Energy Use in the U.S. Food System

John S. Steinhart and Carol E. Steinhart

In a modern industrial society, only a tiny fraction of the population is in frequent contact with the soil, and an even smaller fraction of the population raises food on the soil. The proportion of the population engaged in farming halved between 1920 and 1950 and then halved again by 1962. Now it has almost halved again, and more than half of these remaining farmers hold other jobs off the farm (*1*). At the same time the number of work animals has declined from a peak of more than 22×10^6 in 1920 to a very small number at present (*2*). By comparison with earlier times, fewer farmers are producing more agricultural products and the value of food in terms of the total goods and services of society now amounts to a smaller fraction of the economy than it once did.

Energy inputs to farming have increased enormously during the past 50 years (*3*), and the apparent decrease in farm labor is offset in part by the growth of support industries for the farmer. With these changes on the farm have come a variety of other changes in the U.S. food system, many of which are now deeply embedded in the fabric of daily life. In the past 50 years, canned, frozen, and other processed foods have become the principal items of our diet. At present, the food processing industry is the fourth largest energy consumer of the Standard Industrial Classification groupings (*4*). The extent of transportation engaged in the food system has grown apace, and the proliferation of appliances in both numbers and complexity still continues in homes, institutions, and stores. Hardly any food is eaten as it comes from the fields. Even farmers purchase most of their food from markets in town.

Present energy supply problems make this growth of energy use in the food system worth investigating. It is our purpose in this article to do so. But there are larger matters at stake. Georgescu-Roegen notes that "the evidence now before us—of a world which can produce automobiles, television sets, etc., at a greater speed than the increase in population, but is simultaneously menaced by mass starvation—is disturbing" (*5*). In the search for a solution to the world's food problems, the common attempt to transplant a small piece of a highly industrialized food system to the hungry nations of the world is plausible enough, but so far the outcome is unclear. Perhaps an examination of the energy flow in the U.S. food system as it has developed can provide some insights that are not available from the usual economic measures.

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Measures of Food Systems

Agricultural systems are most often described in economic terms. A wealth of statistics is collected in the United States and in most other technically advanced countries indicating production amounts, shipments, income, labor, expenses, and dollar flow in the agricultural sector of the economy. But, when we wish to know something about the food we actually eat, the statistics of farms are only a tiny fraction of the story.

Energy flow is another measure available to gauge societies and nations. It would have made no sense to measure societies in terms of energy flow in the 18th century when economics began. As recently as 1940, four-fifths of the world's population were still on farms and in small villages, most of them engaged in subsistence farming.

Only after some nations shifted large portions of the population to manufacturing, specialized tasks, and mechanized food production, and shifted the prime sources of energy to move society to fuels that were transportable and usable for a wide variety of alternative activities, could energy flow be used as a measure of societies' activities. Today it is only in one-fifth of the world where these conditions are far advanced. Yet we can now make comparisons of energy flows even with primitive societies. For even if the primitives, or the euphemistically named "underdeveloped" countries, cannot shift freely among their energy expenditures, we *can* measure them and they constitute a different and potentially useful comparison with the now traditional economic measures.

What we would like to know is: How does our present food supply system compare, in energy measures, with those of other societies and with our own past? Perhaps then we can estimate the value of energy flow measures as an adjunct to, but different from, economic measures.

Energy in the U.S. Food System

A typical breakfast includes orange juice from Florida by way of the Minute Maid factory, bacon from a midwestern meat packer, cereal from Nebraska and General Mills, eggs and milk from not *too* far away, and coffee from Colombia. All of these things are available at the local supermarket (several miles each way in a 300-horsepower automobile), stored in a refrigerator-freezer, and cooked on an instant-on stove.

The present food system in the United States is complex, and the attempt to analyze it in terms of energy use will introduce complexities and questions far more perplexing than the same analysis carried out on simpler societies. Such an analysis is worthwhile, however, if only to find out where we stand. We have a food system, and most people get enough to eat from it. If, in addition, one considers the food supply problems present and future in societies where a smaller fraction of the people get enough to eat, then our experience with an industrialized food system is even more important. There is simply no gainsaying that many nations of the world are presently attempting to acquire industrialized food systems of their own.

Food in the United States is expensive by world standards. In 1970 the average annual per capita expenditure for food was about $600 (*3*). This amount is larger than the per capita gross domestic product of more than 30 nations of the world which contain the majority of the world's people and a vast majority of those who are under-

← *Courtesy U.S. Department of Agriculture, Washington, D.C.*

fed. Even if we consider the diet of a poor resident of India, the annual cost of his food at U.S. prices would be about \$200—more than twice his annual income (*3*). It is crucial to know whether a piece of our industrialized food system can be exported to help poor nations, or whether they must become as industrialized as the United States to operate an industrialized food system.

Our analysis of energy use in the food system begins with an omission. We will neglect that crucial input of energy provided by the sun to the plants upon which the entire food supply depends. Photosynthesis has an efficiency of about 1 percent; thus the maximum solar radiation captured by plants is about 5×10^3 kilocalories per square meter per year (*3*).

Seven categories of energy use on the farm are considered here. The amounts of energy used are shown in Table 1. The values given for farm machinery and tractors are for the manufacture of new units only and do not include parts and maintenance for units that already exist. The amounts shown for direct fuel use and electricity consumption are a bit too high because they include some residential uses of the farmer and his family. On the other hand, some uses in these categories are not reported in the summaries used to obtain the values for direct fuel and electricity usage. These and similar problems are discussed in the references. Note the relatively high energy cost associated with irrigation. In the United States less than 5 percent of the cropland is irrigated (*1*). In some countries where the "green revolution" is being attempted, the new high-yield varieties of plants require irrigation where native crops did not. If that were the case in the United States, irrigation would be the largest single use of energy on the farm.

Little food makes its way directly from field and farm to the table. The vast complex of processing, packaging, and transport has been grouped together in a second major subdivision of the food system. The seven categories of the processing industry are listed in Table 1. Energy use for the transport of food should be charged to the farm in part, but we have not done so here because the calculation of the energy values is easiest (and we believe most accurate) if they are taken for the whole system.

After the processing of food there is further energy expenditure. Transportation enters the picture again, and some fraction of the energy used for transportation should be assigned here. But there are also the distributors, wholesalers, and retailers, whose freezers, refrigerators, and very establishments are an integral part of the food system. There are also the restaurants, schools, universities, prisons, and a host of other institutions engaged in the procurement, preparation, storage, and supply of food. We have chosen to examine only three categories: the energy required for refrigeration and cooking, and for the manufacture of the heating and refrigeration equipment (Table 1). We have made no attempt to include the energy used in trips to the store or restaurant. Garbage disposal has also been omitted, although it is a persistent and growing feature of our food system; 12 percent of the nation's trucks are engaged in the activity of waste disposal (*1*), of which a substantial part is related to food. If there is any lingering doubt that these activities—both the ones included and the ones left out—are an essential feature of our present food system, one need only ask what would happen if everyone should attempt to get on without a refrigerator or freezer or stove? Certainly the food system would change.

