0.35003E+16
(42)	3800	Prim. Nonferr. met.	0.17338E+11	0.93197E+05	0.16445E+16	0.16910E+06	0.18883E+16
(43)	3900	Metal containers	0.32559E+10	0.13025E+06	0.42096E+15	0.15556E+06	0.48264E+15
(44)	4000	Heating, plumbing	0.10454E+11	0.11806E+06	0.12199E+16	0.14537E+06	0.13785E+16
(45)	4100	Screw mach. prod.	0.62784E+10	0.98934E+05	0.62118E+15	0.11837E+06	0.67945E+15
(46)	4200	Fab. metal prod.	0.98429E+10	0.95259E+05	0.94597E+15	0.11961E+06	0.10492E+16
(47)	4300	Engines, turbines	0.27782E+10	0.98931E+05	0.27535E+15	0.11682E+06	0.27769E+15
(48)	4400	Farm machinery	0.37282E+10	0.10612E+06	0.39701E+15	0.12389E+06	0.41871E+15
(49)	4500	Const., mining eq.	0.51551E+10	0.98196E+05	0.50736E+15	0.11451E+06	0.53597E+15
(50)	4600	Mat. handling eq.	0.18164E+10	0.96104E+05	0.17484E+15	0.10581E+06	0.18288E+15
(51)	4700	Metal working eq.	0.59703E+10	0.90545E+05	0.55230E+15	0.96586E+05	0.54690E+15
(52)	4800	Spec. ind. mach.	0.44549E+10	0.96015E+05	0.42403E+15	0.99457E+05	0.41440E+15
(53)	4900	Gen. ind. mach.	0.60436E+10	0.98349E+05	0.59433E+15	0.10778E+06	0.59384E+15
(54)	5000	Mach. shop prod.	0.30583E+10	0.82801E+05	0.25735E+15	0.93780E+05	0.26887E+15
(55)	5100	Ofc. comput. mach.	0.38901E+10	0.75530E+05	0.29296E+15	0.84144E+05	0.30097E+15
(56)	5200	Service ind. mach.	0.31348E+10	0.10576E+06	0.32763E+15	0.12044E+06	0.35887E+15
(57)	5300	Elec. ind. apparat.	0.69020E+10	0.97717E+05	0.67844E+15	0.11143E+06	0.70247E+15
(58)	5400	H'hold appliance	0.43252E+10	0.11635E+06	0.48735E+15	0.14461E+06	0.54528E+15
(59)	5500	Elec. light eq.	0.35760E+10	0.98840E+05	0.35236E+15	0.10564E+06	0.35520E+15
(60)	5600	R–TV commun. eq.	0.12866E+11	0.84156E+05	0.10918E+16	0.94874E+05	0.11527E+16
(61)	5700	Electronic comp.	0.32643E+10	0.11613E+06	0.37029E+15	0.14826E+06	0.41406E+15
(62)	5800	Electrical equip.	0.26465E+10	0.72630E+05	0.20097E+15	0.95951E+05	0.24174E+15
(63)	5900	Motor veh. and eq.	0.48812E+11	0.10100E+06	0.49309E+16	0.12024E+06	0.55516E+16
(64)	6000	Aircraft and parts	0.17895E+11	0.84633E+05	0.15166E+16	0.93023E+05	0.15447E+16
(65)	6100	Transport equip.	0.59529E+10	0.11039E+06	0.65088E+15	0.12807E+06	0.70176E+15

Table 7 (continued)

No.	I–O Code	Sector name	Dollar output ($1972)	DIRECT Emb. energy intensity (Btu/$	DIRECT Emb. energy input (Btu)	DEC Emb. energy intensity (Btu/$)	DEC Emb. energy input (Btu)
(66)	6200	Prof., scient. supp.	0.47672E+10	0.76158E+05	0.37245E+15	0.85691E+05	0.40100E+15
(67)	6300	Optical supplies	0.25066E+10	0.78960E+05	0.19892E+15	0.11313E+06	0.24192E+15
(68)	6400	Misc. manufact.	0.77409E+10	0.87555E+05	0.67037E+15	0.10632E+06	0.74791E+15
(69)	6501	Railroad	0.13290E+11	0.11620E+06	0.15338E+16	0.13297E+06	0.10012E+16
(70)	6502	Local transport	0.60762E+10	0.11998E+06	0.72731E+15	0.10264E+06	0.31698E+15
(71)	6503	Motor fgt. transp.	0.20881E+11	0.10288E+06	0.21408E+16	0.88388E+05	0.12776E+16
(72)	6504	Water transport	0.51844E+10	0.10497E+06	0.54417E+15	0.20519E+06	0.39006E+15
(73)	6505	Air transport	0.51653E+10	0.19475E+06	0.10027E+16	0.19566E+06	0.33679E+15
(74)	6506	Pipe line transp.	0.86848E+09	0.20938E+06	0.18139E+15	0.23352E+06	0.61644E+14
(75)	6507+73	Tran. busnss. serv.	0.41016E+11	0.58045E+05	0.23767E+16	0.60623E+05	0.20536E+16
(76)	66+67	Communications	0.18463E+11	0.53738E+05	0.10068E+16	0.53487E+05	0.79926E+15
(77)	6803	Water sanit. serv.	0.18640E+10	0.97664E+05	0.18180E+15	0.13494E+06	0.84464E+14
(78)	6900	Whole, retail tr.	0.16029E+12	0.78682E+05	0.12553E+17	0.75686E+05	0.94214E+16
(79)	7000	Finance, insurance	0.53882E+11	0.69144E+05	0.36737E+16	0.72121E+05	0.33454E+16
(80)	7100	Real estate	0.97834E+11	0.36986E+05	0.36188E+16	0.31943E+05	0.30078E+16
(81)	7200	Hotels, pers. serv.	0.21192E+11	0.70594E+05	0.14829E+16	0.71663E+05	0.12108E+16
(82)	7500	Auto repair	0.15962E+11	0.66835E+05	0.10627E+16	0.62136E+05	0.87967E+15
(83)	7600	Amusements	0.11168E+11	0.63041E+05	0.69840E+15	0.65972E+05	0.66003E+15
(84)	7700	Med., educ. serv.	0.54205E+11	0.66290E+05	0.35904E+16	0.69334E+05	0.29390E+16
(85)	78+79	Govt. enterprises	0.15223E+11	0.36464E+05	0.10998E+16	0.38929E+05	0.76945E+15
(86)	—	Government	0.26667E+12	0.61572E+05	0.16419E+17	0.64401E+05	0.14837E+17
(87)	—	Households	0.78598E+12	0.78484E+05	0.61687E+17	0.78159E+05	0.42438E+17

Table 8
I–O energy analysis results for 1967. I–O code refers to the BEA sector definitions included in out 87 order sectors. Results for both direct energy input vectors listed in table 4 are given.

