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ENERGY AND ECONOMIC MYTHS*

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> So you can now all go home and sleep peacefully in your beds tonight secure in the knowledge that in the sober and considered opinion of the latest occupant of the second oldest Chair in Political Economy in this country, although life on this Earth is very far from perfect there is no reason to think that continued economic growth will make it any worse.
>
> Wilfred Beckerman

I. INTRODUCTION

There is an appreciable grain of truth in one of Percy Bridgman's remarks that the economic profession is the most opportunistic of all. Indeed, economists' attention has continually shifted from one problem to another, the problems often being not even closely related. Search all economic periodicals of the English-speaking world before 1950, for example, and you will hardly find any mention of "economic development." It is curious, therefore, that economists have over the last hundred years remained stubbornly attached to one particular idea, the mechanistic epistemology which dominated the orientation of the founders of the Neoclassical School. By their own proud admission, the greatest ambition of these pioneers was to build an economic science after the model of mechanics—in the words of W. Stanley Jevons—as "*the mechanics of utility and self-interest*" [48, 23]. Like almost every scholar and philosopher of the first half of the nineteenth century, they were fascinated by the spectacular successes of the science of mechanics in astronomy and accepted Laplace's famous apotheosis of mechanics [53, 4] as the evangel of ultimate scientific knowledge. They thus had some attenuating circumstances, which cannot, however, be invoked by those who came long after the mechanistic dogma had been banished even from physics [23, 69–122; 5].

The latter-day economists, without a single second thought, have apparently been happy

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to develop their discipline on the mechanistic tracks laid out by their forefathers, fiercely fighting any suggestion that economics may be conceived otherwise than as a sister science of mechanics. The appeal of the position is obvious. At the back of the mind of almost every standard economist there is the spectacular feat of Urbain Leverrier and John Couch Adams, who discovered the planet Neptune, not by searching the real firmament, but "at the tip of a pencil on a piece of paper." What a splendid dream to be able to predict by some paper-and-pencil operations alone where a particular stock will be on the firmament of the Stock Exchange Market tomorrow or, even better, one year from now!

The consequence of this indiscriminate attachment to the mechanistic dogma, whether in an explicit or a tacit manner, is the viewing of the economic process as a mechanical analogue consisting—as all mechanical analogues do—of a principle of conservation (transformation) and a maximization rule. The economic science itself is thus reduced to a *timeless* kinematics. This approach has led to a mushrooming of paper-and-pencil exercises and increasingly complicated econometric models which often serve only to conceal from view the most fundamental economic issues. Everything now turns out to be just a pendulum movement. One business "cycle" follows another. The pillar of equilibrium theory is that, if events alter the demand and supply propensities, the economic world always returns to its previous conditions as soon as these events fade out. An inflation, a catastrophic drought, or a stock-exchange crash leaves absolutely no mark on the economy. Complete reversibility is the general rule, just as in mechanics.[1]

Nothing illustrates better the basic epistemology of standard economics than the usual graph by which almost every introductory manual portrays the economic process as a self-sustaining, circular flow between "production" and "consumption."[2] But even money does not circulate back and forth within the economic process; for both bullion and paper money ultimately become worn out and their stocks must be replenished from external sources [31]. The crucial point is that the economic process is not an isolated, self-sustaining process. This process cannot go on without a continuous exchange which alters the environment in a cumulative way and without being, in its turn, influenced by these alterations. Classical economists, Malthus in particular, insisted on the economic relevance of this fact. Yet, both standard and Marxist economists chose to ignore the problem of natural resources completely, so completely that a distinguished and versatile economist recently confessed that he had just decided that he "ought to find out what economic theory has to say" about that problem [75, 1f].

One fundamental idea dominated the orientation of both schools. A. C. Pigou stated it most explicitly: "In a stationary state factors of production are stocks, unchanging in amount, out of which emerges a continuous flow, also unchanging in amount, of real income" [68, 19]. The same idea—that a constant flow can arise from an unchanging structure—is at the basis of Marx's diagram of simple reproduction [61, II, ch. xx]. In the diagram of expanded reproduction [61, II, ch. xxi], Marx actually anticipated the modern models—such as that with which W. W. Leontief swept the profession off its feet—which ignore the problem of the primary source of the flow even in the case of a

[1] Some economists have insisted that, on the contrary, irreversibility characterizes the economic world [e.g., 60, 461, 808; 25], but the point, though never denied, was simply shelved away. It is in vain that some now try to claim that standard equilibrium analysis has always considered negative feedbacks [4, 334]. The only feedbacks in standard theory are those responsible for maintaining equilibrium, not for evolutionary changes.

