Physics and Environment

Impact of energy demands

Noise. Dirt. Air and water pollution. Bad odors.
Must all these accompany production of the power we need?
Not if we develop imaginative technologies.

Ali B. Cambel

A fundamental difference between Man and other animals is Man's ability to develop methods and devices that increase his energy supply far beyond what his muscles can provide. Whereas early man consumed about 2000 calories per day, the average US citizen currently uses about 200 000 calories daily. This tremendous increase in energy consumption affects our life style not only in degree but also in kind. We can no longer treat energy as a subject in physics alone but must consider it as a social force.

Energy, in many ways the Dr Faustus of our age, presents trade-offs between human comfort and the right to enjoy *an environment fit for human beings.* My purpose here is to comment on the intricate relationship between energy and environment, which I interpret to be the ensemble of physical and biological as well as social, cultural and spiritual conditions affecting the nature and behavior of men. Power production is, no doubt, the main source of the environmental blight that engulfs us everywhere, and, to all appearances, the situation is likely to get worse rather than better. Yet the solution is not in forbidding the growth of the energy industries, because it is the availability of cheap and abundant energy that makes an improved standard of living possible. We must develop counter-technologies that better exploit the potentialities of the laws of thermodynamics and electrodynamics, and physicists must help.

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Reliance on energy production

Hostility toward energy appears to be caused by two factors: the revulsion of our youth and many of their elders toward the affluence symbolized by a fast-moving, computerized and, at times, *dehumanized society,* and the *objection* to the effluents generated when large amounts of power are produced and consumed.

Some people have suggested that we return to a horse-and-buggy kind of life, so that fossil fuels can be preserved and pollution reduced. Although this suggestion may sound romantic, we should also consider that there are about 2×10^8 cars in the world, about half of them in the US.[1] Suppose for a moment that all motor vehicles are banned (what a problem in solid-waste disposal!) and that a two-horse carriage replaces each automobile. The consequences of a horse-and-buggy economy would be interesting indeed. But who would really want it?

A return to animate power to supply energy for modern industry would be inconceivable not only technologically but on moral grounds as well. Were we to try, naively, to substitute animate power for electrical power we would need to increase the animal population of this food-hungry world immensely.

New awareness

I recall advocating to some groups, as recently as 1964, the need for a new way of looking at energy problems and *being told that energy was not a problem.* There seemed, after all, to be no cause for alarm because the cost of electricity was declining while the price of consumer products was increasing.[2] Less than a year ago, one of these groups asked me to serve as a member of a study team on the same subject. What happened in the intervening five years?

The 1965 Northeast blackout made it plain to everyone that indeed a problem might exist. Several government reports, written by scientists and engineers, that identified the problem facing

CONSOLIDATED EDISON CO.

us, were picked up and publicized by citizen–lobbyists. Conservationists made the potential damage of increased power generation their first target. As they articulated the problem and sought injunctions to delay, if not prevent, the construction of new plants, "brownouts" began to occur in various parts of the US. By the time "Earthday" was proclaimed, on 22 April 1970, the art of deploring energy-converting devices had become as respectable as apple pie.

Why was the impending energy shortage and the effluence of power production not noticed earlier? The public must have observed the construction of new power plants and read about the rise of automobile production. One cause for the lack of alarm was the supreme efficiency and reliability of the energy industries; they could and did deliver energy at any place and any time. In retrospect, this reliability was not unusually difficult, because utility companies are really monopolies and also because the heat and light bill constitutes only a small fraction of a family's total budget and is not usually questioned.

Another change in the past few years is that, in the early 1960's, prominent academicians and industrialists were complaining that bright young degree holders were not interested in mundane assignments such as energy and the environment. They were more exhilarated by the excitement of the aerospace and electronics industries. Budgetary cuts have now mutilated these industries, and our youth is clamoring for jobs that will contribute to the betterment of Man's environment. Yet there are few opportunities for these young people to practice their métier.

