Goods and Services: Energy Costs

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Glossary

embodied energy The energy consumed “upstream” to facilitate a flow of goods or services (units = energy).

energy cost of living The energy required to facilitate a household’s consumption of goods and services (units = energy/year).

energy intensity (ε) The energy required to facilitate a flow of one unit of a specified good or service (units = energy/gloof).

gloof Generic term to cover the range of goods and services; for example, a pound of fertilizer, the dollar value of an airline ticket, or a liter of water.

indirect effect Necessary costs not considered “direct.” For example, auto fuel is usually considered direct energy, whereas energy to build roads is considered indirect. It depends on the definition and system boundary.

input–output (I–O) analysis A subdiscipline of economics that explicitly determines indirect effects.

net energy analysis A comparison of the energy costs and the energy produced by an energy technology such as a coal mine or photovoltaic panel.

power Energy per unit time (units = energy/time).

system boundary The limit up to which costs, benefits, impacts, and consequences are considered; can refer to spatial, temporal, or conceptual issues.

trophic position (TP) An indicator of dependence of an organism or group of organisms on solar-driven photosynthesis in an ecosystem. If the system has a linear food chain, it is called trophic level (dimensionless).

vertical analysis (also known as process analysis) A method to determine energy cost by tracing back through the production process.

Energy analysis determines the total energy required to produce a good or service, including the indirect effects through the chain of production and delivery. This energy is commonly called energy cost, although it does not mean the monetary cost of energy. Once the energy cost is known, the energy requirements of different patterns of production/consumption of goods and services can be analyzed. In this article, the imprecise term energy is used, although the preferred, thermodynamically correct term is free energy.

1. *INTRODUCTION*

Most of us know intellectually that energy—solar and fossil—supports all of our life-support systems, from agriculture to transportation, commerce, and medicine. Some of us know this more viscerally as well; ecologists and farmers see every day that “all flesh is grass.” Readers may remember the U.S. east coast blackout of 1965, the oil crisis of 1973 (long waiting lines at gas stations), or even the California electricity shortages during the summer of 2001. I first “got it” while sitting in traffic in 1971 in Oak Ridge, Tennessee. Ahead of me was a car towing a trailer on which there was an aluminum pleasure boat. Because there was increasing controversy in the Tennessee Valley regarding electricity powered by strip-mined coal and nuclear reactors and also from dams, energy was on my mind. I knew that aluminum is an energy-intensive metal, and I realized that I was looking at “embodied” energy, and hence embodied environmental damage and controversy.

On that day, I started 30 years of work in energy analysis. When I see bread, autos, baby carriages, lawn sprinklers, hospitals, playgrounds, orchestral concerts, haircuts, blue jeans, orthodontic braces, street artists, aircraft carriers, or banjoes, I see energy. The question was and is the following: How much embodied energy? In this article, I present methods used to quantify energy cost and illustrate how it is used in several applications.

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Energy cost is an example of an indirect effect. Once we realize that a good or service "embodies" an input that is not evident, we are free to calculate the energy cost of an orange, the orange cost of energy, the water cost of hamburger, or how much pollution is released when a Sierra Club book (or this encyclopedia) is published. However, then we are vexed with how far to go in the calculation. For example, how much energy is required to allow a car to travel 1 mile? Here are possible answers to the question:

1. The fuel burned
2. Plus the energy to extract, refine, and transport the fuel
3. Plus the energy to manufacture the car (prorated to 1 mile's use)
4. Plus the energy to produce tires, replacement parts, etc.
5. Plus the energy to build and maintain roads.
6. Plus the energy to maintain auto repair shops, government regulation and registration services, etc.
7. Plus the energy to produce and maintain that portion of the health system used to care for accident victims and sufferers of auto-related health problems.
8. Plus …

Where to stop depends on how we bound the issue, and in the end this decision should be made by the users of the result.

Also, there are additional steps. A similar expanding wave of concern and impact ripples out from, for example, the energy to make the car, which could include

1. The energy consumed at the assembly plant
2. Plus the energy used to make the steel, glass, rubber, etc.
3. Plus the energy used at the iron mine, sand pit, and sulfur mine
4. Plus …

even including the cars used by the iron mine so that the process runs in circles, although successive steps become smaller.