[2] For a highly significant sample, see G. L. Bach, *Economics*, 2d ed. Englewood Cliffs, N.J.: Prentice-Hall, 1957, p. 60; Paul A. Samuelson, *Economics*, 8th ed. New York: McGraw-Hill, 1970, p. 72; Robert L. Heilbroner, *The Economic Problem*, 3rd ed. Englewood Cliffs, N.J.: Prentice-Hall, 1972, p. 177.

growing economy. The only difference is that Marx preached overtly that nature offers us everything gratis, while standard economists merely went along with this tenet tacitly. Both schools of thought shared, therefore, the Pigouvian notion of a stationary state in which a material flow emerges from an invariable source. In this idea there lies the germ of an economic myth which, as we shall see (Section VIII), is now preached by many concerned ecologists and some awakened economists. The myth is that a stationary world, a zero-growth population, will put an end to the ecological conflict of mankind. Mankind will no longer have to worry about the scarcity of resources or about pollution—another miracle-program to bring the New Jerusalem into the earthly life of man.

Myths have always occupied a prominent role in the life of man. To be sure, to act in accord with a myth is the distinctive characteristic of man among all living beings. Many myths betray man's greatest folly, his inner compulsion to believe that he is above everything else in the actual universe and that his powers know no limits. In Genesis man proclaimed that he was made in the image of God Himself. At one time, he held that the entire universe revolves around his petty abode—at another, that only the sun does so. Once, man believed that he could move things without consuming any energy, which is the myth of perpetual motion of the first kind—certainly, an essentially economic myth. The myth of perpetual motion of the second kind, which is that we may use the same energy over and over again, still lingers on in various veiled forms.

Another economic myth—that man will forever succeed in finding new sources of energy and new ways of harnessing them to his benefit—is now propounded by some scientists, but especially by economists of both standard and Marxist persuasions (Section VI). Come what may, "we will [always] think up something" [4, 338]. The idea is that, if the individual man is mortal, at least the human species is immortal. Apparently, it is below man's dignity to accept the verdict of a biological authority such as J. B. S. Haldane that the most certain fate of mankind is the same as that of any other species, namely, extinction. Only, we do not know when and why it will come. It may be sooner than the optimists believe or much later than the pessimists fear. Consequences of the accumulation of environmental deterioration may bring it about; but some persistent virus or a freak infertility gene may also cause it.

The fact is that we know little about why any species bowed out in the past, not even why some seem to become extinct before our own eyes. If we can predict approximately how long a given dog will live and also what will most probably end its life, it is only because we have had repeated occasions to observe a dog's life from birth to death. The predicament of the evolutionary biologist is that he has never observed another human species being born, aging, and dying [29, 91; 32, 208–210]. However, a species reaches the end of its existence by a process analogous to the aging of any individual organism. And even though aging is still surrounded by many mysteries [32, 205], we know that the causes which bring about the end of a species work slowly, but *persistently and cumulatively,* from the first moment of its birth. The point is that everyone of us ages with each minute, nay, with each blink, even though we are unable to realize the difference.

It is utterly inept to argue—as some economists implicitly do—that since mankind has not met with any ecological difficulty since the age of Pericles, it will never meet with one (Section VI). If we keep our eyes open, however, we will detect, as time goes by, some sufficiently apparent symptoms which may help us arrive at some general idea of the probable causes of aging and, possibly, of death. True, man's needs and the kinds of resources required for their satisfaction are far more complex than those of any other species. In exchange, our knowledge of these factors and their interrelations is, naturally, more extensive. The upshot is that even a simple analysis of the energy aspects of man's existence may help us reach at least a general picture of the ecological problems and arrive at a few, but relevant, conclusions. This, *and nothing else,* is what I have endeavored to do in this paper.