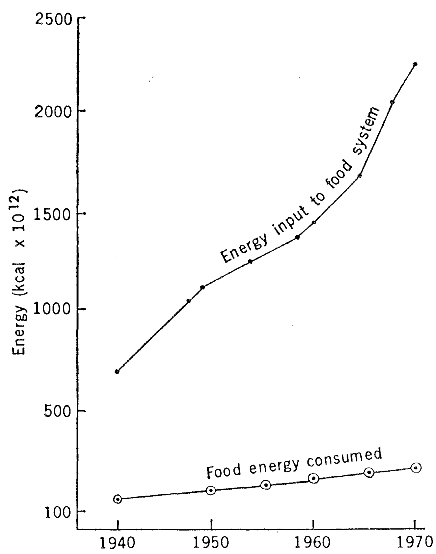


Fig. 1. Energy use in the food system, 1940 through 1970, compared to the caloric content of food consumed.

Table 1 and the related references summarize the numerical values for energy use in the U.S. food system, from 1940 to 1970. As for many activities in the past few decades, the story is one of continuing increase. The totals are displayed in Fig. 1 along with the energy value of the food consumed by the public. The food values were obtained by multiplying the daily caloric intake by the population. The differences in caloric intake per capita over this 30-year period are small (*1*), and the curve is primarily an indication of the increase in population in this period.

Omissions and Duplications for Food System Energy Values

Several omissions, duplications, and overlaps have been mentioned. We will now examine the values in Table 1 for completeness and try to obtain a crude estimate of their numerical accuracy.

The direct fuel and electricity usage on the farm may be overstated by some amounts used in the farmer's household, which, by our approach, would not all be chargeable to the food system. But about 10 percent of the total acreage farmed is held by corporate farms for which the electrical and direct fuel use is not included in our data. Other estimates of these two categories are much higher [see Table 1 (*15, 16*)].

No allowance has been made for food exported, which has the effect of overstating the energy used in our own food system. For the years prior to 1960 the United States was at times a net importer of food, at times an exporter, and at times there was a near balance in this activity. But during this period the net flow of trade was never more than a few percent of the total farm output. Since 1960 net exports have increased to about 20 percent of the gross farm product (*1, 3*). The items comprising the vast majority of the exports have been rough grains, flour, and other plant products with very little processing. Imports include more processed food than exports and represent energy expenditure outside the United States. Thus the overestimate of energy input to the food system might be 5 percent with an upper limit of 15 percent.

The items omitted are more numerous. Fuel losses from the wellhead or mineshaft to end use total 10 to 12 percent (*6*). This would represent a flat addition of 10 percent or more to the totals, but we have not included this item because it is not customarily charged to end uses.

We have computed transport energy

for trucks only. Considerable food is transported by train and ship, but these items were omitted because the energy use is small relative to the consumption of truck fuel. Small amounts of food are shipped by air, and, although air shipment is energy-intensive, the amount of energy consumed appears small. We have traced support materials until they could no longer be assigned to the food system. Some transportation energy consumption is not charged in the transport of these support materials. These omissions are numerous and hard to estimate, but they would not be likely to increase the totals by more than 1 or 2 percent.

A more serious understatement of energy usage occurs with respect to vehicle usage (other than freight transport) on farm business, food-related business in industry and commercial establishments, and in the supporting industries. A special attempt to estimate this category of energy usage for 1968 suggests that it amounts to about 5 percent of the energy totals for the food system. This estimate would be subject to an uncertainty of nearly 100 percent. We must be satisfied to suggest that 1 to 10 percent should be added to the totals on this account.

Waste disposal is related to the food system, at least in part. We have chosen not to charge this energy to the food system, but, if one-half of the waste disposal activity is taken as food-related, about 2 percent must be added to the food system energy totals.

We have not included energy for parts and maintenance of machinery, vehicles, buildings, and the like, or lumber for farm, industry, or packaging uses. These miscellaneous activities would not constitute a large addition in any case. We have also excluded construction. Building and replacement of farm structures, food industry structures, and commercial establishments are all directly part of the food system. Construction of roads is in some measure related to the food system, since nearly half of all trucks transport food and agricultural items [see Table 1 (*27*)]. Even home construction could be charged in part to the food system since space, appliances, and plumbing are, in part, a consequence of the food system. If 10 percent of housing, 10 percent of institutional construction (for institutions with food service), and 10 percent of highway construction is included, about 10 percent of the total construction was food-related in 1970. Assuming that the total energy consumption divides in the same way that the Gross National Product does (which overstates energy use in construction), the addition to the total in Table 1 would be about 10 percent or 200×10^{12} kcal. This is a crude and highly simplified calculation, but it does provide an estimate of the amounts of energy involved.

The energy used to generate the highly specialized seed and animal stock has been excluded because there is no easy way to estimate it. Pimentel *et al.* (*3*) estimate that 1800 kcal are required to produce 1 pound (450 grams) of hybrid corn seed. But in addition to this amount, some energy use should be included for all the schools of agriculture, agricultural experiment stations, the far-flung network of county agricultural agents [one local agent said he traveled over 50,000 automobile miles (80,000 kilometers) per year in his car], the U.S. Department of Agriculture, and the wide-ranging agricultural research program that enables man to stay ahead of the new pest and disease threats to our highly specialized food crops. These are extensive activities but we cannot see how they could add more than a few percent to the totals in Table 1.

Finally, we have made no attempt to include the amount of private automobile usage involved in the delivery system from retailer to home, or other food-related uses of private autos. Rice (*7*) reports 4.25×10^{15} kcal for the energy cost of autos in 1970, and shopping constitutes 15.2 percent of all automobile usage (*8*). If only half of the shopping is food-related, 320×10^{12} kcal of energy use is at stake here.

Table 1. Energy use in the United States food system. All values are multiplied by 10^{12} kcal.

