Human Energy Production as a Process in the Biosphere

In releasing the energy stored in fossil and nuclear fuels man accelerates slow cycles of nature. The waste products of power generation then interact with the fast cycles of the biosphere

by S. Fred Singer

As other articles in this issue of *Scientific American* have noted, the earth in general and the biosphere in particular have grand-scale pathways of energy metabolism. For example, solar energy falls on the earth, green plants utilize a tiny fraction of it to manufacture energy-rich compounds and some of these compounds are stored in the earth's crust as what we have come to call fossil fuels. The primary fission fuel uranium and the potential fusion fuel deuterium were originally "cooked" in the interior of stars. In releasing the energy of these chemical and nuclear fuels man is in effect racing the slow cycles of nature, with inevitable effects on the cycles themselves.

Before 1800 the power available to human societies was limited to solar energy that had only recently been radiated to the earth. The most direct form of such power was human or animal power; the energy came from the metabolism of food, which is to say from the biological oxidation of compounds storing solar energy. The burning of wood or oils of animal or vegetable origin to provide light and heat also represented the conversion of recently stored solar energy. By the same token the use of moving air or falling water to drive mills or pumps constituted the use of recently arrived solar energy. Among the other limitations of such power sources was the fact that they could not be readily transported and that their energy could not be transmitted any considerable distance.

This picture has of course changed completely since 1800, and it has assumed significant new dimensions in the past two decades with the advent of nuclear power. The most striking measure of these changes is the increased per capita consumption of energy in the developed countries. Indeed, the correlation between a nation's per capita use of energy and its level of economic development is almost linear [*see illustration on page 178*]. The minimum per capita consumption of energy is what is required in food for a man to stay alive, namely about 2,000 kilocalories or 100 watts (thermal) per day. Today the per capita use of energy in the U.S. is 10,000 watts per day, and the figure is rising by some 2.5 percent per year.

Hand in hand with the advance in the rate of energy consumption has gone the introduction of the new sources of energy: fossil and nuclear fuels. In contrast to the sources used before 1800, fossil and nuclear fuels represent energy that reached the earth millions and even some billions of years ago. Except occasionally for political reasons, it matters little where the new fuels are found; they can be transported readily, and the energy produced from them can be transmitted over great distances.

On first consideration it might seem that fossil and nuclear fuels are fundamentally different, in that the energy of one is released by oxidation, or burning, and the energy of the other is released by fission or fusion. In a deeper sense, however, the two kinds of fuel are closely related. Fossil fuels store the radiant energy originally produced by nuclear reactions in the interior of the sun. Nuclear fuels store energy produced by another set of nuclear reactions in the interior of certain stars. When such stars exploded, they showered into space the elements that had been synthesized within them. These elements then went into the formation of younger stars such as the sun, together with its family of planets.

The production of fossil fuels is based on the carbon cycle that has been described in the article by Bert Bolin [*page 124*]. In the process of photosynthesis plants use radiant energy from the sun to convert carbon dioxide and water into carbohydrates, at the same time releasing oxygen into the atmosphere. When the plant materials decompose or are eaten by animals, the process is reversed: oxygen is used to convert carbohydrates into energy plus carbon dioxide and water.

The amount of carbon dioxide involved in photosynthesis annually is about 110 billion tons, or roughly 5 percent of the carbon dioxide in the atmosphere. The consumption of carbon dioxide through photosynthesis is matched to one part in 10,000 by the annual release of carbon dioxide to the atmosphere through oxidation. Under normal conditions the amounts of carbon dioxide and oxygen in the atmosphere re-

WASTE HEAT that is an inevitable accompaniment of the human use of energy is evident in the thermal infrared image of New York on the opposite page. The thermogram was made with a Barnes thermograph that depicts emissions of energy on a color scale ranging from black for the coolest objects through green, yellow and red to red-purple for the hottest ones. Some of the emissions represent solar energy stored in the walls of buildings, but a large fraction is waste heat from the human consumption of energy. The rectangular elements of the image result from digitized output of thermograph. Empire State Building is at center.

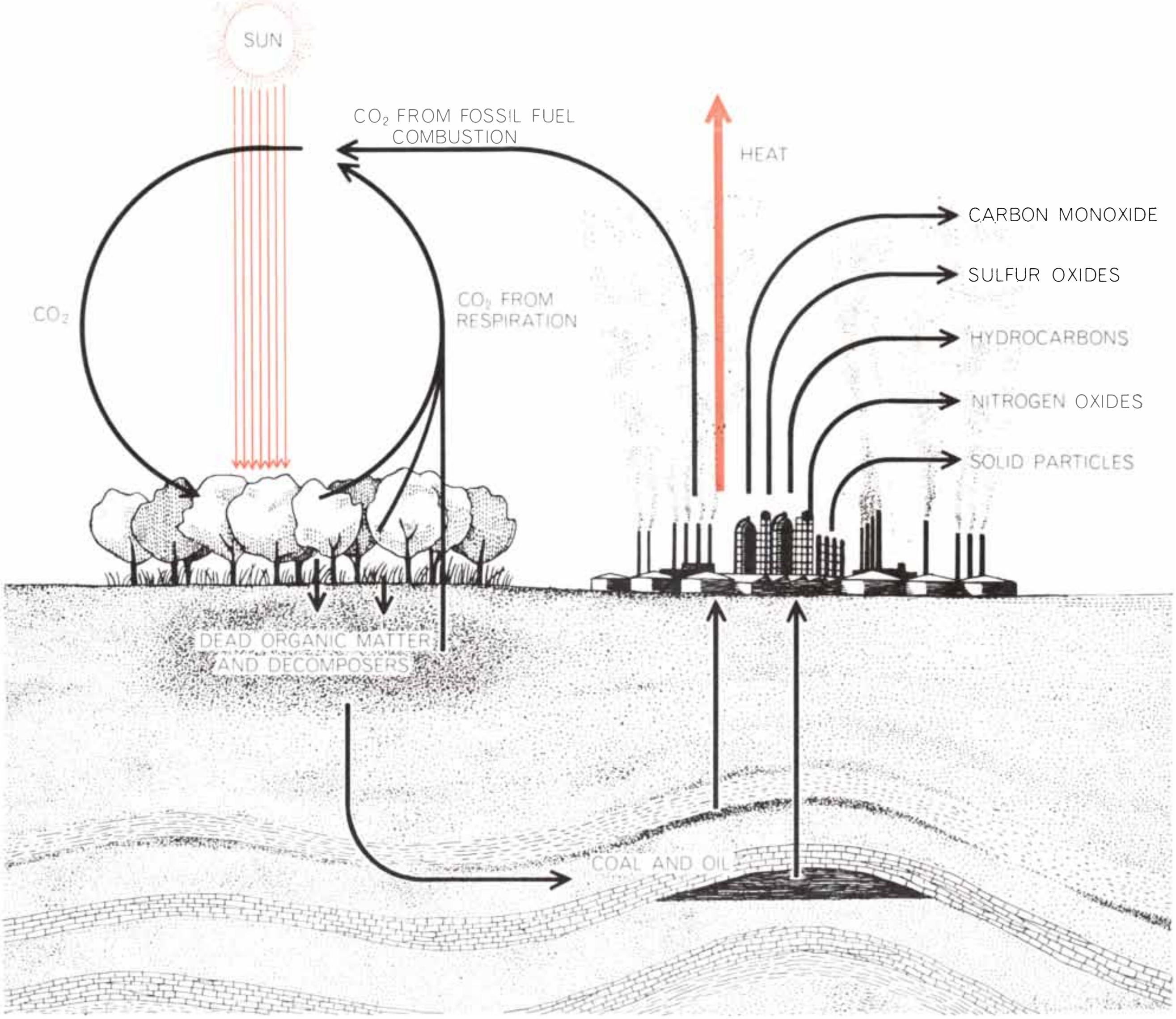
main approximately in equilibrium from year to year.

