Myths about Energy and Matter

NICHOLAS GEORGESCU-ROEGEN

TECHNOLOGICAL PROGRESS has never bestowed upon mankind such miraculous physical powers as during the past few decades.[1] We can now fly to the moon. We can see in full color what is happening now even at the antipode of where we are. By making it possible for information to be transmitted from one place to another with the speed of light and for people to travel with a velocity comparable to that of sound, modern technology has shrunk, as it were, our earthly abode. We can now contemplate it just as if it were a small backyard. But in spite of the marvelous achievements of modern science and technology, the picture of the world we can thus piece together reveals that mankind has never been in a more critical situation in its entire known history. We speak of this and that endangered species, but we do not seem to realize that we are perhaps the most endangered one.

Technology also enables us with the help of a computer to compute in a few hours one million decimal digits of the number π and even more than that if we wanted to. Leibnitz, the man who thought up the formula on which that work of the computer was based, would have needed not less than 30,000 years to perform the same calculation. Yet all the computers in the world cannot help us find out what will happen to the human species over the next few decades, let alone over its probable life span. How long can we hope this life span to be, shorter or longer than that of the dinosaurs, which lasted 120 million years?

To try to provide this question with even a tentative answer is an impossible task. The fact is that we do not know what has caused other species to bow out of existence, nor even why some species seem to become extinct while we are watching them. If we can predict approximately how long the average dog will live and what will most probably end its life, it is because and only because we have had repeated occasions to observe a dog's life from birth to death. But we have not had and will never have the opportunity of observing another species similar to ours being born, aging, and becoming extinct, even though there must be an immense number of them in the vastness of the universe. This is the predicament of any student of evolution, whether in biology, sociology, or technology.[2]

Professor Nicholas Georgescu-Roegen was Visiting Benedum Professor of Energy Economics at West Virginia University, Regional Research Institute, at the time of the conference.

We may brag about the power of science as much as we like, not only as much as we properly should; but all that science can do for this particular problem is to enable us to have, not a bird's view, but a worm's view of our existence. Like a worm, we can see only extremely little in front of us, and often not even that much.

Nowadays this truth is perhaps more important than at any other time in history. For whether we are optimists or pessimists, by now we all recognize that the issue of whether mankind will be able to maintain for long the level of industrial comfort to which we are now irremediably addicted is not an idle one. Witness the apparently endless number of energy experts who expatiate to their hearts' delight on the problem, more often than not contributing to the confusion of the public at large.

The Role of Natural Resources

People from all times have known that resources are exhaustible. Iron and copper mines have been abandoned continually because in the end the ore was no longer sufficiently rich. Take the famous Ploesti oil fields in Romania, which constituted an important strategic objective during the last two world wars and which, at one time, placed Romania in the third rank among oil-producing countries. Today they are dry. And what happened to those fields as well as to many others (the Pennsylvania oil fields are also a good example) will in the end happen to all oil fields.

The importance of natural resources in the life of our species is written on the face of history. The Great Migration that moved tribe after tribe from Asia to Europe during the first thousand years of our era was triggered by the exhaustion of soil nutrients after millenia of sheep grazing and overgrazing. All wars have been fought for the possession or the control of natural resources, even though as a rule the rallying cry was ideological. The "limited" wars that nowadays spring up in one place and then in another leave no doubt about this truth.

In spite of all this, the modern school of economics has paid no attention to the role of natural resources in the economic process. Its servants may have been influenced by the mechanistic dogma which dominated scientific thought almost to the end of the past century. We may recall that W. Stanley Jevons proudly proclaimed that he wanted to erect the science of economics as *"the mechanics of utility and self-interest."* But modern economists may also have been blinded by the unique affluence of the past hundred years, which was made possible by unparalleled technological advance supported by a fantastic mineral bonanza. But whereas economists may invoke such attenuating circumstances for their past orientation, nothing can absolve them for persisting in the same position and for defending it with senseless arguments that fringe on myths.