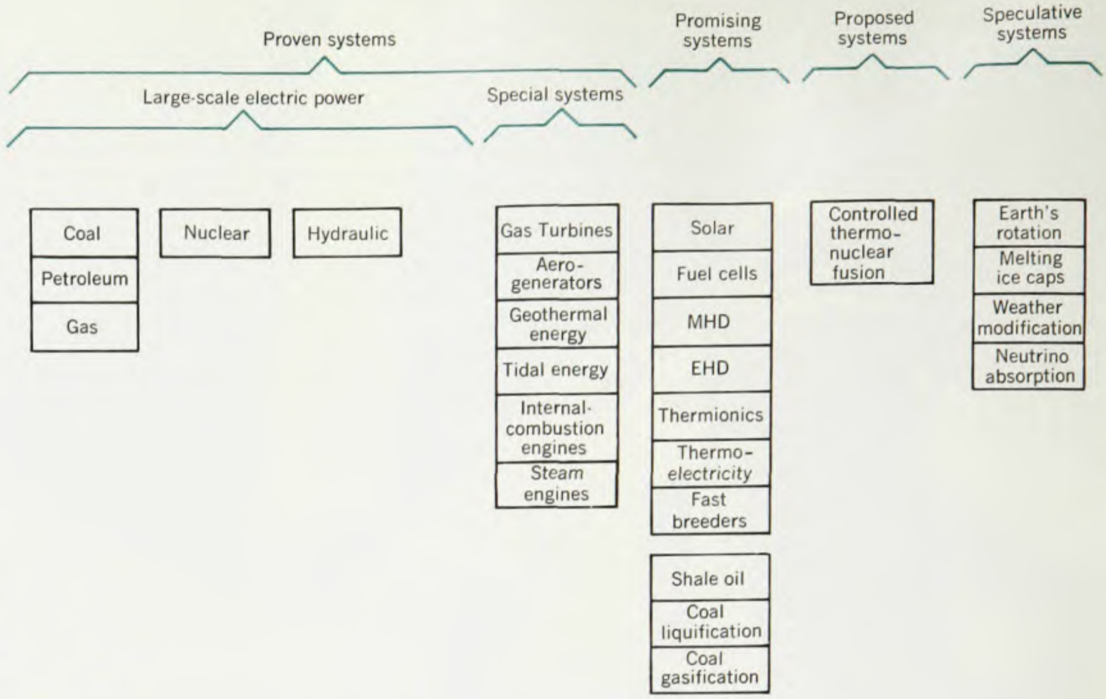
Who will do the research?

Industry is not interested because it calls environmental problems a societal concern. The government is not interested because of budgetary limitations, and because it has been suggested that whatever is really worth doing will be done by private industry.

Academic institutions pay lip service to societal affairs, but are unable to do anything significant because, for years, universities have convinced their faculty members that specialization is desirable and that application is unsophisticated and unbecoming to a scholar. (Universities would be in a better position today had they heeded Hermann von Helmholtz: "The most practical thing is a good theory." They could have had the best of all worlds and we would have available the cadre of modern "renaissance men" that our society so badly needs.) The lack of funds, of course, exacerbates matters.

Utility companies, being monopolies, have seen no reason for engaging in research and development. As privately owned corporations, utility companies must provide dividends to their stockholders. Because they are de facto monopolies, they are regulated by government agencies. Thus utility companies must walk along the razor's edge between showing a profit and not overcharging the consumer. Any energy research and development is, in general, done by the manufacturers who try to sell their equipment to utility companies. We see then, that no one sector of society or the economy is completely capable of solving the existing power and energy crisis. I believe the solution will be through the creation of new technological competitions.

