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30. Unpublished data.
31. According to R. K. Mortimer (University of California, Berkeley), strain S288C was first isolated as an α-haploid. Later it changed spontaneously to an *a*/α-diploid, which consequently was isogenic with the exception of the mating type locus. This diploid was sporulated to yield the haploids of opposite mating type, now designated X2180-1A(*a*) and X2180-1B(α).
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49. We thank the students and colleagues who, since the beginning of this project, have contributed many of the facts and ideas that provide the basis of this article. We are indebted to Professors S. Fogel and R. K. Mortimer for assistance in the genetic analysis of yeast mannan mutants. The work was supported by NSF grants GB-19199 and GB-35229X, and by PHS grant AM884.

Food-Related Energy Requirements

The energy used by the U.S. food cycle constitutes about 12 percent of the national energy budget.

Eric Hirst

In this article I discuss the quantities of energy required to grow, process, transport, wholesale, retail, refrigerate, and cook food in the United States for the year 1963, and use the data available for that year (*1*) to estimate the annual energy consumption for food during the period 1960 to 1970. Energy requirements per unit of food energy and of food protein are computed for the major food groups.

Because food accounts for 20 percent of disposable personal income in the United States, it seems likely that the energy used in moving food through the economy also comprises a sizable percentage of the total U.S. energy budget. The study I describe here was initiated as a result of the energy problems now facing the nation: fuel shortages, rapidly rising fuel prices, brownouts, adverse environmental impacts of fuel cycles, and continued growth in energy demand. In this study, an analysis was made of the impact of food on energy consumption, this being a necessary first step in evaluating methods to increase the efficiency of energy use in delivering food to consumers. The results obtained can also be used to assess the impact of increased fuel prices on food prices.

Personal consumption expenditures (PCE) (*2*) for food totaled $132 billion in 1970 (*3*). Between 1960 and 1970 the percentage of food dollars spent away from home (eating out) increased from 20 percent to 22 percent. This, plus a shift to more expensive food, accounted for an increase in food expenses. Although expenses rose during this decade, personal income grew more rapidly, so that food accounted for a smaller portion of the family budget in 1970 than in 1960.

Per capita food consumption (by weight, energy, and protein) remained comparatively stable during this decade (*3, 4*). Per capita expenditures increased significantly, but much of this was due to inflation. If one deflates the expenditure figures according to the food price index (*4*), one finds that the 25 percent increase in real (deflated) food expenditures was due in nearly equal measure to population growth and changes in consumption patterns. During the 1960's, per capita consumption of meat, poultry, fish, and processed fruits and vegetables increased, while consumption of fresh fruits and vegetables declined. Thus there was a slow but steady shift toward: expensive foods, such as beef; processed foods; and consumption of food away from home. These factors increased expenditures without affecting per capita consumption.

Energy Requirements for 1963

Table 1 summarizes the total costs, in terms of dollars, primary energy, and the amounts of electricity used, for personal consumption of food (PCE) in the United States in 1963 (*1, 5, 6*). The dollar cost for all food-related activities was $94 billion, 23 percent of disposable personal income. A total of 6100 trillion British thermal units, 12 percent of the total U.S. energy budget (*7*) for that year, was devoted, directly and indirectly (*8*), to the production, processing, transportation, sale, and consumption of food (*9*). This includes 190 billion kilowatt-hours, 22 percent of the total amount of electricity used in that year. Thus food accounts for a major part of the U.S. energy and electricity budgets (*10*).

Agriculture and processing together accounted for just over half of the food-related energy budget (Fig. 1). The household sector accounted for a surprisingly large percentage of the budget: 30 percent for cooking, refrigeration, freezing, and food shopping by car. Trade accounted for another 16 percent. Thus services associated with food used almost as much energy as did farming and processing.

The electricity used for food (Table 1) was distributed in a very different manner, with more than half of the kilowatt-hours used being devoted to residential use and only 30 percent to farming and processing.

Figure 1 presents primary energy results for 1963 on a per capita basis to show how the 32 million Btu per person was built up in the various sectors. This figure also shows the flow of energy from farming through process-

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Table 1. The total costs of food in the United States, in terms of dollars, energy, and electricity in 1963.