The Myth of the Price Mechanism

The main myth is the belief in the all-powerful market mechanism. One does not need to worry about any ecological crisis because the market mechanism, if well supervised so as to have it function "right," will take care of any shortages. Some economists have even argued in a self-defeating way that the market mechanism will prevent the exhaustion of resources because at one time their prices will be so high that no one could afford to buy them anymore. Others maintain that as the prices of natural resources continue to rise because of increasing depletion, *other factors* will be substituted for them in production.[3] Now, by factors other than natural resources, they can mean only labor or capital (land is already scarce enough). If labor is going to be substituted for natural resources on an increasing scale, the solution leads to an economy in which only labor services would count and, in the limit, to a society living on music, theater, dance, or "back scratching." If, on the other hand, capital is to be substituted for natural resources—as some of the recent more sophisticated papers insist—one may naturally wonder at the miracle of producing more capital with less natural resources. Unfortunately, the miracle is a mere conjuring trick on paper, based on the famous Cobb-Douglas production function and on the ignorance of the essential difference between flows and funds in the economic process.[4] In this thesis, the global output, Q, is determined by the production function,

(1) $Q = K^{\alpha}H^{\beta}R^{\gamma}$,

where K is capital; H, labor; R, natural resources; and $\alpha + \beta + \gamma = 1$, with $\alpha, \beta, \gamma > 0$. With this formula, one easily shows that Q may be sustained with H constant and with as little R as one may wish, provided K is sufficiently large. The argument obviously ignores the fact that an increased K requires an increased amount of natural resources for producing the additional capital and for maintaining the entire capital stock.[5]

The crisis into which mankind is stepping with great speed has also brought up the question of allocation of resources among generations. For this problem economists have again clung to their idea of the all-powerful market mechanism. It is true that the market is influenced by the interests of the participants within their time horizon; this time horizon certainly includes the interests of the next immediate and perhaps of the second generation. This algorithm has functioned from time immemorial, but its interpretation by the standard economist is faulty. If in his present actions Mr. A does not take into consideration the interests of, say, his fourth generation, that generation is not protected by those actions. The present energy shortage would not be so acute now if the generations before us had acted so as to protect our needs, too.

It is not surprising that economists also argue that "resources are properly measured in economic, not physical, terms."[6] There is no denying that, for certain purposes, prices—imperfect though they are—are the only means for distributing the product and its cost among the members of the same generation. But for the purposes of energy analysis, prices are wholly inappropriate. The price illusion is, however, so hard set that even most engineers and other specialists abide by the economist's dogma in establishing energetic efficiency on the basis of prices.

Any argument claiming that prices are the right measure for arriving at optimal allocation or at the highest efficiency of resources must imply that we can also determine the prices of resources in situ, since these resources are part of the real cost of everything else. But how can we attribute a price to a piece of coal in situ? Coal in situ is just as free a commodity as solar radiation (only, solar radiation is far more abundant than all the reserves of coal).[7] Nature does not have a check-out line for us to pay for the resources we take out; money royalties are set up by people, not by nature. On the other hand, resources in situ, being irreproducible, cannot have a cost of production on which to base a price determination.

To be sure, there is the elementary economic principle according to which the value of any irreproducible object—whether some coal in situ or the Mona Lisa of Leonardo da Vinci—is its auction price. But this principle must be corrected by adding "provided that absolutely everyone interested in the object is allowed to bid." For if only my neighbor and myself were to bid on the Mona Lisa, I might perhaps have it for only a few dollars, if my neighbor happened not to like Renaissance art. Therefore, in order to establish a *valid* price for any resource according to the above principle, all future generations should also be allowed to bid. The earth is as much their inheritance as it is ours. And since they cannot be present to bid, we can have no valid price for the resources in situ, and hence for any commodity produced with their aid.

History offers us ample proofs that the price mechanism cannot defend our ecological interests. The savage deforestation which at one time menaced all the woods in the world was the result of the fact that the prices were "right." And it was not brought to a halt by the price mechanism, but only by the introduction of some quantitative restrictive rules. It was precisely because the prices of coal and oil were right after World War II that the automobile industry turned to producing mammoth gasoline guzzlers, while coal technology lagged behind and poverty spread in Appalachia.[8] And if the cheetah is now an endangered species, it is because the price of a cheetah pelt is just right for some people to hunt one animal after another.

Let me add that the idea "the polluter pays" is utterly inept. First, most pollution, like all depletion, being irreversible, does not have a cost. Second, and most important, if we were to apply the same principle to the pollution of crime, then this would make crime really pay!