I can not accept the nihilism about our future that is becoming so prevalent. After all, the first commandment for any species on a purely biological level is: Survive. We have, in our evolutionary pattern, emphasized reason; now we must depend on it. The



Proven, promising and speculative systems. Nearly all the energy that we now consume comes from the first group of systems, and the others are largely neglected. From reference 8. Figure 1

solution to the conflict between energy and the environment must not be in curtailing energy supply but in reducing the irreversible and dissipative effects when we convert and consume energy. As a people, we must learn not to waste energy through use of scientifically and technologically obsolete equipment.

Deciding what we want

Scientists have contended that they must be neutral as well as objective, and that society is responsible for the proper use of their findings. Although Albert Einstein, Norbert Wiener and Albert Szent-Gyorgi have warned us against this attitude, the objectivity if not the neutrality of science must be defended. Society has demonstrated an uncanny intuition in identifying what it needs and deciding what it wants. In the latter part of the 19th century, for example, society asked for electric generators and the industrialization made possible by generator–motor sets. Had it opted for applications of the cathode-ray tube, which William Crookes had just invented, we might have had radar during World War I and television could have enlivened parties during the Prohibition era.

Society's demands today exceed available resources very significantly, and the demand for energy is likely to continue to increase. World population is growing by about 2% yearly, less in the developed countries and more rapidly in the developing nations. Energy consumption, however, is increasing at about 3–5% a year, so that we can conclude that the standard of living of individuals is improving and that industrialization is accelerating. If improvements in standard of living and in acceleration of industrialization are to be realized, a 5% annual increase in energy consumption is probably needed. Energy consumption in the US has been growing at a faster and faster rate; it is now 7–10% a year.

A variety of energy converters is available (see figures 1 and 2), and there is no reason why we should not diversify our sources of energy. But we can not decide on the basis of scientific feasibility alone; we must consider the entire system, and here intuition is insufficient as a guide. Scientists must establish rapport with the body politic to identify priorities and develop methods for comprehensive systems analysis. We must form interdisciplinary teams of physicists, engineers, economists, sociologists, life scientists, conservationists, physicians, political scientists, industrialists and policy makers. Perhaps we should even include a theologian, because meeting the demand for energy sometimes leads to considerations of morality. Scientists and technologists must develop those devices and processes that maximize positive benefits and minimize possible dangers. The energy industries are full of opportunities for exercising this philosophy while pursuing the most sophisticated form of research and development and while engaging in the most brain-taxing, interdisciplinary exchange of ideas among the "hard" and "soft" sciences.

Table 1. Types of Energy Consumption

	1960				2000 Part-Fuel and Part-Electric Economy				2000 All-Electric Economy	
Energy Use	Direct (10^{15} Btu)	Electric (10^9 kWh)	Losses (10^9 kWh)	Total Electric (10^9 kWh)	Direct (10^{15} Btu)	Electric (10^9 kWh)	Losses (10^9 kWh)	Total Electric (10^9 kWh)	Direct (10^{15} Btu)	Total Electric (10^9 kWh)
Residential	6.63	193	24	217	8.05	1188	114	1302	0	3898
Commercial	2.44	103	14	127	4.55	544	53	607	0	2074
Transportation	9.19	0	0	0	37.19	0	0	0	4.83	11 211
Industrial	11.58	355	43	398	35.20	2375	223	2598	3.52	12 719
Other	6.22	92	11	103	13.15	188	16	204	8.77	1488
Total	36.05	753	92	845	98.15	4305	406	4711	17.12	31 390