There are, however, small long-term imbalances in the carbon cycle, and it is owing to them that the fossil fuels being exploited today all derive from plants and animals that lived long ago. Over a span of geologic history extending back into the Cambrian period of some 500 million years ago, a small fraction of these organisms have been buried in sediments or mud under conditions that prevented complete oxidation. Various chemical changes have transformed them into fossil fuels: coal, oil, natural gas, lignite, tar and asphalt. Although the same geological processes are still operative, they function over vast periods of time, and so the amount of new fossil fuel that is likely to be produced during the next few thousand years is inconsequential. Therefore one can assume that the existing fossil fuels constitute a nonrenewable resource.

Coal has been burned for some eight centuries, but it was consumed in negligible amounts until early in the 19th century. Since the middle of that century the rise in the consumption of coal has been spectacular: in 1870 the world production rate of coal was about 250 million metric tons per year, whereas this year it will be about 2.8 billion tons. The rate of increase, however, is lower now than it was at the beginning of the period, having declined from an average of 4.4 percent per year to 3.6 percent, largely because of the rapid increase in the fraction of total industrial energy contributed by oil and gas. In the U.S. that fraction rose from 7.9 percent in 1900 to 67.9 percent in 1965, whereas the contribution of coal declined from 89 percent to 27.9 percent.

World production of crude oil was negligible as recently as 1890; now it is close to 12 billion barrels per year. The rise in the rate of production has been nearly 7 percent per year, so that the amount of oil extracted has doubled every 10 years. As yet there is no sign of a deceleration in this rate.

Nonetheless, the finiteness of the earth's fossil fuel supplies gives rise to the question of how long they will last. M. King Hubbert of the U.S. Geological Survey has estimated that the earth's



ENERGY CYCLE involved in the combustion of fossil fuels begins with solar energy employed in photosynthesis millions of years ago. A small fraction of the plants is buried under conditions that prevent complete oxidation. The material undergoes chemical changes that transform it into coal, oil and other fuels. When they are burned to release their stored energy, only part of the energy goes into useful work. Much of the energy is returned to the atmosphere as heat, together with such by-products of combustion as carbon dioxide and water vapor. Other emissions in fossil fuel combustion are listed at right in the relative order of their volume.

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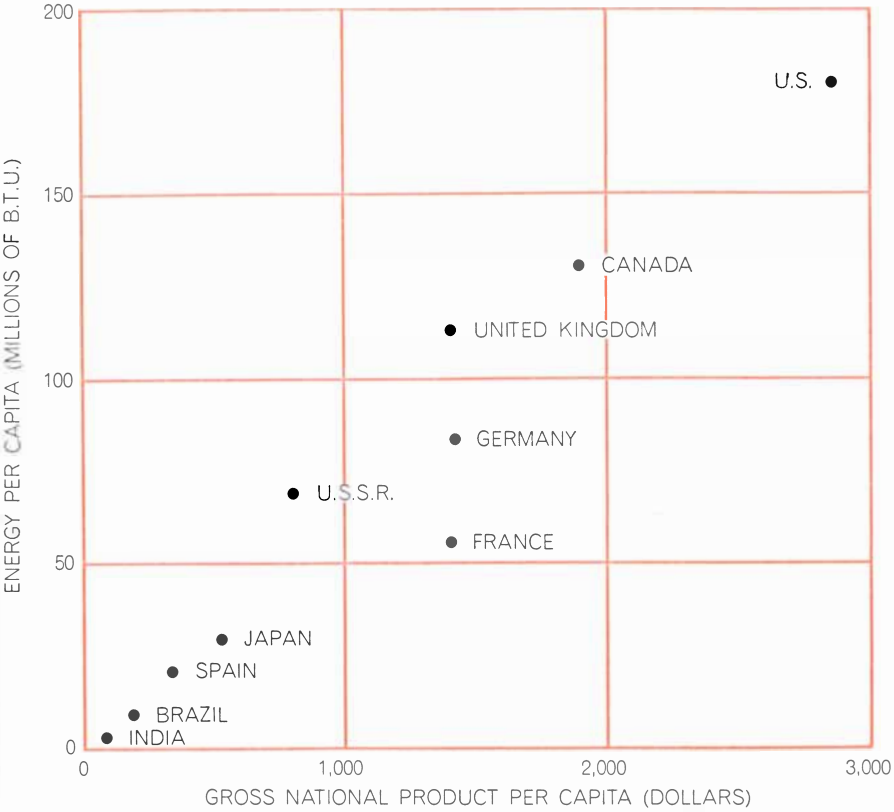

CLOSE RELATION between a nation's consumption of energy and its gross national product is depicted on the basis of a study made by the Office of Science and Technology in 1961. Most of the nations covered beyond the 10 shown would be in the lower left-hand rectangle.

coal supply can serve as a major source of industrial energy for another two or three centuries. His estimate for petroleum is 70 to 80 years. However much these periods may be stretched by unforeseen discoveries and improved technology, the end of the fossil fuel era will inevitably come. From the perspective of that time—perhaps the 23rd century—the period of exploitation of fossil fuels will be seen as only a brief episode in the span of human history.