The Myth of Technology

All the tenets mentioned so far belong to the category of analytical fallacies rather than myths. The real myth of the standard economist concerns the power of technology to solve any crisis between the human species and the environmental supply of energy and matter. It is best expressed by paraphrasing Beckerman: "Come what may, we shall find a way." Those who had invested immense intellectual effort in theories of growth based on the notion that exponential growth is not only a desirable state but the normal one as well now maintain in all earnestness that technology progresses exponentially.[9] That during the past hundred years growth has proceeded at a positive rate, varying, however, from year to year, is an undeniable fact. During this time mankind had the benefit of bonanzas of all kinds and of a territorial expansion in the New Worlds. But history is not bound to repeat itself, especially since mankind is now under the pressure of limitations from multiple directions.

It is true that, as many have observed in favor of their cornucopian thesis, mankind has continually progressed since as far back as the time of Pericles. But one may with equal force retort that in the matter of evolutionary processes wars have been lost by countries which had never lost one before; an eye cataract also is not repeated history in the life of an individual. As Miernyk[10] so wittily put it, to keep preaching that technology will come along just at the right moment to get us out of an environmental ditch is to swear by Walt Disney's First Law: "Wishing Will Make It So."

Unfortunately, economists are not the only academic profession to tell the people, as Beckerman did at the end of his inaugural lecture as professor at University College, London, to go home and sleep peacefully, secure in their knowledge that an economic authority assures them that economic growth can go on forever without increased difficulty or penalty. Regrettably, some natural scientists also hold out for the same type of talk. Alvin Weinberg is well known for his grand plan for supplying a population of 20 billion for millions of years with twice as much energy per capita as the current consumption of the United States of America.[11] We just need to construct not more and not less than 32,000 breeder reactors and to crush rock after rock in order to obtain the necessary uranium and thorium. Glenn Seaborg, for another illustrious example, told us that science will ultimately eliminate all technical inefficiency and supply us with such an abundance of energy that we shall be able to keep the whole planet intact while exploiting it.[12] The word spread by John von Newmann, a mathematical and physical authority, also was that one day energy will become a free good, "just like the unmetered air."[13]

The Myth of Entropy Bootlegging

Perhaps the most insidious way of feeding the sanguine hopes for a world in which energy would be free (or almost free) is based on the so-called probabilistic interpretation of thermodynamic laws—that is, of those laws that govern the transformation of energy. This interpretation is due to Ludwig Boltzmann, although J. Willard Gibbs also followed with a somewhat different approach. From all we can judge, Boltzmann's endeavor had its roots in the attraction our minds feel with the tenacity of original sin for any mechanistic interpretation. Before Boltzmann, it was an accepted thermodynamic fact that heat *always* flows *by itself* (that is, without any other change in the universe) from the hotter to the colder body. The proposition even represented one formulation of the Second Law of Thermodynamics, the Entropy Law. But such a law clashed with the analytical foundation of Newtonian mechanics. According to that foundation, every movement, every wave, can go both forward and backward. In mechanics there is no place for one-way phenomena. The conflict was resolved by accepting the validity of the entropic process (that is, the irrevocable and irreversible tendency of temperature to become equalized and of available energy to dissipate into unavailable energy) as an independent necessity. But the acceptance was made reluctantly. Mechanics had just acquired a new gem in her crown by Leverrier's discovery of the planet Neptune, made not by scanning the sky with the telescope but at the tip of his pencil after a series of calculations based on the equations of Newtonian mechanics.

Boltzmann's idea was to explain the thermodynamic phenomena by the laws of mechanics blended with a peculiar notion of probability that has never been precisely defined. According to this contradictory mixture of thorough determinism and loose uncertainty, the spontaneous reversal of heat from the colder to the hotter body—say, from the condenser to the boiler—so that the same heat could again be converted into work is only a highly improbable, but not an impossible, event. Now, since the event is *possible*, we ought to be able by an ingenious device to cause the reversal to happen as often as we please, just as an adroit sharper can throw a "six" almost at will.[14] Around the 1930s, there were so many schemes of this sort ventilated that P. W. Bridgman, one of the greatest authorities on thermodynamics, felt it necessary to write an article just to expose the fallacy of the idea that one may fill one's pockets with money by "bootlegging entropy."[15]