No.	I–O Code	Sector name	Dollar output ($1972)	DIRECT Emb. energy intensity (Btu/$)	DIRECT Emb. energy input (Btu)	DEC Emb. energy intensity (Btu/$)	DEC Emb. energy input (Btu)
(1)	700	Coal mining	0.51574E+10	0.33649E+07	0.25460E+16	0.64562E+05	0.32083E+15
(2)	800	Crude petro, gas	0.15634E+11	0.25915E+07	0.17124E+16	0.35719E+05	0.54261E+15
(3)	3101	Petro refin. prod.	0.24785E+11	0.15828E+07	0.35249E+17	0.48503E+05	0.15787E+16
(4)	6801	Electric util.	0.23380E+11	0.47244E+06	0.86409E+16	0.62285E+05	0.10074E+16
(5)	6802	Gas utilities	0.16546E+11	0.79260E+06	0.11964E+17	0.40677E+05	0.59398E+15
(6)	100	Livestock	0.40270E+11	0.71002E+05	0.28273E+16	0.76724E+05	0.25093E+16
(7)	200	Misc. ag. products	0.31625E+11	0.10131E+06	0.30801E+16	0.92440E+05	0.20960E+16
(8)	300	Forest, fish prod.	0.24560E+10	0.44682E+05	0.10971E+15	0.43337E+05	0.57043E+14
(9)	400	Ag., for., fish serv.	0.27762E+10	0.53711E+05	0.14881E+15	0.58709E+05	0.15089E+15
(10)	500	Iron ore mining	0.11899E+10	0.96058E+05	0.11417E+15	0.15435E+06	0.90050E+14
(11)	600	Nonferr. mining	0.14700E+10	0.94792E+05	0.13913E+15	0.14548E+06	0.13322E+15
(12)	900	Stone clay min.	0.24875E+10	0.12169E+06	0.30784E+15	0.12349E+06	0.16793E+15
(13)	1000	Chem. mineral min.	0.75400E+09	0.91931E+05	0.76674E+14	0.26672E+06	0.55304E+14
(14)	1100	New construction	0.10943E+12	0.93495E+05	0.10231E+17	0.10278E+06	0.10052E+17
(15)	1200	Maint., rep. const.	0.32933E+11	0.89000E+05	0.29310E+16	0.96067E+05	0.28950E+16
(16)	1300	Ordnance	0.11058E+11	0.89455E+05	0.98754E+15	0.10544E+06	0.10436E+16
(17)	1400	Food	0.10418E+12	0.85253E+05	0.88694E+16	0.94688E+05	0.85897E+16
(18)	1500	Tobacco	0.94198E+10	0.67196E+05	0.63303E+15	0.71669E+05	0.64888E+15
(19)	1600	Fabric and mills	0.17469E+11	0.94944E+05	0.16529E+16	0.14047E+06	0.20342E+16
(20)	1700	Textile goods	0.41112E+10	0.96984E+05	0.39678E+15	0.14448E+06	0.52646E+15
(21)	1800	Apparel	0.25402E+11	0.83963E+05	0.21298E+16	0.10517E+06	0.25504E+16
(22)	1900	Fab. textile prod.	0.36096E+10	0.89649E+05	0.32411E+15	0.11629E+06	0.39206E+15
(23)	2000	Wood products	0.17440E+11	0.76547E+05	0.13394E+16	0.82897E+05	0.11792E+16
(24)	2100	Wood containers	0.65619E+09	0.78856E+05	0.51646E+14	0.86202E+05	0.50165E+14
(25)	2200	H'hold furniture	0.58430E+10	0.85940E+05	0.50240E+15	0.97078E+05	0.52876E+15
(26)	2300	Furn., fixtures	0.30734E+10	0.92535E+05	0.28422E+15	0.10282E+06	0.29172E+15
(27)	2400	Paper products	0.16666E+11	0.12518E+06	0.20607E+16	0.19344E+06	0.17429E+16
(28)	2500	Paperboard cont.	0.67423E+10	0.10483E+06	0.70571E+15	0.13894E+06	0.85535E+15

Table 8 (continued)

No.	I–O Code	Sector name	Dollar output ($1972)	DIRECT Emb. energy intensity (Btu/$	DIRECT Emb. energy input (Btu)	DEC Emb. energy intensity (Btu/$)	DEC Emb. energy input (Btu)
(29)	2600	Printing, publ.	0.27299E+11	0.63553E+05	0.16741E+16	0.90160E+05	0.19956E+16
(30)	2700	Chem. products	0.19596E+11	0.13388E+06	0.26890E+16	0.34706E+06	0.26699E+16
(31)	2800	Plastics	0.69912E+10	0.13876E+06	0.95225E+15	0.28107E+06	0.12454E+16
(32)	2900	Drugs, toil. prep.	0.12466E+11	0.74873E+05	0.98012E+15	0.99608E+05	0.11882E+16
(33)	3000	Paints	0.33135E+10	0.10702E+06	0.35560E+15	0.14830E+06	0.45119E+15
(34)	3102	Paving	0.68071E+09	0.42451E+06	0.27284E+15	0.52987E+06	0.54190E+14
(35)	3103	Asphalt	0.73172E+09	0.25845E+06	0.18563E+15	0.42060E+06	0.61599E+14
(36)	3200	Rubber Products	0.14002E+11	0.89194E+05	0.12554E+16	0.13313E+06	0.15710E+16
(37)	3300	Leather products	0.14014E+10	0.80810E+05	0.11337E+15	0.96380E+05	0.11381E+15
(38)	3400	Footwear	0.50479E+10	0.79040E+05	0.39933E+15	0.91822E+05	0.44006E+15
(39)	3500	Glass products	0.47454E+10	0.90319E+05	0.42790E+15	0.14439E+06	0.36331E+15
(40)	3600	Stone clay prod.	0.13149E+11	0 12918E+06	0.16862E+16	0.18570E+06	0.11874E+16
(41)	3700	Prim. ir., stl. manu.	0.37787E+11	0.21405E+06	0.78418E+16	0.23206E+06	0.40587E+16
(42)	3800	Prim. nonferr. met.	0.20903E+11	0.90525E+05	0.19348E+16	0.17533E+06	0.23364E+16
(43)	3900	Metal containers	0.41825E+10	0.13094E+06	0.52817E+15	0.14682E+06	0.56090E+15
(44)	4000	Heating plumbing	0.13860E+11	0.11904E+06	0.16304E+16	0.13602E+06	0.17147E+16
(45)	4100	Screw mach. prod.	0.10697E+11	0.11123E+06	0.11765E+16	0.12507E+06	0.12097E+16
(46)	4200	Fab. metal prod.	0.12700E+11	0.95600E+05	0.12176E+16	0.11235E+06	0.12514E+16
(47)	4300	Engines, turbines	0.38923E+10	0.10116E+06	0.39351E+15	0.11150E+06	0.38985E+15
(48)	4400	Farm machinery	0.51897E+10	0.10551E+06	0.54770E+15	0.11603E+06	0.54951E+15
(49)	4500	Const., Mining eq.	0.69695E+10	0.10158E+06	0.70487E+15	0.10940E+06	0.68531E+15
(58)	4600	Mat. handling eq.	0.27344E+10	0.96807E+05	0.26395E+15	0.10412E+06	0.26949E+15
(51)	4700	Metalworking eq.	0.87130E+10	0.93225E+05	0.81896E+15	0.94872E+05	0.76819E+15
(52)	4800	Spec. ind. mach.	0.61370E+10	0.93093E+05	0.56649E+15	0.95897E+05	0.54928E+15
(53)	4900	Gen. ind. mach.	0.82119E+10	0.97053E+05	0.79875E+15	0.10453E+06	0.78657E+15
(54)	5000	Mach. shop prod.	0.50452E+10	0.94660E+05	0.47795E+15	0.90373E+05	0.41062E+15
(55)	5100	Ofc. comput. mach.	0.61726E+10	0.79552E+05	0.48305E+15	0.88986E+05	0.50803E+15
(56)	5200	Service ind. mach.	0.47235E+10	0.94739E+05	0.44937E+15	0.11019E+06	0.48639E+15
(57)	5300	Elec. ind. apparat.	0.97929E+10	0.95199E+05	0.92460E+15	0.10663E+06	0.93304E+15