II. MECHANICS VERSUS THERMODYNAMICS

No analysis of a material process, whether in the natural sciences or in economics, can be sound without a clear and comprehensive analytical picture of such a process. The picture must first of all include the boundary—an abstract and void element which separates the process from its "environment"—as well as the duration of the process. What the process needs and what it does are then described analytically by the complete time schedule of all inputs and outputs, i.e., the precise moments at which each element involved crosses the boundary from outside or from inside. But where we draw the abstract boundary, what duration we consider, and what qualitative spectrum we use for classifying the elements of the process depend on the particular purpose of the student, and by and large on the science in point.[3]

Mechanics distinguishes only mass, speed, and position, on which it bases the concept of kinetic and potential energy. The result is that mechanics reduces any process to locomotion and a change in the distribution of energy. The constancy of total mechanical energy (kinetic plus potential) and the constancy of mass are the earliest principles of conservation to be recognized by science. A few careful economists, such as Marshall [60, 63], did observe that man can create neither matter nor energy. But in doing so, they apparently had in mind only the *mechanical* principles of conservation, for they immediately added that man can nevertheless produce utilities by moving and rearranging matter. This viewpoint ignores a most important issue: How can man do the moving? For anyone who remains at the level of mechanical phenomena, every bit of matter and every bit of mechanical energy which enter a process must come out in exactly the same *quantity* and *quality*. Locomotion cannot alter either.

To equate the economic process with a mechanical analogue implies, therefore, the myth that the economic process is a circular merry-go-round which cannot possibly affect the environment of matter and energy in any way. The obvious conclusion is that there is no need for bringing the environment into the analytical picture of that process.[4] The old tenet of Sir William Petty, that keen student of human affairs who insisted that labor is the father and nature the mother of wealth, has long since been relegated to the status of a museum piece [29, 96; 31, 280]. Even the accumulation of glaring proofs of the preponderant role played by natural resources in mankind's history failed to impress standard economists. One may think of the Great Migration of the first millenium which was the ultimate response to the exhaustion of the soil of Central Asia following a long period of persistent grazing. Remarkable civilizations—Maya is one example—crumbled away from history because their people were unable to migrate or to counteract by adequate technical progress the deterioration of their environment. Above all, there is the indisputable fact that all struggles between the Great Powers have not turned idly around ideologies or national prestige but around the control of natural resources. They still do.

Because mechanics recognizes no qualitative change but only change of place, any

[3] For a detailed discussion of the analytical representation of a process, see Georgescu-Roegen [32, ch. ix].

[4] If "land" appears as a variable in some standard production functions, it stands only for Ricardian land, i.e., for mere space. The lack of concern for the true nature of the economic process is also responsible for the inadequacy of the standard production function from other, equally crucial, viewpoints. See Georgescu-Roegen [27; 30; 33].

mechanical process may be reversed, just as a pendulum, for instance, can. No laws of mechanics would have been violated if the earth had been set in motion in the opposite direction. There is absolutely no way for a spectator to discover whether a movie of a purely mechanical pendulum is projected in the direction in which it was taken or in the reverse. But actual phenomena in all their aspects do not follow the story of the famous Mother Goose rhyme in which the brave Duke of York kept marching his troops up the hill and down the hill without giving battle. Actual phenomena move in a definite direction and involve qualitative change. This is the lesson of thermodynamics, a peculiar branch of physics, so peculiar that purists prefer not to consider it a part of physics because of its anthropomorphic texture. Even though it is hard to see how the basic texture of any science could be otherwise than anthropomorphic, the case of thermodynamics is unique.

Thermodynamics grew out of a memoir by a French engineer, Nicolas Sadi Carnot, on the efficiency of heat engines (1824). Among the first facts it brought to light is that man can use only a particular form of energy. Energy thus came to be divided into *available* or *free* energy, which can be transformed into work, and *unavailable* or *bound* energy, which cannot be so transformed.[5] Clearly, the division of energy according to this criterion is an anthropomorphic distinction like no other in science.

The distinction is closely related to another concept specific to thermodynamics, namely, to entropy. This concept is so involved that one specialist judged that "it is not easily understood even by physicists" [40, 37].[6] But for our immediate purpose we may be satisfied with the simple definition of entropy as an *index* of the amount of unavailable energy in a given thermodynamic system at a given moment of its evolution.