I took up this issue in *The Entropy Law and the Economic Process* precisely because I thought that an economist should not be induced to believe that the probabilistic interpretation of thermodynamics offers scientific support to the vision of a world in which energy is a "free" good. In great detail I went over the objections that have been raised by a series of most eminent men of science against the logical inconsistency of the probabilistic interpretation. The first objection came from one of Boltzmann's colleagues, J. Loschmidt, who is well known for the number bearing his name. Loschmidt argued that the Entropy Law, as justified by Boltzmann, can be refuted by simply reversing the velocities of all the molecules. If, in the initial system, entropy were increasing, in the reverse system it must decrease. Later, E. Zermelo, a pupil of Max Planck and a famous mathematician, pointed out that according to a theorem of H. Poincaré, any mechanical system that does not extend to infinity returns as near as we wish to any of its previous states. Hence, Zermelo argued, entropy cannot keep increasing forever. Poincaré, who wrote a much appreciated thermodynamic manual and also was an authority on probability, concluded that one will probably have to abandon the hybrid foundation of Boltzmann's theory and seek elsewhere the explanation of irreversibility.[16]

The dissatisfaction has never completely died away. Witness the fact that the monograph on the issue written by Paul and Tatiana Ehrenfest in 1912 was translated in 1959 into English. Probabilistic thermodynamics nevertheless became the accepted theory. The reason given for this compromise—for few are those who have felt otherwise—is that Boltzmann's formulae agree with facts (although it is seldom mentioned that this is not true for all facts). But no logical contradiction of a scientific theory can remain covered by a compromise for long. Very recently, through the contributions which earned him the Nobel Prize in chemistry, Ilya Prigogine brought the skeleton out of the closet and proved that Boltzmann's " 'mechanical theory' of the evolution of matter [is based on] intuitive arguments [and] *the program was never realized, despite frequent affirmation to the contrary*" (my italics).[17] One should hope that at long last Prigogine's new thermodynamics will settle a long-debated issue and, especially, put an end to hopeful entropy bootleggers.[18]

The Energetic Dogma

Ever since the oil embargo of 1973-74, only those few who still believe in some grand plan of unmetered energy are not concerned about the imminent energy crisis. Yet the economic process needs not only energy; it needs matter, too. We cannot handle energy without a material instrument, either a receptor or a transmitter. Everything around us is made of matter. And so are we; earthly life cannot exist without a body. That the public at large speaks only of the energy crisis, thus completely ignoring the need for matter, may be due to the plain object lesson of the oil embargo. The same can hardly be assumed of scholars, especially of natural scientists. If they usually also ignore the problems related to matter, it must be only because thermodynamics completely ignores the purely material phenomena—friction, viscosity, metal fatigue, cracking, splitting, etc.—which are truly hard nuts to crack.

Indeed, we find natural scientists proclaiming long before the oil embargo what may be called the energetic dogma. As Harrison Brown and his associates expressed it: "All we need do is to add sufficient energy to the system and we can obtain whatever materials we desire."[19] More recently, a distinguished ecologist, H. T. Odum, revived an old idea of Fred Cottrell's according to which the efficiency of any process is measured by the net energy it produces.[20] Another approach, endorsed by a group of British analysts, also reduces everything to energy alone.[21] Clearly, if 1 ton of oil is used in extracting 10 tons of shale oil, there is a net gain of energy of 9 tons. But by the same token, we should speak of a net matter of copper in any production of that metal. That is not all; in the case of the last process, we should speak of a *negative* net energy.

The energetic dogma obviously implies that in some manner or another every material object may be produced by energy alone in a process that may be determined by a wholesale consolidation of all productive processes. Alternatively, the energetic dogma takes it for granted that—as Kenneth Boulding claimed—"there is, fortunately, no law of increasing material entropy."[22]

In practice, these various views boil down to the notion that *recycling can be complete*. In that case, a thermodynamic steady state would need only a flow of environmental energy in order to perform internal mechanical work at a constant rate forever. It would need neither an input flow of environmental matter nor an output flow of material waste. The same amount of matter would be used over and over again by complete recycling. A system such as the one just described is a closed steady state in thermodynamic terminology. But because it is also supposed to perform mechanical work indefinitely at a steady rate, we may refer to it as perpetual motion of the third kind. And since my position is that such a perpetual motion is impossible, we may view this impossibility as the expression of a fourth law of thermodynamics.[23]

Perhaps the simplest way to prove the impossibility of complete recycling (hence, of perpetual motion of the third kind) is to think of a pearl necklace that has broken in a room. No one would doubt that, with a little patience, all the pearls can be picked up and the necklace reassembled. It would naturally take a greater effort and more time to achieve the same result if the necklace broke in a movie house, and some unimaginable effort and time if the necklace broke somewhere in Manhattan. To reassemble, however, all the copper molecules dissipated to the four corners of the world from a penny by continuous use would be an impossible feat. This feat would take a practically infinite time (let alone the indescribable amount of energy consumed and the legions of objects worn out by the operation). The possibility of perpetual motion of the third kind must therefore be rejected. It is instructive to note that the main reason is the same as that which precludes actual reversible motions. A motion is reversible only if its speed is infinitesimally slow, in which case any finite movement would require an infinite time.