Component	1940	1947	1950	1954	1958	1960	1964	1968	1970	References
On farm										
Fuel (direct use)	70.0	136.0	158.0	172.8	179.0	188.0	213.9	226.0	232.0	(*13–15*)
Electricity	0.7	32.0	32.9	40.0	44.0	46.1	50.0	57.3	63.8	(*14, 16*)
Fertilizer	12.4	19.5	24.0	30.6	32.2	41.0	60.0	87.0	94.0	(*14, 17*)
Agricultural steel	1.6	2.0	2.7	2.5	2.0	1.7	2.5	2.4	2.0	(*14, 18*)
Farm machinery	9.0	34.7	30.0	29.5	50.2	52.0	60.0	75.0	80.0	(*14, 19*)
Tractors	12.8	25.0	30.8	23.6	16.4	11.8	20.0	20.5	19.3	(*20*)
Irrigation	18.0	22.8	25.0	29.6	32.5	33.3	34.1	34.8	35.0	(*21*)
Subtotal	124.5	272.0	303.4	328.6	356.3	373.9	440.5	503.0	526.1	
Processing industry										
Food processing industry	147.0	177.5	192.0	211.5	212.6	224.0	249.0	295.0	308.0	(*13, 14, 22*)
Food processing machinery	0.7	5.7	5.0	4.9	4.9	5.0	6.0	6.0	6.0	(*23*)
Paper packaging	8.5	14.8	17.0	20.0	26.0	28.0	31.0	35.7	38.0	(*24*)
Glass containers	14.0	25.7	26.0	27.0	30.2	31.0	34.0	41.9	47.0	(*25*)
Steel cans and aluminum	38.0	55.8	62.0	73.7	85.4	86.0	91.0	112.2	122.0	(*26*)
Transport (fuel)	49.6	86.1	102.0	122.3	140.2	153.3	184.0	226.6	246.9	(*27*)
Trucks and trailors (manufacture)	28.0	42.0	49.5	47.0	43.0	44.2	61.0	70.2	74.0	(*28*)
Subtotal	285.8	407.6	453.5	506.4	542.3	571.5	656.0	787.6	841.9	
Commercial and home										
Commercial refrigeration and cooking	121.0	141.0	150.0	161.0	176.0	186.2	209.0	241.0	263.0	(*13, 29*)
Refrigeration machinery (home and commercial)	10.0	24.0	25.0	27.5	29.4	32.0	40.0	56.0	61.0	(*14, 30*)
Home refrigeration and cooking	144.2	184.0	202.3	228.0	257.0	276.6	345.0	433.9	480.0	(*13, 29*)
Subtotal	275.2	349.0	377.3	416.5	462.4	494.8	594.0	730.9	804.0	
Grand total	685.5	1028.6	1134.2	1251.5	1361.0	1440.2	1690.5	2021.5	2172.0	

Between 8 and 15 percent should be added to the totals of Table 1, depending on just how one wishes to apportion this item.

It is hard to take an approach that might calculate smaller totals but, depending upon point of view, the totals could be much larger. If we accumulate the larger estimates from the above paragraphs as well as the reductions, the total could be enlarged by 30 to 35 percent, especially for recent years. As it is, the values for energy use in the food system from Table 1 account for 12.8 percent of the total U.S. energy use in 1970.

Performance of an Industrialized Food System

The difficulty with history as a guide for the future or even the present lies not so much in the fact that conditions change—we are continually reminded of that fact—but that history is only one experiment of the many that might have occurred. The U.S. food system developed as it did for a variety of reasons, many of them not understood. We would do well to examine some of the dimensions of this development before attempting to theorize about how it might have been different, or how parts of this food system can be transplanted elsewhere.

Energy and Food Production

Figure 2 displays features of our food system not easily seen from economic data. The curve shown has no theoretical basis but is suggested by the data as a smoothed recounting of our own history of increasing food production. It is, however, similar to most growth curves and suggests that, to the extent that the increasing energy subsidies to the food system have increased food production, we are near the end of an era. Like the logistic growth curve, there is an exponential phase which lasted from 1920 or earlier until 1950 or 1955. Since then, the increments in production have been smaller despite the continuing growth in energy use. It is likely that further increases in food production from increasing energy inputs will be harder and harder to come by. Of course, a major change in the food system could change things, but the argument advanced by the technological optimist is that we can always get more if we

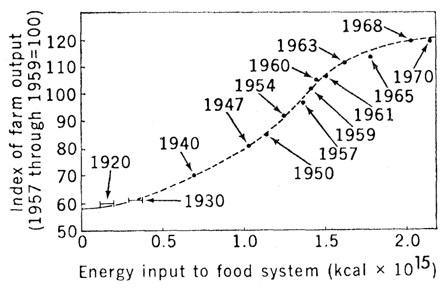


Fig. 2. Farm output as a function of energy input to the U.S. food system, 1920 through 1970.

have enough energy, and that no other major changes are required. Our own history—the only one we have to examine—does not support that view.

Energy and Labor in the Food System

One farmer now feeds 50 people, and the common expectation is that the labor input to farming will continue to decrease in the future. Behind this expectation is the assumption that the continued application of technology—and energy—to farming will substitute for labor. Figure 3 shows this historic decline in labor as a function of the energy supplied to the food system, again the familiar S-shaped curve. What it implies is that increasing the energy input to the food system is unlikely to bring further reduction in farm labor unless some other, major change is made.

The food system that has grown in this period has provided much employment that did not exist 20, 30, or 40 years ago. Perhaps even the idea of a reduction of labor input is a myth when the food system is viewed as a whole, instead of from the point of view of the farm worker only. When discussing

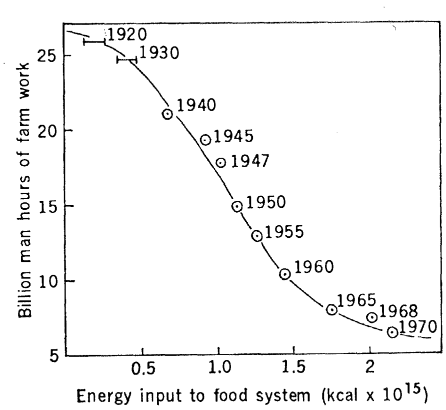


Fig. 3. Labor use on farms as a function of energy use in the food system.

inputs to the farm, Pimentel *et al.* (*3*) cite an estimate of two farm support workers for each person actually on the farm. To this must be added employment in food-processing industries, in food wholesaling and retailing, as well as in a variety of manufacturing enterprises that support the food system. Yesterday's farmer is today's canner, tractor mechanic, and fast food carhop. The process of change has been painful to many ordinary people. The rural poor, who could not quite compete in the growing industrialization of farming, migrated to the cities. Eventually they found other employment, but one must ask if the change was worthwhile. The answer to that question cannot be provided by energy analysis anymore than by economic data, because it raises fundamental questions about how individuals would prefer to spend their lives. But if there is a stark choice between long hours as a farmer or shorter hours on the assembly line of a meat-packing plant, it seems clear that the choice would not be universally in favor of the meat-packing plant. Thomas Jefferson dreamed of a nation of independent small farmers. It was a good dream, but society did not develop in that way. Nor can we turn back the clock to recover his dream. But, in planning and preparing for our future, we had better look honestly at our collective history, and then each of us should closely examine his dreams.

The Energy Subsidy to the Food System

The data in Fig. 1 can be combined to show the energy subsidy provided to the food system for the recent past. We take as a measure of the food supplied the caloric content of the food actually consumed. This is not the only measure of the food supplied, as the condition of many protein-poor peoples of the world clearly shows. Nevertheless, the comparison between caloric input and output is a convenient way to compare our present situation with the past, and to compare our food system with others. Figure 4 shows the history of the U.S. food system in terms of the number of calories of energy supplied to produce 1 calorie of food for actual consumption. It is interesting and possibly threatening to note that there is no real suggestion that this curve is leveling off. We appear to be increasing the energy input even more. Fragmentary data for 1972 suggest that the increase continued unabated. A graph like Fig. 4 could approach zero. A natural ecosystem has no fuel input at all, and those primitive people who live by hunting and gathering have only the energy of their own work to count as input.