This year the U.S. will consume some 685,000 million million B.T.U. of energy, most of it derived from fossil fuels. (One short ton of coal has a thermal value of 25.8 million B.T.U. The thermal value of one barrel of oil is 5.8 million B.T.U.) Industry takes more than 35 percent of the total energy consumption. About a third of industry's share is in the form of electricity, which, as of 1960, was generated roughly 50 percent from coal, 20 percent from water power, 20 percent from natural gas and 10 percent from oil.

The nation's homes use almost as much energy as industry does. A major consumer is space heating, which for the average home requires as much energy as the average family car: about 70 million B.T.U. per year, or the equivalent of 900 gallons of oil. The other domestic uses are for cooking, heating water, lighting and air conditioning.

Transportation accounts for 20 percent of the annual energy consumption, mainly in the form of gasoline for automobiles. Another 10 percent goes for commercial consumption in stores, offices, hotels, apartment houses and the like. Agriculture probably consumes no more than 1 percent of all the energy, chiefly for the operation of tractors and for running irrigation and drainage equipment.

Looking at the use of fossil fuels from another viewpoint, one finds that most of the coal goes into the generation of electricity. Oil and natural gas tend to be used directly, either for heating purposes or to provide motive power for vehicles. Fossil fuels are also used as the raw materials for the petrochemical industry. Notwithstanding that industry's rapid growth, however, it still accounts for less than 2 percent of the annual consumption of fossil fuels.

Clearly the production of energy from fossil fuels on the scale typical of a modern industrial nation represents an enormous amount of combustion, with

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attendant effects on the biosphere. By far the greatest effect is the emission of carbon dioxide. Combustion also injects a number of pollutants into the air. In the U.S. the five most common air pollutants, listed in the order of their annual tonnage, are carbon monoxide, sulfur oxides, hydrocarbons, nitrogen oxides and solid particles. The major sources are automobiles, industry, electric power plants, space heating and refuse disposal. The burning of fossil fuels also produces effects on water: chemical effects when the air pollutants are washed down by water and thermal effects arising from the dispersal of waste heat from thermal power plants.

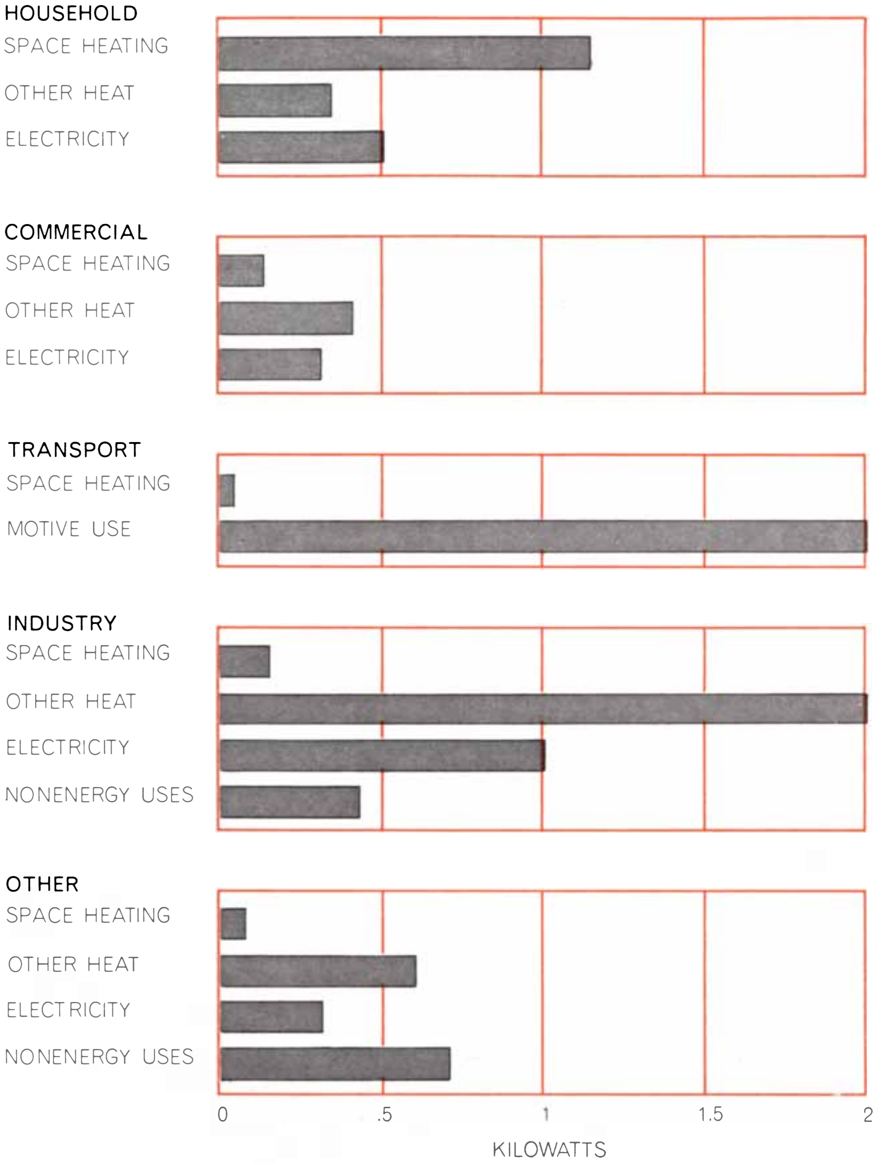
Carbon dioxide is the only combustion product whose increase has been documented on a worldwide basis. The injection of large quantities of carbon dioxide into the atmosphere in the past few decades has been extremely sudden in relation to important natural time scales. For example, although the surface of the sea can adjust to changes in the level of carbon dioxide in the atmosphere in about five years, the deeper layers require some hundreds or thousands of years to adjust. If the oceans were perfectly mixed at all times, carbon dioxide added to the atmosphere would distribute itself about five-sixths in the water and about one-sixth in the air. In actuality the distribution is about equal.