The fact that recycling cannot be complete proves that matter, just like energy, continuously and irrevocably dissipates. Matter is not lost; it only ultimately becomes *unavailable* to us. Briefly, matter, too, is subject to entropic degradation.

One might think that Einstein's famous equivalence, $E = mc^2$, could upset my argument concerning the impossibility of perpetual motion of the third kind. But the idea does not work. If the equivalence is interpreted as written without any restrictions, then we should be entitled to speak indifferently of an energy crisis or of a matter crisis. Since this would be senseless, then something is wrong. The rub is that between matter and energy there is an important asymmetry which, curiously, seems to be ordinarily passed over in silence. The Einsteinian equivalence works mainly for the conversion of mass into energy, as in the case not only of the sun but also of every match we light. Moreover, energy can be converted only into *additional* matter. Matter cannot be obtained from energy alone, for matter means atoms and the atoms need protons and neutrons, heavy-mass particles. It is for this reason that the current theories about the origin of the universe assume that at the beginning there were not only massless photons but atoms of hydrogen and helium as well.[24]

The important conclusion is that matter, per se, also matters. This bears especially upon the relation between energy analysis and economic valuation and upon technology assessment. There are writers who claim that energy analysis (based on energetic dogma) should be substituted for economic valuation, since money prices represent "after all nothing more than a highly sophisticated value judgment."[25] A closer examination of the economic valuation—they claim—would show that prices should be determined by the energy components of goods. Even though prices are parochial elements of the economic system,[26] they cannot possibly be proportional to the energy content of the commodity. If Huettner[27] arrived at such a proportionality, it was only because he followed the fallacious practice of standard economists of ignoring the essential difference between the flow and the fund elements of the economic process.[28] The economic process is entropic in all its fibers, yet it cannot be reduced to a vast thermodynamic system. Economic valuation proceeds over a web of anthropomorphic, not physicochemical, categories—utility, disutility, and distribution. No one, it must be emphasized, has been able to prove the existence of a general quantitative relationship between these human attributes and the energy consumed or spent in their production.

Even the energy analysis based on the energetic dogma loses its significance as a criterion of efficiency.[29] Matter being, as we have seen, an independent element alongside of energy must also be taken into account. And since matter, M, and energy, E, at the macro level cannot be reduced to a common denominator, there is no family of isoquants, $F(M, E) =$ constant, on which to base our criterion of efficiency. The choice between two technologies, T_1 (M_1, E_1) and $T_2(M_2, E_2)$, that have the same effect but $M_1 > M_2$ and $E_1 < E_2$, cannot be decided on purely physicochemical grounds. This decision remains a matter of economics.

When we hear nowadays that this or that technical recipe cannot succeed economically because the initial investment is too high, the statement hides the fact that the recipe requires an excessive amount of matter. We can even formulate a rough, but useful, rule concerning the relation between the material requirement and the intensity of energy. The use of medium-intensity energy —the chemical energy of fossil fuels—requires proportionately the smallest amount of matter. We can burn coal, for example, with practically no installation. High-intensity energy requires a proportionately higher amount of matter, simply because it must be contained in a relatively small (and safe) space. Harnessing the low-intensity energy of solar radiation also requires a large amount of matter—to concentrate it to the level necessitated by our industrial activities. This is perhaps a commonplace. Yet we do not seem to take it into account in our technology assessment.

Two concepts must be clearly distinguished for this purpose—namely, the feasible recipe and the viable technology. To quarry the moon, for example, is a feasible recipe. Yet it cannot be part of any viable technology. The technology based on fossil fuels is viable because it can produce and maintain its own scaffold (as long as the necessary natural resources are accessible).

The point bears upon the idea, now so fascinating, of a technology based on solar energy. The foregoing discussion of the necessary role of matter enables us to prove that no technology based on any of the recipes presently known for the direct use of solar energy is viable.