Energy, regardless of quality,[7] is subject to a strict conservation law, the First Law of Thermodynamics, which is formally identical to the conservation of mechanical energy mentioned earlier. And since work is one of the multiple forms of energy, this law exposes the myth of perpetual motion of the first kind. It does not, however, take account of the distinction between available and unavailable energy; *by itself the law does not preclude the possibility that an amount of work should be transformed into heat and this heat reconverted into the initial amount of work.* The First Law of Thermodynamics thus allows any process to take place both forward and backward, so that everything is again just as it was at first, with no trace left by the happening. With only that law we are still in mechanics, not in the domain of actual phenomena, which certainly includes the economic process.

The irreducible opposition between mechanics and thermodynamics stems from the Second Law, the Entropy Law. The oldest of its multiple formulations is also the most transparent for the nonspecialist: "Heat flows by itself only from the hotter to the colder body, never in reverse." A more involved but equivalent formulation is that the entropy of a *closed* system continuously (and irrevocably) increases toward a maximum; i.e.,

[5] The technical definition of available (unavailable) energy does not coincide with that of free (bound) energy. But the difference is such that we may safely ignore it in the present discussion.

[6] This judgment is vindicated by the discussion of the Entropy Law in [44, 17]. Even the familiar notion of heat raises some delicate issues, with the result that some physicists may go wrong on it, too. See *Journal of Economic Literature*, X (December 1972), p. 1268.

[7] Let us also note that even energy does not lend itself to a simple, formal definition. The familiar one, that energy is the capacity of a system to perform work, clashes with the definition of unavailable energy. We must then explain that all energy can in principle be transformed into work provided that the corresponding system is brought in contact with another which is at the absolute zero of temperature. This explanation has only the value of a pure extrapolation because, according to the Third Law of Thermodynamics, this temperature can never be reached.

the available energy is continuously transformed into unavailable energy until it disappears completely.[8]

In broad lines, the story is relatively simple: *All kinds of energy are gradually transformed into heat and heat becomes so dissipated in the end that man can no longer use it.* Indeed, a point that goes back to Carnot is that no steam engine can provide work if the same temperature, however high, prevails in the boiler and the cooler.[9] To be available, energy must be distributed unevenly; energy that is completely dissipated is no longer available. The classical illustration is the immense heat dissipated into the water of the seas, which no ship can use. Although ships sail on top of it, they need available energy, the kinetic energy concentrated in the wind or the chemical and nuclear energy concentrated in some fuel. We may see why entropy came to be regarded also as an index of disorder (of dissipation) not only of energy but also of *matter* and why the Entropy Law in its present form states that *matter, too, is subject to an irrevocable dissipation.* Accordingly, the ultimate fate of the universe is not the Heat Death (as it was believed at first) but a much grimmer state—Chaos. No doubt, the thought is intellectually unsatisfactory.[10] But what interests us is that, according to all the evidence, our immediate environment, the solar system, tends toward a thermodynamic death,[11] at least as far as life-bearing structures are concerned.

III. THE ENTROPY LAW AND ECONOMICS

Perhaps no other law occupies a position in science as singular as that of the Entropy Law. It is the only natural law which recognizes that even the material universe is subject to an irreversible qualitative change, to an evolutionary process.[12] This fact led some natural scientists and philosophers to suspect an affinity between that law and life phenomena. By now, few would deny that the *economy* of any life process is governed, not by the laws of mechanics, but by the Entropy Law [32, xiii, 191–194]. The point, as we shall now see, is most transparent in the case of the economic process.

Economists have occasionally maintained that, since some scientists trespass into economics without knowing much about the subject, they, too, are justified in talking about science, notwithstanding their ignorance in that domain [4, 328f]. The thought reflects an error, which unfortunately is general with economists. But whatever the economic expertise of other scientists, economists could not fare continuously well in their own field without some solid understanding of the Entropy Law and its consequences.[13] As I argued some years ago, thermodynamics is at bottom a physics of economic value—as Carnot unwittingly set it going—and the En-

[8] A system is closed if it exchanges no matter and no energy with its "environment." Clearly, in such a system the amount of matter-energy is constant. However, the constancy of this amount alone does not warrant the increase of entropy. Entropy may even decrease if there is exchange.

[9] There is no truth, therefore, in Holdren's idea [44, 17] that temperature measures "the usefulness" of heat. The most we can say is that the *difference* of temperature is a rough index of the usefulness of the hotter heat.

[10] One alternative, supported by statistical thermodynamics (Section VI), is that entropy may decrease in some parts of the universe so that the universe both ages and rejuvenates. But no substantial evidence exists for this possibility. Another hypothesis, set forth by a group of British astronomers, is that the universe is an everlasting steady state in which individual galaxies are born and die continuously. But facts do not fit this hypothesis either. The issue of the true nature of the universe is far from settled [32, 201f, 210].