Sector	Cost (billion $)	Energy use (trillion Btu)	Electricity use (billion kw-hr)
Agriculture			
To PCE	4.5	231	4.1
To processing*	(15.8)	(862)	(15.6)
Food processing*	51.5	2868	51.3
Transportation	2.0	170	1.0
Trade	29.9	982	26.0
Households	6.1	1868	104.4
Total	94.0	6119	186.8

* Agricultural output delivered to processing (shown in parentheses) also appears in the figures for food processing.

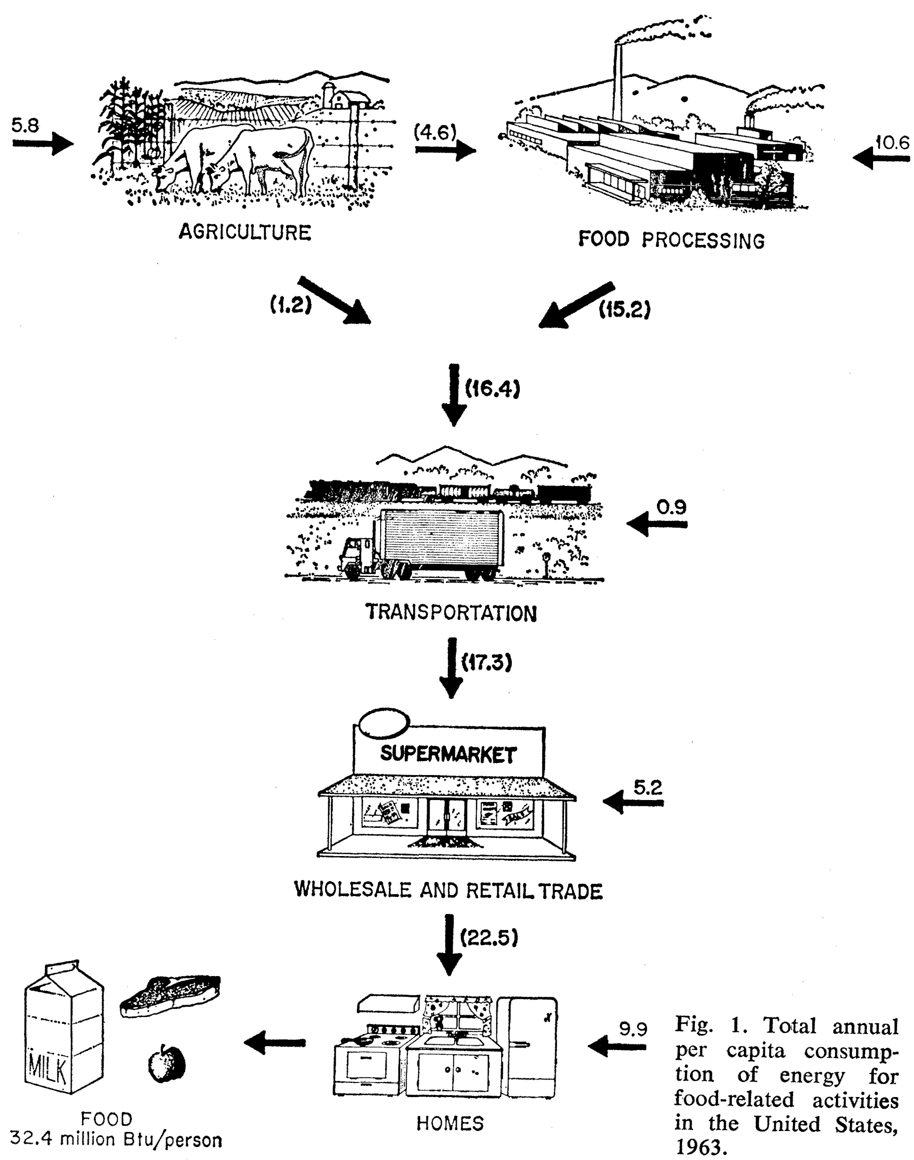

Fig. 1. Total annual per capita consumption of energy for food-related activities in the United States, 1963.

ing. The following paragraphs provide a few details (*1*) concerning the farming, processing, transportation, trade, and household sectors to show the basis for the figures given in Table 1 and Fig. 1.

In 1963, agricultural output (both food and nonfood products) totaled \$54 billion, of which 28 percent was consumed within the agricultural sectors themselves (consumption on farms, losses, and sales from one farm to another). Food processors purchased 42 percent, and other producers 14 percent; the remaining 16 percent was sold directly to final demand (consumers, exporters, and governments) (*11*).