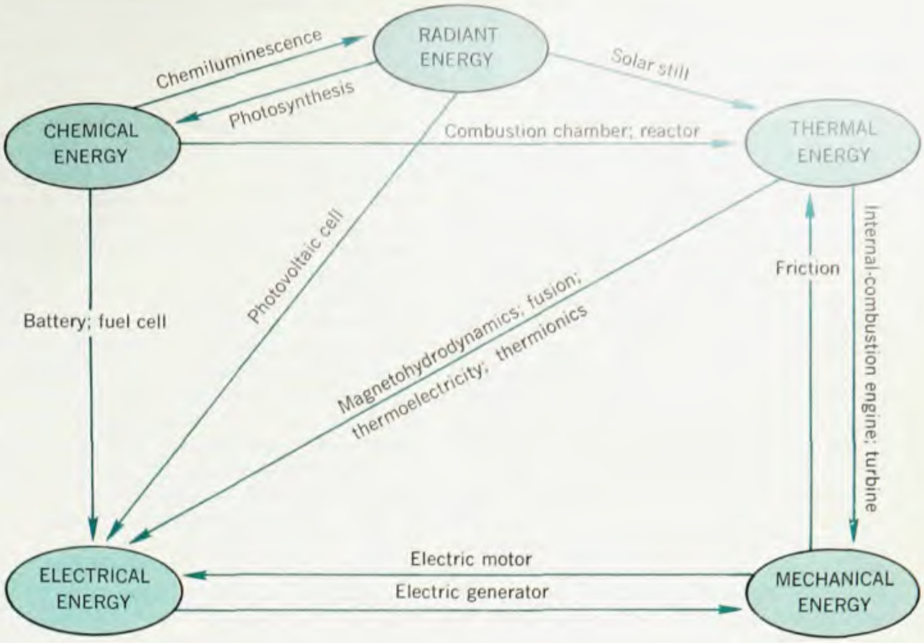
What are some of the choices? Immediate expedients include expanding the interconnections among utility systems or installing gas turbine and diesel generating units. Had we not drastically curtailed the associated research and development funds, we could now be on the verge of having magnetohydrodynamics as an option.

Table 1 shows the 1960 distribution of energy consumption over various sectors of society and two extrapolations to the year 2000.[9] One extrapolation is based on a mixed-energy economy and the other on an all-electric economy. Some drastic changes are clearly possible. A primarily electric economy offers advantages, but also worsens certain environmental problems.

Large-capacity nuclear reactors reduce the cost of power, but to prevent thermal pollution, such units would probably have to be installed on the seacoasts. Fear of thermal pollution, although it has a basis, should be handled without hysteria. Instead of rejecting nuclear plants outright, we should be trying harder to determine the levels of thermal pollution produced at the reactor site. We should be exhaustively studying the judicious design of transmission lines as well as the distribution of plant sites. The power generated could be transmitted and distributed by superconducting underground cables.[3] Such cables, although still in the research stage, are believed feasible (see pages 42–43). An all-electric economy such as we have been describing could also alleviate the gas shortage that is becoming noticeable in certain parts of the U.S.

As we see in table 2, transportation and the automobile consume large amounts of energy; automobiles are also major polluters. Automobile manufacturers might modify themselves into transportation companies (we would have to protect them from antitrust suits); if they were allowed to diversify, they might have a chance of developing passive cars. We might educate the public not to demand all-purpose traditional cars, so that special markets might be developed for some of the power plants demonstrated by college students during the 1970 Clean Air Car race. This race was won by an internal-combustion engine powered car that was equipped with platinum-catalyst pollution-abatement equipment and used lead-free fuel.

We should emphasize the development of practical electric cars; the problem here is the unavailability of proper batteries. An electric car would now cost more to buy than a comparable traditional car. And we simply do not have sufficient reserve electric power to charge millions of car batteries, even at night. Building power plants to supply the necessary electricity would be like robbing Peter to pay Paul, because the reduction in conventional automobile pollution would be made up by the increase in pollution from the additional conventional power plants. We must consider the pollution from stationary plants and from automobiles concurrently.