2. *METHODS TO DETERMINE ENERGY COST*

2.1 Vertical Analysis

The previous process is called vertical analysis or process analysis; I call it following your nose. Fig. 1 indicates the stepwise process of producing a product such as a car. The auto factory is the box on the far left. To produce an auto, the factory receives inputs from three other sectors—for example, steel, glass, and rubber. Each of these receives inputs from other sectors, and so on. Vertical analysis traces this web of inputs backward. At each node, it evaluates the amount of the desired input (e.g., energy) at that point and prorates it on the basis of that sector's output. Given the complexity of a modern economy, vertical analysis is labor-intensive and data-demanding.

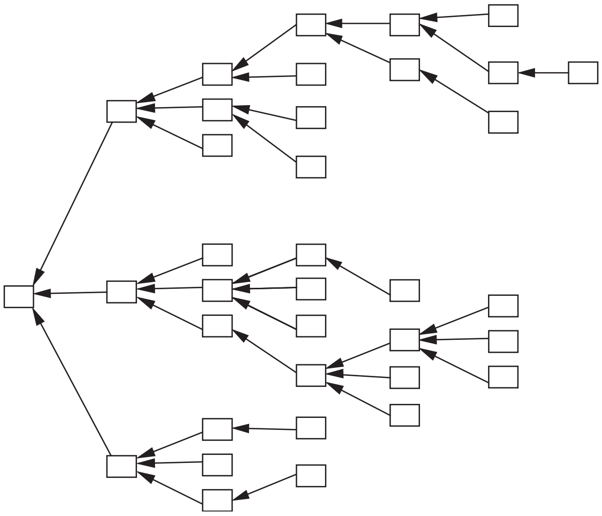


FIGURE 1 Schematic representation of vertical analysis (also called process analysis) to determine energy cost.

2.2 Input–Output Analysis

Economic input–output (I–O) analysis is a well-established method to trace indirect effects in monetary terms. The U.S. Department of Commerce prepares detailed information on the dollar transactions among 350–500 sectors covering the U.S. economy. Many other nations have similar programs. Using several assumptions, one can use the analytical machinery of I–O to combine these data with supplementary information on energy use to determine energy cost.

We start with an economy with *N* sectors, each with an output flow measured in units of gloof/time. Gloof can be almost anything: tons of steel, pounds of butter, hours in a dentist's chair, dollars worth of day care, etc. It can even vary from compartment to compartment (as in the following example). The assumptions are as follows:

1. Every flow in the system that we wish to count (units = gloof/time) has an associated energy

intensity according to its source compartment (units = energy/gloof).

2. Embodied energy flows everywhere there are flows that we consider important, and the magnitude of the embodied energy flow (units = energy/time) is the product of the energy intensity (units = energy/gloof) times the original flow (units = gloof/time). This assumes that the flow variable is a good surrogate for embodied energy, which is a judgment call by the user.

3. Embodied energy is conserved in each compartment—that is, the amount "in" equals the amount "out."

Assumption 3 is stated by Eq. (1) and illustrated in Fig. 2.

$$\sum_{i=1}^{N} \varepsilon_i X_{ij} + E_j = \varepsilon_j X_j, \qquad (1)$$

where X_{ij} is the actual gloof flow from compartment i to compartment j (units = gloof_i/time), X_j is the sum of all output flows from compartment j (units = gloof_j/time), E_j is the actual energy input flow to compartment j from outside the system (units = energy/time), and ε_j is the energy intensity of output of compartment j (units = energy/gloof_j). Equation (1) is assumed to hold for each of the N compartments, yielding N equations in N unknowns. We know the X_{ij}'s and E_j's, so we can solve for the ε_j's. Equation (1) formalizes the allocation of indirect effects in a self-consistent manner and can be used to allocate indirect anything, not just energy.

2.3 An Example of the Calculation of Energy Cost

Figure 3A shows a two-sector economy burning oil to produce steel and cars. We use Eq. (1) to determine the energy intensities:

$$\text{Steel sector: } 10.8 + 1\varepsilon_{\text{car}} = 12\varepsilon_{\text{steel}}$$
$$\text{Car sector: } 10\varepsilon_{\text{steel}} + 2 = 10\varepsilon_{\text{car}}$$

Solving these two equations gives $\varepsilon_{\text{steel}} = 1$ barrel oil/ton steel and $\varepsilon_{\text{car}} = 1.2$ barrel oil/car. The embodied energy flows are obtained by multiplying the flows in Fig. 3A by the intensities, giving the result shown in Fig. 3B. Each sector is in embodied energy balance, as we assumed in Eq. (1). In addition, the whole system is in balance: 12.8 barrels of oil enters and is burned, and 12.8 barrels of embodied oil is contained in the shipments of steel and cars to final consumption. Furthermore, only 2/12 of the energy to produce a car is used directly (i.e., burned in the auto factory).