[11] To preclude some erring, we should emphasize the point that a reversal of this trend would be just as bad for the preservation of life on earth.

[12] Rudolf Clausius coined "entropy" from a Greek word meaning "transformation," "evolution." See [32, 130].

[13] As we shall see later on, some highly interesting examples are provided by Harry G. Johnson [49] and, in an unceremonious, assertive manner, by Robert A. Solo [73]. As for Robert M. Solow, who at first also refused to swerve a hair from the standard position [74], he recently found it opportune to concede that "it takes economics and the law of entropy" to deal with the problem of resources [75, 11]. But at bottom, he still remained attached to his old creed.

tropy Law is the most economic in nature of all natural laws [29, 92–94; 32, 276–283].

The economic process, like any other life process, is irreversible (and irrevocably so); hence, it cannot be explained in mechanical terms alone. It is thermodynamics, through the Entropy Law, that recognizes the qualitative distinction which economists should have made from the outset between the inputs of valuable resources (low entropy) and the final outputs of valueless waste (high entropy). The paradox suggested by this thought, namely, that all the economic process does is to transform valuable matter and energy into waste, is easily and instructively resolved. It compels us to recognize that the real output of the economic process (or of any life process, for that matter) is not the *material flow* of waste, but the still mysterious *immaterial flux* of the enjoyment of life.[14] Without recognizing this fact we cannot be in the domain of life phenomena.

The present laws of physics and chemistry do not explain life completely. But the thought that life may violate some natural law has no place in science. Nevertheless, as has long been observed—and more recently in an admirable exposition by Erwin Schrödinger [71, 69–72]—life seems to evade the entropic degradation to which inert matter is subject. The truth is that any living organism simply strives at all times to compensate for its own continuous entropic degradation by sucking low entropy (negentropy) and expelling high entropy. Clearly, this phenomenon is not precluded by the Entropy Law, which requires only that the entropy of the entire system (the environment *and* the organism) should increase. Everything is in order as long as the entropy of the environment increases by more than the compensated entropy of the organism.

Equally important is the fact that the Entropy Law is the only natural law that does not predict quantitatively. It does not specify how great the increase should be at a future moment or what particular entropic pattern will result. Because of this fact, there is an entropic indeterminateness in the real world which allows not only for life to acquire an endless spectrum of forms but also for most actions of a living organism to enjoy a certain amount of freedom [32, 12]. Without this freedom, we would not be able to choose between eating beans or meat, between eating now or later. Nor could we aspire to implement economic plans (at any level) of our own choosing.

It is also because of the entropic indeterminateness that life does matter in the entropic process. The point is no mystical vitalism, but a matter of brute facts. Some organisms slow down the entropic degradation. Green plants store *part* of the solar radiation which in their absence would immediately go into dissipated heat, into high entropy. That is why we can burn now the solar energy saved from degradation millions of years ago in the form of coal or a few years ago in the form of a tree. All other organisms, on the contrary, speed up the march of entropy. Man occupies the highest position on this scale, and this is all that environmental issues are about.

Most important for the student of economics is the point that the Entropy Law is the taproot of economic scarcity. Were it not for this law, we could use the energy of a piece of coal over and over again, by transforming it into heat, the heat into work, and the work back into heat. Also, engines, homes, and even living organisms (if they could exist at all) would never wear out. There would be no economic difference between material goods and Ricardian land. In such an imaginary, purely mechanical world, there would be no true scarcity of energy and materials. A population as large as the space of our globe would allow could live indeed forever. An increase in the real income per capita could be supported in part

[14] It seems idle therefore to ask—as Boulding [8, 10] does—whether well-being is a flow or a stock.

by a greater velocity of use (just as in the case of money circulation) and in part by additional mining. But there would be no reason for any real struggle, whether intra-species or inter-species, to arise.

