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Encyclopedia of ENERGY

Encyclopedia of
ENERGY

DANIEL N. LAPEDES Editor in Chief

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Preface

Energy, the mainspring that keeps life's clock ticking on Earth, is present in many forms. It is in the heat and light radiated by the Sun: in the carbohydrates and wood in plants; in coal, oil, and natural gas, and in oil shale and tar sands; in geothermal wells; in the wind that sweeps over the land and sea; in the water coursing to the oceans; and in the atomic nucleus.

Some of these forms of energy are the fossil fuels – coal and oil – that are the end result of a process that has been taking place under the Earth's surface for several hundred million years. We have been using coal and oil for some time – slowly at first and then from the time of the Industrial Revolution at an increasing pace. Projections based on present consumption of oil indicate that 80% of that energy resource will be used up worldwide by the beginning of the 21st century. The projection made for coal foresees a supply for the United States until the middle of the 21st century.

The situation became critical for the industrialized nations when the OPEC (Organization of Petroleum Exporting Countries) embargo in 1973 effectively reduced the flow of crude oil to their refineries. This affected the supply and price of electric power, heating oil, and gasoline, as well as the output of industries that use crude oil or fractions of it as a raw material. The embargo accelerated a worldwide recession and changed the manner in which people and their governments regard energy.

It is generally accepted that we have been profligate in our use of energy resources – particularly those such as coal, oil, and natural gas that are finite and exhaustible – and have neglected development of other resources. Society through its governmental institutions is attempting to make decisions that will ensure an energy supply base for the future. The individuals involved in the decision-making process face a complex problem that has deep sociological, economic, and technological overtones. They must weigh curtailment of certain energy-intensive activities on one side of the scale against achievement of desirable conservation practices on the other – activities such as automobile use with a mandate for lower-horsepower cars, and modernization of factories to use less energy; they must weigh the effect on the environment of using high-sulfur coal and oil, and of strip mining to recover coal deposited near the surface; and they must explore the development of other forms of energy.

The *McGraw-Hill Encyclopedia of Energy* with its more than 300 articles written by specialists is designed to aid the student, librarian, scientist, engineer, teacher, and lay reader with information on any aspect of energy from the economic and political to the environmental and technological. The Encyclopedia is arranged in two parts. The first part, "Energy Perspectives," has six feature articles: Energy Consumption, Outlook for Fuel Reserves, Exploring Energy Choices, World Energy Economy, U.S. Policies and Politics, and Protecting the Environment. The second part, "Energy Technology," with its 300 alphabetically arranged articles, contains information on such subjects as coal mining, nuclear power, laser-induced fusion, wind power, solar power, and hydroelectric power. The articles, some drawn from the *McGraw-Hill Encyclopedia of Science and Technology* (3d ed., 1971) and its YearBooks (1971 – 1976), and some written especially for this volume, were selected or suggested by the Board of Consultants. All articles are signed, and the authors and their affiliations are provided in the List of Contributors beginning on page 739. Almost every article opens with a definition of the subject and ends with a bibliography for further reading. The Appendix, beginning on page 747, aids the reader in converting U.S. Customary Units to metric and System International units. The cross-references to other articles and the analytic index beginning on page 759 interrelate the articles.

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Editor in Chief

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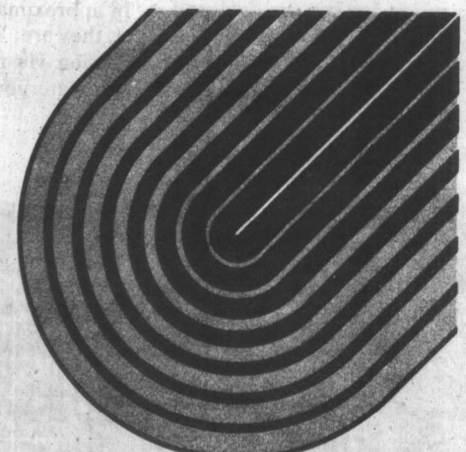
Energy Consumption

- flow of energy
- trends and patterns
- quantification of energy
- work and heat
- electricity consumption



Dr. John C. Fisher

People have adapted energy to a wide range of personal and industrial uses. The most significant personal uses are for cooking, comfort heating and cooling, illumination, transportation, hot water, refrigeration, and communication. These uses extend far beyond the bare essentials for life, and they provide increasingly for comfort and convenience. The most significant industrial uses are for heat and power.

Nonindustrialized societies still are heavily dependent on the traditional energy sources—local solar energy that is made available through the agencies of food, work-animal feed, nonmineral fuels (wood, dung, and agricultural wastes), wind power, and direct waterpower. Energy consumption per person is very small, only a few times the food energy required to sustain life.

In contrast, industrialized societies use large quantities of fossil fuel (coal, oil, and natural gas) and electricity, and consumption of energy per person is as much as a hundred times the energy contained in food. Figure 1 illustrates the tremendous per capita consumption of fossil fuels and hydropower in the industrialized nations compared with the rest of the world. These two forms of energy provide a twelvefold increase in energy for the industrialized regions, compared with a twofold increase for the nonindustrialized regions. When one speaks of energy in an industrialized society, one ordinarily refers only to energy for heat, light, power, and communication, leaving aside the energy content of food. In keeping with this custom, food energy will not be further considered in this article.

Fairly accurate records exist for the overall energy consumption of the United States, particularly in recent decades, since it is known how much coal, oil, natural gas, hydropower, nuclear power, and other forms of energy are consumed each year. But the records are incomplete with respect to energy consumption for most specific purposes or end uses. There are good records for some, for example, energy in the form of gasoline for automobiles. Suppliers know how much energy in the form of electricity is delivered to each home, but the proportions that are used for cooking, heating, light, refrigeration, television, and other purposes can only be estimated.

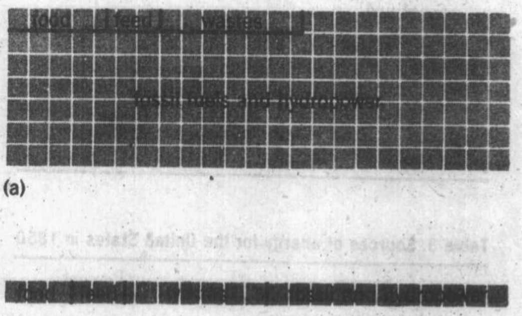


Fig. 1. Per capita consumption of energy in 1970 for (*a*) industrialized regions (30% of world population) and (*b*) nonindustrial regions (70% of world population). Each square represents 1,000,000 Btu per person per year. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

Table 1. Consumption pattern of energy for significant end uses, as an approximate percentage of total consumption, in the United States during the mid-1970s*

	Segment of the Economy			
End use	Industrial	Residential and personal	Commercial and public	Total
Transportation	1	16	9	26
Comfort heat	2	11	7	20
Process steam	16	—	—	16
Direct heat	11	—	—	11
Electric drive	9	—	—	9
Lighting	1	1	3	5
Hot water	—	3	1	4
Air conditioning	—	1	2	3
Refrigeration	—	1	1	2
Cooking	—	1	—	1
Electrochemistry	1	—	—	1
Other (mostly electric)	—	1	1	2
Total	41	35	24	100

*Based on a study by the Stanford Research Institute updated by a task force of the National Academy of Engineering, and on data obtained by the U.S. Bureau of the Census.

Table 1 shows the approximate pattern of energy consumption in the United States during the mid-1970s. Energy can be transformed to electricity before it is used, as for lighting and for powering machine tools in industry. Wherever this is done, the table shows the energy content of the fuel required to make the electricity. There is no doubt that the major features of the nation's energy consumption pattern are correctly portrayed in the table, but individual percentage entries are probably not accurate to better than one percentage point. Wherever there is a dash in the table, the energy consumption for that segment of the economy is estimated to be less than ½% of the nation's total consumption.

THE FLOW OF ENERGY

A number of different sources have provided significant energy inputs to the United States at one time or another. In approximate order of their historical development, they are:

Solar energy: Conversion via fuel wood, work-animal feed, wind power, waterpower.