This is the I–O approach for two sectors. Calculation for systems with more sectors is operationally the same but tediously complicated—a job easily handled by computers. Typical results are shown in Table I. In addition, one may show that a vertical analysis of Fig. 3A yields the same results as the I–O approach. Because of the feedback of cars to steel, the analysis has an infinite number

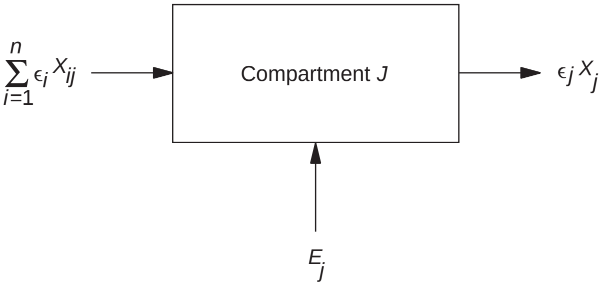


FIGURE 2 Input–output approach to determine energy cost. It is assumed that the embodied energy in = embodied energy out. E_j is the energy flow into sector j (units = energy/time), X_{ij} is the flow of product i to sector j (units = gloof/time), X_j is the total output of sector j (units = gloof/time), and ε_j is the energy intensity of product j (units = energy/gloof).

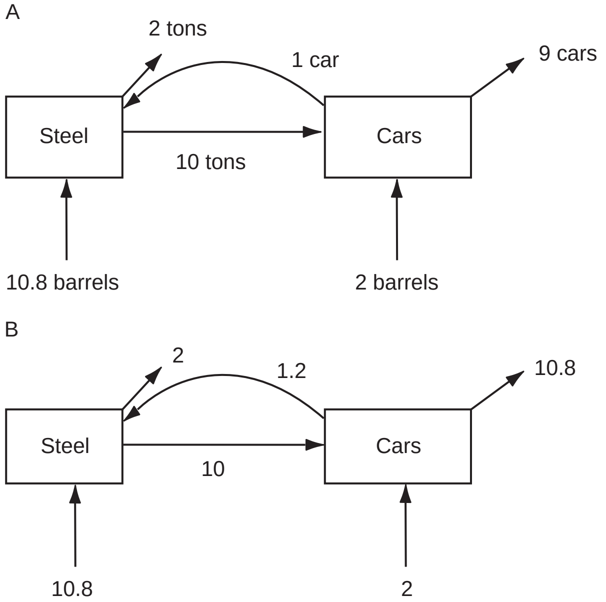


FIGURE 3 A two-sector economy illustrating the calculation of energy cost. (A) Original flows per unit time. Diagonal arrows represent shipments to final consumption. Energy inputs are in barrels of oil. (B) Embodied energy flows (units = barrels/unit time). All flows are assumed steady over time.

TABLE I

Energy Intensities for Personal Consumption Categories, 1972–1973[a]

Consumption category	Energy intensity (103 Btu/$1972)	Consumption category	Energy intensity (103 Btu/$1972)
Food at home	54	Auto insurance	19
Food away from home	44	Auto registration and fees	0[a]
Alcoholic beverage	51	Local bus and train, commuting	56
Tobacco	30	Local bus and train, school	56
Rented dwelling	14	Local bus and train, other	56
Owned dwelling	12	Transportation to school away from home	132
Other shelter, lodgings	21	Plane, trip outside commuting area	167
Fuel oil and kerosene	890	Train and bus, trip outside commuting area	68
Coal and wood	795	Ship, trip outside commuting area	129
Other fuels	795	Limousine and taxi, trip outside commuting area	56
Gas main	915		
Gas in bottles and tanks	999	Car rental	38
Electricity	616	Health insurance	19
Water, sewage, trash	26	Health care	47
Telephone, telegraph, cable	24	Personal care	48
Domestic service	0[a]	Owned vacation home	12
Household textiles	59	Other transportation costs on vacation	91
Furniture	45	All-expense tours, summer camps	31
Floor coverings	71	Other vacation expenses	33
Major appliances	66	Boats, aircraft, motorcycles	65
Small appliances	65	Television	48
Housewares	57	Other recreation	41
Miscellaneous house furnishings	48	Reading	43
Dry cleaning, laundry	44	Private education	35
Clothing	44	Public education	37
Vehicle purchase	68	Miscellaneous consumption expenditure	41
Vehicle purchase finance charges	27	Personal insurance and pensions	20
Gasoline and oil	443	Gifts and contributions	41
Tires and lubrication	69	Increase in savings	47
Batteries	59	Housing purchase and improvement	40
Auto repair and service	37	Increase in investment	47