Economists have been insisting that "there is no free lunch," by which they mean that the price of anything must be equal to the cost; otherwise, one would get something for nothing. To believe that this equality also prevails in terms of entropy constitutes one of the most dangerous economic myths. *In the context of entropy, every action, of man or of an organism, nay, any process in nature, must result in a deficit for the entire system.* Not only does the entropy of the environment increase by an additional amount for every gallon of gasoline in your tank, but also a substantial part of the free energy contained in that gasoline, instead of driving your car, will turn directly into an additional increase of entropy. As long as there are abundant, easily accessible resources around, we might not really care how large this additional loss is. Also, when we produce a copper sheet from some copper ore we decrease the entropy (the disorder) of the ore, but only at the cost of a much greater increase of the entropy in the rest of the universe. If there were not this entropic deficit, we would be able to convert work into heat, and, by reversing the process, to recuperate the entire initial amount of work—as in the imaginary world of the preceding paragraph. In such a world, standard economics would reign supreme precisely because the Entropy Law would not work.

IV. ACCESSIBLE ENERGY AND ACCESSIBLE MATTER

As we have seen, the distinction between available and unavailable energy (generalized by that between low and high entropy) was introduced in order that thermodynamics may take into account the fact that only one particular state of energy can be used by man. But the distinction does not mean that man can *actually* use any available energy regardless of the place and form in which it is found. If available energy is to have any value for mankind, it must also be *accessible*. Solar energy and its by-products are accessible to us with practically no effort, no consumption of additional available energy. In all other cases, we have to spend some work and materials in order to tap a store of available energy. The point is that even though we may land on Mars and find there some gas deposits, that available energy will not be accessible to us if it will take more than the equivalent energy of a cubic foot of gas *accessible on earth* to bring a cubic foot of gas from that planet. There certainly are oil shales from which we could extract one ton of oil only by using more than one ton of oil. The oil in such a shale would still represent available, but not accessible, energy. We have been reminded ad nauseam that the real reserves of fossil fuel are certainly greater than those known or estimated [e.g. 58, 331]. But it is equally certain that a substantial part of the real reserves does not constitute accessible energy.

The distinction regards efficiency in terms of energy, not in terms of economics. Economic efficiency implies energetic efficiency, but the converse is not true. The use of gas, for example, is energetically more efficient than the use of electricity, but electricity happens to be cheaper in many instances [79, 152]. Also, even though we can make gas from coal, it is cheaper to extract gas from natural deposits. Should the natural resources of gas become exhausted before those of coal, we will certainly resort to the method that is now economically inefficient. The same idea should be borne in mind when discussing the future of direct uses of solar radiation.

Economists, however, insist that "resources are properly measured in economic, not physical, terms" [51, 663; also 3, 247]. The advice reflects one of the most enduring myths of the profession (shared also by others). It is the myth that the price mechanism can offset any shortages, whether of land, energy or materials.[15] This myth will be duly examined later on, but here we need only emphasize the point that from the point of view of the longrun it is only efficiency in terms of energy that counts in establishing accessibility. To be sure, actual efficiency depends at any one time on the state of the arts. But, as we know from Carnot, in each particular situation *there is a theoretical limit independent of the state of the arts, which can never be attained in actuality*. In effect, we generally remain far below it.

Accessibility, as here defined, bears on the fact that although mankind's spaceship floats within a fantastic store of available energy, only an infinitesimal part of this store is potentially accessible to man. For even if we were to travel in space with the greatest speed, that of light, we would still be confined to a speck of cosmos. A journey just to scout the nearest sun outside the solar system for possible, yet uncertain, earth-like satellites would take nine years! If we have learned anything from the landing on the moon, it is that there is no promise of resources in interplanetary, let alone intersidereal, travel.

Still narrower limits to the accessible energy are set by our own biological nature, which is such that we cannot survive at too high or too low a temperature or when exposed to some radiations. It is for this reason that the mining of nuclear fuel and its use on a large scale has raised issues which now divide laymen as well as authorities on the subject (Section IX). There are also limits set by some purely physical obstacles. The sun cannot possibly be mined even by a robot. From the sun's immense radiating energy, only the small amount which reaches the earth counts in the main (Section IX). Nor can we harness the immense energy of the terrestrial thunders. Unique physical obstacles also stand hopelessly in the way of the peaceful use of thermonuclear energy. The fusion of deuterium requires the fantastic temperature of 0.2 billion°F, one order of magnitude hotter than the sun's interior. The difficulty concerns the material container for that reaction. As has been explained in layman's terms, the solution now sought is similar to holding water inside a mesh of rubber bands. In this connection we may recall that the chemical energy of dynamite and gunpowder, although in use for a long time, cannot be controlled so as to drive a turbine or a motor. Perhaps the use of thermonuclear energy will also remain confined to a "bomb." [16] Be this as it may, with or without thermonuclear energy, the amount of accessible energetic low entropy is finite (Section IV).