Let us illustrate our argument by the case of solar collectors. For a technology based on this recipe, it is necessary that the solar collectors be self-sustaining. In other words, it is necessary that the energy, x_{11}, harnessed by the collectors should suffice to produce the collectors, x_{21}, worn out during the process, and also supply some energy to the rest of the economy. Let x_{12} be the energy necessary for producing x_{21}. In this case, a necessary condition of viability is $x_{11} > x_{12}$. But the simple fact that no enterprise is at present manufacturing collectors only with the aid of the energy produced by collectors is sufficient proof that the corresponding technology is not viable.

What happens today is that the solar collectors, x_{21}, are produced with the help of some energy other than solar radiation—primarily, with the energy of fossil fuels. Consequently, at present, all direct uses of solar radiation represent parasites of the fossil fuel technology. That is not all. If y_{12} denotes the fossil fuel energy consumed in the production of x_{21} solar collectors, we are confronted with three alternatives: $x_{11} - y_{12} < 0, = 0$, or > 0. In view of the immense propaganda for the solar-heated homes, we must hope that $x_{11} - y_{12} < 0$ is not true. But the case must not rest here; data must show which alternative is actually true.

Denis Hayes, therefore, is not exact in his recent claim that "we can use solar energy now [because] the technology is here."[30] Only the recipes are here. The technology is not. Of course, the situation may change overnight, in principle at least. But in this particular case, one may doubt it. Unlike nuclear energy, solar radiation from collectors has been used for almost a hundred years now. During this long time, no really important improvement has been forthcoming. The same applies to the intensive R and D of the past years. In hailing solar radiation as a readily available substitute, we must exercise great discretion, lest we repeat the sales talk for nuclear energy which has recently proved to have been overenthusiastic. In both cases, perhaps the constraint is not energy—which certainly is there—but matter—which does not seem to respond to a viable technology.

The Myth of Salvation by Computers

I cannot close this paper without mentioning what I consider the greatest myth of all. People have long since been aware of the fact that resources, beginning with the topsoil and ending with the subsoil, are irrevocably exhaustible. More than one scholar, not only Malthus, has argued that since Earth also is finite, mankind will ultimately be confronted with some environmental crisis. But Dennis Meadows and his associates did a very good service in proving in *Limits to Growth*, with the aid of some sophisticated tools, that such crises are not simple phantoms. A proof of this kind was absolutely necessary to deal with the cornucopian quibblers. But a series of other researchers have since set out to program computers so as to answer any of your questions—provided your question furnishes the most important element of the prediction. Still others, also using complicated computer work, have tried to predict future "supply" and "demand." There are no reasons to accept these predictions to the letter, and there are none to reject them. We are still in the dark. What we can conclude is that all these works without exception confirm Meadows' finding concerning the imminent "gap" between supply and needs. The publicity surrounding all these endeavors, together with the sales talks about this or that new gadget that is supposed to solve the environmental crisis, tends to orient the general public in the wrong direction. Our most urgent task is to convince the public that the consumption of energy and matter must be drastically curtailed in the developed countries, while greater amounts must be devoted to saving from hunger and squalor the large masses of the underdeveloped countries.[31] To think that concentrating on various exercises with the computers is a substitute for the right action is the greatest myth at the present crossroads for our species.[32]