Energy-conversion pathways. Some of these possible conversion routes remain unexploited in practice. From reference 9. Figure 2

In choosing among the possible stationary and locomotive power plants and energy converters, we must develop criteria of performance in addition to efficiency, cost, specific fuel consumption, power per mass or volume ratio and length of life. We need standards based on environmental criteria; figure 3 is an analysis of the pollution possible at each step in the development of a stationary power plant. Currently, we have no well established standards for most of the pollutants identified in figure 3.[4]

Global pollution

In his book, *The Last Judgment*, J. B. S. Haldane, the geneticist, has a Venusian announcer say: "It was characteristic of dwellers on Earth that they never looked ahead more than a million years and the amount of energy was ridiculously squandered." Although science-fiction writers have often been more prophetic than scientists themselves, I believe that Haldane was absolutely wrong: The limitation of energy consumption lies not in any shortage of resources but in the degree to which we can safely alter our environment.

There is no agreement in energy-resource estimates,[5] but, at present, world energy consumption is about 0.1 Q per year, where Q equals 10^{18} Btu's. The US uses about 60% of this total. We have about 22 Q available in known recoverable fossil-fuel reserves, and about 12 500 Q more in potential fossil-fuel reserves. Uranium and thorium in the earth's crust give us potential reserves that could last 3×10^9 years, even if annual energy consumption increased to 15 Q.[6] To these reserves we add the energy available from deuterium in sea water, and in essentially nondepletable forms, such as solar and tidal energies. We clearly need not fear a shortage for thousands of millions of years, although some fuels are limited in supply and must be treated gingerly.

But what would the environmental effect of drastically increasing our energy consumption be? In addition to the "local" effects that we have discussed in figure 3 and in table 2 are the global limitations. The earth absorbs and reradiates about 1500 Q of solar energy annually, about 15 000 times our present energy consumption. I believe, although all scientists do not agree, that not more than 1%, or 15 Q, of the total energy should be reradiated. This figure may be too conservative, but we can not afford to experiment. In how many years will the world's energy consumption rise from 0.1 Q to 15 Q? At the rate of 4% annual increase, this will happen in about 165 years. Obviously, less energy must be dissipated and wasted if we are to fulfill our needs without rationing.

Closely related to the radiation problem is the amount of carbon dioxide that we may safely allow to enter the atmosphere. CO_2, although substantially transparent to ultraviolet radiation, is a strong absorber in the infrared region

Superconducting power transmission

Superconductivity, the laboratory curiosity that was discovered in 1911, described phenomenologically in the 1930's and microscopically in the 1950's, and utilized as the basis for commercial products in the 1960's may, in coming decades, be widely exploited for high-capacity power transmission. Use of electrical energy in the US continues to increase exponentially with time, and we must increase the size of generation and transmission systems to get the capacity we need. We should enlarge this capacity economically and with the least possible harm to the environment.

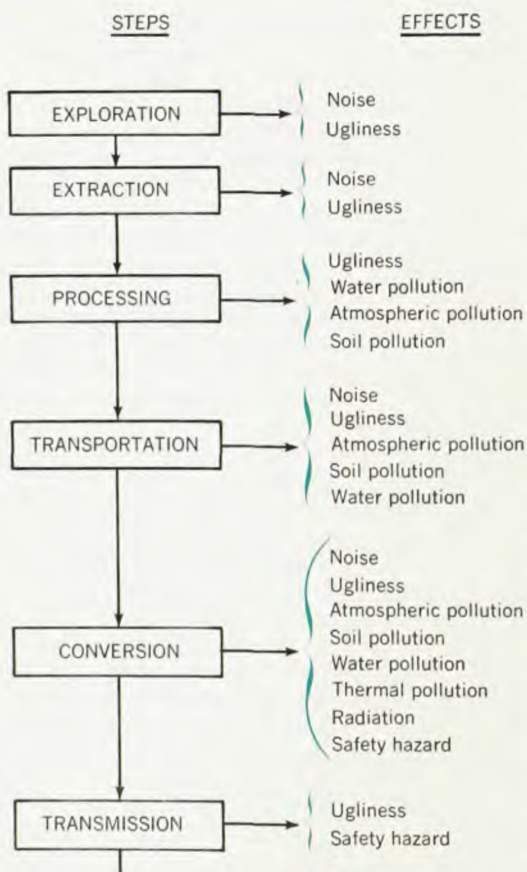
For transmission, underground cables, which avoid ugly towers as well as the high cost of buying rights-of-way above ground, will become increasingly important near cities. The design of high-capacity underground transmission lines for the 1980's is still very undecided. The lines *could* be superconducting; results from the physics laboratory have been favorable, and preliminary engineering designs show no insurmountable obstacles. Economic estimates have also been favorable. But economic estimates tend to be optimistic; various published estimates suggest that a superconductor,[1] or a normal metal at 20 K,[2] or a normal metal at 77 K,[3] or a compressed-gas insulated line at 300 K[4] is economically the "best choice" for an underground transmission line. Such estimates are at best educated guesses and show only that none of the candidates has definitely been eliminated. Indeed, a system may eventually be chosen only because the most development effort was spent on it.