(58)	5400	H'hold appliance	0.55475E+10	0.10094E+06	0.55317E+15	0.12188E+06	0.59980E+15
(59)	5500	Elec. light eq.	0.44630E+10	0.81863E+05	0.37052E+15	0.98723E+05	0.40352E+15
(60)	5600	R-TV commun. eq.	0.17860E+11	0.75700E+05	0.13676E+16	0.84884E+05	0.14429E+16
(61)	5700	Electronic comp.	0.70304E+10	0.95567E+05	0.65919E+15	0.11964E+06	0.73469E+15
(62)	5800	Electrical equip.	0.33222E+10	0.76134E+05	0.26054E+15	0.99505E+05	0.30860E+15
(63)	5900	Motor veh. and eq.	0.50531E+11	0.98568E+05	0.49888E+16	0.11167E+06	0.52922E+16
(64)	6000	Aircraft and parts	0.25355E+11	0.88363E+05	0.22422E+16	0.92609E+05	0.21948E+16
(65)	6100	Transport equip.	0.91262E+10	0.10358E+06	0.94193E+15	0.11562E+06	0.98377E+15
(66)	6200	Prof. scient. supp.	0.62214E+10	0.78362E+05	0.49372E+15	0.88470E+05	0.52386E+15
(67)	6300	Optical supplies	0.44417E+10	0.63995E+05	0.29171E+15	0.88226E+05	0.36673E+15
(68)	6400	Misc. manufact.	0.95030E+10	0.83480E+05	0.78296E+15	0.97971E+05	0.86005E+15
(69)	6501	Railroad	0.15829E+11	0.10838E+06	0.16642E+16	0.11586E+06	0.10858E+16
(70)	6502	Local transport	0.60168E+10	0.91023E+05	0.54694E+15	0.92953E+05	0.32009E+15
(71)	6503	Motor fgt. transp.	0.24930E+11	0.11922E+06	0.29615E+16	0.84520E+05	0.15856E+16
(72)	6504	Water transport	0.54772E+10	0.12468E+06	0.67912E+15	0.22274E+06	0.50519E+15
(73)	6505	Air transport	0.99192E+10	0.16093E+06	0.15923E+16	0.19190E+06	0.62647E+15
(74)	6506	Pipe line transp.	0.12297E+10	0.19262E+06	0.23638E+15	0.19072E+06	0.85387E+14
(75)	6507+73	Tran. busnss. serv.	0.56911E+11	0.57173E+05	0.32494E+16	0.61166E+05	0.30831E+16
(76)	66+67	Communications	0.25239E+11	0.50929E+05	0.13110E+16	0.53733E+05	0.11623E+16
(77)	6803	Water sanit. serv.	0.19664E+10	0.81045E+05	0.15910E+15	0.97541E+05	0.82646E+14
(78)	6900	Whole, retail tr.	0.19587E+12	0.78347E+05	0.15274E+17	0.80762E+05	0.12257E+17
(79)	7000	Finance, insurance	0.64810E+11	0.66035E+05	0.42150E+16	0.70166E+05	0.40825E+16
(80)	7100	Real estate	0.12185E+12	0.37161E+05	0.45281E+16	0.31341E+05	0.35228E+16
(81)	7200	Hotels, pers. serv.	0.25535E+11	0.79694E+05	0.20009E+16	0.85126E+05	0.15176E+16
(82)	7500	Auto repair	0.19938E+11	0.72487E+05	0.14410E+16	0.75280E+05	0.12007E+16
(83)	7600	Amusements	0.11993E+11	0.65174E+05	0.77281E+15	0.69126E+05	0.73289E+15
(84)	7700	Med., educ. serv.	0.65499E+11	0.73980E+05	0.48421E+16	0.80598E+05	0.39017E+16
(85)	78+79	Govt. enterprises	0.18544E+11	0.36668E+05	0.12946E+16	0.59465E+05	0.94593E+15
(86)	—	Government	0.32506E+12	0.65952E+05	0.21438E+17	0.71659E+05	0.19377E+17
(87)	—	Households	0.92531E+12	0.79136E+05	0.73226E+17	0.79741E+05	0.51748E+17

Table 9

I–O energy analysis results for 1972. I–O code refers to the BEA sector definitions included in our 87 order sectors. Results for both direct energy input vectors listed in table 4 are given.

				DIRECT		DEC	
No.	I–O Code	Sector name	Dollar output ($1972)	Emb. energy intensity (Btu/$)	Emb. energy input (Btu)	Emb. energy intensity (Btu/$)	Emb. energy input (Btu)
(1)	700	Coal mining	0.54424E+10	0.30608E+07	0.24739E+16	0.69555E+05	0.35977E+15
(2)	800	Crude petro, gas	0.17819E+11	0.25791E+07	0.23035E+16	0.35763E+05	0.61237E+15
(3)	3101	Petro refin. prod.	0.29581E+11	0.16047E+07	0.43304E+17	0.57363E+05	0.18744E+16
(4)	6801	Electric util.	0.31665E+11	0.56190E+06	0.14336E+17	0.70907E+05	0.16013E+16
(5)	6802	Gas utilities	0.20138E+11	0.89265E+06	0.16526E+17	0.46244E+05	0.81828E+15
(6)	100	Livestock	0.43339E+11	0.76938E+05	0.33577E+16	0.78979E+05	0.31169E+16
(7)	200	Misc. ag. products	0.35080E+11	0.84628E+05	0.29846E+16	0.95657E+05	0.20657E+16
(8)	300	Forest., fish prod.	0.19705E+10	0.89878E+05	0.17710E+15	0.11603E+06	0.11120E+15
(9)	400	Ag., for., fish serv.	0.35657E+10	0.11432E+06	0.40732E+15	0.10110E+06	0.29998E+15
(10)	500	Iron ore mining	0.12325E+10	0.12528E+06	0.15425E+15	0.19404E+06	0.86259E+14
(11)	600	Nonferr. mining	0.22700E+10	0.94867E+05	0.21743E+15	0.13463E+06	0.16709E+15
(12)	900	Stone clay min.	0.28471E+10	0.11979E+06	0.36057E+15	0.13700E+06	0.18466E+15
(13)	1000	Chem. mineral min.	0.77460E+09	0.13102E+06	0.10612E+15	0.32819E+06	0.50899E+14
(14)	1100	New construction	0.12958E+12	0.97375E+05	0.12618E+17	0.10996E+06	0.12513E+17
(15)	1200	Maint. rep. const.	0.36417E+11	0.10117E+06	0.36843E+16	0.11196E+06	0.32780E+16
(16)	1300	Ordnance	0.70841E+10	0.93187E+05	0.66035E+15	0.10010E+06	0.62904E+15
(17)	1400	Food	0.11830E+12	0.82543E+05	0.97809E+16	0.93817E+05	0.96640E+16
(18)	1500	Tobacco	0.92269E+10	0.61078E+05	0.56356E+15	0.66434E+05	0.58318E+15
(19)	1600	Fabric and mills	0.17632E+11	0.10556E+06	0.18508E+16	0.15881E+06	0.23013E+16
(20)	1700	Textile goods	0.59584E+10	0.10304E+06	0.61396E+15	0.14847E+06	0.77802E+15
(21)	1800	Apparel	0.30183E+11	0.90078E+05	0.27220E+16	0.11295E+06	0.31890E+16
(22)	1900	Fab. textile prod.	0.49226E+10	0.95506E+05	0.47190E+15	0.12081E+06	0.56762E+15
(23)	2000	Wood products	0.21511E+11	0.10921E+06	0.23495E+16	0.10523E+06	0.18274E+16
(24)	2100	Wood containers	0.46570E+09	0.10373E+06	0.48469E+14	0.11040E+06	0.43175E+14
(25)	2200	H'hold furniture	0.72816E+10	0.91088E+05	0.66507E+15	0.10152E+06	0.67988E+15
(26)	2300	Furn., fixtures	0.37275E+10	0.99734E+05	0.37128E+15	0.11273E+06	0.37401E+15
(27)	2400	Paper products	0.19833E+11	0.13485E+06	0.26414E+16	0.19738E+06	0.20739E+16
(28)	2500	Paperboard cont.	0.79097E+10	0.11350E+06	0.89645E+15	0.14349E+06	0.10201E+16