The total amount of energy consumed in producing this agricultural output was 2190 trillion Btu, equal to 4.4 percent of the 1963 U.S. energy budget. Of this total amount of energy used for agriculture, 44 percent was consumed directly on farms for the operation of tractors, trucks, and other farm machinery and for irrigation, heating, ventilating, and crop conditioning. The remaining 56 percent (indirect energy use) was consumed in other sectors to produce fertilizers and other agricultural chemicals, petroleum products, and other farm supplies.

The total amount of electricity consumed in producing agricultural output was 36.3 billion kilowatt-hours, equal to 4.4 percent of the total amount of electricity used in the United States in 1963. Of this electricity used for agricultural output, 13.6 billion kilowatt-hours (37 percent) was consumed directly on farms for production purposes.

About half of the 1963 agricultural output was delivered to consumers (PCE), either directly or through food processors. A total of 1090 trillion Btu was consumed, directly and indirectly,

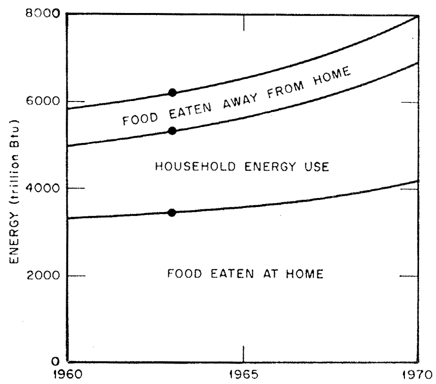

Fig. 2. Total energy requirements for farming, processing, transportation, delivery, and consumption of food in the United States.

by agriculture in providing food to PCE; this includes 19.7 billion kilowatt-hours of electricity. Considerably more energy (and electricity) was associated with meat than with plant products, although personal consumption of plant products is greater than consumption of meat on a weight basis.

About three-fourths of the appropriate totals (money, energy, electricity) flow through processing rather than directly to consumers, which suggests that most food receives some processing before delivery to final demand. The extent to which food is processed is related to the concentration of population in urban areas, family income, and the value of convenience. Of the \$74.3-billion gross output from food processing in 1963, 17 percent was consumed within the processing industry itself, 11 percent was sold to other producers, and the remaining 72 percent was delivered to final demand. Thus most of the processing output goes directly to consumers, rather than to other producers.

The total amount of energy consumed in producing processed food was 3540 trillion Btu, equal to 7.2 percent of the 1963 U.S. energy budget. Of this total, 28 percent was consumed directly by food processors. About half of the energy used indirectly for food processing flowed through the agricultural sectors as they delivered part of their output to processors.

The total amount of electricity used to process food was 63.4 billion kilowatt-hours, equal to 7.6 percent of the total amount of electricity used in the United States in 1963. Of this, the processing sector directly consumed 18.1 billion kilowatt-hours (28 percent). Again, about half of the electricity used indirectly for food processing flowed through agriculture.

A total of 2870 trillion Btu was consumed in 1963, directly and indirectly, by processors in providing food to PCE; this includes 51.3 billion kilowatt-hours of electricity. The major energy consumers were meat products, fluid milk, bakery products, and beverages.

Food is transported from farms and processing plants to wholesalers by railroad, truck, waterway, and airplane. In 1963, transportation of food to PCE cost \$2.0 billion, about 5 percent of the gross output from the transportation sector. The concomitant figures for energy and electricity use were 170 trillion Btu and 0.97 billion kilowatt-hours. These figures include indirect costs such as those related to the manufacture of trucks. (If the energy consumed in transporting materials to the agricultural and processing sectors and in transporting food from stores to homes by car were included here, the amount of energy used in association with the delivery of food to PCE would be more than tripled. This additional energy used for transportation is included in the figures for agriculture, processing, and households.)

Wholesale food trade used 250 trillion Btu (including 5 billion kilowatt-hours of electricity) in 1963. Retail trade consumed an additional 730 trillion Btu (including 21 billion kilowatt-hours) that year. The total bill for food trade then was 980 trillion Btu, 2 percent of the total amount of energy used nationally. This includes 26 billion kilowatt-hours, 3 percent of the total amount of electricity used. These figures again include indirect costs such as those for the construction of supermarkets and the manufacture of food storage equipment. Food trade consumed almost as much primary energy

Table 2. Estimates of food-related energy consumption.