Capital costs rather than operating costs are dominant in the economics of transmission, so that superconducting lines, which can carry high current density, are one of the most promising new methods of power transmission, despite refrigeration problems. Of most interest at present are alternating-current superconducting lines, because the high-capacity lines are wanted first for the relatively short underground runs into cities, and short runs favor ac transmission.

Although capital costs are of prime importance, we also want to minimize losses during transmission, and we must keep this factor in mind when looking for appropriate conductor materials. Type-I superconductors are not suitable because their relatively low critical fields imply low current capacity. But type-II superconductors, with their high transition temperatures and extremely high current capacities are not completely suitable either, because of the relatively high ac losses of the large self-fields that the high currents generate. We must weigh the two factors. Above the lower critical H_{c1} a hysteresis-loss mechanism occurs as fluxoids (quantized units of magnetic flux) are swept in and out of the material. The lattice impedes the motion of these fluxoids, resulting in loss. We must choose the ac transmission-line configuration to minimize these losses; a coaxial geometry is the most favored.

Choice of conductor. Most proposals for ac superconducting transmission lines have suggested niobium, a type-II superconductor, as the conducting material, to make use of the lossless region below H_{c1}. Niobium has the highest H_{c1} of all type-II materials, higher than the critical field H_c of any type-I material. Both the Linde Division of Union Carbide Corp in the US[5] and the Central Electricity Research Laboratory in the UK[6,7] have been studying niobium superconducting transmission lines; they are investigating not only conductor properties but also engineering problems, such as refrigeration and choice of a dielectric medium.

The most striking, and apparently general, result of the Linde work is that there *are* losses below H_{c1}, and these losses vary approximately as the current I cubed. Other studies have shown that the loss below H_{c1} in niobium is strongly dependent on surface treatment, which implies that it is produced by the interaction of fluxoids with various surface imperfections. The Linde data show, how-



Pollution and power. To minimize the harmful effects of power production, we must identify the pollutants and their sources. Figure 3

of the spectrum. An increasing CO_2 content in the atmosphere would increase the temperature of the lower strata. It has been estimated that a 25% increase of atmospheric CO_2, with an associated increase in temperature of about 1/2 deg C to 4 deg C might occur as early as the turn of the century. One need not be very imaginative to envision the threatening chain effect if the amount of CO_2 presently spewed into the atmosphere is not reduced.

A number of preventive suggestions have been made; electric automobiles and nuclear power plants are typical proposals. But the situation is not so straightforward for the cities. There is evidence that the pollution and the particulate matter caused by man's activities in cities lead to nuclei that give rise to rain, hail and thunderstorms.[7] These phenomena lower the ambient temperature. Therefore, whereas the temperature tends to rise because of excessive energy dissipation and an increase in atmospheric CO_2, the increase in precipitation is likely to result in lower temperatures. We may suffocate from environmental pollution while remaining in an isothermal state!

Counter-technologies

Man has created technologies to protect himself against Nature's ravishes. In doing so he has created an environever, that acceptable values for the loss can be achieved without special surface treatment.