[a] Labor and government services are assumed to have zero energy intensity relative to the consumer. For labor, this is done to avoid double counting. For government, the energy requirement is not lost but rather charged against government expenditures.

of steps, but a computational trick makes this manageable.

For typical energy studies, the following assumptions have usually been made: Energy inputs are coal, petroleum, natural gas, and a "fossil equivalent" of hydro, wind, photovoltaic, and nuclear electricity. Solar energy input to silviculture and agriculture is usually considered a free input and not counted for economic systems. However, solar energy is usually counted in energy analysis of ecosystems.

3. ILLUSTRATIONS/APPLICATIONS OF ENERGY COST

3.1 Auto Manufacture and Use

Energy analysis showed that approximately 12% of the energy to produce and market a U.S. automobile was consumed in the automobile sector vs. 37% in the primary metals sectors. In addition, the fuel in the tank was only approximately 60% of the energy to provide auto transport; the other 40% was car

TABLE II

Energy Cost of Corn Production in Illinois, 1996

Type of agiculture:	Conventional
Crop:	Yellow corn
Field size:	76 acres
Yield:	168 bushels/acre
Calorific energy of crop	5.13×10^9 Btu (402×10^3 Btu/bushel)
Crop energy/input energy:	8.4

	\$1996 Cost or Btu	**Energy intensity (10^3 Btu/\$1996 or Btu/Btu)**	**Energy (10^6 Btu)**	**% of total**
Seed	\$2284	26.2	59.8	9.8
Fertilizer	\$4725	769.7	363.7	59.6
Herbicide	\$2179	26.2	57.0	9.3
Pesticide	0	26.2	0	0.0
Machines	\$2017	10.7	43.0	7.0
Farm fuel	52×10^6 Btu	1.20[a]	62.3	10.2
Custom application	\$2129	11.6	24.7	4.0
Total			610.4	100.0

[a] Twenty percent extra energy is consumed in extracting, refining, and transporting fuel to point of use. This is an experimental plot; in commercial practice, typically some pesticides would be applied.

manufacture (8%), energy cost of energy (9%), tires, maintenance, road construction, parking, insurance, etc. This is an old result from the 1970s, but it is still compelling.

3.2 Grain Production

The ecologist Howard T. Odum said we eat "potatoes made of oil," a reflection of the energy demands of modern mechanized agriculture. Table II shows typical energy requirements for a corn crop. In the rich soil and favorable climate of Illinois, the fossil energy inputs sum to only one-eighth of the crop's calorific value (the sun is not counted). Note that fertilizer and herbicides account for 2/3 of total energy input, while farm fuel is only 10%. It is debatable whether fossil fuel inputs should be compared with the calorific content of food. More compelling are studies that show that the fossil energy input per unit of food output has increased during the past several centuries. Likewise, if we move to the right on any of these spectra—good → marginal soil and climate, grain → flesh, low → high processing and packaging, near → distant—the energy inputs typically increase. For the average food as delivered to American mouths, the fossil energy input is 5–10 times the calories delivered.

3.3 Household Energy (Energy Cost of Living)

Once obtained, energy intensities can be used to link everyday personal consumption patterns with their impact in resource use, as indicated in Eq. (2):

$$\text{Energy} = \sum_{i=1}^{N} (\text{energy intensity of consumer good } i) \times (\text{consumption of consumer good } i). \quad (2)$$

As with much energy analysis, effort peaked in the 1970s and 1980s, but here I present an update.