Fossil fuel: Combustion of coal, petroleum, natural gas.

Nuclear fuel: Fission of uranium.

Other sources of potential significance for large-scale energy production include:

Solar energy: Conversion via new technologies.

Fossil fuel: Combustion of hydrocarbons from oil shale, tar sand.

Nuclear fuel: Fission of thorium.

Sources of energy are judged to be potentially significant where the available quantities are large and where technological and economic considerations show that costs are competitive or close to competitive. Other potential sources such as tidal power, geothermal power, fusion power, and trash combustion are likely to be of less significance for large-scale energy production because of limited availability or because of economic or technological barriers, although they may have limited applications at special locations or in special situations.

Some energy sources are more abundant than others. Solar energy is dilute, but large in magnitude and unlimited in time. Fossil fuels are con-

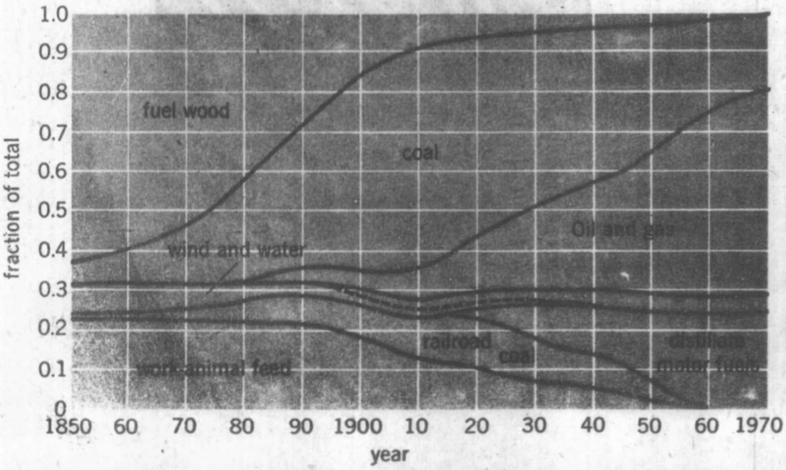


Fig. 2. Segmentation of fuel input to the United States, 1850 to 1970. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

Table 2. Sources of energy for the United States in 1970

Source	Percent
Fossil fuel	
Coal	20
Petroleum	41
Natural gas	33
Solar energy	
Hydroelectricity	4
Other	2
	100

Table 3. Sources of energy for the United States in 1850

Source	Percent
Solar energy	
Fuel wood	64
Work-animal feed	22
Wind and water	7
Fossil fuel	
Coal	7
	100

centrated and inexpensive to recover, but can become exhausted after several centuries. Nuclear fuels are practically inexhaustible, particularly if breeder reactors are able to utilize the common isotopes of uranium and thorium. Broadly speaking, for the industrialized societies of the world, the years of significance for fuel wood, work-animal feed, and wind power have passed; and the years of significance for nuclear fuels are just beginning. The energy sources of current significance are fossil fuels and waterpower (Table 2).

SHIFTS IN EMPHASIS

The 1970 emphasis on fossil fuels in the United States represents a strong shift from the 1850 emphasis on wood (for heat) and animal feed (for farm work and transportation) (Table 3). The years from 1850 to 1970 saw five major substitutions of the new energy forms for the old, as shown in Fig. 2. Fuel wood, used primarily for heating, was largely replaced by coal between 1850 and 1910. Since 1910, coal has been progressively replaced by fluid hydrocarbons (gas and oil). Work-animal feed, used primarily for motive power in transportation and on farms, was partially replaced by railroad coal in the late 1800s and early 1900s. Then, as the country adopted automobiles and tractors and as railroads converted to oil, both animal feed and railroad coal were largely replaced by gasoline and other distillate motor fuels in the years 1920–1950. Direct wind power and waterpower were replaced by hydroelectricity in the years 1890–1940.

A final substitution, not shown in Fig. 2, is a steady increase in the proportion of energy converted to electricity prior to its ultimate consumption. The percentage of primary energy input converted to electricity grew steadily from about 9% in 1925 to nearly 27% in 1970 (Fig. 3). It is important to keep in mind that most of the growth in electric energy consumption has resulted from this substitution of electric energy for other forms of energy. Waterpower used to be harnessed directly to factory machinery by waterwheels, pulleys, and belts, but now it is harnessed indirectly through electricity. Hydroelectric power has substituted for direct waterpower. Fuels used to be burned on the users' premises for illumination, stationary work, and heat, but increasingly fuels are burned off the users' premises in electric power plants.

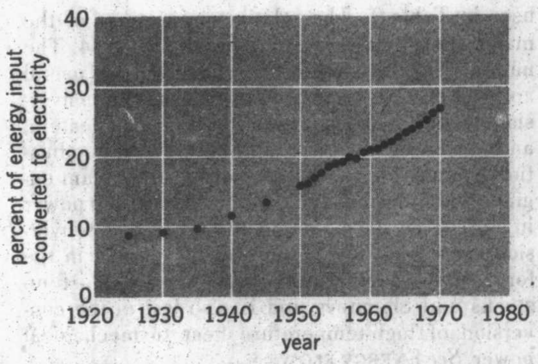


Fig. 3. Conversion of primary energy into electric energy in the United States, 1925 to 1970. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

Energy flows through the United States economy from the sources shown in Fig. 2 to the end

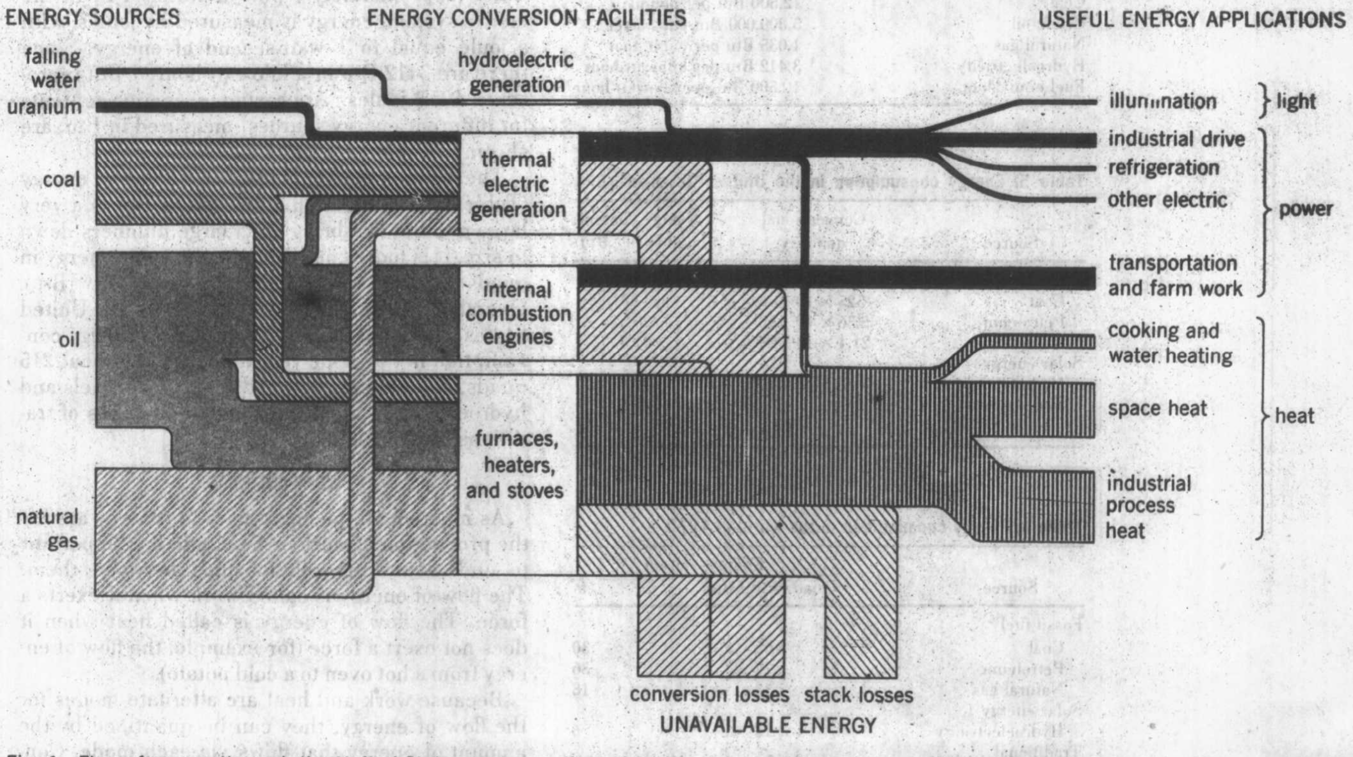


Fig. 4. Flow of energy through the United States economy in the mid-1970s, from major energy sources (left) through conversion facilities (middle) to useful applications (right), and unavailable energy at the bottom. Width of a channel is proportional to the amount of energy.