The group has estimated that a 16-km, 138-kV, 1690-MVA superconducting line would cost about $550 per MVA-km, including capitalized operating costs[8]—appreciably less than the cost of a comparable conventional underground cable. Union Carbide has announced a 12-year, $8-million research and development program that would yield a prototype in 1974 and an operational system by 1981.[9]

Because the expectation of zero loss in niobium below H_{c1} has not been met, the choice of conductor material is still open. Calculations show that the expected losses in a high-T_c material are comparable to those measured for niobium. And high T_c offers other advantages; refrigeration costs are less and thermal stability under fault or overload conditions is easier to attain. A disadvantage is that helium, a probable dielectric in superconducting transmission lines, has a dielectric strength that varies as $1/T$, so that the conductor may have to be very large.

A team at Gulf General Atomic Co.[10] has been studying the ac properties of Nb_3Sn cylinders. Their most striking finding is that loss below a surface-current density of 500 amp/cm varies approximately as the square of current density. These I^2 losses may actually be due to a surface phenomenon. But there is as yet no satisfactory understanding of why there is a temperature-independent I^2 loss in Nb_3Sn whereas in niobium the loss is proportional to I^3 and is temperature dependent. Nb_3Sn now appears a good contender for the conductor in a superconducting line. Its losses and current capacity at 10–12 K are comparable to those of niobium at 4.2 K, and the higher T_c should yield appreciable savings.

The especially far-sighted (or perhaps the most adventurous) dreamers look beyond the need for transmitting a few thousand megawatts into a densely populated area to the time when the entire power-generation capacity of the US will consist of large nuclear generating stations, located on the east and west coasts or on the continental divide, with large-capacity underground transmission lines feeding power to consumers throughout the nation. Because of their current capacity, superconductors may be the only possible conductors in such lines.

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Adapted from a paper given by Donald P. Snowden (Gulf General Atomic Co.) at the AIP Corporate Associates meeting.

References

1. E. C. Rodgers, *Proceedings of the 1969 Conference on Low Temperatures and Electric Power*, London, UK, page 83 (1969).
2. S. Neal, Cryo. Engr. News **13**, no. 8, 30 (1968).
3. P. Graneau, IEEE Trans. on Power Apparatus and Systems, PAS-89, 1 (1970).
4. B. L. Johnson, H. C. Doepken, J. G. Trump, IEEE Trans. on Power Apparatus and Systems, PAS-88, 369 (1969).
5. L. K. Eigenbrod, H. M. Long, J. Notaro (to be published).
6. D. N. H. Cairns, R. H. Minors, W. T. Norris, D. A. Swift, ref. 1, page 16.
7. M. T. Taylor, ref. 1, page 61.
8. "EEI Research Project on Superconducting Cable Systems," Edison Electric Institute Bulletin, May 1969, page 158.
9. Industrial Research **11**, no. 8, 19, August 1969.
10. R. H. Hammond, D. P. Snowden, C. H. Meyer Jr, J. H. Pereue Jr, G. M. Kelly, M. O. Stern, J. Appl. Phys. **40**, 2010 (1969).

ment that appears to suffocate him physically, physiologically, intellectually and spiritually. Now he must create new counter-technologies to prevent further deterioration of, and indeed improve upon, the natural environment he originally sought to modify. How might this be done?

▶ The US government can establish a think tank on energy and the environment, including representatives from the White House National Goals Staff as well as from the Atomic Energy Commission, the Department of the Interior, the Federal Power Commission, the Office of Science and Technology, the Council of Economic Advisors and, of course, the Environmental Council.

▶ The US government should provide subsidies or tax write-offs for energy–environment research and development as it did for the aerospace and electronics industries.

▶ We should encourage technological enterprises by creating competitions among different fuels and energy converters. One competition would be created by developing household hydrocarbon fuel cells that obtain their gas supply from the gasification of coal, with nuclear electric power plants providing their thermal energy. External electric wiring would be abandoned, but internal house wiring would continue in use. Such a hydrocarbon fuel-cell electric supply would compete with the local electric-utility company.