3.3.1 Energy Intensities

Very few vertical analyses have been performed on specific products, such as automobiles and agricultural chemicals. The remaining energy intensities have been calculated for approximately 350 sectors covering the full range of economic expenditures in the U.S. I–O economic tables. One assumes that dollars are a satisfactory numeraire for allocating embodied energy. Energy data compatible with I–O data are provided by the U.S. Department of Energy, Energy Information Administration. These are used with a version of Eq. 1.

One immediate question is whether the energy intensities do vary among sectors. If not, the energy

TABLE III

Energy Intensities of Consumer Expenditures, Updated (by Approximations) to 1999

Expenditure category	Energy intensity (Btu/$1999)
Food	9095
Alcohol and tobacco	5457
Housing	5457
Residential energy	105000
Gasoline and motor oil	115000
Auto purchase, maintenance	10914
Public transportation	20000
Apparel	8025
Health, personal care	8560
Entertainment and communication	5457
Education and reading	7276
Miscellaneous	7490
Contributions	7490
Insurance, pension	3638
Asset change	8560

consequences of spending a dollar for any good or service would be the same, and the details of expenditures would be irrelevant. We already know that the primary metals industry is energy intensive compared with a service industry, but we are interested in consumption options open to individuals and households, which generally covers finished products. Even so, there is a significant variation, as shown in Table I. For example, the energy intensity of gasoline was 443,000 Btu/$ 1972, whereas that of private education was 35,000 Btu/$ 1972, a variation of a factor of 13. Among nonenergy, nontransportation categories, there was a variation of a factor of 5, from rental dwellings (14,000 Btu/$ 1972) to floor coverings (71,000 Btu/$ 1972). In Table III, the consumption categories have been aggregated to 15 and updated to 1999.

3.3.2 Household Consumption Data

The U.S. Bureau of Labor Statistics (BLS) periodically performs detailed surveys of consumption "market baskets" of U.S. households. A total of 19,000+ households were surveyed in 1972 and 1973, with expenditures broken down into 61 categories as given in Table I. In the updated analysis here, I use results of a smaller BLS survey for 1999. The system boundary thus is defined by what the household purchases.

Combining expenditures and intensities using Eq. (2) yields Fig. 4, which shows the energy cost taken back to the mine mouth or wellhead, of the market basket of average households in lowest and highest expenditure quintiles and for the overall average household. Of the 15 consumption categories, 2 are direct energy expenditures (residential fuel and electricity and auto fuel). For the average households, these amount to 5% of monetary expenditures (Fig. 4A) but 44% of the household's total energy cost (Fig. 4B). Figure 4B also shows that for the lowest quintile, the direct energy requirement is approximately 57% of the total, and for the top quintile it is approximately 33%. There seems to be an upper limit on how much auto fuel a household can use but not on football tickets, clothing, furniture, plane tickets, second homes, etc. For the average expenditure level and above, one would miss more than half of the energy cost of living by examining only direct energy.

Under certain assumptions, the energy cost of living can be used for two more speculative purposes: to predict the economic effects of energy price increases on different households (this has been done), and in the analysis of sprawl issues (because more auto use and larger residences are associated with living further from urban centers).

3.4 Appliances: Energy to Operate vs Energy to Produce/Maintain/Dispose

What fraction of the energy use for a refrigerator or a toaster is used to manufacture, market, maintain, and mash it, and what fraction is used to operate it? The answer is useful in evaluating different strategies to reduce energy use, such as increasing operational efficiency, decreasing energy use in manufacture, or increasing the device's lifetime. This is an example of life cycle cost in energy terms. Consider all the energy associated with an appliance:

$$E_{\text{life}} = \text{manufacturing energy} + \text{maintenance energy} + \text{disposal energy} + \text{operational energy}.$$

The average total power is the lifetime energy divided by the lifetime, T:

$$\begin{aligned} p_{\text{tot}} &= \frac{E_{\text{life}}}{T} \\ &= \left(\frac{\text{manufacturing} + \text{maintenance} + \text{disposal}}{E_{\text{life}}} + 1\right) \\ &\quad \times p_{\text{operation}}. \end{aligned} \tag{3}$$

For electric appliances, energy is measured in kilowatt-hours, and power is measured in kilowatts.