FOOTNOTES

1. I intend this paper as a token of my gratitude to William H. Miernyk and of my intellectual sympathy with him.

2. Nicholas Georgescu-Roegen, *Energy and Economic Myths: Institutional and Analytical Economic Essays* (New York: Pergamon, 1976).
3. Robert M. Solow, "The Economics of Resources or the Resources of Economics," *American Economic Review*, vol. 64, no. 2 (May 1974), pp. 1-14 and Robert M. Solow, "Is the End of the World at Hand?" *Challenge*, vol. 16, no. 1 (March/April 1973), pp. 39-50.
4. For this difference, see Nicholas Georgescu-Roegen, *The Entropy Law and the Economic Process* (Cambridge, Mass.: Harvard U. Press, 1971), pp. 228-75.
5. Among the several economists who still defend this way of reasoning about actual economic phenomena, I may cite J. E. Stiglitz, "A Neoclassical Analysis of the Economics of Natural Resources," in *Resources of Environmental Constraints to Economic Growth and Well-Being*, ed. J. V. Krutilla, V. Kerry Smith, and R. Kapp (Baltimore: Johns Hopkins U. Press for Resources for the Future, forthcoming). See also Nicholas Georgescu-Roegen's criticism, "Comments on the Papers by Daly and Stiglitz," in the same volume.
6. Carl Kaysen, "The Computer That Printed Out W*O*L*F*," *Foreign Affairs*, vol. 50, no. 4 (July 1972), pp. 660-68. See also Wilfred Beckerman, "Economists, Scientists, and Economic Catastrophe," *Oxford Economic Papers*, vol. 24, no. 3 (November 1972), pp. 327-44.
7. According to the most optimistic estimation of all the reserves of fossil fuels, these reserves could not produce more than a few weeks of sunlight (if burned at the necessary intensity).
8. William H. Miernyk, "Regional Employment Impacts of Rising Energy Prices," *Labor Law Journal*, vol. 26, no. 8 (August 1975), pp. 518-23.
9. Beckerman, op. cit., Kaysen, op. cit., and Solow, "The Economics of Resources or the Resources of Economics."
10. William H. Miernyk, Frank Giarratani, and Charles F. Socher, *Regional Impacts of Rising Energy Prices* (Cambridge, Mass.: Ballinger, 1978).
11. Alvin Weinberg, "Energy as an Ultimate Raw Material," *Physics Today*, vol. 12, no. 1 (1959), pp. 18-25.
12. Glenn Seaborg, "The Erehwon Machine: Possibilities for Reconciling Goals by Way of New Technology," in *Energy, Economic Growth, and the Environment*, ed. S. H. Schurr (Baltimore: Johns Hopkins U. Press, 1972), pp. 125-38.
13. Harold Barnett and Chandler Morse, *Scarcity and Growth* (Baltimore: Johns Hopkins U. Press, 1963).
14. Nicholas Georgescu-Roegen, *Energy and Economic Myths: Institutional and Analytical Economic Essays.*
15. P. W. Bridgman, "Statistical Mechanics and the Second Law of Thermodynamics," in *Reflections of a Physicist*, 2nd ed. (New York: Philosophical Library, 1955), pp. 236-68.
16. The arguments on each side are, as expected, highly involved. The reader may find them cast in a simple, accessible form in Georgescu-Roegen, *The Entropy Law and the Economic Process.*
17. See Ilya Prigogine, "Time, Structure, and Entropy," in *Time in Science and Philosophy*, ed. Jiří Zeman (New York: Elsevier, 1971), pp. 89-99; Ilya Prigogine, "Irreversibility as a Symmetry-breaking Process," *Nature*, vol. 246, no. 5428 (9 November 1973), pp. 67-71; and Ilya Prigogine, C. George, F. Henin, and L. Rosenfeld, " A Unified Formulation of Dynamics and Thermodynamics," *Chemica Scripta*, vol. 4, no. 1 (1973), pp. 5-32.
18. Peter L. Auer, a professor at Cornell University and a former consultant to the chairman of the Atomic Energy Commission, quite recently denounced my telling the readers that there is a fundamental conflict between the reversible concepts of classical mechanics and the irreversible ones of thermodynamics and asserted that in this I am *"just plain wrong"* (my italics). To justify this academic sally, Auer resorts to dropping three names (the third out of place): "We have Ludwig Boltzmann, J. Willard Gibbs, and David Hilbert, among others, to thank for having laid the issue to rest." Perhaps Auer still believes in entropy bootlegging, for the drift of his article is that the Entropy Law is not an obstacle to unlimited economic growth. But it is far more probable that he spoke out of just plain ignorance. See Peter L. Auer, "Does Entropy Production Limit Economic Growth?" in *Prospects for Growth*, ed. K. D. Wilson (New York: Praeger, 1977), pp. 314-34.
19. Harrison Brown, James Bonner, and John Weir, *The Next Hundred Years* (New York: Viking, 1957). In fairness to Brown's excellent scholarship, I wish to add that, curiously, in the same volume we also find some of the most cogent arguments against the energetic dogma. Harrison Brown, "Human Materials Production as a Process in the Biosphere," *Scientific American*, vol. 223, no. 3 (September 1970), pp. 194-208, is most illuminating.
20. H. T. Odum, "Energy, Ecology, and Economics," *Ambio*, vol. 2, no. 6 (1973), pp. 220-27.
21. Malcolm Slesser, "Accounting for Energy," *Nature*, vol. 254, no. 5497 (20 March 1975), pp. 170-72.
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