▶ Research and development associated with controlled thermonuclear energy should at least double. Some 15 years elapsed between the experimental reactor pile in Stagg Field, Chicago and the first commercially feasible plant in Dresden, Illinois. As yet we do not have the counterpart of the Stagg Field reactor in controlled thermonuclear fusion, and even when we do it is unlikely that the time between laboratory feasibility and commercial application will be as short as 15 years. The US can not afford to lose the lead in developing fusion energy.

▶ Utility companies should switch as much as possible to nuclear energy, saving coal for the manufacturing industries and for eventual use in liquification and gasification. With any such switch, we should begin a vastly accelerated research program on the genetic effects of nuclear power plants, on thermal pollution and on site location.

▶ All utility companies now using fossil fuels should be required to install pollution-abatement equipment, and the cost of such equipment should be covered by tax write-offs.

▶ The automobile pollution standards announced in San Clemente, California in 1969 should be made mandatory through public acts, and the cost of these improvements should be tax write-

Table 2. Major Contributors to Air Pollution

Source	Carbon monoxide	Sulfur oxides	Hydrocarbons	Nitrogen oxides	Particulate matter	Other	Total	%
	(Millions of tons per year)							
Transportation	66	1	12	6	1	<1	86	60.2
Industry	2	9	4	2	6	2	25	17.1
Electricity Generation	1	12	<1	3	3	<1	20	14.0
Space Heating	2	3	1	1	1	<1	8	5.6
Waste Disposal	1	<1	1	<1	1	<1	4	2.8
Total	72	25	18	12	12	4	143	100.0

Source: US Public Health Service

offs for the automobile manufacturers.

▶ The Antitrust Division of the Department of Justice, the Internal Revenue Service and the Department of Transportation should sponsor legislation enabling automobile companies to expand into transportation companies.

▶ Every conceivable fiscal encouragement should be given to manufacturers who develop appliances that exploit the second law of thermodynamics. These applications include microwave ovens and stoves, ultrasonic dishwashers and washing machines, electrochemiluminescent lighting panels, thermoelectric refrigeration and air-conditioning units and improved insulation material. In short, energy research and development should be oriented toward less dissipation of energy but not toward curtailing human comfort. We can not return to the preindustrial era, we must forge ahead towards the postindustrial era of creativity.

Of course, there is a very valid question. Who will pay for this utopia? Obviously we the citizens will pay for it. The cost of damage from energy-related pollution is about $\$12 \times 10^9$ per year, excluding the health damage that is immeasurable. It is estimated that private industry is paying about $\$2.5 \times 10^9$ per year to reduce pollution. Clearly one should not go on watering a tree with an eye dropper. The tree must be allowed to grow. Its roots, however, need not demolish the foundations of adjacent buildings. This balance requires a new science and technology directed by environmental considerations.

References

1. *The American Almanac: The Statistical Abstract of the US Department of Commerce,* Grosset and Dunlap, New York (1970).
2. *National Power Survey,* A Report by the Federal Power Commission, US Government Printing Office, Washington, D. C. (1964).
3. P. H. Rose, Science **170**, 267 (1970).
4. R. S. Morse and others, *The Automobile and Air Pollution,* US Government Printing Office, Washington, D. C. (1967).
5. V. E. McKelvey, "Contradictions in Energy Resource Estimates" in *Energy,* Northwestern U. P., Evanston, Illinois (1968), page 13.
6. H. Lane, private communications.
7. The Climate of the Cities, US Government Printing Office, Washington, D.C. (1969).
8. A. B. Cambel, "Energy for a Restless World," in *Science and Technology in the World of the Future,* (A. B. Brownell, ed.) Interscience, New York (1970).
9. A. B. Cambel, "Ecological Aspects of the Affluence and Effluents of Energetics," Archives of Environmental Health **18**, 276, Feb. 1969. □