(29)	2600	Printing, publ.	0.29635E+11	0.66760E+05	0.20634E+16	0.99577E+05	0.23375E+16
(30)	2700	Chem. products	0.24041E+11	0.14883E+06	0.36042E+16	0.31147E+06	0.29066E+16
(31)	2800	Plastics	0.96840E+10	0.13690E+06	0.12981E+16	0.25998E+06	0.14891E+16
(32)	2900	Drugs, toil. prep.	0.17228E+11	0.78111E+05	0.14007E+16	0.89680E+05	0.14551E+16
(33)	3000	Paints	0.36101E+10	0.11988E+06	0.43596E+15	0.15717E+06	0.51958E+15
(34)	3102	Paving	0.90260E+09	0.49398E+06	0.42526E+15	0.54128E+06	0.76830E+14
(35)	3103	Asphalt	0.94700E+09	0.33993E+06	0.33095E+15	0.49245E+06	0.88694E+14
(36)	3200	Rubber products	0.20648E+11	0.94741E+05	0.19762E+16	0.13244E+06	0.23236E+16
(37)	3300	Leather products	0.10524E+10	0.98537E+05	0.10363E+15	0.12340E+06	0.10726E+15
(38)	3400	Footwear	0.45291E+10	0.86354E+05	0.39160E+15	0.10133E+06	0.42949E+15
(39)	3500	Glass products	0.55834E+10	0.10568E+06	0.58988E+15	0.15913E+06	0.47392E+15
(40)	3600	Stone clay prod.	0.15267E+11	0.13260E+06	0.20283E+16	0.18380E+06	0.14353E+16
(41)	3700	Prim. ir., stl. manuf.	0.36440E+11	0.19237E+06	0.68477E+16	0.24561E+06	0.43238E+16
(42)	3800	Prim. nonferr. met.	0.23874E+11	0.10709E+06	0.25788E+16	0.19467E+06	0.30697E+16
(43)	3900	Metal containers	0.48236E+10	0.12594E+06	0.60382E+15	0.16010E+06	0.70933E+15
(44)	4000	Heating, plumbing	0.15304E+11	0.11467E+06	0.17484E+16	0.13787E+06	0.19174E+16
(45)	4100	Screw mach. prod.	0.11135E+11	0.11566E+06	0.12766E+16	0.13942E+06	0.13839E+16
(46)	4200	Fab. metal prod.	0.14141E+11	0.10223E+06	0.14483E+16	0.12486E+06	0.15265E+16
(47)	4300	Engines, turbines	0.54095E+10	0.97906E+05	0.53047E+15	0.11380E+06	0.56789E+15
(48)	4400	Farm machinery	0.55662E+10	0.92672E+05	0.52504E+15	0.10770E+06	0.54721E+15
(49)	4500	Const., mining eq.	0.78886E+10	0.95367E+05	0.76050E+15	0.10937E+06	0.78055E+15
(50)	4600	Mat. handling. eq.	0.28090E+10	0.98438E+05	0.27679E+15	0.11012E+06	0.28584E+15
(51)	4700	Metalworking eq.	0.71480E+10	0.96626E+05	0.70102E+15	0.10010E+06	0.64497E+15
(52)	4800	Spec. ind. mach.	0.58633E+10	0.95709E+05	0.56651E+15	0.10375E+06	0.55945E+15
(53)	4900	Gen. ind. mach.	0.81320E+10	0.10447E+06	0.84541E+15	0.11067E+06	0.80321E+15
(54)	5000	Mach. shop prod.	0.44433E+10	0.10850E+06	0.48114E+15	0.10450E+06	0.41001E+15
(55)	5100	Ofc. comput. mach.	0.80508E+10	0.76523E+05	0.62702E+15	0.84903E+05	0.64663E+15
(56)	5200	Service ind. mach.	0.84954E+10	0.90200E+05	0.76970E+15	0.10334E+06	0.80278E+15
(57)	5300	Elec. ind. apparat.	0.10392E+11	0.95838E+05	0.99378E+15	0.11107E+06	0.10096E+16
(58)	5400	H'hold appliance	0.66589E+10	0.88272E+05	0.59249E+15	0.11020E+06	0.66218E+15
(59)	5500	Elec. light eq.	0.55221E+10	0.81844E+05	0.46823E+15	0.10078E+06	0.51565E+15
(60)	5600	R–TV commun. eq.	0.17950E+11	0.80753E+05	0.14589E+16	0.91074E+05	0.15286E+16
(61)	5700	Electronic comp.	0.83929E+10	0.88982E+05	0.74143E+15	0.10832E+06	0.78013E+15
(62)	5800	Electrical equip.	0.42767E+10	0.81532E+05	0.35898E+15	0.10419E+06	0.41254E+15
(63)	5900	Motor veh. and eq.	0.65080E+11	0.90038E+05	0.58900E+16	0.10616E+06	0.64995E+16
(64)	6000	Aircraft and parts	0.17021E+11	0.90362E+05	0.15429E+16	0.98020E+05	0.15118E+16
(65)	6100	Transport equip.	0.12763E+11	0.99941E+05	0.12764E+16	0.11448E+06	0.13630E+16
(66)	6200	Prof. scient. supp.	0.69807E+10	0.83314E+05	0.58633E+15	0.90597E+05	0.58678E+15

Table 9 (continued)

No.	I–O Code	Sector name	Dollar output ($1972)	DIRECT Emb. energy intensity (Btu/$)	DIRECT Emb. energy input (Btu)	DEC Emb. energy intensity (Btu/$)	DEC Emb. energy input (Btu)
(67)	6300	Optical supplies	0.65269E+10	0.69182E+05	0.45995E+15	0.81939E+05	0.48720E+15
(68)	6400	Misc. manufact.	0.11979E+11	0.93679E+05	0.11121E+16	0.10652E+06	0.11485E+16
(69)	6501	Railroad	0.15067E+11	0.10987E+06	0.16607E+16	0.12441E+06	0.10647E+16
(70)	6502	Local transport	0.74063E+10	0.13874E+06	0.10232E+16	0.95782E+05	0.47643E+15
(71)	6503	Motor fgt transp.	0.29993E+11	0.10629E+06	0.31862E+16	0.90985E+05	0.18652E+16
(72)	6504	Water transport	0.73075E+10	0.15265E+06	0.10977E+16	0.24494E+06	0.83384E+15
(73)	6505	Air transport	0.13134E+11	0.16748E+06	0.21983E+16	0.19162E+06	0.83686E+15
(74)	6506	Pipe line transp.	0.16167E+10	0.16596E+06	0.26829E+15	0.16157E+06	0.97559E+14
(75)	6507+73	Tran. busnss. serv.	0.70346E+11	0.72104E+05	0.50988E+16	0.67547E+05	0.44079E+16
(76)	66+67	Communications	0.36078E+11	0.43236E+05	0.17161E+16	0.47483E+05	0.15946E+16
(77)	6803	Water sanit. ser.	0.25822E+10	0.95565E+05	0.24677E+15	0.98433E+05	0.19295E+15
(78)	6900	Whole. retail tr.	0.26493E+12	0.77371E+05	0.20498E+17	0.79248E+05	0.16485E+17
(79)	7000	Finance, insurance	0.77886E+11	0.65656E+05	0.51122E+16	0.67301E+05	0.46664E+16
(80)	7100	Real estate	0.17458E+12	0.32605E+05	0.56923E+16	0.31021E+05	0.47807E+16
(81)	7200	Hotels, pers. serv.	0.30504E+11	0.86630E+05	0.26303E+16	0.82911E+05	0.18934E+16
(82)	7500	Auto repair	0.24340E+11	0.79060E+05	0.19243E+16	0.77333E+05	0.17281E+16
(83)	7600	Amusements	0.12745E+11	0.73535E+05	0.93693E+15	0.75976E+05	0.83663E+15
(84)	7700	Med., educ. serv.	0.84900E+11	0.77769E+05	0.66026E+16	0.79814E+05	0.52143E+16
(85)	78+79	Govt. enterprises	0.18919E+11	0.41237E+05	0.15300E+16	0.57458E+05	0.10576E+16
(86)	—	Government	0.41622E+12	0.55567E+05	0.23128E+17	0.58533E+05	0.19981E+17
(87)	—	Households	0.12834E+13	0.71033E+05	0.91163E+17	0.69804E+05	0.62447E+17

Table 10

Summary statistics for embodied energy estimates calculated using the alternative direct energy input vectors shown in table 4. R^2 estimates are for a linear regression of dollar output by sector on embodied energy input (see tables 7–9 for listings of these series and fig. 2 for plots). All R^2 values are significant at the 0.001 level. Coefficient of variation (*COV*) estimates are for the embodied energy intensity vectors listed in tables 7–9.

Year	Sectors included in statistics	DIRECT		DEC	
		R^2	*COV*	R^2	*COV*
1963	1–87	0.800	2.35	0.981	0.67
	6–87	0.986	0.69	0.981	0.67
	1–85	0.239	2.34	0.858	0.67
	6–85	0.884	0.69	0.858	0.67
1967	1–87	0.814	2.43	0.984	0.64
	6–87	0.987	0.69	0.984	0.64
	1–85	0.251	2.42	0.866	0.64
	6–85	0.873	0.69	0.866	0.64
1972	1–87	0.805	2.25	0.978	0.64
	6–87	0.986	0.61	0.978	0.64
	1–85	0.247	2.24	0.851	0.64
	6–85	0.876	0.61	0.851	0.64

The present study also indicates the relative merits (as a predictor of market value) of calculations of embodied energy based on alternative treatments of the direct energy input vector, ***E***. We also find that the results for the three different years are very similar, indicating a stable pattern over the time interval of the data.