Some Economic Features of the U.S. Food System

The markets for farm commodities in the United States come closer than most to the economist's ideal of a "free market." There are many small sellers and many buyers, and thus no individual is able to affect the price by his own actions in the marketplace. But government intervention can drastically alter any free market, and government intervention in the prices of agricultural products (and hence of food) has been a prominent feature of the U.S. food system for at least 30 years. Between 1940 and 1970, total farm income has ranged from $4.5 to $16.5 billion, and the National Income originating in agriculture (which includes indirect income from agriculture) has ranged from $14.5 to $22.5 billion (*1*). Meanwhile, government subsidy programs, primarily farm price supports and soil bank payments, have grown from $1.5 billion in 1940 to $6.2 billion in 1970. In 1972 these subsidy programs had grown to $7.3 billion, despite foreign demand of agricultural products. Viewed in a slightly different way, direct government subsidies have accounted for 30 to 40 percent of the farm income and 15 to 30 percent of the National Income attributable to agriculture for the years since 1955. This point emphasizes once again the striking gap between the economic description of society and the economic models used to account for that society's behavior.

This excursion into farm price supports and economics is related to energy questions in this way: first, so far as we know, government intervention in the food system is a feature of all highly industrialized countries (and, despite the intervention, farm incomes still tend to lag behind national averages); and, second, reduction of the energy subsidy to agriculture (even if we could manage it) might decrease the farmer's income. One reason for this state of affairs is that the demand for food quantity has definite limits, and the only way to increase farm income is then to increase the unit price of agricultural products. Consumer boycotts and protests in the early 1970's suggest that there is considerable resistance to this outcome.

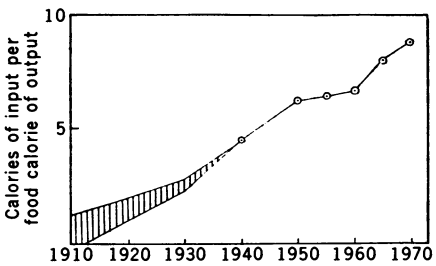


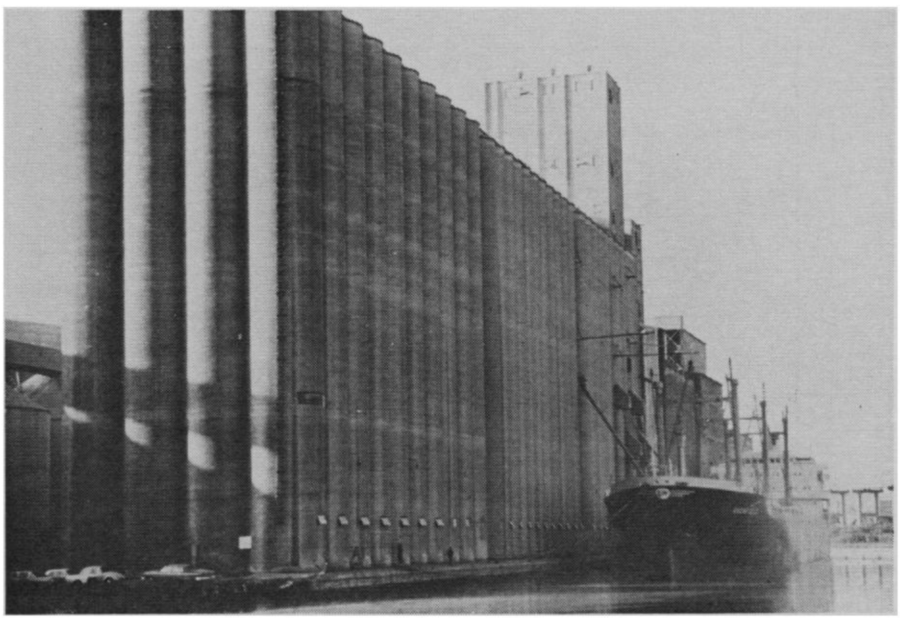
Fig. 4. Energy subsidy to the food system needed to obtain 1 food calorie.

Government intervention in the functioning of the market in agricultural products has accompanied the rise in the use of energy in agriculture and the food supply system, and we have nothing but theoretical suppositions to suggest that any of the present system can be deleted.

Some Energy Implications for the World Food Supply

The food supply system of the United States is complex and interwoven into a highly industrialized economy. We have tried to analyze this system on account of its implications for future energy use. But the world is short of food. A few years ago it was widely predicted that the world would suffer widespread famine in the 1970's. The adoption of new high-yield varieties of rice, wheat, and other grains has caused some experts to predict that the threat of these expected famines can now be averted, perhaps indefinitely. Yet, despite increases in grain production in some areas, the world still seems to be headed toward famine. The adoption of these new varieties of grain—dubbed hopefully the "green revolution"—is an attempt to export a part of the energy-intensive food system of the highly industrialized countries to nonindustrialized countries. It is an experiment, because, although the whole food system is not being transplanted to new areas, a small part of it is. The green revolution requires a great deal of energy. Many of the new varieties of grain require irrigation where traditional crops did not, and almost all the new crops require extensive fertilization.

Meanwhile, the agricultural surpluses of the 1950's have largely disappeared. Grain shortages in China and Russia have attracted attention because they have brought foreign trade across ideological barriers. There are other countries that would probably import considerable grain, if they could afford it. But only four countries may be expected to have any substantial excess agricultural production in the next decade. These are Canada, New Zealand, Australia, and the United States. None of these is in a position to give grain away, because each of them needs the foreign trade to avert ruinous balance of payments deficits. Can we then export energy-intensive agricultural methods instead?



Giant grain elevators are only a first step in the storage, processing, and distribution portions of the food system. [Source: Marine Studies Center, University of Wisconsin]

Energy-Intensive Agriculture Abroad

It is quite clear that the U.S. food system cannot be exported intact at present. For example, India has a population of 550×10^6 persons. To feed the people of India at the U.S. level of about 3000 food calories per day (instead of their present 2000) would require more energy than India now uses for all purposes. To feed the entire world with a U.S. type food system, almost 80 percent of the world's annual energy expenditure would be required just for the food system.

The recourse most often suggested to remedy this difficulty is to export methods of increasing crop yield and hope for the best. We must repeat as plainly as possible that this is an experiment. We know that our food system works (albeit with some difficulties and warnings for the future). But we cannot know what will happen if we take a piece of that system and transplant it to a poor country, without our industrial base of supply, transport system, processing industry, appliances for home storage, and preparation, and, most important of all, a level of industrialization that permits higher costs for food.

Fertilizers, herbicides, pesticides, and in many cases machinery and irrigation are needed for success with the green revolution. Where is this energy to come from? Many of the nations with the most serious food problems are those nations with scant supplies of fossil fuels. In the industrialized nations, solutions to the energy supply problems are being sought in nuclear energy. This technology-intensive solution, even if successful in advanced countries, poses additional problems for underdeveloped nations. To create the bases of industry and technologically sophisticated people within their own countries will be beyond the capability of many of them. Here again, these countries face the prospect of depending upon the goodwill and policies of industrialized nations. Since the alternative could be famine, their choices are not pleasant and their irritation at their benefactors—ourselves among them—could grow to threatening proportions. It would be comfortable to rely on our own good intentions, but our good intentions have often been unresponsive to the needs of others. The matter cannot be glossed over lightly. World peace may depend upon the outcome.