uses in Table 1. The relative proportions of the major energy flows are illustrated in Fig. 4. The nation's energy sources are converted for useful applications by means of various energy conversion facilities. These include furnaces, heaters, and stoves for generating heat, internal combustion engines for generating power, and steam engines and other heat engines for generating power in electric power plants. In the process of conversion there is a flow of unavailable energy in the form of low-temperature heat which is lost up stacks and chimneys and is also lost in the conversion of high-temperature heat to mechanical power. *See* ENERGY FLOW.

QUANTIFICATION OF ENERGY

When considering the quantitative aspects of energy consumption, miners deal in tons of coal, oil suppliers in barrels of oil, gas suppliers in cubic feet of gas, and electric utility people in kilowatt-hours of hydroelectricity. Some uniform standard of measurement is required for comparing the quantities of energy from these various sources. Sources that customarily are used for the production of heat can be quantified by the amounts of heat they are capable of generating. More specifically, the numerical energy values for fossil fuels, fuel wood, and animal feed are the amounts of heat they would generate during combustion. The values for nuclear fuels are the amounts of heat generated by nuclear fission in electric power plants.

Table 4. Approximate energy contents for selected energy sources

Source	Approximate energy content
Coal	12,500 Btu per pound
Crude oil	5,800,000 Btu per barrel
Natural gas	1,035 Btu per cubic foot
Hydroelectricity	3,412 Btu per kilowatt-hour
Fuel equivalent	10,500 Btu per kilowatt-hour

Table 5. Energy consumption in the United States in 1970

Source	Conventional quantity	Energy content, quad (=10^{15} Btu)
Fossil fuel		
Coal	525 × 10^6 tons	12.8
Petroleum	5.36 × 10^9 bbl	26.5
Natural gas	21.4 × 10^{12} ft³	21.3
Solar energy		
Hydroelectricity	253 × 10^9 kWhr	2.6
Other		1.3
		64.5

Table 6. Energy consumption in the world in 1970

Source	Energy content Quad (=10^{15} Btu)	%
Fossil fuel		
Coal	65	30
Petroleum	77	36
Natural gas	38	18
Solar energy		
Hydroelectricity	13	6
Traditional		
Wood, waste, feed	22	10
	215	100

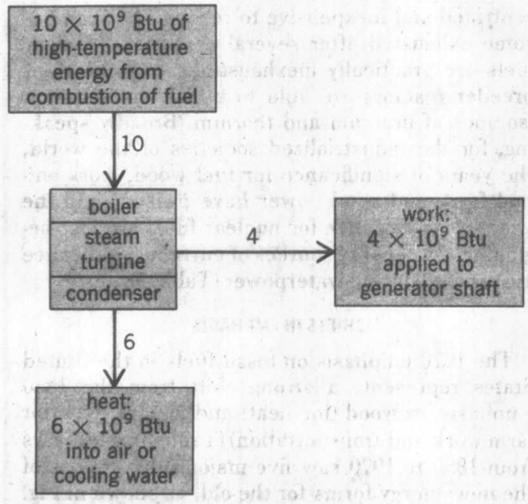


Fig. 5. Flow of energy through a modern boiler-turbine-condenser heat engine. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

Hydroelectricity presents a special problem. Its energy content can be measured either by the amount of heat it would generate in an electric heater or by the larger amount of heat that would be required to generate the same amount of electricity in a fuel-burning power plant. Except for Figs. 4 and 14, the second of these measures—the fuel equivalent of hydroelectricity—is used in this article because it more accurately reflects hydroelectricity's economic significance.

Heat and other forms of energy can be measured in terms of British thermal units (Btu). One Btu is the amount of energy it takes to warm up 1 lb of water (approximately 1 pint of water) 1°F. In the metric system, energy is measured by joules, with a joule equal to 1 watt-second of energy. Since there are 3412 Btu in a kilowatt-hour, 1 Btu represents 1055 joules. Approximate energy contents for different energy sources, measured in Btu, are shown in Table 4.

The United States consumes so much energy (Table 5) that the annual amount in Btu is a very large number. To bring such large numbers down to size, it is more convenient to measure energy in quads (1 quad = 1 quadrillion Btu = 10^{15} Btu). Overall in 1970, the energy input to the United States amounted to 64.5 quads. World energy consumption in the same year amounted to about 215 quads, comprising 193 quads of mineral fuels and hydroelectricity and an estimated 22 quads of traditional fuels (Table 6).

WORK AND HEAT

As mentioned, the major uses for energy are for the production of work or heat, and it is important to understand the relationships between them. The flow of energy is called work when it exerts a force. The flow of energy is called heat when it does not exert a force (for example, the flow of energy from a hot oven to a cold potato).

Because work and heat are alternate modes for the flow of energy, they can be quantified by the amount of energy that flows via each mode. Consider as an example the operation of a modern steam turbine used to drive an electric generator, shown in Fig. 5. The fuel burned in the boiler generates 10×10^9 Btu of energy each hour of operation. A portion of this energy, amounting to 4×10^9 Btu per hour, flows through the rotating turbine shaft in the form of work, where it is used to turn the shaft of an electric generator. The rest of the energy, amounting to 6×10^9 Btu per hour, is discharged into the air or into cooling water. Thus, only 40% of the energy in the fuel was actually used for the purpose for which it was intended. The engine therefore has an efficiency of 40%. *See* HEAT; WORK.

Reversible heat engines. Many engines, including jet engines, automobile engines, and steam turbines, receive energy at high temperature, transform some to work, and discharge the rest of it as heat at a lower temperature. Much study has been devoted to the potential efficiency of these engines, and the concept of a "reversible heat engine" has emerged as an idealization against which the lesser performance of real engines can be measured. Imagine a reservoir of energy at a high temperature T_1 and a second reservoir of energy at a low temperature T_2. Imagine that a reversible heat engine, with a rotatable shaft along which work can flow (Fig. 6), is in contact with both reservoirs and is able to exchange heat with both.

When utilized to generate work, a reversible heat engine draws heat from the high-temperature reservoir, delivers work along the rotating shaft, and discharges heat to the low-temperature reservoir. It is the idealization of a steam turbine power plant. Figure 7 shows what happens to a quantity Q_1 of heat that flows into the engine from the hotter reservoir: part of it, Q_2, goes to the colder reservoir and part of it, $Q_1 - Q_2$, comes out as work.

Now suppose that the shaft is twisted in the opposite direction by means of some outside agency, so that work flows into the engine instead of out. The engine then draws heat from the low-temperature reservoir and delivers heat to the high-temperature reservoir. It operates as a heat pump, the idealization of an air conditioner or refrigerator. Figure 8 shows the flows of work and heat associated with the delivery of a quantity Q_1 of energy to the hotter reservoir: part of it, Q_2, comes from the colder reservoir and part, $Q_1 - Q_2$, comes in through the shaft as work. This picture is the same as the previous one except that everything is flowing in the opposite direction. This is the meaning of reversibility.

Heat engine efficiency. The efficiency of a reversible heat engine depends only on the absolute temperatures T_1 and T_2, as shown in Eq. (1). No

$$\text{Theoretical efficiency} = \frac{T_1 - T_2}{T_1} \qquad (1)$$

practical heat engine can actually achieve this theoretical maximum efficiency. For a steam turbine where T_1 is the temperature of the steam in the boiler (540°C = 1460°R) and T_2 is the temperature in the condenser where cold steam is converted back to water (50°C = 580°R), the theoretical maximum efficiency is about 60%. Modern engineering practice has achieved a respectable 40%, but there is still room for improvement.