It appears that between 1860 and the present the concentration of carbon dioxide in the atmosphere has increased from about 290 parts per million to about 320 parts per million, an increase of more than 10 percent. Precise measurements by Charles D. Keeling of the Scripps Institution of Oceanography have established that the carbon dioxide content increased by six parts per million between 1958 and 1968. Reasonable projections indicate an increase of 25 percent (over 1970) to about 400 parts per million by the turn of the century and to between 500 and 540 parts per million by 2020.

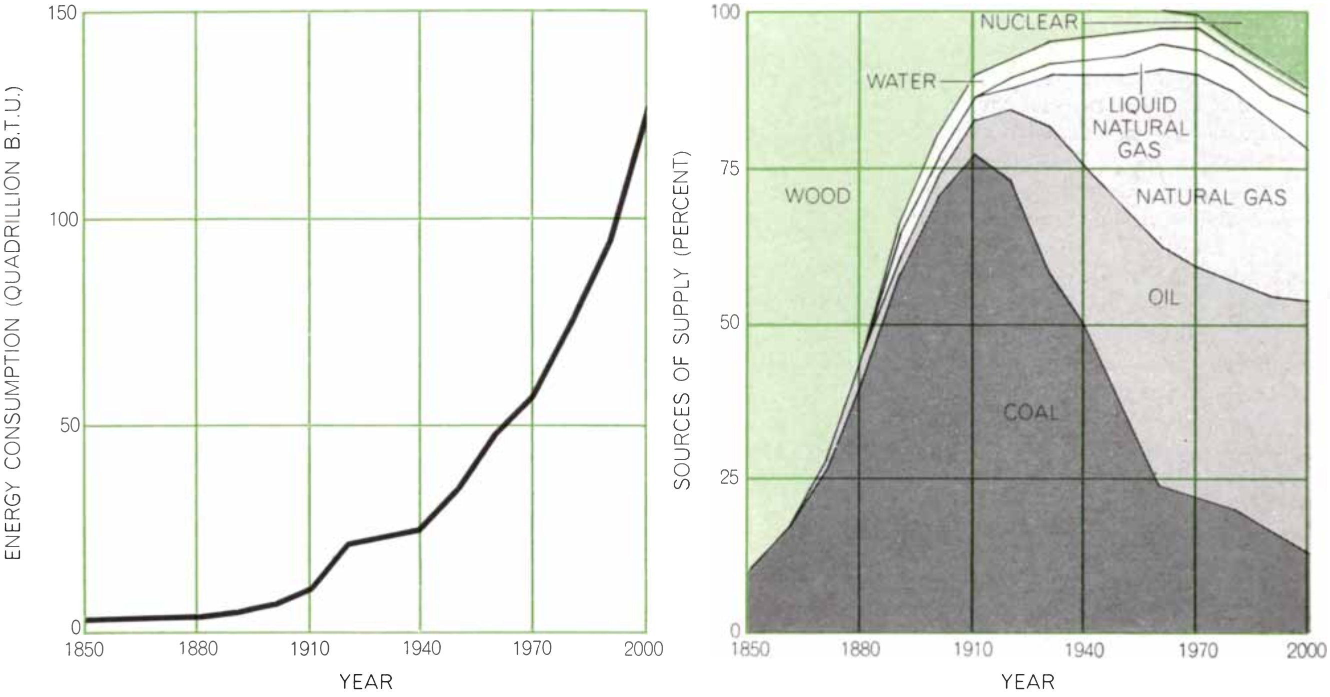
The most widely discussed matter related to these increases is the possibility that they will lead to a worldwide rise in temperature. The molecule of carbon dioxide has strong absorption bands, particularly in the infrared region of the spectrum at wavelengths of from 12 to 18 microns. This is the spectral region where most of the thermal energy radiating from the earth into space is concentrated. By increasing the absorption of this radiation and by reradiating it at a lower temperature corresponding to the temperature of the upper atmosphere the carbon dioxide reduces the amount of heat energy lost by the earth to outer space. The phenomenon has been called the "greenhouse effect," although the analogy is inexact because a real greenhouse achieves its results less from the fact that the glass blocks reradiation in the infrared than from the fact that it cuts down the convective transfer of heat.

The possibility that additional carbon dioxide from the burning of fossil fuels could produce a worldwide increase in temperature seems to have been raised initially by the American geologist P. C. Chamberlain in 1899. In 1956 Gilbert N. Plass calculated that a doubling of the carbon dioxide content of the atmosphere would result in a rise of 6.5 degrees Fahrenheit at the earth's surface. In 1963 Fritz Möller calculated that a 25 percent increase in atmospheric carbon dioxide would increase the average temperature by one to seven degrees F., depending on the effects of water vapor in the atmosphere. The most extensive calculations have been made by Syukuro Manabe and R. T. Wetherald, who estimate that a rise in atmospheric carbon dioxide from 300 to 600 parts per million would increase the average surface temperature by 4.25 degrees, assuming average cloudiness, and by 5.25 degrees, assuming no clouds.

Unfortunately the problem is more complicated than these calculations imply. An increase of temperature at the



USE OF ENERGY in the U.S. is expressed in terms of thermal kilowatts per capita per day in 1967. All together the consumption averages 10,000 watts per person per day, which is 100 times the food-intake level of 100 watts that is barely exceeded in many nations.