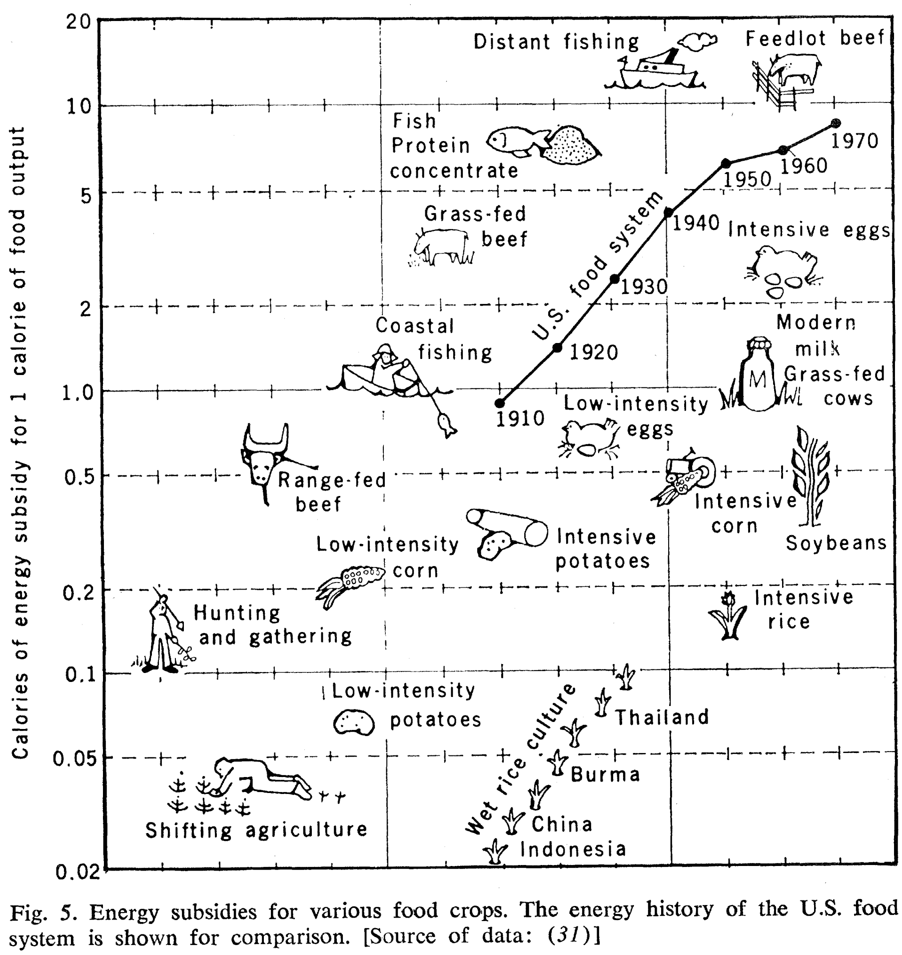


Fig. 5. Energy subsidies for various food crops. The energy history of the U.S. food system is shown for comparison. [Source of data: (*31*)]

Choices for the Future

The total amount of energy used on U.S. farms for the production of corn is now near 10^3 kcal per square meter per year (*3*), and this is more or less typical of intensive agriculture in the United States. With this application of energy we have achieved yields of 2×10^3 kcal per square meter per year of usable grain—bringing us to almost half of the photosynthetic limit of production. Further applications of energy are likely to yield little or no increase in this level of productivity. In any case, no amount of research is likely to improve the efficiency of the photosynthetic process itself. There is a further limitation on the improvement of yield. Faith in technology and research has at times blinded us to the basic limitations of the plant and animal material with which we work. We have been able to emphasize desirable features already present in the gene pool and to suppress others that we find undesirable. At times the cost of the increased yield has been the loss of desirable characteristics—hardiness, resistance to disease and adverse weather, and the like. The farther we get from characteristics of the original plant and animal strains, the more care and energy is required. Choices need to be made in the directions of plant breeding. And the limits of the plants and animals we use must be kept in mind. We have not been able to alter the photosynthetic process or to change the gestation period of animals. In order to amplify or change an existing characteristic, we will probably have to sacrifice something in the overall performance of the plant or animal. If the change requires more energy, we could end with a solution that is too expensive for the people who need it most. These problems are intensified by the degree to which energy becomes more expensive in the world market.

Where Next to Look for Food?

Our examination in the foregoing pages of the U.S. food system, the limitations on the manipulation of ecosystems and their components, and the risks of the green revolution as a solution to the world food supply problem suggests a bleak prospect for the future. This complex of problems should not be underestimated, but there are possible ways of avoiding disaster and of mitigating the severest difficulties.

These suggestions are not very dramatic and may be difficult of common acceptance.

Figure 5 shows the ratio of the energy subsidy to the energy output for a number of widely used foods in a variety of times and cultures. For comparison, the overall pattern for the U.S. food system is shown, but the comparison is only approximate because, for most of the specific crops, the energy input ends at the farm. As has been pointed out, it is a long way from the farm to the table in industrialized societies. Several things are immediately apparent and coincide with expectations. High-protein foods such as milk, eggs, and especially meat, have a far poorer energy return than plant foods. Because protein is essential for human diets and the amino acid balance necessary for good nutrition is not found in most of the cereal grains, we cannot take the step of abandoning meat sources altogether. Figure 5 does show how unlikely it is that increased fishing or fish protein concentrate will solve the world's food problems. Even if we leave aside the question of whether the fish are available—a point on which expert opinions differ somewhat—it would be hard to imagine, with rising energy prices, that fish protein concentrate will be anything more than a by-product of the fishing industry, because it requires more than twice the energy of production of grass-fed beef or eggs (*9*). Distant fishing is still less likely to solve food problems. On the other hand, coastal fishing is relatively low in energy cost. Unfortunately, without the benefit of scholarly analysis fisherman and housewives have long known this, and coastal fisheries are threatened with overfishing as well as pollution.

The position of soybeans in Fig. 5 may be crucial. Soybeans possess the best amino acid balance and protein content of any widely grown crop. This has long been known to the Japanese who have made soybeans a staple of their diet. Are there other plants, possibly better suited for local climates, that have adequate proportions of amino acids in their proteins? There are about 80,000 edible species of plants, of which only about 50 are actively cultivated on a large scale (and 90 percent of the world's crops come from only 12 species). We may yet be able to find species that can contribute to the world's food supply.

The message of Fig. 5 is simple. In "primitive" cultures, 5 to 50 food calories were obtained for each calorie of energy invested. Some highly civilized cultures have done as well and occasionally better. In sharp contrast, industrialized food systems require 5 to 10 calories of fuel to obtain 1 food calorie. We must pay attention to this difference—especially if energy costs increase. If some of the energy subsidy for food production could be supplied by on-site, renewable sources—primarily sun and wind—we might be able to continue an energy-intensive food system. Otherwise, the choices appear to be either less energy-intensive food production or famine for many areas of the world.