Table IV summarizes energy use for selected household appliances. Most appliances tend to have

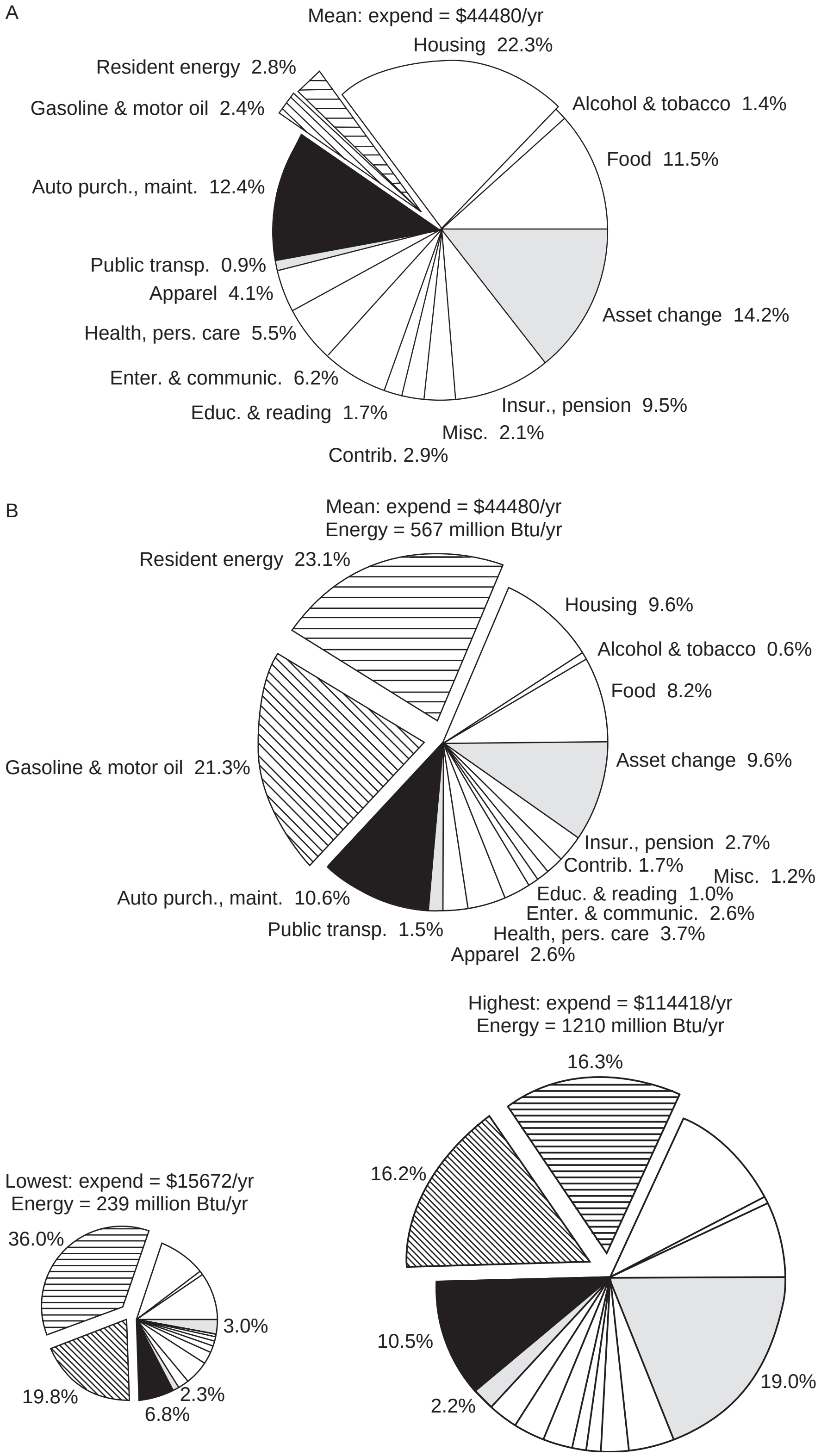


FIGURE 4 Energy cost of living, 1999. (A) Annual expenditures for average U.S. household. (B) Energy costs of expenditures in Fig. 4A and for lowest and highest expenditure quintiles as well. Figure 4B is obtained from Fig. 4A by multiplying energy intensities by expenditures (Eq. 2). In Fig. 4B, the area of the circle is proportional to the total household energy impact.