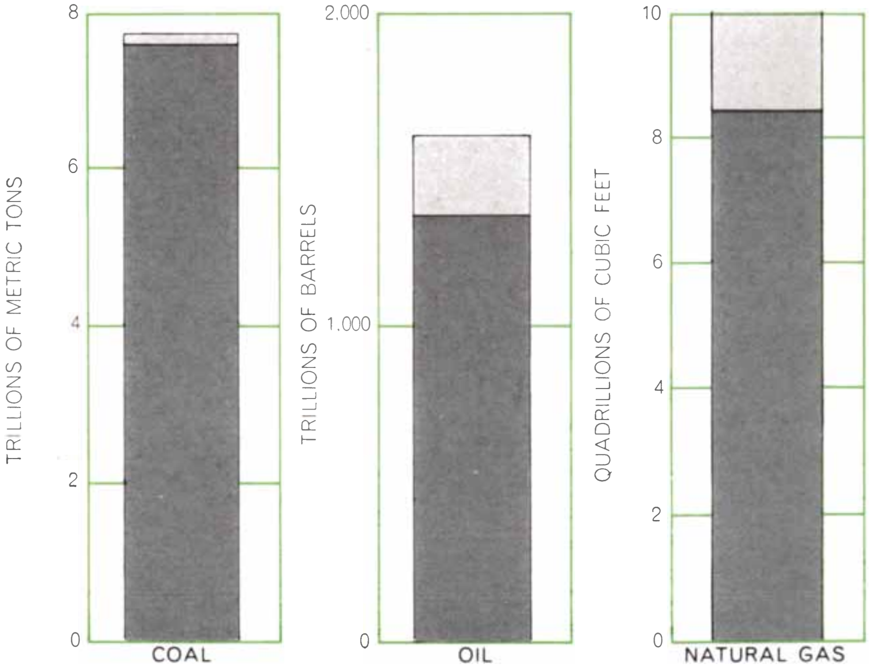
CHANGING SOURCES of energy in the U.S. since 1850 are compared (*right*) with total consumption (*left*) over the same period. At right one can see that in 1850 fuel wood was the source of 90 percent of the energy and coal accounted for 10 percent. By 2000 it is foreseen that coal will be back to almost 10 percent and that other sources will be oil, natural gas, liquid natural gas, hydroelectric power, fuel wood and nuclear energy. The estimates were made by Hans H. Landsberg of Resources for the Future, Inc.

surface of the earth and in the lower levels of the atmosphere not only increases evaporation but also changes cloudiness. Changes of cloudiness alter the albedo, or average reflecting power, of the earth. The normal average albedo is about 30 percent, meaning that 30 percent of the sunlight reaching the earth is immediately reflected back into space. Changes in cloudiness, therefore, can have a pronounced effect on the atmospheric temperature and on climate.

The situation is further complicated by atmospheric turbidity. J. Murray Mitchell, Jr., of the Environmental Science Services Administration has determined that atmospheric temperatures rose generally between 1860 and 1940. Between 1940 and 1960, although warming occurred in northern Europe and North America, there was a slight lowering of temperature for the world as a whole. Mitchell finds that a cooling trend has set in; he believes it is owing partly to the dust of volcanic eruptions and partly to such human activities as agricultural burning in the Tropics. (In the future the condensation trails left by jet airplanes may contribute to this problem.)

In sum, the fact that the carbon dioxide content of the atmosphere has increased is firmly established by reliable measurements. The effect of the increase on climate is uncertain, partly because no good worldwide measurements of radiation are available and partly because of the counteractive effects of changes in cloudiness and in the turbidity of the atmosphere. An exciting technological possibility is the use of a weather satellite to keep track of the energy radiated back into space by the earth. The data would provide a basis for the first reliable and standardized measurement of the "global radiation climate."

In any event, the higher levels of carbon dioxide may not persist for long. For one thing, the oceans, which contain 60



FOSSIL FUEL SUPPLIES remaining in the world are indicated by a scheme wherein the entire gray bar represents original resources, light gray portion shows how much has been extracted and dark gray area shows what remains. Figures reflect estimates by M. King Hubbert of the U.S. Geological Survey and could be changed by unforeseen discoveries.

times as much carbon dioxide as the atmosphere does, will begin to absorb the excess as the mixing of the intermediate and deeper levels of water proceeds. For another, the increased atmospheric content of carbon dioxide will stimulate a more rapid growth of plants—a phenomenon that has been utilized in greenhouses. It is true that the carbon dioxide thus removed from the atmosphere will be returned when the plants decay. Forests, however, account for about two-thirds of the photosynthesis taking place on land (and therefore for nearly half of the world total), and since forests are long-lived, they tend to spread over a long period of time the return of carbon dioxide to the atmosphere.

The five major air pollutants resulting from the combustion of fossil fuels also interact with the biosphere in various ways, not all of them clearly understood. One tends to think of pollutants as harmful, but the situation is not that simple, as becomes apparent in a consideration of the pollutants and their known effects.

Carbon monoxide appears to be almost entirely a man-made pollutant. The only significant source known is the imperfect combustion of fossil fuels, resulting in incomplete oxidation of the carbon. Although carbon monoxide is emitted in large amounts, it does not seem to accumulate in the atmosphere. The mechanism of removal is not known, but it is probably a biological sink, such as soil bacteria.

Sulfur, which occurs as an impurity in fossil fuels, is among the most troublesome of the air pollutants. Although there are natural sources of sulfur dioxides, such as volcanic gases, more than 80 percent is estimated to come from the combustion of fuels that contain sulfur. The sulfur dioxide may form sulfuric acid, which often becomes associated with atmospheric aerosols, or it may react further to form ammonium sulfate. A typical lifetime in the atmosphere is about a week.