A Wisconsin farm about 1910. Extensive changes in food production and farm life are part of the food system. [Source: Wisconsin Historical Society]

Energy Reduction in Agriculture

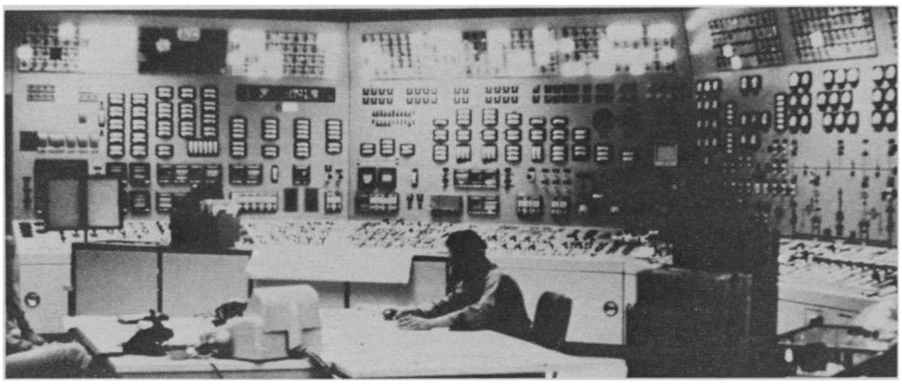
It is possible to reduce the energy required for agriculture and the food system. A series of thoughtful proposals by Pimentel and his associates (*3*) deserves wide attention. Many of these proposals would help ameliorate environmental problems, and any reductions in energy use would provide a direct reduction in the pollutants due to fuel consumption as well as more time to solve our energy supply problems.

First, we should make more use of natural manures. The United States has a pollution problem from runoff from animal feedlots, even with the application of large amounts of manufactured fertilizer to fields. More than 10^6 kcal per acre (4×10^5 kcal per hectare) could be saved by substituting manure for manufactured fertilizer (*3*) (and, as a side benefit, the soil's condition would be improved). Extensive expansion in the use of natural manure will require decentralization of feedlot operations so that manure is generated closer to the point of application. Decentralization might increase feedlot costs, but, as energy prices rise, feedlot operations will rapidly become more expensive in any case. Although the use of manures can help reduce energy use, there is far too little to replace all commercial fertilizers at present (*10*). Crop rotation is less widely practiced than it was even 20 years ago. Increased use of crop rotation or interplanting winter cover crops of legumes (which fix nitrogen as a green manure) would save 1.5×10^6 kcal per acre by comparison with the use of commercial fertilizer.

Second, weed and pest control could be accomplished at a much smaller cost in energy. A 10 percent saving in energy in weed control could be obtained by the use of the rotary hoe twice in cultivation instead of herbicide application (again with pollution abatement as a side benefit). Biologic pest control —that is, the use of sterile males, introduced predators, and the like—requires only a tiny fraction of the energy of pesticide manufacture and application. A change to a policy of "treat when and where necessary" pesticide application would bring a 35 to 50 percent reduction in pesticide use. Hand application of pesticides requires more labor than machine or aircraft application, but the energy for application is reduced from 18,000 to 300 kcal per acre (*3*). Changed cosmetic standards, which in no way affect the taste or the edibility of foodstuffs, could also bring about a substantial reduction in pesticide use.

Third, plant breeders might pay more attention to hardiness, disease and pest resistance, reduced moisture content (to end the wasteful use of natural gas in drying crops), reduced water requirements, and increased protein content, even if it should mean some reduction in overall yield. In the longer run, plants not now widely cultivated might receive some serious attention and breeding efforts. It seems unlikely that the crops that have been most useful in temperate climates will be the most suitable ones for the tropics where a large portion of the undernourished peoples of the world now live.

Commercial and institution food service has grown by almost 20 percent in the past decade. [Source: Marine Studies Center, University of Wisconsin]


Use of electricity in the food system has been growing at least as rapidly as for the United States as a whole. This nuclear power plant control room is another part of the food system. [Source: Marine Studies Center, University of Wisconsin]

Behind the food system at every stage is the fuel production, refining, and distribution system. [Source: Marine Studies Center, University of Wisconsin]

A dramatic suggestion, to abandon chemical farming altogether, has been made by Chapman (*11*). His analysis shows that, were chemical farming to be ended, there would be much reduced yields per acre, so that most land in the soil bank would need to be put back into farming. Nevertheless, output would fall only 5 percent and prices for farm products would increase 16 percent. Most dramatically, farm income would rise 25 percent, and nearly all subsidy programs would end. A similar set of propositions treated with linear programming techniques at Iowa State University resulted in an essentially similar set of conclusions (*12*).

The direct use of solar energy farms, a return to wind power (modern windmills are now in use in Australia), and the production of methane from manure are all possibilities. These methods require some engineering to become economically attractive, but it should be emphasized that these technologies are now better understood than the technology of breeder reactors. If energy prices rise, these methods of energy generation would be attractive alternatives, even at their present costs of implementation.

Energy Reduction in the U.S. Food System

Beyond the farm, but still far from the table, more energy savings could be introduced. The most effective way to reduce the large energy requirements of food processing would be a change in eating habits toward less highly processed foods. The current aversion of young people to spongy, additive-laden white bread, hydrogenated peanut butter, and some other processed foods could presage such a change if it is more than just a fad. Technological changes could reduce energy consumption, but the adoption of lower energy methods would be hastened most by an increase in energy prices, which would make it more profitable to reduce fuel use.

Packaging has long since passed the stage of simply holding a convenient amount of food together and providing it with some minimal protection. Legislative controls may be needed to reduce the manufacturer's competition in the amount and expense of packaging. In any case, recycling of metal containers and wider use of returnable bottles could reduce this large item of energy use.

The trend toward the use of trucks in food transport, to the virtual exclusion of trains, should be reversed. By reducing the direct and indirect subsidies to trucks we might go a long way toward enabling trains to compete.

Finally, we may have to ask whether the ever-larger frostless refrigerators are needed, and whether the host of kitchen appliances really means less work or only the same amount of work to a different standard.

Store delivery routes, even by truck, would require only a fraction of the energy used by autos for food shopping. Rapid transit, giving some attention to the problems with shoppers with parcels, would be even more energy-efficient. If we insist on a high-energy food system, we should consider starting with coal, oil, garbage—or any other source of hydrocarbons—and producing in factories bacteria, fungi, and yeasts. These products could then be flavored and colored appropriately for cultural tastes. Such a system would be more efficient in the use of energy, would solve waste problems, and would permit much or all of the agricultural land to be returned to its natural state.

Energy, Prices, and Hunger

If energy prices rise, as they have already begun to do, the rise in the price of food in societies with industrialized agriculture can be expected to be even larger than the energy price increases. Slesser, in examining the case for England, suggests that a quadrupling of energy prices in the next 40 years would bring about a sixfold increase in food prices (*9*). Even small increases in energy costs may make it profitable to increase labor input to food production. Such a reversal of a 50-year trend toward energy-intensive agriculture would present environmental benefits as a bonus.