Heat pump performance. In addition to their role in generating mechanical power, heat engines are used to pump energy from a cooler place to a warmer place. When the purpose is to cool an area, the heat engine is an air conditioner or a refrigerator. When the purpose is to warm an area, the heat engine is simply a heat pump.

The performance of a heat pump is evaluated by the coefficient of performance (COP), that is, the ratio of the energy delivered to the warmer reservoir (the desired result) to the work required to operate the pump (the necessary input). When a reversible heat engine is used as a heat pump, its COP is simply the reciprocal of its efficiency as an engine. Hence, for a reversible heat pump, COP is determined by Eq. (2). This relationship shows the

$$\text{COP} = \frac{T_1}{T_1 - T_2} \qquad (2)$$

theoretical maximum amount of energy that can be

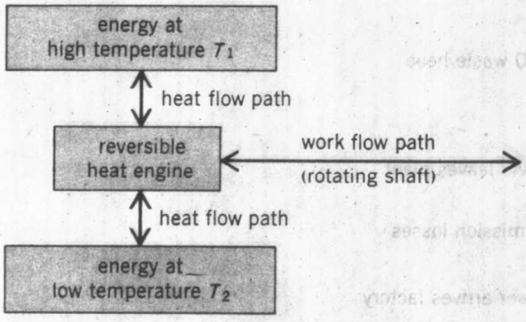


Fig. 6. Idealized reversible heat engine. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

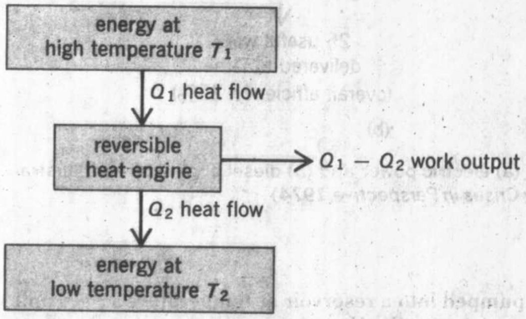


Fig. 7. Reversible heat engine used to perform work. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

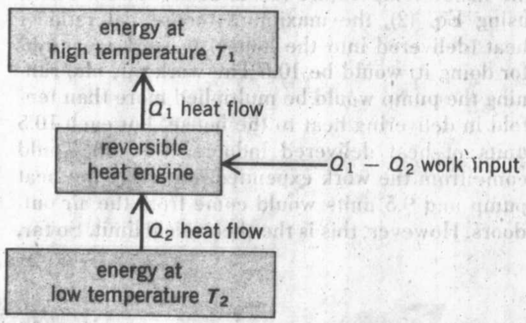


Fig. 8. Reversible heat engine used to pump heat. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

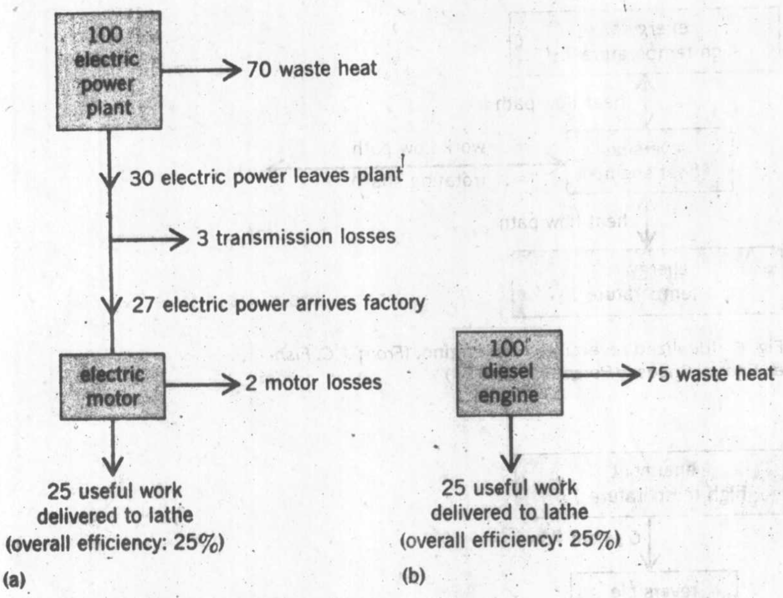


Fig. 9. Overall efficiencies of (a) electric power and (b) diesel engine power (illustrative). (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

pumped into a reservoir at temperature T_1 per unit work input. *See* HEAT PUMP.

As an example, consider the possibility of heating a house by means of a heat pump. Suppose that the outside air temperature (T_2) is −7°C (480°R) and the inside temperature (T_1) is 21°C (530°R). Then, using Eq. (2), the maximum theoretical ratio of heat (delivered into the house) to work (required for doing it) would be 10.6 The work put into running the pump would be multiplied more than tenfold in delivering heat to the house. For each 10.5 units of heat delivered indoors, 1.0 unit would come from the work expended in driving the heat pump and 9.5 units would come from the air outdoors. However, this is the theoretical limit. So far, a commercial heat pump working between 7 and 21°C is able to deliver only about three times as much energy in the form of heat as the energy content of the electricity that drives it.

ROLE OF ELECTRICITY

Electricity is not a primary source of energy, but rather the most highly refined form of energy. There is no alternative to electricity for some purely electrical and electronic end uses of energy. But for most other end uses of energy, consumers have a choice of burning fuel on their own premises or of utilizing electricity generated in an electric power plant, and over the years consumers have opted increasingly for electricity.

Stationary work. The flow of electric energy is equivalent to the flow of work. Work can be transmitted from one place to another by a long rotating shaft, or by a belt stretched over pulleys, or by electricity along conducting wires. Once generated, electricity can be utilized with very little additional waste.

Consider two alternatives for delivering work to a lathe in a factory: (1) burning oil in a power plant to make electricity, then transmitting the electricity to a factory where it turns an electric motor that turns a lathe; and (2) burning oil in a diesel engine that turns the lathe directly. The two alternatives are compared in Fig. 9. The comparison uses an older power plant with only 30% efficiency, which is characteristic of the average around the country. It uses a small diesel engine with only 25% efficiency, also characteristic of the average around the country. As far as generating unavailable heat is concerned, there is an approximate standoff. The power plant is more efficient than the diesel engine, but there are additional losses in transmission and in the electric motor that tend to even things up. Hence electrification of industrial drive does not increase or decrease the amount of unavailable or waste heat associated with powering industry, but merely shifts its location from factories to power plants.

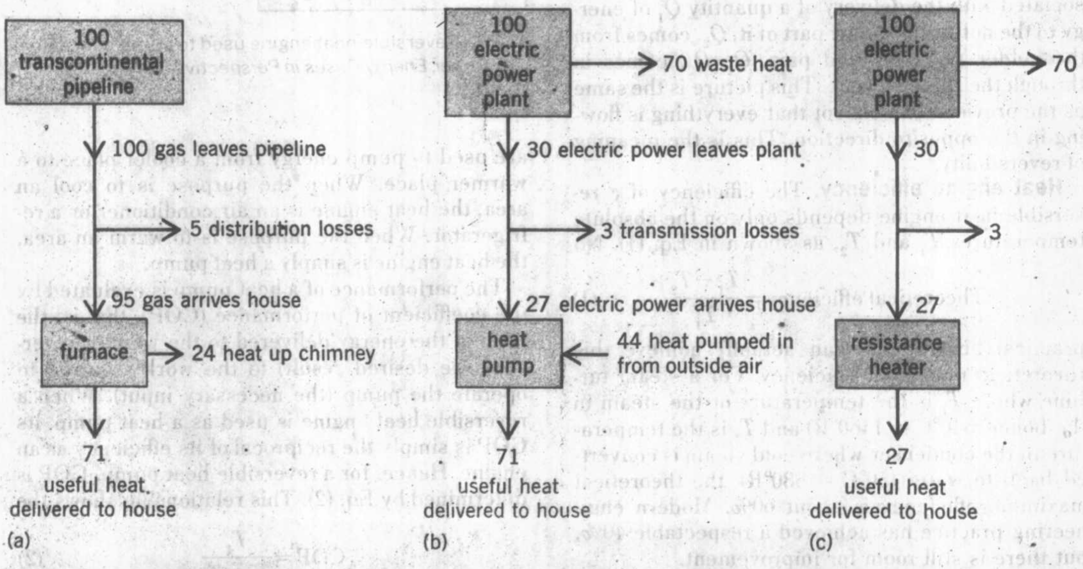


Fig. 10. Overall performance of (a) direct combustion of natural gas, (b) electric heat pump, and (c) electric resistance heating (illustrative). (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