Year	Primary energy use (trillion Btu)				Total per capita (million Btu)	Fraction of total U.S. energy budget (%)
	Food eaten		House-hold use	Total		
	At home*	On site†				
1960	3350	800	1660	5810	32.3	13.0
1963	3340	910	1870	6120	32.4	12.4
1965	3590	870	2090	6550	33.9	12.3
1967	3660	960	2280	6900	34.9	11.8
1970	4190	1090	2730	8010	39.3	11.9
	Average annual growth rate (%)					
	2.3	3.1	5.1	3.3	2.0	

* Food eaten at home includes food purchased for "off-premise" consumption and food produced and consumed on farms. † Food eaten on site includes purchased meals and beverages and food furnished to government and commercial employees.

as (and more electricity than) agriculture did in producing that food.

The residential sector consumes energy in storing food (refrigerators and freezers), in preparing food (stoves), and in transporting food from stores to homes (autos). In addition, energy is consumed by producers in delivering fuels to homes and in manufacturing and selling household kitchen equipment. Altogether, these activities cost \$6.1 billion and consumed 1870 trillion Btu (including 104 billion kilowatt-hours) in 1963. About 85 percent of this energy was associated with the operation of freezers, stoves, and refrigerators. The remainder was split evenly between appliance production and food shopping by car. This energy figure is 50 percent greater than energy used in growing food on farms.

Temporal Changes

The major part of this article deals with food-related energy for the year 1963, because that is the most recent year for which complete data are available. To estimate changes in patterns of energy consumption, one must know (i) how food expenditures changed and (ii) how energy coefficients changed. Answers to (i) are available in Department of Commerce (*3*) and Department of Agriculture (*4*) publications. Herendeen (*6*) suggests a simple, but approximate, method for scaling energy coefficients with time: the ratio of total national energy use to total gross national product.

Table 2 and Fig. 2 present estimates of the amount of energy used in food-related activities from 1960 to 1970. During this period, food-related energy use increased at an estimated annual rate of 3.3 percent, more than double the rate of population growth. Increased per capita food-related energy use accounted for 60 percent of the decade's increase in food-related energy use, while population growth accounted for 40 percent. The increase in per capita food-related energy use was due primarily to increased energy use for refrigerators, stoves, freezers, and automobiles. Changes in eating habits also contributed to increases in energy consumption.

Table 2 also shows that, while the amount of energy used in food-related activities increased during the 1960's, the fraction of the total national energy budget devoted to food declined slightly from 13 to 12 percent.

Energy Costs of Major Food Groups

The energy required to produce and deliver various types of food to consumers can be computed by matching energy flows through each input-output sector (*1*) with nutrient estimates from the Department of Agriculture (*4*). Figures 3 and 4 compare primary energy consumption for food with the energy content of food (that is, the amount of energy the food provides) and the protein content of food. The national averages for 1963 were 6.4 Btu of primary energy per British thermal unit of energy provided by food and 840 Btu of primary energy per gram of food protein. Thus the overall primary energy efficiency of the U.S. food system was 16 percent.

American agriculture required 0.011 Btu of human energy plus 1.14 Btu of primary energy per British thermal unit of agricultural output. Primitive societies that use no fuels require about six times as much human energy per unit of farm output (*12*). American farming achieves such high labor productivity by substituting fuels for labor, at a rate of 21 units of primary energy per unit of human energy. (This comparison of farming methods ignores likely differences in diet and nutrition.)

Figures 3 and 4 show the considerable variation in energy intensiveness among food groups. Processed fruits