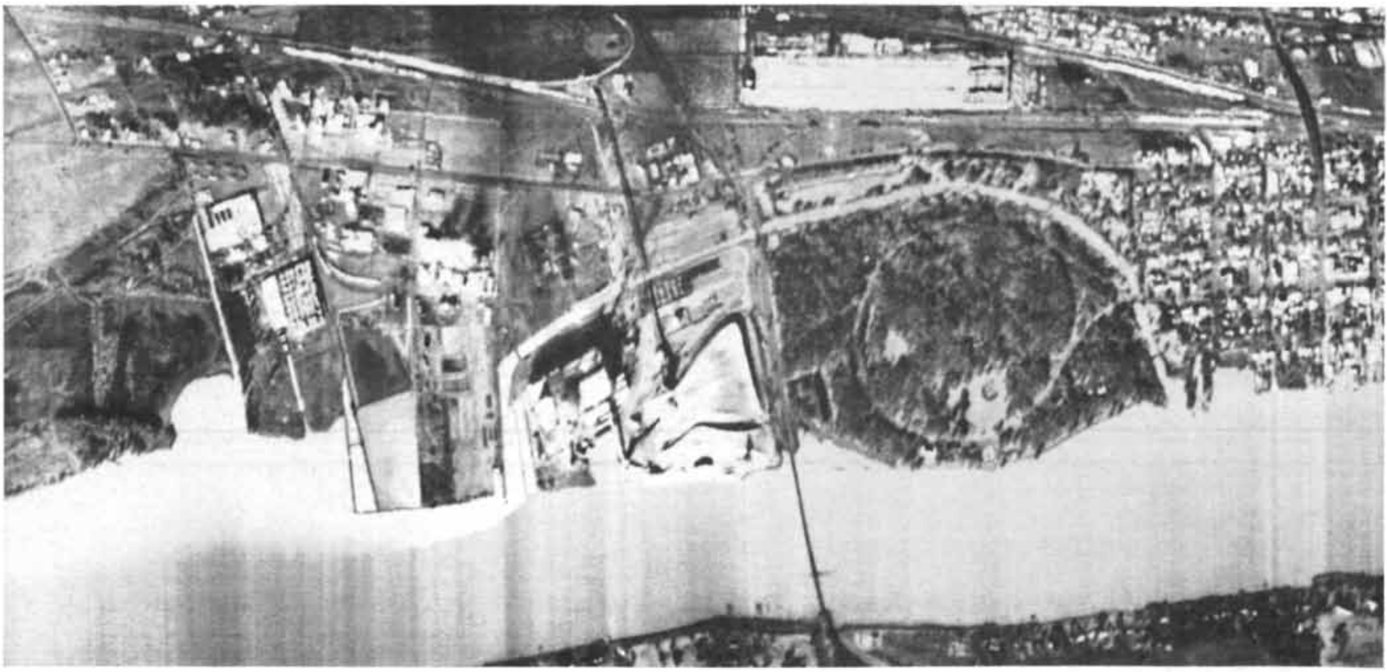
When the sulfur products are removed from the atmosphere by precipitation, they increase the acidity of the rainfall. Values of *p*H of about 4 have been found in the Netherlands and Sweden, probably because of the extensive industrial activity in western Europe. As a result small lakes and rivers have begun to show increased acidity that endangers the stability of their ecosystems. Certain aquatic animals, such as salmon, cannot survive if the *p*H falls below 5.5.

Nothing is known about the global effects of sulfur emission, but they are believed to be small. In any case most of the sulfur ends up in the oceans. It is possible, however, that sulfur compounds are accumulating in a layer of sulfate particles in the stratosphere. The layer's mechanism of formation, its effects and its relation to man-made emissions are not clear. The fine particles of the layer could have an effect on radiation from the upper atmosphere, thereby affecting mean global temperatures.

Hydrocarbons are emitted naturally into the atmosphere from forests and vegetation and in the form of methane from the bacterial decomposition of organic matter. Human activities account for only about 15 percent of the emissions, but these contributions are concentrated in urban areas. The main contributor is the processing and combustion of petroleum, particularly gasoline for the internal-combustion engine.

The reactions of hydrocarbons with nitrogen oxides in the presence of ultraviolet radiation produce the photochemical smog that appears so often over Los Angeles and other cities. The biological effects of several of the products of the reactions, including ozone and complex organic molecules, can be quite severe. Some of the products are thought to be carcinogenic. Ozone has highly detrimental effects on vegetation, but fortunately they are localized. As yet no regional or worldwide effects have been discovered.

Hydrocarbon pollutants in the form of oil spills are well known to have drastic ecological effects. The spill in the Santa Barbara Channel last year, which involved some 10,000 tons, and the *Torrey Canyon* spill in 1967, involving about 100,000 tons, produced intense local concentrations of oil, which is toxic to many marine organisms. Besides these



SOURCES OF WASTE HEAT are evident in a thermal infrared image, made at an altitude of 2,000 feet, of an industrial concentration along the Detroit River in Detroit. The whiter an object is, the hotter it was when the image was made. The complex at left well-publicized events there is a yearly worldwide spillage from various oil operations that adds up to about a million tons, even though most of the individual spills are small. There are also natural oil seeps of unknown magnitude. Added to all of these is the dumping of waste motor oil; in the U.S. alone about a million tons of such oil is discarded annually. Up to the present time no worldwide effects of these various oil spills are detectable. It can therefore be assumed that bacteria degrade the oil rapidly.

Nitrogen oxides occur naturally in the atmosphere as nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2). Nitrous oxide is the most plentiful at .25 part per million and is relatively inert. Nitrogen dioxide is a strong absorber of ultraviolet radiation and triggers photochemical reactions that produce smog. In combination with water it can form nitric acid.

The production of nitrogen oxides in combustion is highly sensitive to temperature. It is particularly likely to result from the explosive combustion taking place in the internal-combustion engine. If this engine is ever replaced by an external-combustion engine that operates at a steady and relatively low temperature rather than at high peaks, the emission of nitrogen oxides will be greatly reduced.

Solid particles are injected into the lower atmosphere from a number of sources, with the combustion of fossil fuels making a major contribution. The technology of pollution control is adequate for limiting such emissions. If it is applied, solid particles will become insignificant pollutants.

Although the fossil fuels still predominate as sources of power, the introduction of nuclear fuels into the generation of power is changing both the scale of energy conversion and the effects of that conversion on the biosphere. Nuclear energy can be considered as a heat source differing from coal or oil, but once the energy has been released in the form of heat it is used in the same way as heat from other sources. Therefore the problem of waste heat is the same. The pollution characteristics of nuclear energy, however, differ from those of the fossil fuels, being radioactive rather than chemical.

Two processes are of concern: the fission of heavy nuclei such as uranium and the fusion of light nuclei such as deuterium. The fission reaction has to start with uranium 235, because that is the only naturally occurring isotope that is fissioned by the capture of slow neutrons. On fissioning the uranium 235 supplies the neutrons needed to carry out other reactions.