Comparison of the various alternatives in table 10 brings out some interesting points. The R^2 values for alternative 1, (DIRECT) including only sectors 6–87 or 6–85 in the regression, are much higher than with the primary energy sectors (1–5) included, and are very close to those for alternative 2 (DEC) with or without the primary energy sectors. Alternative 1 represents direct energy input to the economy (specifically to the primary energy sectors) while alternative 2 represents consumption of that energy distributed through the economy. Distribution is the key word here, since this is the major difference between the two alternatives. The primary energy sectors distribute energy to the rest of the economy, and if this distribution function is factored out by excluding the primary energy sectors from the regression or by predistributing the energy by looking at consumption rather than production (i.e., alternative 2), then higher correlations result. The degree of departure of the energy sectors from the regression line in alternative 1 (fig. 2) can thus be viewed as a measure of the net energy input to the system.

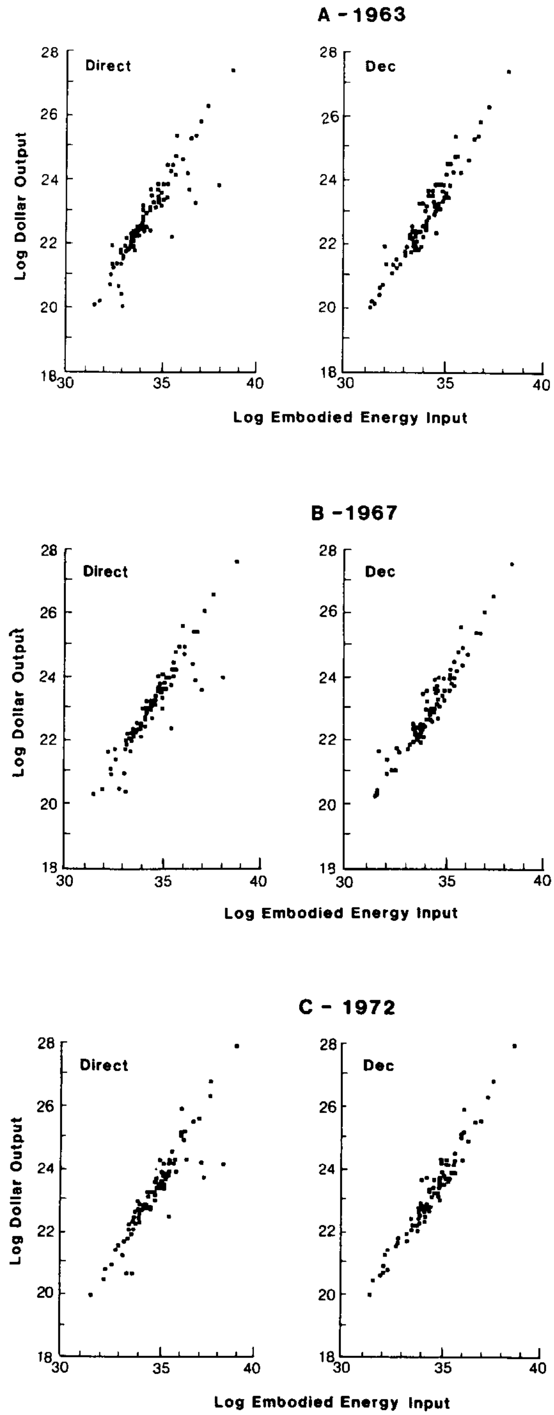

Fig. 2. Log–log plots of embodied energy inputs vs. dollar output for the 87 sector data, for three years and two alternative direct energy input vectors.

The primary energy sectors functions are like the transportation sectors, which alse require special treatment in I–O analysis based on the difference between the services they provide and their physical inputs and outputs. If a strictly physical interpretation were applied to the transportation sectors, they would receive almost all goods produced in the whole economy as inputs and redistribute them as output, masking information on transfers of goods between sectors. For this reason, the transportation sectors in I–O analysis are thought of as providing transportation services that are purchased by the producing sector, preserving the connection between the producing and consuming sector but adding a 'transportation margin'. For analogous reasons, the primary energy sectors should be thought of as providing a 'transportation service' in moving primary energy from nature to the consuming sectors. The DEC energy input vector incorporates this interpretation.

In a previous article [Herendeen (1981)] it was shown that the necessary and sufficient conditions for constant energy intensities in an I–O analysis are that the direct energy input vector be proportional to the dollar value of net input (the remaining components of value added). With the boundaries and approximations used in this study, the dollar value of net input is equal to property type income (*PTI*), and there is, in fact a relatively high correlation between *PTI* and direct energy consumption (DEC) across sectors. This explains the relatively constant energy intensities calculated for alternative 2. For alternative 1, however, this correlation is very low, since only the energy sectors (1–5) have direct energy inputs under this alternative. The energy intensities are still relatively constant, however, except for the energy sectors (1–5). The distributive function of the energy sectors is responsible for this phenomenon. In the appendix we prove that if and only if the sum of the energy rows (1–5 in our case) of U is proportional to net dollar input (PTI in our case) then ε is constant except for the energy sectors.

5. The effects of adding labor and government sectors: The mathematical artifact argument

Several critics of this approach have argued that closing the input–output matrix as we do here must inevitably lead to a reduction in the variance of the energy intensities, or, in the terms of this paper, an inevitably high correlation between economic value and embodied energy [Herendeen (1981), Huettner (1982), Reister (personal comment)]. (This is not worrisome, of course, if inclusion of the household and government sectors is uncontroversial.) In this section we present the mathematical artifact argument in some detail, establish several theorems which aim in the right direction, and finally present results of some empirical tests.

The manipulations we have performed 'close' the matrix by converting two parts of final demand to producing sectors whose outputs (labor and government services), previously a part of value added, are now listed as a consumed input by all sectors. The rank of the I–O matrix is increased by two, while the 'closedness' increases. We define closedness as

$$1-\left(\sum_{i=1}^{n} Y_i \Big/ \sum_{i=1}^{n} X_i\right), \tag{4}$$

where

Y_i = net output of sector i,
X_i = gross output of sector i.

Closedness thus varies between 0 (possible only for a trivial one-sector system) and 1 (for a system with no net output at all).

The new inputs (labor and government services) tend to be fairly large fractions of all inputs, and are non-zero for almost every sector. Therefore one suspects a homogenizing effect on the energy intensities (ε's), which has been stated thus [Herendeen (1981, p. 671)]:

> 'The intuitive argument that inclusion of labor and government as producing as well as consuming sectors ought to force the ε's in the direction of a common value is this: every economic sector pays wages (and practically every one pays taxes), and these expenditures are a large fraction of the expenditures for all inputs. (Labor costs are typically 30%–50% of the total, Bureau of Economic Analysis, 1980). Thus the inclusion of labor requires every sector to have a large input flow from the same sector. Referring to fig. 1, we see that the reason that the ε's can be different is that each sector can, in principle, have a different input mix. Inclusion of the (necessarily large) labor input to all sectors reduces that possibility.'

To demonstrate this argument, we will use the 4×4 example shown in table 11. In the language of table 11, we ask what happens to the coefficient of variation (standard deviation divided by the mean) of ε_1, ε_2, and ε_3 as L_1, L_2, and L_3 increase from zero up to their maximum allowable values, equal to total value added before the inclusion of labor. In this example we make endogenous only one sector (labor), vs. two (labor and government) in the actual data, since this simplifies the discussion and does not cause any loss of generality. The inputs to the labor sector (personal consumption) expand in such a way that their total just equals the production of labor. For discussion, we will use the normalized labor ($\boldsymbol{l}=\boldsymbol{L}\boldsymbol{V}^{T-1}$) and energy input ($\boldsymbol{e}=\boldsymbol{E}\boldsymbol{V}^{T-1}$) vectors. We can test the following hypotheses:

Hypothesis 1 (*the 'strong hypothesis'*). Starting with $l_1=l_2=l_3=0$, use of any admissable positive l_i will always decrease the coefficient of variation of the 3 ε's. We will call the coefficient of variation of the ε's '*COVE*'. Thus *COVE3* is the coefficient of variation of the 3 ε's in our example.

Table 11
Example 4×4 input–output table. All units are dollars except for the direct energy inputs, which are Btu's.