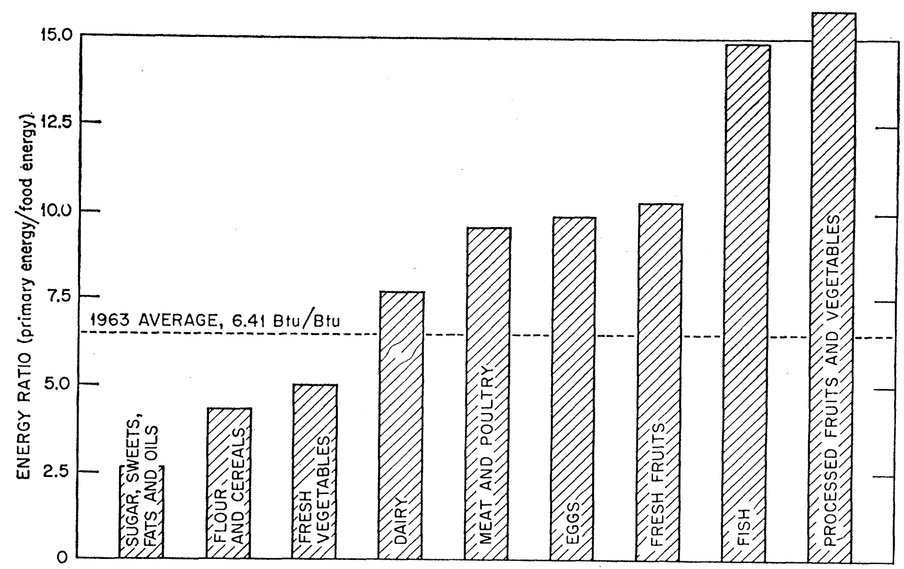

Fig. 3. Ratio of primary energy use to food energy content for major food groups, 1963.

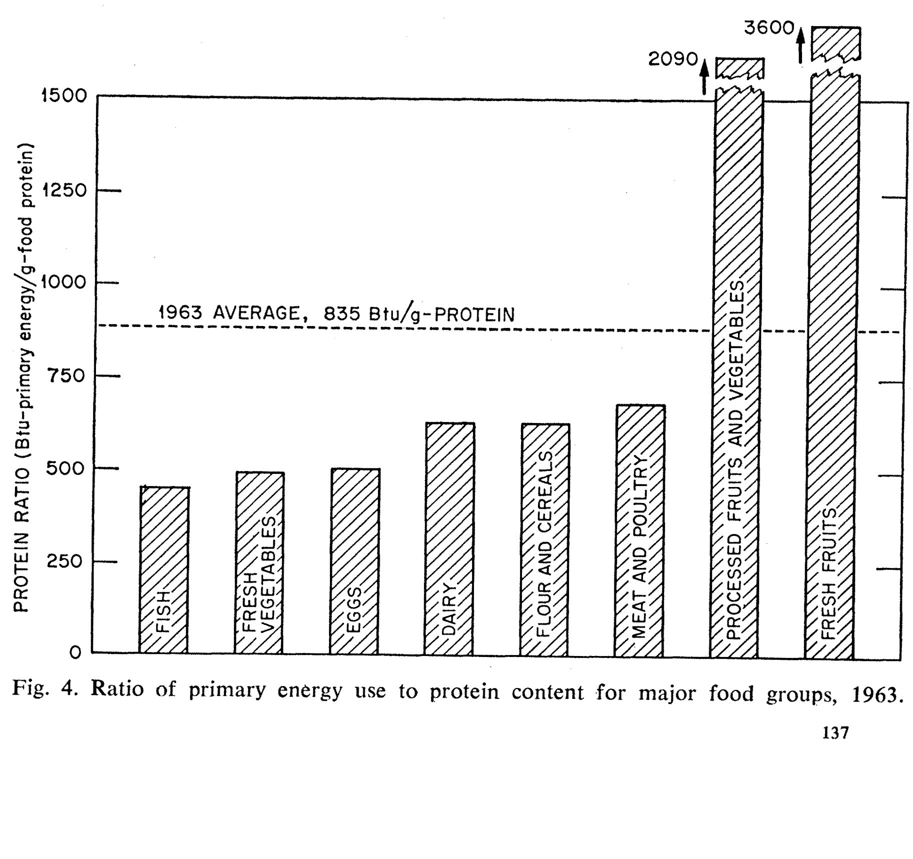

Fig. 4. Ratio of primary energy use to protein content for major food groups, 1963.

and vegetables are particularly energy-intensive with regard to both the energy they provide and their protein content. Flour and cereals, fresh vegetables, and dairy products, on the other hand, require relatively small energy inputs per unit of food nutrient. Also, fresh vegetables are a more energy-efficient source of protein than is meat.

Figure 5 shows how the total amount of energy used for food-related activities during 1963 was distributed among the major food groups. The largest proportion of energy was used for the meat, poultry, and fish group; followed by fruits and vegetables; and dairy products.