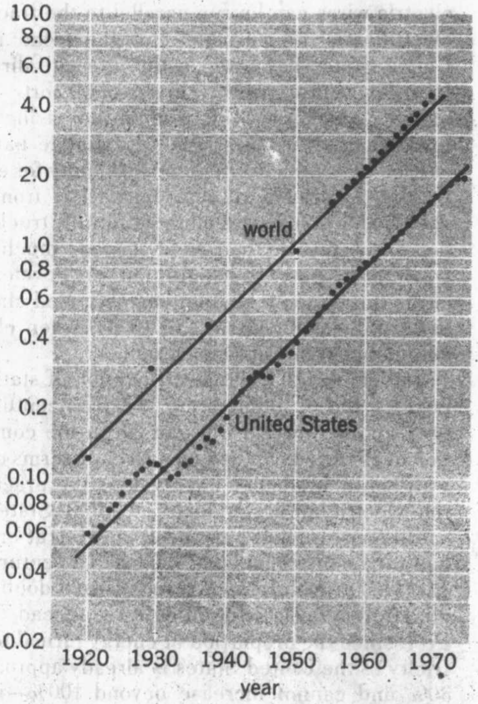


Fig. 11. Generation of electric power over the past half century, for selected years worldwide and annually for the United States. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

Overall cost. From the standpoint of overall cost, the comparison favors electricity. Fuel is cheaper for the power plant, and per unit of work delivered to a lathe, the cost of a power plant plus transmission system plus electric motor is less than the cost of a diesel engine. This is largely because the power plant is more fully utilized. Whereas a diesel engine might run 40 hr a week at an average 30% of its maximum rating for an overall utilization factor of about 7%, the power plant, by providing electricity to a number of users whose demands occur at different and partly overlapping times, might have an overall utilization factor of 65%, thereby achieving a much better utilization of the invested capital. Operating and maintenance costs are less for the power plant for much the same reason. Factory layout can be rearranged much more easily and cheaply when electricity provides the power. And, of increasing importance as the country turns its concern to pollution abatement, large power plants generally are able to burn fuel more thoroughly than many small engines operating independently, substantially lessening pollution.

Illumination. Illumination is another instance of substantial benefits and savings through electrification. Compared with the alternative of direct combustion, electricity gives more light at less cost with less bother, less pollution, and greater safety. Fuel is also conserved, for a gallon of oil burned in a power plant gives more light from an electric lamp than a gallon burned directly in an oil lamp.

Heating. Electric resistance heating is of particular value for producing very high temperatures, including the 5000°C plasma in a mercury-vapor lamp and even the 100,000,000°C plasmas being studied in thermonuclear fusion research. Resistance heating stays competitive down to lower temperatures such as 1540°C at which iron melts, even though such temperatures can be reached by combustion, because combustion heating tends to become less efficient as the temperature increases through loss of hot combustion products up the chimney.

At low-to-moderate temperatures, however, combustion heating tends to be more efficient because the products of combustion can give up a larger proportion of their energy as they cool down before going up the chimney. For end uses such as space heating, hot-water supply, cooking, and much industrial heating, direct combustion is inexpensive and efficient. Electricity has found only limited application to these end uses, and it is instructive to compare the two methods of electric heating—resistance heating and the electrically

Table 7. Approximate electrification of the United States in 1968

End uses	Percent electrified	Percent of United States energy	Percent of United States electricity
Electrified			
Electric drive	nearly 100%	22.0	84.4
Lighting			
Air conditioning			
Refrigeration			
Electrochemistry			
Other			
Heating	8% average		
Clothes drying	70%	0.4	1.0
Cooking	40%	1.4	2.1
Hot water	38%	4.2	6.2
Direct heat	6%	11.0	2.6
Comfort heat	5%	20.8	3.3
Process steam	—	14.6	—
		52.4	15.2
Transportation			
All forms	½%	25.6	0.4

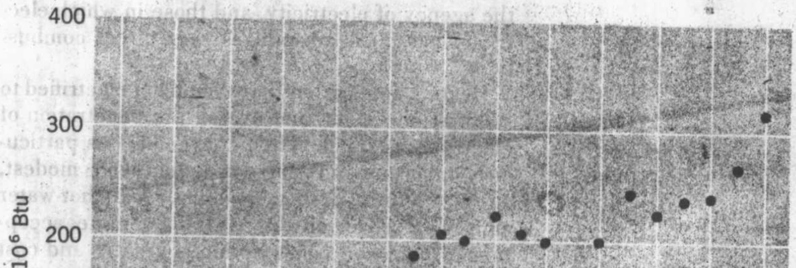


Fig. 12. Per capita consumption of energy in the United States, 1850 to 1970. (*From J. C. Fisher, Energy Crises in Perspective, 1974*)

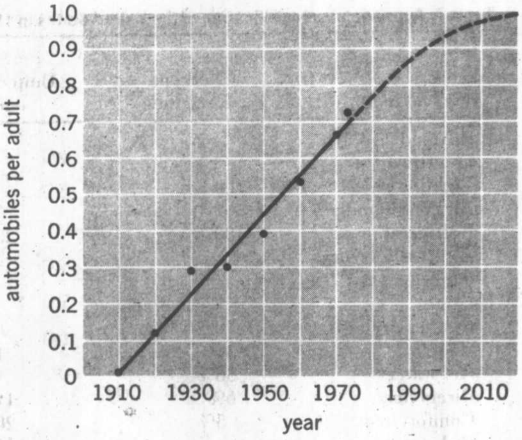


Fig. 13. Average number of automobiles per adult (age 18 and over) in the United States, 1910 to 1973 and projected to 2020.

driven heat pump—with direct combustion to see why electricity has made so little headway (Fig. 10).

From the standpoint of fuel conservation and overall cost, electric resistance heating is not attractive. More fuel is required, and the cost is greater. Yet where only small amounts of heat are desired and where convenience is an important consideration, resistance heating is frequently chosen. Heat pumps and direct combustion stand more or less at a draw when fuel conservation is considered, but heat pumps are more expensive than furnaces. In centrally air-conditioned buildings this does not matter as much, because a reversible heat pump can both cool and heat, but cost nevertheless remains a factor in favor of direct combustion.

Electrification patterns. In viewing the pattern of electrification of the United States, it is instructive to classify end uses according to the degree of electrification, as is done in Table 7. Three groupings emerge: completely electrified uses, heating uses, and transportation.

First consider the electrified end uses. These uses include those that are possible only through the agency of electricity, and those in which electricity has clear advantages over direct combustion.

Heating applications have not been electrified to so great an extent, and overall the penetration of electricity is small. When convenience is particularly important and energy consumption is modest, as in clothes drying, cooking, and hot-water supplying, electricity has won moderate acceptance. But when consumption is greater and cost looms larger relative to convenience, direct combustion of fuel on the premises is ordinarily the rule. For electric heating to make solid inroads against direct combustion, technological progress along two lines is essential: the efficiency of electric generation from fossil fuels must be increased, and the performance of heat pumps must be improved.