Sector	1	2	3	Personal consumption (PC)	Net output	Total output
1	1	1	2	$0.3(L_1+L_2+L_3)$	$6-(PC_1)$	10
2	1	2	1	$0.4(L_1+L_2+L_3)$	$6-(PC_2)$	10
3	1	3	1	$0.3(L_1+L_2+L_3)$	$5-(PC_3)$	10
Wages	L_1	L_2	L_3	0	0	$L_1+L_2+L_3$
Profits	$7-L_1$	$4-L_2$	$6-L_3$	0	0	$17-(L_1+L_2+L_3)$
Energy	E_1	E_2	E_3	E_4		

For above: ($l=L/10$, $G=UV^{T-1}\Lambda$ $e=EV^{T-1}$)

$I-G$	=	0.9	−0.1	−0.2	−0.3
		−0.1	0.8	−0.1	−0.4
		−0.1	−0.3	0.9	−0.3
		l_1	l_2	l_3	1
e	=	$0.1E_1$	$0.1E_2$	$0.1E_3$	$0.1E_4$

Table 12
Coefficient of variation of the first three epsilons (*COVE 3*) for various combinations of the normalized direct energy input vector (e) and the normalized labor vector (l). See table 11 for details.

Labor input l_1 l_2 l_3 l_4	Closed-ness	Normalized energy input ($e=EV^{T-1}$) (1111)	(1000)	(0100)	(0010)	Proportional to 1st row of G
(1) *No labor* 0 0 0 0	0.43	0.1300	0.7425	0.9688	0.6886	0.2066
(2) *'Actual'* 0.5 0.2 0.2 0	0.79	0.1043	0.4573	0.4189	0.2516	0.0744
(3) *Prop. to VA* 0.37 0.21 0.32 0	0.79	0.0458	0.3600	0.4251	0.3282	0.0582
(4) *Constant* 0.3 0.3 0.3 0	0.79	0.1300	0.3108	0.4929	0.3349	0.1320
(5) *Mirror image* 0.1 0.4 0.4 0	0.79	0.2927	0.1663	0.5975	0.4500	0.3272

Conclusion 1. This hypothesis is false by counter-example. In table 12 we see that it is violated for $e=(1, 1, 1, 1)$, and $l=(0.1, 0.4, 0.4, 0)$. However, from table 12 the hypothesis appears true for the restricted case of e having just one non-zero element and also not satisfying Hypothesis 3 below.

Hypothesis 2. Use of a labor vector $\boldsymbol{l}$ such that normalized profits are proportional to $\boldsymbol{e}$, results in $COVE3=0$.

Conclusion 2. This hypothesis is true in general, and was proved previously [Herendeen (1981)].

Hypothesis 3. Use of any $\boldsymbol{l}$ whose first three entries are proportional to the first three entries of $\boldsymbol{e}$ results in the same value for $COVE3$.

Conclusion 3. This hypothesis is true in general, and is proved in the appendix.

Hypothesis 4. By examining certain values from $G(=UV^{T-1})$, $\boldsymbol{l}$, and $\boldsymbol{e}$ it is possible to predict when $COVE3$ will decrease without actually calculating it.

Conclusion 4. This hypothesis is as yet unproven.

Hypothesis 5 (the 'weak hypothesis'). While it can be shown by hypothesis 1–3 above that $COVE3$ can be reduced to zero, remain unchanged, or increase on the addition of some positive $\boldsymbol{l}$, and while Hypothesis 4 is unproven, it is still true that for a wide class of reasonable $\boldsymbol{l}$ it will very likely decrease.

Conclusion 5. This is the strongest statement that can now be made of the mathematical artifact argument, and is obviously sensitive to the definitions of 'wide class', 'very likely', and 'reasonable $\boldsymbol{l}$'. At this point we see no way to proceed except by empirical test applied to the 4×4 example and to the actual 87-sector data.

What, then, are reasonable values for $\boldsymbol{l}$, besides those obtained by the analysis of the first section of this paper? We choose several options and illustrate them by reference to the 4×4 example. We then proceed to the 87-sector data.

(1) $\boldsymbol{l}=\boldsymbol{0}$ This is the base case. The labor sector is assumed to be exogenous.
(2) $\boldsymbol{l}=$actual values used, as in the previous section. For the 4×4 example, we (arbitrarily, in this case) pick $\boldsymbol{l}=(0.5, 0.2, 0.2)$.
(3) $\boldsymbol{l}$ proportional to the normalized value added (profit including labor costs). In the example this would give $\boldsymbol{l}$ proportional to (0.7, 0.4 0.6). This assumes that labor is a constant fraction of value added, sector by sector.
(4) $\boldsymbol{l}=$constant fraction of total inputs. This assumes that a fixed fraction of the value of output is spent on labor. Both 3 and 4 have some justification in reality. Labor is usually the largest component of value added.
(5) $\boldsymbol{l}=$mirror image of the actual $\boldsymbol{l}$ in 2. This is an attempt to use an $\boldsymbol{l}$ which is 'opposite' from or inversely correlated with the actual one. This could be done in many ways. By mirror image we mean that $l_{i,\mathrm{mirror}}$ is set

equal to $l_{\text{mean}}-(l_{i,\text{actual}}-l_{\text{mean}})$, where l_{mean} denotes the average labor input. In the example, $l_{\text{mean}}=(0.5+0.2+0.2)/3=0.3$. Then $l_{1,\text{mirror}}=0.3-(0.5-0.3)=0.1$, $l_{2,\text{mirror}}=0.3-(0.2-0.3)=0.4$, etc. Caution is needed to avoid allowing the $l_{i,\text{mirror}}$ to get too large. In this particular example this doesn't happen.

In the example (table 12) we have constrained all 'options' so that $L_1+L_2+L_3=9$, which corresponds to a constant closedness of $1-8/(30+9)=0.79$ vs. $1-17/30=0.43$ for $L_1=L_2=L_3=0$.

In fig. 3 we present the results shown in table 12. In fig. 3a there seems to be only one systematic pattern: that for any non-zero values of $\boldsymbol{l}$ the coefficient of variation of all the ε's (*COVE3*) decreases relative to that for $l_1=l_2=l_3=0$, as long as only one entry in $\boldsymbol{e}$ is non-zero. However, for $\boldsymbol{e}=(1,1,1,1)$, this is no longer true. Otherwise, there is apparently no connection between the options. The 'mirror image' can produce a *COVE3* that is greater or smaller than that for the 'actual'.

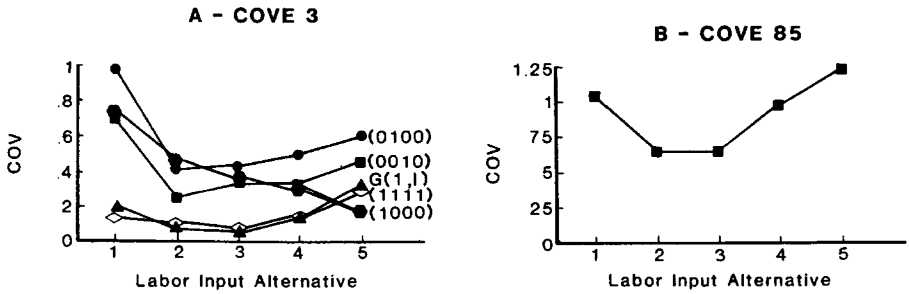

Fig. 3. Coefficients of variation (*COV*) for alternative labor input vectors for the 4×4 example (A) and the 87 sector model using 1967 data (B). Labels on A are the normalized direct energy input vector used for each plot. Labor input alternatives are: (1) no labor (labor sector is exogenous); (2) the 'actual' labor vector; (3) labor proportional to value added; (4) labor proportional to total input; (5) labor is the 'mirror image' of actual labor input. Note that the order of these alternatives is arbitrary.

Based on this limited example, we come to the following empirical conclusion: For $\boldsymbol{e}$ containing only one non-zero element, *COVE3* is reduced as $\boldsymbol{l}$ is increased from $\boldsymbol{0}$. Otherwise, no conclusion can be made about *COVE3* based on the relationship of the two $\boldsymbol{l}$ vectors, unless they satisfy hypothesis 2 (in which case *COVE3*$=0$) or hypothesis 3 (in which case *COVE3* is unchanged). Thus, for a general $\boldsymbol{e}$ with many non-zero elements, even the weak hypothesis is not true, and the mathematical artifact argument appears false.