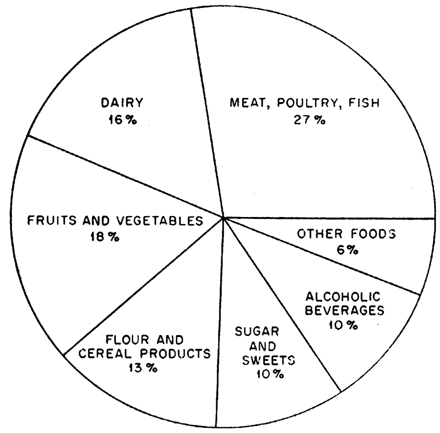

Fig. 5. Distribution of primary energy use for food by major food groups, 1963.

Conclusions

I have used data from input-output studies to determine the quantities of primary and electric energy consumed in the agricultural, processing, transportation, wholesale and retail trade, and household sectors for personal consumption of food.

Before one draws conclusions from these results, it is important to note the assumptions and approximations used in this analysis. First, the economic input-output data published by the Department of Commerce are subject to a number of inaccuracies, including lack of complete coverage for an industry, restriction of data for proprietary reasons, and use of different time periods for different data.

Second, aggregation can combine within the same sector industries whose energy intensities differ widely. For example, eating and drinking establishments probably consume more energy per dollar of sales (because of refrigerators, stoves, and freezers) than do department stores. However, both types of establishment are included in retail trade. Thus energy use for food-related retail trade may be underestimated because of aggregation.

Third, the energy coefficients are subject to error. In particular, the coefficients for the agricultural and trade sectors are vulnerable because energy use within these sectors is not well documented.

Finally, the scaling factor used to estimate food-related energy use for the 1960's is approximate, in that it neglects the possibility that these energy coefficients changed differently with time. Because of these limitations, which are described more fully by Herendeen (*6*), a number of important issues were not addressed here, such as relative energy requirements for fresh, frozen, and canned vegetables; and for soybeans as compared to beef.

This analysis shows that the U.S. food cycle consumes a considerable amount of energy, about 12 percent of the total national energy budget. The residential sector, which accounts for 30 percent of the total, is the most energy-intensive sector in terms of energy consumed per dollar of food-related expenditure. This is because food-related expenditures in homes are primarily for fuel to operate kitchen appliances and automobiles.

The electricity consumed in these activities constitutes 22 percent of the total amount used in the United States. More than half of the electricity is used in homes, and more than two-thirds in the trade and household sectors. Thus agriculture and processing consume little electricity relative to the total amount used.

From past trends, it appears that the amount of energy used in food-related activities will continue to increase at a rate faster than the population, principally because of growing affluence, that is, the use of processed foods, purchase of meals away from home, and the use of kitchen appliances equipped with energy-intensive devices, such as refrigerators with automatic icemakers. However, fuel shortages, rapidly increasing fuel prices, the growing need to import oil, and a host of other problems related to our use of energy suggest that these past trends will not continue. Fortunately, there are many ways to reduce the amounts of energy used for food-related activities.

In the home, for example, smaller refrigerators with thicker insulation would use less electricity than do present units. If closer attention were given to the use of ranges and ovens (for example, if oven doors were not opened so often) energy would be saved. Changes in eating habits could also result in energy savings. Greater reliance on vegetable and grain products, rather than meats, for protein would reduce fuel use. Similarly, a reduction in the amounts of heavily processed foods consumed—TV dinners and frozen desserts—would save energy.

Retailers could save energy by using closed freezers to store food and by reducing the amount of lighting they use. Processors could use heat recovery methods, more efficient processes, and less packaging. Shipping more food by train rather than by truck would also cut energy use.

Farmers could reduce their fuel use by combining operations (for example, by harrowing, planting, and fertilizing in the same operation), by reducing tillage practices, by increasing the use of diesel rather than gasoline engines, and by increasing labor inputs. A partial return to organic farming (that is, greater use of animal manure and crop rotation) would save energy because chemical fertilizers require large energy inputs for their production.

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6. R. A. Herendeen, *The Energy Cost of Goods and Services* (Oak Ridge National Laboratory Report ORNL-NSF-EP-58, Oak Ridge, Tenn., October 1971).
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8. Total energy use is the sum of direct and indirect energy uses. Direct energy is that energy consumed within the sector considered; indirect energy is energy consumed in other producing sectors whose output is (in part) required to deliver output from the sector considered.
9. One British thermal unit is equivalent to 1055 joules.
10. Primary energy refers to the energy content of the basic fuels—coal, oil, natural gas, falling water, nuclear fuels. Electricity is a secondary energy form since it is derived from the basic fuels.
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