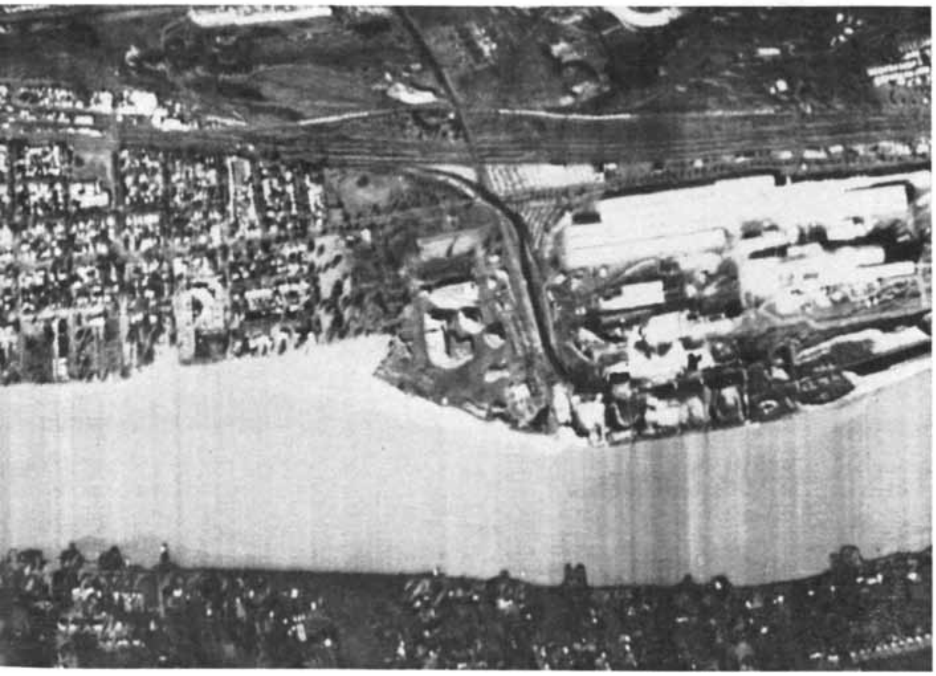
Each fission event of uranium 235 releases some 200 million electron volts of energy. One gram of uranium 235 therefore corresponds to 81,900 million joules, an energy equivalent of 2.7 metric tons of coal or 13.7 barrels of crude oil. A nuclear power plant producing 1,000 electrical megawatts with a thermal efficiency of 33 percent would consume about three kilograms of uranium 235 per day.

A nuclear "burner" uses up large amounts of uranium 235, which is in short supply since it has an abundance of only .7 percent of the uranium in natural ore. If reactor development proceeds as foreseen by the Atomic Energy Commission, inexpensive reserves of uranium (costing less than $10 per pound) would be used up within about 15 years and medium-priced fuel (up to $30 per pound) would be used up by the year 2000. Hence there has been concern that present reactors will deplete these supplies of uranium before converter and breeder reactors are developed to make fissionable plutonium 239 and uranium 233. Either of these isotopes can be used as a catalyst to burn uranium 238 or thorium 232, which are relatively abundant. Thorium and uranium together have an abundance of about 15 parts per million in the earth's crust, representing therefore a source of energy millions of times larger than all known reserves of fossil fuel.

The possibility of generating energy by nuclear fusion is more remote. Of the two processes being considered—the deuterium-deuterium reaction and the deuterium-tritium reaction—the latter is somewhat easier because it proceeds at a lower temperature. In it lithium 6 is the basic fuel, because it is needed to make tritium by nuclear bombardment. The amount of energy available in this way is limited by the abundance of lithium 6 in the earth's crust, namely about two parts per million. The deuterium-deuterium reaction, on the other hand, would represent a practically inexhaustible source of energy, since one part in 5,000 of the hydrogen in the oceans is deuterium.

One must hope, then, that breeder reactors and perhaps fusion reactors will be developed commercially before the supplies of fossil fuel and uranium 235 are exhausted. With inexhaustible (but not cheap) supplies of nuclear energy, automobiles may run on artificially produced ammonia or methane; coal and oil shale will be used as the basis for chemicals, and electricity generated in large breeder or fusion reactors will be used for such purposes as the manufacture of ammonia and methane, the reduction of ores and the production of fertilizers.

It is difficult at this stage to predict



center, identifiable by a distinctly warm effluent entering the river, is a power plant. Group of hot buildings at right is a steel mill. Cool land area at bottom is part of Windsor, Ontario.

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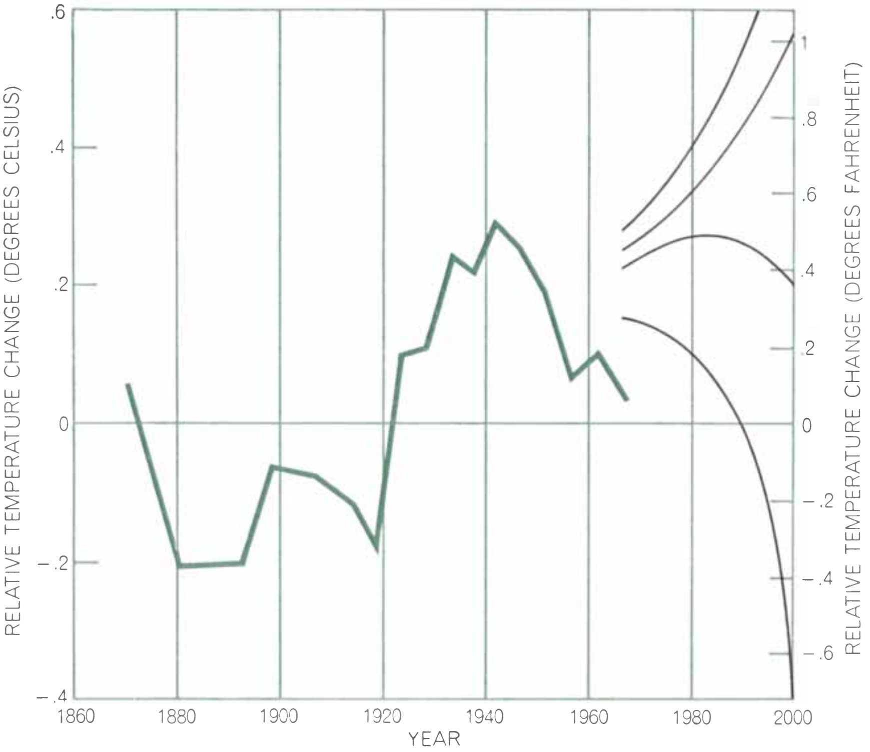
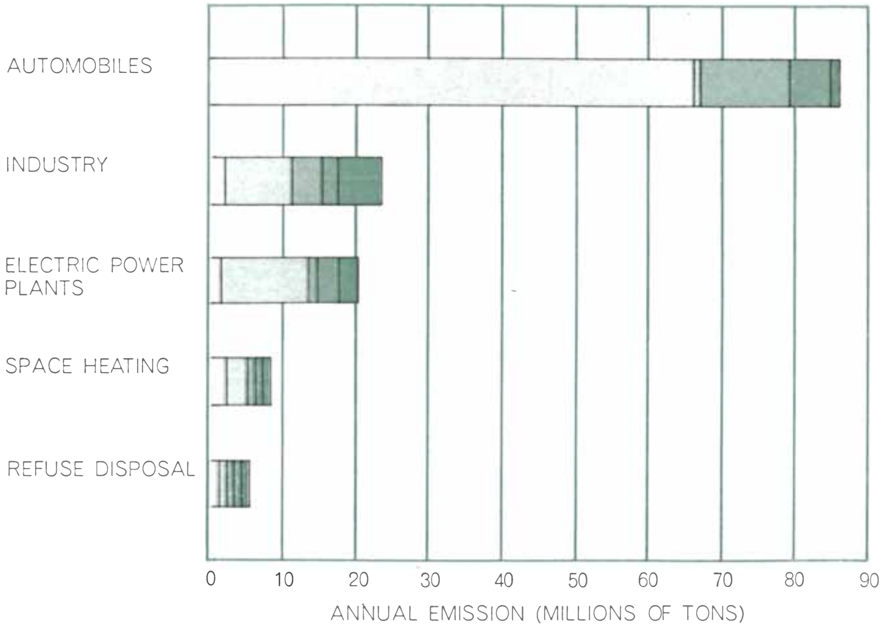