One additional aspect needs mention. The most general formulation of the energy intensity problem allows for the possibility that energy inputs can occur for any sector, so that $\boldsymbol{E}$ is not constrained. In the U.S. economy there are several energy sectors (e.g., coal, refined petroleum), which are the only ones with $\boldsymbol{E} \neq \boldsymbol{0}$. However, these sectors consume little energy (usually an exception is electric utilities) and pass the bulk of their input on as energy to be consumed or sequestered by their customers. If the purpose of $\boldsymbol{E}$ is to show where energy is finally consumed, then $\boldsymbol{E}$ should actually be the same as the energy rows of $\boldsymbol{U}$, or DEC in the 87-sector examples, which includes non-zero entries for all sectors.

In this case it is particularly easy to calculate $\boldsymbol{\varepsilon}$. In the appendix we prove that if and only if $\boldsymbol{e} = k\boldsymbol{G}_e$ (where $\boldsymbol{G}_e$ means the energy row of $\boldsymbol{G}$), then

$$\boldsymbol{\varepsilon} = k[(\boldsymbol{I} - \boldsymbol{G})^{-1} - \boldsymbol{I}]. \tag{5}$$

Except for the $-\boldsymbol{I}$ in the bracket this is identical to calculating $\boldsymbol{\varepsilon}$ when $\boldsymbol{e}$ is zero for all sectors except an entry k in the eth column.

For this special case, one might suspect a connection with the case of having only one non-zero element in $\boldsymbol{e}$, for which we can make a definite statement about the behavior of *COVE3* as $\boldsymbol{l}$ increases from zero. However, applying eq. 5 to the 4×4 example quickly shows that for $\boldsymbol{e}$ equal to the first row of $\boldsymbol{G}$, *COVE3* is 0.327 for the mirror image labor case vs. 0.207 for $\boldsymbol{l} = 0$ (see table 12). Even for this special case, the mathematical artifact argument does not hold.

6. 87-sector tests

We performed the tests outlined in the previous section for the full 87-sector model. Since there was little variation in the overall findings between the three years, we limited our tests to only one year's I–O model: 1967. The results of using labor input vectors 1–5 above for the 1967 87-sector data are given in table 13, and plotted in fig. 3b. Table 13 indicates that adding a labor vector does not in itself guarantee a lower coefficient of variation of the ε's, or a higher R^2 between embodied energy and dollar output. The mirror image labor vector, for example, produced a lower R^2 (0.013) and a higher *COV* (1.22) than vector 1 ($\boldsymbol{l} = \boldsymbol{0}$, $R^2 = 0.394$, $COVE85 = 1.02$). Labor vectors 3 and 4 produced less variation in the ε's than vector 1, but more than vector 2 (the actual input). Vector 4 was not a significant improvement on vector 1, but vector 3 (labor input proportional to total value added) was. This is to be expected since the actual labor vector is a relatively large and constant component of value added.

Table 13

Results of alternative labor vector tests on the full 87 sector model. Tests were performed on the 1967 data with DEC energy input vector. For comparison with the 4 × 4 system, statistical indicators are calculated for sectors 1–85 only.

Labor vector	R^2	*COVE85*
(1) $l=0$	0.394	1.02
(2) $l=$actual	0.866	0.64
(3) $l \propto$ value added	0.832	0.65
(4) $l \propto$ total input	0.457	0.97
(5) $l \propto$ mirror image	0.013	1.22

7. Conclusions

We conclude from this analysis that the mathematical artifact argument is not valid for a 'reasonable' set of labor vectors. The reduction in *COVE85* and the high degree of correlation between embodied energy and dollar value found using the 'actual' labor vector are therefore representative of real relationships and constraints in the economy and are not simply artifacts of the method used to incorporate labor and government energy costs. If they were artifacts, we would expect *COVE* to decrease dramatically on addition of any large labor vector, which tables 12 and 13 and fig. 3 show is not the case.

It seems that the only remaining objections to this analysis are philosophical ones concerning the propriety of removing humans from their 'controlling' position outside the economy and making them endogenous and therefore themselves 'controlled' to a larger extent [cf. Daly (1981)]. This is analogous to the 'positive vs. normative' debate in economics. We believe that there is no one universally correct position on either of these questions, but that the answer is dependent on the intended uses of the analysis. In the case of calculating a static measure of total energy cost it seems appropriate to consider humans to be endogenous, since they have already made their energy consumption choices and we merely want to look at the repercussions of them. For making projections into the future, however, it is still debatable whether humans should be considered endogenous, exogenous, or some complex combination of the two.

In any case, our analysis has definitely strengthened the case that embodied energy (calculated the way we suggest) is a good, non-trivial, static correlate of the economic value of the relatively large aggregates of goods and services that make up the entries in I–O tables. This does not imply that: (1) the market is perfect; (2) this relationship would continue to hold at the level of individual microeconomic transactions; or (3) absolutely no improvements in energy efficiency are possible. It is a relationship that applies to large aggregates, analogous to the way that the gas laws apply only to large assemblages of molecules. The gas laws are, nonetheless, very powerful tools when used to predict the overall behavior of ideal gasses, and we think that embodied energy may be an equally powerful tool to help predict the overall behavior of economic systems.

Appendix

Two theorems regarding predicting certain attributes of the energy intensities from propertiesof EV^{T-1} and G.

Theorem 1. If and only if EV^{T-1} is proportional to the pth row of G then

$$\varepsilon = c[(I-G)^{-1} - I]_p, \tag{A.1}$$

where c is the constant of proportionality and the subscript p means the pth row.

Proof of sufficiency. Assume $(EV^{T-1})_k = c(G)_{pk}$, c = constant.. Substituting in eq. (3):

$$(\varepsilon)_l = \sum_k (EV^{T-1})_k (I-G)_{kl}^{-1} = c \sum_k (G)_{pk} (I-G^{-1})_{kl},$$

$$(\varepsilon)_l = c[G(I-G)^{-1}]_{pl}. \tag{A.2}$$

For any invertible matrix $(I-G)$,

$$(I-G)(I-G)^{-1} = I \quad \text{and} \quad G(I-G)^{-1} = (I-G)^{-1} - I. \tag{A.3}$$

Substituting eq. (A.3) into (A.2) proves sufficiency.

Proof of necessity. Rewrite eq. (3):

$$EV^{T-1} = \varepsilon(I-G). \tag{A.4}$$

Assume

$$(\varepsilon)_l = d[I-G)^{-1} - I]_{pl}, \qquad d = \text{constant}. \tag{A.5}$$

Substituting eq. (A.5) in eq. (A.4):

$$(EV^{T-1})_k = d \sum_l [(I-G)^{-1} - I]_{pl} (I-G)_{lk},$$

$$(EV^{T-1})_k = d\{[(I-G)^{-1} - I](I-G)\}_{pk}. \tag{A.6}$$

Substituting eq. (A.3) in eq. (A.6):

$$(\boldsymbol{EV}^{T-1})_k = d[\boldsymbol{G}(\boldsymbol{I}-\boldsymbol{G})^{-1}(\boldsymbol{I}-\boldsymbol{G})]_{pk},$$

$$\boldsymbol{EV}^{T-1} = d(\boldsymbol{G})_p, \qquad \text{which was to be proved.}$$

Theorem 2. For $\boldsymbol{G}$ *of the form*

$$\begin{pmatrix} G_{1,1} & \cdots & G_{1,n} & G_{1,n+1} \\ \vdots & & \vdots & \vdots \\ G_{n,1} & \cdots & G_{n,n} & G_{n,n+1} \\ l_1\, l_2 & \cdots & l_n & l_{n+1} \end{pmatrix}.$$

For $m=n$ *or* $n+1$ *the following is true:*

If the first m *entries of* $\boldsymbol{EV}^{T-1}$ *are proportional to the first* m *entries of* $\boldsymbol{l}$ *(i.e., to* $l_1, l_2, \ldots, l_m$*), then the coefficient of variation of the first* m *elements of*

$$\boldsymbol{\varepsilon} = \boldsymbol{EV}^{T-1}(\boldsymbol{I}-\boldsymbol{G})^{-1} \tag{A.7}$$

is independent of the magnitude of $\boldsymbol{l}$.