TABLE IV

Comparison of Operating and (Manufacuring + Maintenance + Disposal) Energy for Selected Appliances

Electric appliance	$p_{\text{operation}}$ (kWh/year)	T(year)	Indirect fraction (manufacturing–maintenance + disposal) as fraction of life energy	Classification ($p_{\text{operation}}$/indirect fraction)[b]
Blender	17	14	0.34	Low/high
Mixer	14	14	0.35	Low/high
Refrigerator	750	14	0.13	High/low
Water heater	4700	8	0.01	High/low
75-W incandescent bulb[b]	657	0.1	0.02	High/low
17-W compact fluorescent bulb[b]	146	1.14	0.08	High/low
Coffee maker	83	8	0.07	Low/low
Toaster	43	8	0.19	Low/low
Personal computer (at work)[c]	160	7	0.5	High/high

[a] Classification: $p_{\text{operation}}$: <100 kWh/year = low; ≥ 100 kWh/year = high. Indirect fraction: <0.25 = low; ≥ 0.25 = high.

[b] Assumes bulbs are on continuously. These two bulbs provide approximately equal light levels.

[c] Assumes the computer is used 8 h/day, 200 days/year.

high operation power and a low indirect energy fraction [i.e., (manufacturing + maintenance + disposal)/$E_{\text{life}} < 1$] or vice versa. For the appliances usually considered large energy users, such as refrigerators, freezers, water heaters, and light bulbs, the fraction is ≤ 0.25. For smaller appliances, it is ≥ 0.25. This implies, but does not prove, that to save energy one should concentrate on operational energy efficiency for the first group, whereas for the second there is likely potential in both operational and manufacturing efficiency.

The personal computer, if used 8 h a day, 5 days a week, has a high operation power (160 kWh/year) and a high indirect fraction (≈ 0.5).

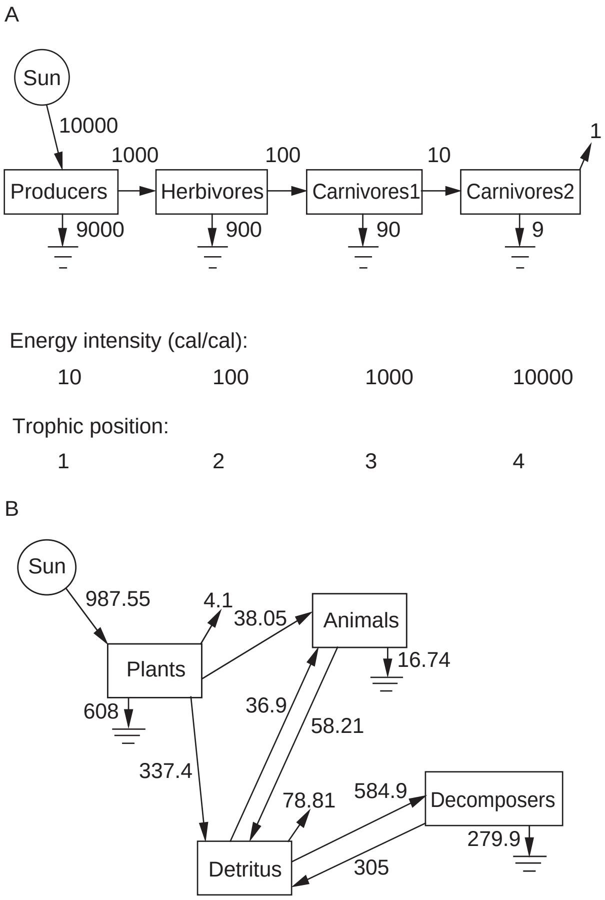
3.5 Energy Cost in Ecosystems

There are several indicator quantities that summarize indirect energy effects in ecosystems. Two that are especially appropriate for quantifying the solar dependence of all life (with the negligible exceptions of deep-sea vent communities, which are based on geochemical energy) are energy intensity and trophic position. Trophic structure refers to the number of energy "transactions" separating the sun (which is assigned trophic position 0) from the compartment in question. Originally, energy flow in ecosystems was visualized in terms of straight food chains, for which trophic positions (called trophic levels in this case) are successive integers (Fig. 5A). However, most ecosystems have web-like energy flows (Fig. 5B). Equation (1) applies to webs, so calculating energy intensities requires no new technique. On the other hand, trophic position needs to be defined. The trophic position of a compartment, TP, is the energy-weighted sum of TPs of inputs +1. Using the language we used for calculating energy intensities, for each compartment,

$$\mathrm{TP}_j = \sum_{i=1}^{N} \left(\frac{X_{ij}}{\sum_{i=1}^{N} X_{ij}} \right) \mathrm{TP}_i + 1. \tag{4}$$

Equation (4) is similar to Eq. (1), but it has two important differences. First, the flows X_{ij} must be in terms of biomass energy because trophic ecology is by definition concerned with energy flow. Second, the factors in the bracket sum to 1 because they are normalized with respect to the input flows, whereas in Eq. (1) normalization is with respect to total output and the factors X_{ij}/X_j need not sum to 1. Equation (4) represents N equations in N unknowns.