Transportation resists electrification because it is difficult to devise an arrangement of wires to supply electricity to a moving motor. If the vehicle runs on rails or some other well-defined track, electric wires can be run parallel to the track and electrification is possible. But the trend in the United States has been in the opposite direction for half a century, with vehicles of all sorts—automobiles, trucks, aircraft, ships—increasingly free to go their own ways. Electric storage batteries carried on a vehicle offer one possibility for electrification of transportation, but aside from low-speed, short-haul uses such as forklift trucks and golf carts, this method has not made much headway. For highway transportation, the development of the internal combustion engine pulled ahead of battery development in the 1890s, when electric automobiles started losing ground.

Largely through the electrification of stationary engines and of illumination, the past century has seen a steady worldwide growth in the consumption of electricity. When measured in terms of kilowatt-hours of electric energy as is the practice of the electric utility industry, United States and world consumption have been growing at an average annual rate of about 7% for half a century (Fig. 11). This growth rate corresponds to a doubling of electric energy consumption every decade. However, since the proportion of energy turned to electricity in the United States is already approaching 30% and cannot increase beyond 100%—it may indeed level off well short of 100%—the growth rate can be expected to slow down in future decades. *See* ELECTRIC POWER GENERATION.

TRENDS IN ENERGY CONSUMPTION

A hundred years ago it took about the same amount of energy to heat a house as it takes today. It took about half as much energy to feed the family horse as it now takes to power the family car. It took about the same amount of energy to cook a meal. People use more energy today, partly because they drive more and partly because they work in offices and factories instead of in open fields, but they still only use about 2½ times as much per person.

Figure 12 shows how energy consumption per person grew between 1850 and 1970. It has been growing very rapidly in recent years. If this growth were to continue, the supplying of the required coal, oil, gas, and uranium would create a strain. The supply problem would not be so serious if energy consumption per person were to level off.

Personal automobile driving is likely to level off by the time every adult has a car to drive. Figure 13 shows how the average number of cars per adult has increased from practically nothing in 1910 to over 0.7 car per adult in the 1970s.

Job-related energy consumption has gone up as more factories and offices have been built. The fraction of the population employed in factories and offices amounted to only about 10% in 1850, but it rose to about 30% a hundred years later. Since 1960 it has risen to about 36% as more and more women have taken jobs outside the home. This trend has a natural limit at about 45% of the population, when everybody of working age will have a job in an office or factory. Growth of the nonfarm labor force will slow down to match overall population growth, and growth of job-related energy consumption will tend to do the same.

As affluence increases, partly through more jobs per family, more energy tends to be consumed in

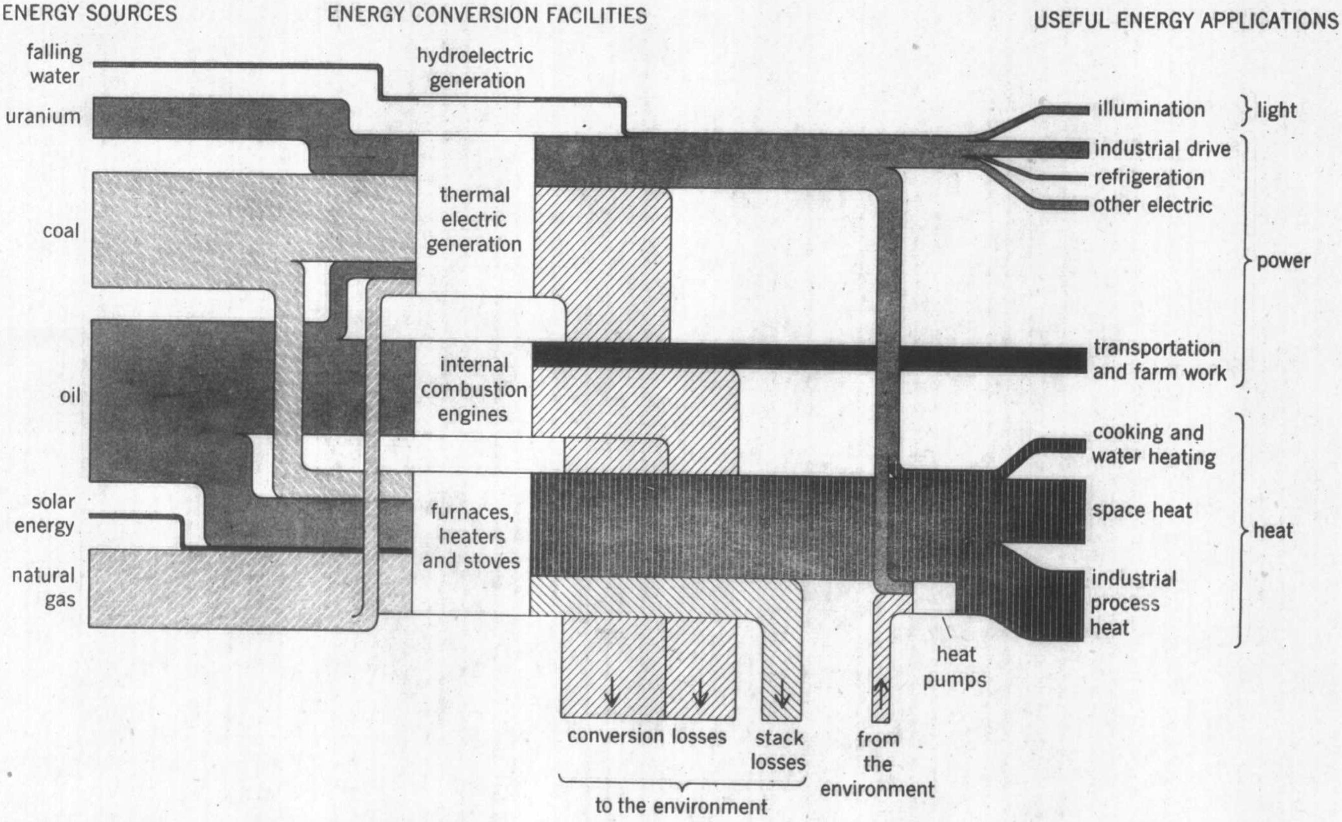


Fig. 14. Possible flow of energy through the United States economy in the 1990s.

the home, mostly for hot water and for comfort heating and cooling. When these basic energy needs are met, energy consumption in the home rises more slowly with increased affluence.

It is anticipated that overall per capita energy consumption may level off. The conservation movement is a welcome expression of people's desire to limit and control energy consumption; indeed, the vitality of the movement may be a symptom, as much as a cause, of the growing achievement of sufficient energy for personal use in society.

The pattern of energy consumption may change in still other ways over the next several decades. Progressive electrification of energy usage is likely to continue. This is the best way to make use of nuclear energy, and improved technology can be expected to increase the efficiencies of electric power generation and application so that electricity will be chosen more often over direct fuel combustion. There is a potential for limited use of solar power, primarily for supplying hot water and for comfort heating.

A possible future pattern for the flow of energy through the United States economy is shown in Fig. 14. Compared with the present as shown in Fig. 4, uranium and coal may provide more of the energy. The efficiency of conversion facilities may improve. Heat pumps, by drawing heat from the air, may augment the effectiveness of electrical heat. More efficient use of energy, as projected in Fig. 14, combined with a leveling off of per capita energy consumption and slower population growth, will tend to moderate the nation's overall energy consumption.

[JOHN C. FISHER]

Bibliography: J. C. Fisher, *Energy Crises in Perspective*, 1974; Stanford Research Institute, for the Office of Science and Technology, Executive Office of the President, Washington, D.C., *Patterns of Energy Consumption in the United States*, January 1972; Task Force on Energy of the National Academy of Engineering, *U.S. Energy Prospects: An Engineering Viewpoint*, 1974; U.S. Bureau of the Census, *Statistical Abstract of the United States: 1974*.

The significance of energy in human affairs can best be appreciated when it is realized that energy is involved in everything that happens on the Earth—everything that moves. The Earth is essentially a closed material system composed of the naturally occurring 92 chemical elements, all but a minute fraction of which are nonradioactive and hence obey the rules of conservation of matter and nontransmutability of the elements of classical chemistry. Into and out of the Earth's surface environment there occurs a continuous influx, degradation, and efflux of energy in consequence of which the mobile materials of the Earth's surface undergo either continuous or intermittent circulation. In addition, there are certain large chemical, thermal, and nuclear stores of energy within minable or drillable depths beneath the Earth's surface.