TEMPERATURE TREND in Northern Hemisphere is portrayed as observed (*color*) and as predicted under various conditions (*black*). The top black curve assumes an effect from carbon dioxide only; the other black curves also take account of dust. Second and third curves assume doubling of atmospheric dust in 20 and 10 years respectively; bottom curve, doubling in 10 years with twice the thermal effect thought most probable. Chart is based on work of J. Murray Mitchell, Jr., of the Environmental Science Services Administration.

the effects of large-scale use of nuclear energy on the biosphere. One must make certain assumptions about the disposal of radioactive wastes. A reasonable assumption is that they will be rendered harmless by techniques whereby long-lived radioactive isotopes are made into solids and buried. (They are potentially dangerous now because of the technique of storing them as liquids in underground tanks.) Short-lived radioactive wastes can presumably be stored safely until they decay.

For both nuclear energy and for proc-



SOURCES OF EMISSIONS from combustion are ranked. Five parts of each bar represent (*from left*) carbon monoxide, sulfur oxides, hydrocarbons, nitrogen oxides and particles.

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esses involving fossil fuels the major problem and the major impact of human energy production is the dissipation of waste heat. The heat has direct effects on the biosphere and could have indirect effects on climate. It is useful to distinguish between local problems of thermal pollution, meaning the problems that arise in the immediate vicinity of a power plant, and the global problem of thermal balance created by the transformation of steadily rising amounts of energy.

The efficiency of a power plant is determined by the laws of thermodynamics. No matter what the fuel is, one tries to create high-temperature steam for driving the turbines and to condense the steam at the lowest possible temperature. Water is the only practical medium for carrying the heat away. Hence more than 80 percent of the cooling water used by U.S. industry is accounted for by electric power plants. For every kilowatt-hour of energy produced about 6,000 B.T.U. in heat must be dissipated from a fossil fuel plant and about 10,000 B.T.U. from a contemporary nuclear plant.

In the U.S., where the consumption of power has been doubling every eight to 10 years, the increase in the number and size of electric power plants is putting a severe strain on the supply of cooling water. By 1980 about half of the normal runoff of fresh water will be needed for this purpose. Even though some 95 percent of the water thus used is returned to the stream, it is not the same: its increased temperature has a number of harmful effects. Higher temperatures decrease the amount of dissolved oxygen and therefore the capacity of the stream to assimilate organic wastes. Bacterial decomposition is accelerated, further depressing the oxygen level. The reduction of oxygen decreases the viability of aquatic organisms while at the same time the higher temperature raises their metabolic rate and therefore their need for oxygen.

In the face of stringent requirements being laid down by the states and the Department of the Interior, power companies are installing devices that cool water before it is returned to the stream. The devices include cooling ponds, spray ponds and cooling towers. They function by evaporating some of the cooling water, so that the excess heat is dissipated into the atmosphere rather than into the stream.

This strategy of spreading waste heat has to be reexamined as the scale of the problem increases. It is already apparent that the "heat islands" characteristic of metropolitan areas have definite meteorological effects—not necessarily all bad. The fact that a city is warmer than the surrounding countryside affects the ecology and biospheric activity in metropolitan areas in numerous ways. For example, the release of heat in a relatively small local area causes a change in the convective pattern of the atmosphere. The addition of large amounts of particulate matter from industry, space heating and refuse disposal provides nuclei for the condensation of clouds. A study in the state of Washington showed an increase of approximately 30 percent in average precipitation over long periods of time as a result of air pollution from pulp and paper mills.

The worldwide consumption of energy can be estimated from the fact that the U.S. accounts for about a third of this consumption. The U.S. consumption of 685,000 million million B.T.U. per year is equivalent to 2.2 million megawatts. World consumption is therefore some 6.6 million megawatts. Put another way, the present situation is that the per capita consumption of energy in the U.S. of 10,000 watts per day compares with somewhat more than 100 watts (barely above the food-intake level) in most of the rest of the world.

Projections for the future depend on the assumptions made. If one assumes that in 50 years the rest of the world will reach the present U.S. level of energy consumption and that the population will be 10 billion, the total man-made energy would be 110 million megawatts per year. The energy would of course be distributed in a patchy manner reflecting the location of population centers and the distributing effects of the atmosphere and the oceans.

That figure is numerically small compared with the amount of solar energy the earth radiates back into space. Over the entire earth the annual heat loss is about 120,000 million megawatts, or more than 1,000 times the energy that would be dissipated by human activity if the level of energy consumption projected for 2020 were reached. It would be incautious to assume, however, that the heat put into the biosphere as a result of human energy consumption can be neglected because it is so much smaller than the solar input. The atmospheric engine is subtle in its operation and delicate in its adjustments. Extra inputs of energy in particular places can have significant and far-reaching consequences.