Proof (of sufficiency only). We will prove that under the conditions above, when $l_1, l_2 \ldots l_m$ are multiplied by a constant, the first m elements of $\boldsymbol{\varepsilon}$ are multiplied by a constant. Therefore any normalized dispersion index of the ε_i, including the coefficient of variation,[1] is unchanged.

Assume that the first n elements of $\boldsymbol{EV}^{T-1}$ are equal to the corresponding elements of $\boldsymbol{l}$, i.e., of the $(n+1)$th row in $\boldsymbol{G}$ (there is no loss of generality of assuming equality rather than just proportionality, as we will show below).

We can then write

$$\boldsymbol{EV}^{T-1} = (\boldsymbol{G})_{n+1} + (0, 0, \ldots, (\boldsymbol{EV}^{T-1})_{n+1} - (\boldsymbol{G})_{n+1,n+1}). \tag{A.8}$$

Using eq. (3) and applying Theorem 1 to the first term on the right-hand side,

$$\boldsymbol{\varepsilon} = [(\boldsymbol{I}-\boldsymbol{G})^{-1} - \boldsymbol{I}]_{n+1} + ((\boldsymbol{EV}^{T-1})_{n+1} - (\boldsymbol{G})_{n+1,n+1})(\boldsymbol{I}-\boldsymbol{G})^{-1}_{n+1}. \tag{A.9}$$

The second term on the right-hand side is just a scalar times the $(n+1)$th row of $(\boldsymbol{I}-\boldsymbol{G})^{-1}$.

[1]
$$COVM \equiv \left[\sum_{i=1}^{m}\left(\varepsilon_i - \frac{1}{m}\sum_{i=1}^{m}\varepsilon_i\right)^2 \Big/ m\right]^{\frac{1}{2}} \Big/ \frac{1}{m}\sum_{i=1}^{m}\varepsilon_i.$$

Now assume that the first n elements of $\boldsymbol{l}$ are multiplied by β. Following the same steps as above leads to

$$\varepsilon' = \frac{1}{\beta}[(\boldsymbol{I}-\boldsymbol{G}')^{-1}-\boldsymbol{I}]_{n+1}$$

$$+\left((\boldsymbol{E}\boldsymbol{V}^{T-1})_{n+1}-\frac{1}{\beta}(\boldsymbol{G}')_{n+1,n+1}\right)(\boldsymbol{I}-\boldsymbol{G}')^{-1}_{n+1}, \tag{A.10}$$

where the primes refer to this second case. $\boldsymbol{G}'$ is identical to $\boldsymbol{G}$ except that all $n+1$ elements of the $(n+1)$th row have been multiplied by β. Rewriting eq. (A.10):

$$\varepsilon' = \left(\overbrace{\frac{1}{\beta}+(\boldsymbol{E}\boldsymbol{V}^{T-1})_{n+1}-\frac{1}{\beta}(\boldsymbol{G}')_{n+1,n+1}}^{A}\right)[(\boldsymbol{I}+\boldsymbol{G}')^{-1}-\boldsymbol{I}]_{n+1}$$

$$+\left((\boldsymbol{E}\boldsymbol{V}_{T-1})_{n+1}-\frac{1}{\beta}(\boldsymbol{G}')_{n+1,n+1}\right)(\boldsymbol{I})_{n+1,n+1}. \tag{A.11}$$

The term A is a scalar and can be factored out of the first term on the right-hand side of eq. (A.11). The question which still remains is how $[(\boldsymbol{I}-\boldsymbol{G})^{-1}-\boldsymbol{I}]$ and $[(\boldsymbol{I}-\boldsymbol{G}')^{-1}-\boldsymbol{I}]$ are related. It turns out that their terms are proportional.

We show this by brute force examination of the elements of the inverses.

For an invertible matrix $(\boldsymbol{I}-\boldsymbol{G}')$,

$$(I-G')^{-1}_{n+1,j} = \frac{1}{\det(\boldsymbol{I}-\boldsymbol{G}')}(-1)^{n+1+j}\cdot \det \text{ of } (\boldsymbol{I}-G')$$

$$\text{with } \begin{pmatrix} j\text{th row} \\ (n+1)\text{th column} \end{pmatrix} \text{ removed} \tag{A.12}$$

[Noble (1969, pp. 200, 210)].

For $j<n$, the numerator of the right-hand side of eq. (A.12) is just β times the numerator of the expression for the inverse of $(\boldsymbol{I}-\boldsymbol{G})$.

Using eq. (A.12), and expanding $\det(\boldsymbol{I}-\boldsymbol{G}')$ by its $(n+1)$th row:

$$[(I-G')^{-1}-I]_{n+1,n+1}$$
$$=\frac{1}{\det(I-G')}\left\{\begin{array}{l}\text{det of } (I-G') \text{ with } \begin{pmatrix}(n+1)\text{th row}\\(n+1)\text{th column}\end{pmatrix}\text{removed}\\ -\left(\sum_{j=1}^{n}(-1)^{n+1+j}\beta l_j\cdot\text{det of } (I-G')\right)\text{ with }\begin{pmatrix}n+1\text{th row}\\ j\text{th column}\end{pmatrix}\text{ removed}\\ +(1-\beta l_{n+1})\text{ det of } (I-G')\text{ with }\begin{pmatrix}n+1\text{th row}\\ n+1\text{th column}\end{pmatrix}\text{removed}\end{array}\right\} \tag{A.13}$$

In eq. (A.13), none of the determinants inside the brackets contains the $(n+1)$th row of $I-G'$; therefore all terms are the same as the corresponding ones of $I-G$. In addition, the only terms not linear in β cancel out. The results is that numerator of eq. (A.13) is also just β times the numerator for a similar expansion of $[(I-G)^{-1}-I]_{n+1,n+1}$.

This establishes that the $n+1$ elements of $[(I-G)^{-1}-I]$ and $[(I-G')^{-1}-I]$ are proportional. Combining this with the fact that the factor A in eq. (A.11) is a constant independent of column, proves the theorem for $m=n$. The existence of the second term on the right-hand side of eq. (A. 11), which is non-zero only for the $n+1$th element of ε, prevents the theorem from applying to $m=n+1$ if the $(n+1)$th elements of EV^{T-1} and l are not proportional.

On the other hand, if all $n+1$ entries in EV^{T-1} are proportional to those of l, the second term on the right-hand side of eq. (A.11) is zero and the theorem applies for $m=n+1$. This completes the proof.[2]

One can wonder why the theorem applies only for $m=n$ or $n+1$, but not a smaller number. The reason seems to be that there would be more than one non-zero element in the second term of eq. (A.8) and that other rows of $(I-G)^{-1}$ besides the $(n+1)$th would be involved in the right-hand term of eq. (A.10), which would then not be easily factorable.

The case of $m=n$ corresponds exactly to the notion of

(1) starting with an $n\times n$ system to which labor is exogenous,
(2) adding a labor sector which has fixed input coefficients (i.e., fixed values of the $(n+1)$th column of (G),
(3) constraining the values of the labor input coefficients (the l_i) to the proportional to EV^{T-1} as states, and yet to vary in absolute magnitude.

[2]Since we chose our initial l to have its first n elements equal to those of EV^{T-1}, the theorem is only strictly proved when we note that the above arguments could be used to compare the results of using two multiplicative factors, say β_1 and β_2. Comparing the results for the two values of β would yield the same conclusion as we quote here.

David Reister [personal communication (25 April 1983)] has obtained a similar but more limited result. In the language of our proof, he

(1) assumes that $G_{n+1}, G_{n+1} = 0$,
(2) looks at one row of $(\boldsymbol{I}-\boldsymbol{G})^{-1}$ at a time, which is equivalent to $\boldsymbol{E}\boldsymbol{V}^{T-1}$ having only one non-zero entry,
(3) assumes that $(\boldsymbol{E}\boldsymbol{V}^{T-1})_j$ is proportional to the jth column sum of $(\boldsymbol{I}-\boldsymbol{G})$.

He finds in this case that for the first n rows of $(\boldsymbol{I}-\boldsymbol{G})^{-1}$, the fractional deviation of each entry from the row mean decreases as the constant of proportionality in his assumption 3 increases.

This result is what is claimed in the mathematical artifact argument, but Reister's assumptions are too restrictive. In particular, use of $\boldsymbol{E}\boldsymbol{V}^{T-1}$ containing many non-zero elements is common. But, all of these proofs, his and ours, admittedly cover special cases.

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