EARTH'S ENERGY SYSTEM

This total energy system of the Earth's surface is depicted graphically in Fig. 1. The horizontal bar near the bottom of the chart represents the surface of the Earth, below which are the energy stores of the fossil fuels and of geothermal, gravitational, and nuclear energy. The upper part of the chart is an energy flow diagram. The main energy influxes into the Earth's surface environment are three: the solar radiation intercepted by the Earth's diametral plane; tidal energy derived from the combined potential and kinetic energy of the Earth-Moon-Sun system; and terrestrial (especially geothermal) energy from inside the Earth. The magnitudes of these three inputs are: solar, $174{,}000 \times 10^{12}$ thermal watts; geothermal, 32×10^{12} thermal watts; and tidal, 3×10^{12} thermal watts. Thus, it is seen that the rate of energy influx from the Sun is roughly 5000 times the sum of the other two.

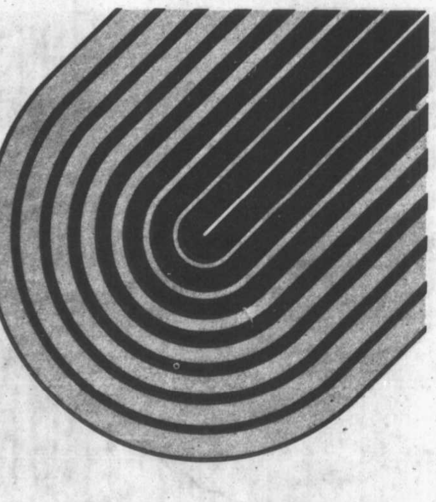
Of the solar power influx, about 30%, the albedo, is reflected and scattered into outer space as short-wavelength visible radiation. The remaining solar-energy flux of approximately $120{,}000 \times 10^{12}$ thermal watts, and the tidal and geothermal sources, are effective in terrestrial processes. With one small exception, the energy from all of these sources undergoes a series of transformations and degradations until it becomes heat at the lowest environmental temperature, after which it leaves the Earth as low-temperature thermal radiation.

The greater part of this energy flux serves to warm the atmosphere, the oceans, and the ground, and to produce atmospheric, oceanic, and hydrologic circulations. Of particular significance, however, is the 40×10^{12} W of solar power which is captured by the green leaves of plants and which by the process of photosynthesis drives the reaction whereby the inorganic compounds H_2O and CO_2 are synthesized into carbohydrates in which the solar energy becomes stored chemically. This then becomes the basic energy source for the physiological requirements of the entire plant and animal kingdoms, including the human species. *See* SOLAR ENERGY.

Nearly all the plant and animal material decays by oxidation and returns to its original constituents, H_2O and CO_2, at the same average rate as it is formed, and the stored energy is released as heat. The small exception pertains to the minute quantities of biologic materials which become deposited in peat bogs or other oxygen-deficient

Outlook for Fuel Reserves

- total energy system of the Earth
- depletion cycle for exhaustible resources
- worldwide reserves
- production capabilities



Dr. M. King Hubbert

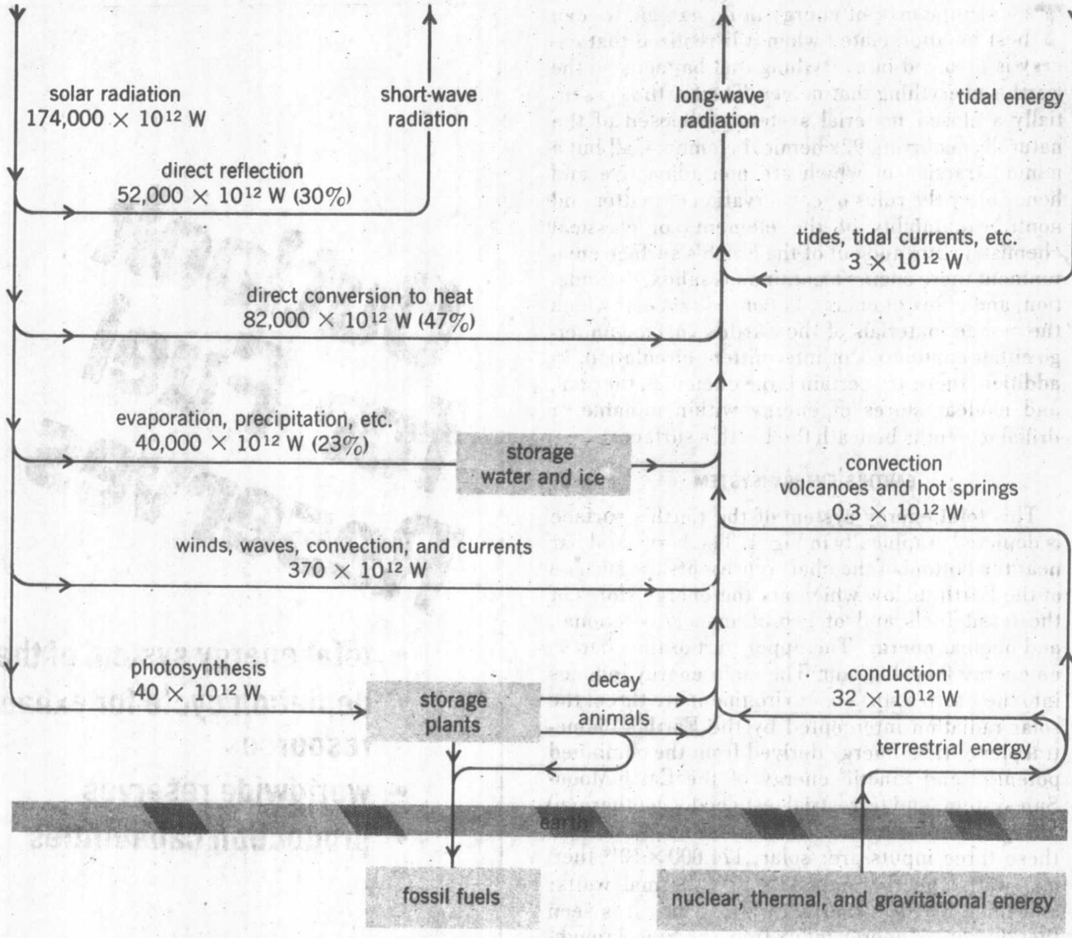


Fig. 1. Energy flow-sheet for the Earth. (*From M. K. Hubbert, U.S. energy resources: A review as of 1972, pt. 1, in A National Fuels and Energy Policy Study, U.S. 93d Congress, 2d Session, Senate Committee on Interior and Insular Affairs, ser. no. 93-40 (92-75), 1974*)

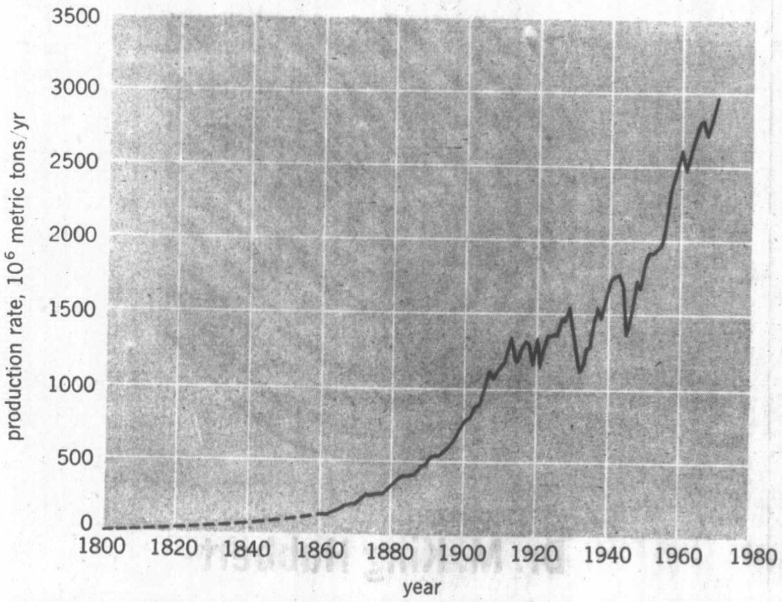


Fig. 2. World production of coal and lignite. Annual statistics are difficult to assemble for years prior to 1860 and have been estimated based on 2% average growth rate during the preceding 8 centuries. (*From Hubbert, op. cit., 1974*)

environments where complete oxidation is impossible and the energy of the material is preserved. This process has been occurring during the last several hundred million years of geologic time, and the accumulated organic debris, after burial under great thicknesses of sedimentary sands, muds, and limes, has been transformed into the Earth's present supply of fossil fuels. *See* FUEL, FOSSIL.