For the (idealized) food chain in Fig. 5A, the weighting factors are all 1, and Eq. (4) gives the trophic positions 1–4. For the (real) food web in Fig. 5B, TPs are 1, 3.43, 3.90, and 4.90. Because plants receive input only from the sun, $\mathrm{TP}_{\text{plants}} = 1$. Because decomposers gets all their input from detritus, $\mathrm{TP}_{\text{decomposers}} = \mathrm{TP}_{\text{detritus}} + 1$. Animals and detritus have more than one input, and their TPs are mixtures. In this accounting, decomposers (e.g., bacteria) are on top of the energy pyramid and the food web.



Compartment	Energy intensity (cal/cal)	Trophic position
Plants	2.60	1.00
Animals	9.56	3.43
Detritus	12.40	3.90
Decomposers	23.80	4.90

FIGURE 5 Energy intensities and trophic positions for food chain and web. (A) Idealized food chain. (B) Boreal bog ecosystem food web. Units for both = g fixed carbon m^{-2} $year^{-1}$. Flows to ground symbols are metabolic losses. Detritus is dead material the origin of which is not visually identifiable. Decomposers include bacteria.

4. CONCLUSIONS

Energy is important, and the idea of energy cost makes intuitive sense. The details of obtaining and using energy cost complicate its usefulness, but when done transparently, it can provide insight and help in decision making. To do it transparently, we require at the least a procedure, a system boundary, and many assumptions. For brevity, I have not discussed most of the assumptions, and I have included only a few applications of energy cost. Others include comparing energy embodied in imported and exported goods and services (energy balance of trade), comparing embodied energy and labor costs to determine the employment effects of energy policy, determining equity effects of energy taxes, and comparing the energy cost with the energy output of an energy source technology such as a power dam. The latter, called net energy analysis, is presented in a separate article in this encyclopedia.

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Further Reading

Bullard, C., and Herendeen, R. (1975). The energy costs of goods and services. *Energy Policy* **3**, 268–278.

Bullard, C., Penner, P., and Pilati, D. (1978). Net energy analysis: Handbook for combining process and input–output analysis. *Resour. Energy* **1**, 267–313.

Finn, J. T. (1976). Measures of ecosystem structure and function derived from analysis of flows. *J. Theor. Biol.* **56**, 115–124.

Hall, C., Cleveland, C., and Kaufmann, R. (1986). “Energy and Resource Quality: The Ecology of the Economic Process.” Wiley, New York.

Herendeen, R. (1988). Net energy considerations. *In* “Economic Analysis of Solar Thermal Energy Systems” (R. West and F. Kreith, Eds.), pp. 255–273. MIT Press, Cambridge, MA.

Herendeen, R. (1998). “Ecological Numeracy: Quantitative Analysis of Environmental Issues.” Wiley, New York. [See Chap. 8].

Herendeen, R., and Fazel, F. (1984). Distributional aspects of an energy conserving tax and rebate. *Resour. Energy* **6**, 277–304.

Herendeen, R., Ford, C., and Hannon, B. (1981). Energy cost of living, 1972–1973. *Energy* **6**, 1433–1450.

Odum, H. T. (1996). “Environmental Accounting.” Wiley, New York.

Schulze, P. (ed.). (1999). Measures of Environmental Performance and Ecosystem Condition. National Academy of Engineering, Washington, D.C.

Slesser, M. (ed.). (1974). Energy analysis workshop on methodology and conventions, August 25–30, Guldsmedhyttan, Sweden. International Federation of Institutes of Advanced Study, Stockholm, Sweden. [Reprinted in Energy accounting as a policy analysis tool, Committee print for the 94th Congress, 2nd session, Serial CC, 68–391. U.S. Government Printing Office, Washington, DC, 1976]