We have tried to show how analysis of the energy flow in the food system illustrates features of the food system that are not easily deduced from the usual economic analysis. Despite some suggestions for lower intensity food supply and some frankly speculative suggestions, it would be hard to conclude on a note of optimism. The world drawdown in grain stocks which began in the mid-1960's continues, and some food shortages are likely all through the 1970's and early 1980's. Even if population control measures begin to limit world population, the rising tide of hungry people will be with us for some time.

Food is basically a net product of an ecosystem, however simplified. Food production starts with a natural material, however modified later. Injections of energy (and even brains) will carry us only so far. If the population cannot adjust its wants to the world in which it lives, there is little hope of solving the food problem for mankind. In that case the food shortage will solve our population problem.

References and Notes

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3. D. Pimentel, L. E. Hurd, A. C. Bellotti, M. J. Forster, I. N. Oka, O. D. Scholes, R. J. Whitman, *Science* **182**, 443 (1973).
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8. Federal Highway Administration, Nationwide Personal Transportation Study Report No. 1 (1971) [as reported in Energy Research and Development, hearings before the Congressional Committee on Science and Astronautics, May 1972, p. 151].
9. M. Slesser, *Ecologist* **3** (No. 6), 216 (1973).
10. J. F. Gerber, personal communication (we are indebted to Dr. Gerber for pointing out that manures, even if used fully, will not provide all the needed agricultural fertilizers).
11. D. Chapman, *Environment (St. Louis)* **15** (No. 2), 12 (1973).
12. L. U. Mayer and S. H. Hargrove [*CAED Rep. No. 38* (1972)] as quoted in Slesser (*9*).
13. We have converted all figures for the use of electricity to fuel input values, using the average efficiency values for power plants given by C. M. Summers [*Sci. Am.* **224** (No. 3), 148 (1971)]. Self-generated electricity was converted to fuel inputs at an efficiency of 25 percent after 1945 and 20 percent before that year.
14. Purchased material in this analysis was converted to energy of manufacture according to the following values derived from the literature or calculated. In doubtful cases we have made what we believe to be conservative estimates: steel (including fabricated and castings), 1.7×10^7 kcal/ton (1.9×10^4 kcal/kg); aluminum (including castings and forgings), 6.0×10^7 kcal/ton; copper and brass (alloys, millings, castings, and forgings), 1.7×10^6 kcal/ton; paper, 5.5×10^6 kcal/ton; plastics, 1.25×10^6 kcal/ton; coal, 6.6×10^6 kcal/ton; oil and gasoline, 1.5×10^6 kcal/barrel (9.5×10^3 kcal/liter); natural gas, 0.26×10^3 kcal/cubic foot (9.2×10^3 kcal/m^3); petroleum wax, 2.2×10^6 kcal/ton; gasoline and diesel engines, 3.4×10^6 kcal/engine; electric motors over 1 horsepower, 45×10^3 kcal/motor; ammonia, 2.7×10^7 kcal/ton; ammonia compounds, 2.2×10^6 kcal/ton; sulfuric acid and sulfur, 3×10^6 kcal/ton; sodium carbonate, 4×10^6 kcal/ton; and other inorganic chemicals, 2.2×10^6 kcal/ton.
15. Direct fuel use on farms: Expenditures for petroleum and other fuels consumed on farms were obtained from *Statistical Abstracts* (*1*) and the *Census of Agriculture* (Bureau of the Census, Government Printing Office, Washington, D.C., various recent editions) data. A special survey of fuel use on farms in the 1964 *Census of Agriculture* was used for that year and to determine the mix of fuel products used. By comparing expenditures for fuel in 1964 with actual fuel use, the apparent unit price for this fuel mix was calculated. Using actual retail prices and price indices from *Statistical Abstracts* and the ratio of the actual prices paid to the retail prices in 1964, we derived the fuel quantities used in other years. Changes in the fuel mix used (primarily the recent trend toward more diesel tractors) may understate the energy in this category slightly in the years since 1964 and overstate it slightly in years before 1964. S. H. Schurr and B. C. Netschert [*Energy in the American Economy, 1850–1975* (Johns Hopkins Press, Baltimore, 1960), p. 774], for example, using different methods, estimate a figure 10 percent less for 1955 than that given here. On the other hand, some retail fuel purchases appear to be omitted from all these data for all years. M. J. Perelman [*Environment (St. Louis)* **14** (No. 8), 10 (1972)] from different data, calculates 270×10^{12} kcal of energy usage for tractors alone.
16. Electricity use on farms: Data on monthly usage on farms were obtained from the "Report of the Administrator, Rural Electrification Administration" (U.S. Department of Agriculture, Government Printing Office, Washington, D.C., various annual editions). Totals were calculated from the annual farm usage multiplied by the number of farms multiplied by the fraction electrified. Some nonagricultural uses are included which may overstate the totals slightly for the years before 1955. Nevertheless, the totals are on the conservative side. A survey of on-farm electricity usage published by the Holt Investment Corporation, New York, 18 May 1973, reports values for per farm usage 30 to 40 percent higher than those used here, suggesting that the totals may be much too small. The discrepancy is probably the result of the fact that the largest farm users are included in the business and commercial categories (and excluded from the U.S. Department of Agriculture tabulations used).
17. Fertilizer: Direct fuel use by fertilizer manufacturers was added to the energy required for the manufacture of raw materials purchased as inputs for fertilizer manufacture. There is allowance for the following: ammonia and related compounds, phosphatic compounds, phosphoric acid, muriate of potash, sulfuric acid, and sulfur. We made no allowance for other inputs (of which phosphate rock, potash, and "fillers" are the largest), packaging, or capital equipment. Source: *Census of Manufactures* (Government Printing Office, Washington, D.C., various recent editions).
18. Agricultural steel: Source, *Statistical Abstracts* for various years (*1*). Converted to energy values according to (*14*).
19. Farm machinery (except tractors): Source, *Census of Manufactures*. Totals include direct energy use and the energy used in the manufacture of steel, aluminum, copper, brass, alloys, and engines converted according to (*14*).
20. Tractors: numbers of new tractors were derived from *Statistical Abstracts* and the *Census of Agriculture* data. Direct data on energy and materials use for farm tractor manufacture was collected in the *Census of Manufactures* data for 1954 and 1947 (in later years these data were merged with other data). For 1954 and 1947 energy consumption was calculated in the same way as for farm machinery. For more recent years a figure of 2.65×10^6 kcal per tractor horsepower calculated as the energy of manufacture from 1954 data (the 1954 energy of tractor manufacture, 23.6×10^{12} kcal, divided by sales of 315,000 units divided by 28.7 average tractor horsepower in 1954). This figure was used to calculate energy use in tractor manufacture in more recent years to take some account of the continuing increase in tractor size and power. It probably slightly understates the energy in tractor manufacture in more recent years.