FOSSIL FUELS

The basic energy for the physiological requirements of the human species—its food supply—is obtained from the photosynthetic channel. However, during the last 2,000,000 years or so, the ancestors of the present human species have been progressively tampering with the Earth's energy system. Initially this consisted in the use of tools and weapons, and clothing and housing, whereby ever-larger fractions of the energy of the photosynthetic channel could be converted to human uses. Later, the ancient Egyptians, Greeks, and Romans began using the channel of wind power, and the Romans that of water power. This made possible a continuous increase in the human population, both in areal density and in geographical extent, but only a slight increase in the energy use per capita.

See the feature article ENERGY CONSUMPTION.

Exploitation of fossil fuels. A large increase in the energy per capita was not possible until exploitation of the large, concentrated quantities of energy stored in the fossil fuels was begun. The exploitation of coal as a continuing enterprise began in northeast England near Newcastle-upon-Tyne about 900 years ago; and the production of petroleum, the second major fossil fuel, was begun in Rumania in 1857 and in the United States in 1859.

World production. A graph of the rate of world production of coal is shown in Fig. 2. Scattered statistics exist to show that the cumulative production by 1860 was about 7×10^9 metric tons. Cumulative coal production by 1970 amounted to 139×10^9 metric tons. Of this, the amount of coal produced since 1940 exceeds somewhat all of the coal produced during the preceding 9 centuries.

During the period from 1860 to World War I, annual coal production increased steadily at an average growth rate of 4.2% per year, with a doubling period of 16.5 years. From the beginning of World War I to the end of World War II, the growth rate was only about 0.8% per year. Since World War II it has been at an intermediate rate of about 3% per year.

World production of crude oil from 1880 to 1970 is shown in Fig. 3. From 1890 to 1970 this increased at a uniform rate of growth of 7% per year, with a doubling period of 10 years. At such a growth rate, the cumulative production also doubles every 10 years, so that the cumulative production from 1960 to 1970 was approximately equal to all the oil produced before 1960.

In terms of their energy contents as measured by the heats of combustion, the contribution of crude oil as compared with that of coal was barely significant until about 1900. Subsequently, the energy contribution of crude oil increased more rapidly than that of coal, and became greater than that of coal by 1970. Were the additional energy contributions of natural gas and natural-gas liquids to be added to that of crude oil, the energy of petroleum fluids would represent about two-thirds and coal about one-third of the total rate of energy production from the fossil fuels.

United States production. Coal production and crude oil production in the United States are shown in Figs. 4 and 5. Coal mining in the United States began about 1820 and increased exponentially until about 1910 at a mean rate of 6.7% per year, with a doubling period of 10.4 years. Since World War I, United States coal production has fluctuated about a constant rate of 500×10^6 metric tons per year. *See* COAL MINING.

Figure 5 shows the growth in the annual production of crude oil in the United States since 1860. From 1880 to 1929 the production rate increased at a steady rate of 8.3% per year, with a doubling period of 8.4 years. After 1929 there was a drop in production during the Depression, and then a gradual slowing down in the growth rate until the peak in the production rate was reached in 1970. After that annual production has declined each succeeding year.

In the United States, as in the world, the rate of energy production from crude oil, natural gas, and natural-gas liquids has increased much faster than that of coal. By 1973, of the total energy produced in the United States from the fossil fuels and from nuclear and water power, only 17.9% was contributed by coal and 5% by nuclear and water power. The remainder, 77.1%, was contributed by oil and natural gas.

In the light of the rates of growth in world coal and oil production, the question unavoidably arises: About how long can the rates of production of

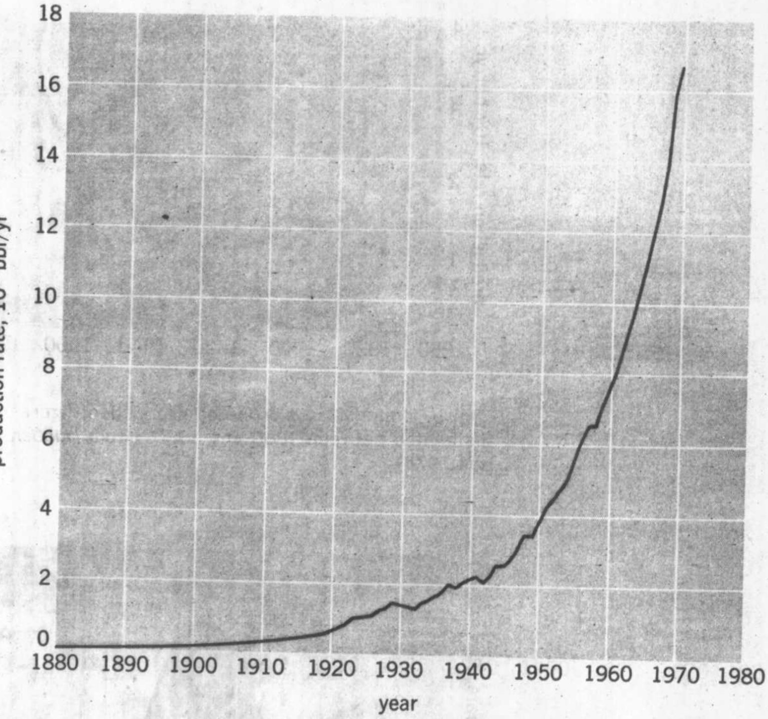


Fig. 3. World crude oil production. (*From Hubbert, op. cit., 1974*)

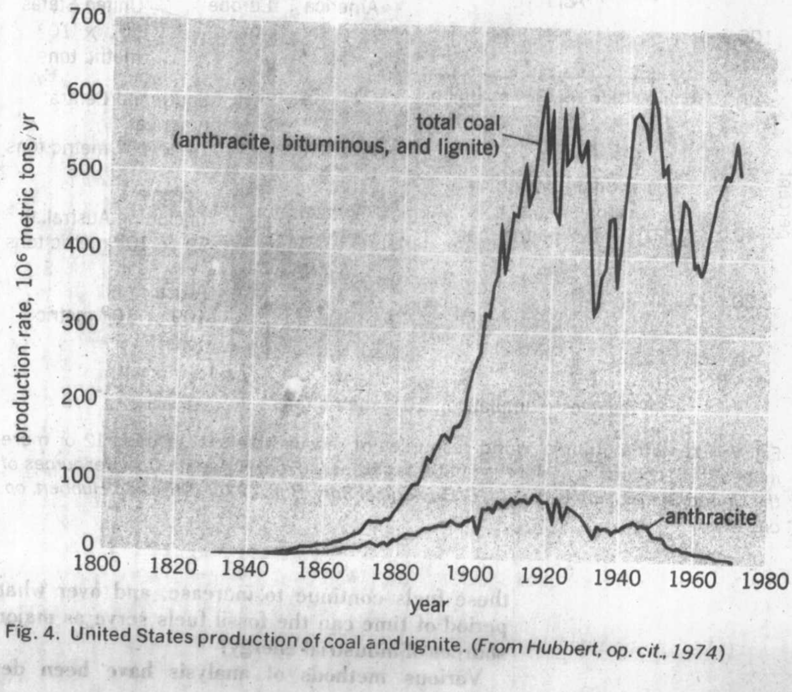


Fig. 4. United States production of coal and lignite. (*From Hubbert, op. cit., 1974*)