21. Irrigation energy: Values are derived from the acres irrigated from *Statistical Abstracts* for various years; converted to energy use at 10^6 kcal per acre irrigated. This is an intermediate value of two cited by Pimentel *et al.* (*3*).
22. Food processing industry: Source, *Census of Manufacturers*; direct fuel inputs only. No account taken for raw materials other than agricultural products, except for those items (packaging and processing machinery) accounted for in separate categories.
23. Food processing machinery: Source, *Census of Manufactures* for various years. Items included are the same as for farm machinery [see (*13*)].
24. Paper packaging: Source, *Census of Manufactures* for various years. In addition to direct energy use by the industry, energy values were calculated for purchased paper, plastics, and petroleum wax, according to (*14*). Proportions of paper products having direct food usage were obtained from *Containers and Packaging* (U.S. Department of Commerce, Washington, D.C., various recent editions). [The values given include only proportional values from Standard Industrial Classifications 2651 (half), 2653 (half), 2654 (all).]
25. Glass containers: Source, *Census of Manufactures* for various years. Direct energy use and sodium carbonate [converted according to (*14*)] were the only inputs considered. Proportions of containers assignable to food are from *Containers and Packaging*. Understatement of totals may be more than 20 percent in this category.
26. Steel and aluminum cans: Source, *Census of Manufactures* for various years. Direct energy use and energy used in the manufacture of steel and aluminum inputs were included. The proportion of cans used for food has been nearly constant at 82 percent of total production (*Containers and Packaging*).
27. Transportation fuel usage: Trucks only are included in the totals given. After subtracting trucks used solely for personal transport (all of which are small trucks), 45 percent of all remaining trucks and 38 percent of trucks larger than pickup and panel trucks were engaged in hauling food or agricultural products, or both, in 1967. These proportions were assumed to hold for earlier years as well. Comparison with ICC analyses of class I motor carrier cargos suggests that this is a reasonable assumption. The total fuel usage for trucks was apportioned according to these values. Direct calculations from average mileage per truck and average number of miles per gallon of gasoline produces agreement to within ± 10 percent for 1967, 1963, and 1955. There is some possible duplication with the direct fuel use on farms, but it cannot be more than 20 percent considering on-farm truck inventories. On the other hand, inclusion of transport by rail, water, air, and energy involved in the transport of fertilizer, machinery, packaging, and other inputs of transportation energy could raise these figures by 30 to 40 percent if ICC commodity proportions apply to all transportation. Sources: *Census of Transportation* (Government Printing Office, Washington, D.C., 1963, 1967); *Statistical Abstracts* (*1*); *Freight Commodity Statistics of Class I Motor Carriers* (Interstate Commerce Commission, Government Printing Office, Washington, D.C., various annual editions).
28. Trucks and trailers: Using truck sales numbers and the proportions of trucks engaged in food and agriculture obtained in (*27*) above, we calculated the energy values at 75×10^6 kcal per trucks for manufacturing and delivery energy [A. B. Makhijani and A. J. Lichtenberg, *Univ. Calif. Berkeley Mem. No. ERL-M310* (revised) (1971)]. The results were checked against the *Census of Manufactures* data for 1967, 1963, 1958, and 1939 by proportioning motor vehicles categories between automobiles and trucks. These checks suggest that our estimates are too small by a small amount. Trailer manufacture was estimated by the proportional dollar value to truck sales (7 percent). Since a larger fraction of aluminum is used in trailers than in trucks, these energy amounts are also probably a little conservative. Automobiles and trucks used for personal transport in the food system are omitted. Totals here are probably significant, but we know of no way to estimate them at present. Sources: *Statistical Abstracts*, *Census of Manufactures*, and *Census of Transportation* for various years.
29. Commercial and home refrigeration and cooking: Data from 1960 through 1968 (1970 extrapolated) from *Patterns of Energy Consumption in the United States* (*6*). For earlier years sales and inventory in-use data for stoves and refrigerators were compiled by fuel and converted to energy from average annual use figures from the Edison Electric Institute [*Statistical Year Book* (Edison Electric Institute, New York, various annual editions] and American Gas Association values [*Gas Facts and Yearbook* (American Gas Association, Inc., Arlington, Virginia, various annual editions] for various years.
30. Refrigeration machinery: Source, *Census of Manufactures*. Direct energy use was included and also energy involved in the manufacture of steel, aluminum, copper, and brass. A few items produced under this SIC category for some years perhaps should be excluded for years prior to 1958, but other inputs, notably electric motors, compressors, and other purchased materials should be included.
31. There are many studies of energy budgets in primitive societies. See, for example, H. T. Odum [*Environment, Power, and Society* (Wiley, Interscience, New York, 1970)] and R. A. Rappaport [*Sci. Am.* **224** (No. 3), 104 (1971)]. The remaining values of energy subsidies in Fig. 5 were calculated from data presented by Slesser (*9*), Table 1.
32. This article is modified from C. E. Steinhart and J. S. Steinhart, *Energy: Sources, Use, and Role in Human Affairs* (Duxbury Press, North Scituate, Mass., in press) (used with permission). Some of this research was supported by the U.S. Geological Survey, Department of the Interior, under grant No. 14-08-0001-G-63. Contribution 18 of the Marine Studies Center, University of Wisconsin–Madison. Since this article was completed, the analysis of energy use in the food system of E. Hirst has come to our attention ["Energy Use for Food in the United States," *ONRL-NSF-EP-57* (Oct. 1973)]. Using different methods, he assigns 12 percent of total energy use to the food system for 1963. This compares with our result of about 13 percent in 1964.

Economic Strategy for Import-Export Controls on Energy Materials

Helmut J. Frank

Lifting the embargo against the United States by the oil-producing Arab countries may alter the nature of the energy question from a temporary crisis to a long-run problem. With this shift, attention is likely to focus once again on fundamental issues such as the role of imported energy sources in total U.S. supplies, the feasibility and cost of pursuing domestic self-sufficiency, the use of agricultural and industrial exports for bargaining or retaliatory purposes, and the policy instruments most suitable for attaining desirable policy objectives. The choice of appropriate foreign trade policies affecting energy can go far toward assuring the country adequate supplies at reasonable costs; the failure to do so could be disastrous for the country's security, its economic strength, or both.

Determining the role of imported energy sources in the total supply stream would not be a problem if normal economic forces could be allowed to govern trade in energy: Trade would follow the law of comparative advantage. The United States would import those goods in which foreign countries have relatively the lowest costs (say, oil) and pay for them by exporting goods in which the U.S. cost advantage is greatest (say, foodstuffs). This trade need not, indeed it should not, be limited to direct bilateral exchange. To obtain maximum benefit from the uneven distribution of natural and human resources, goods and capital should be permitted to move freely across national frontiers in response to normal economic incentives.

The recent oil embargo has brought home to every American the fact that the conditions under which free exchange can function effectively have not been allowed to govern trade in energy materials. During the past few years, the Organization of Petroleum-Exporting Countries (OPEC) has become powerful enough to control production and raise short-run prices to

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