Similar considerations lead to the conclusion that the amount of accessible material low entropy is finite, too. But although in both cases only the amount of low entropy matters, it is important that the two accounts be kept separate in any discussion of the environmental problem. As we all know, available energy and ordered material structures fulfill two distinct roles in mankind's life. However, this anthropomorphic distinction would not be compelling by itself.

There is, first, the physical fact that, despite the Einstein equivalence of mass and energy, there is no reason to believe that we can convert energy into matter except at the atomic scale in a laboratory and only for some special elements.[17] We cannot produce a copper sheet, for example, from energy alone. All the copper in that sheet must exist as copper (in pure form or in some chemical

[15] The evidence is ample [3, 240f; 4, 337f; 49; 51, 663, 665; 74, 46f; 80; 69, 9f, 14f]. The appeal of the myth is seen in that even many on the other side of the fence share it [58; 62, 65; 6, 10, 12; and Frank Notestein, quoted in 62, 130].

[16] The technical difficulties at the present moment are surveyed in [63]. On the other hand, we should remember that in 1933 Ernest Rutherford greatly doubted that atomic energy could be controlled [82, 27].

[17] The point is that even the formation of an atom of carbon from three atoms of helium, for example, requires such a sharp timing that its probability is astronomically small, and hence the event may occur on a large scale only within astronomically huge masses.

compound) beforehand. Therefore, the statement that "energy is convertible into most of the other requirements of life" [83, 412] is, in this unqualified form, apt to mislead. Second, no material macrostructure (whether a nail or a jet) whose entropy is lower than that of its surroundings may last forever in its original form. Even the singular organizations characterized by the tendency to evade the entropic decay—the life-bearing structures—cannot so last. The artifacts which now are an essential part of our mode of life have therefore to be renewed continuously from some sources. The final point is that the earth is a thermodynamic system open only with respect to energy. The amount of meteorite matter, though not negligible, comes already dissipated.

The result is that we can count only on the mineral resources, which, however, are both irreplaceable and exhaustible. Many of a particular kind have been exhausted in one country after another [56, 120f].[18] At present, important minerals—lead, tin, zinc, mercury, precious metals—are scarce over the entire world [17, 72–77; 56]. The widespread notion that the oceans constitute an almost inexhaustible source of minerals and may even become a link in a perpetual, natural recycling system [3, 239; 69, 7f] is denounced as mere hyperbole by geological authorities [17, 85–87].[19]

The only way we can substitute energy for material low entropy is through physicochemical manipulations. By using larger and larger amounts of available energy we can sift copper out from poorer and poorer ores, located deeper and deeper in the earth. But the energy cost of mining low-content ores increases very fast [56, 122f]. We can also recycle "scrap." There are, however, some elements which, because of their nature and the mode in which they participate in the natural and man-conducted processes, are highly dissipative. Recycling, in this case, can hardly help. The situation is particularly distressing for those elements which, in addition, are found in very small supply in the environment. Phosphorus, a highly critical element in biological processes, seems to belong to this category. So does helium, another element with a strictly specific role [17, 81; 38].

An important point—apparently ignored by economists [49, 8; 69, 16, 42]—is that recycling cannot be complete.[20] Even though we can pick up all the pearls from the floor and reconstitute a broken necklace, no actual process can possibly reassemble all the molecules of a coin after it has been worn out.

This impossibility is not a straightforward consequence of the Entropy Law, as Solow believes [75, 2]. Nor is it quite exact to say, with Boulding [8, 7], that "there is, fortunately, no law of increasing material entropy." The Entropy Law does not distinguish between matter and energy. This law does not exclude (at least not in principle) a complete unshuffling of a *partial* material structure, provided that there is enough free energy to do the job. And if we have enough energy, we could even separate the cold molecules of a glass of water and assemble them into ice cubes. If, in practice, however, such operations are impossible, it is only because they would require a practically infinite time.[21]

V. DISPOSABLE WASTE

Since Malthus did not see that waste also raises some economic problems, it was normal for the schools of economic thought which ignored even the input of natural resources to pay no attention to the output of

[18] See the interesting story of the Mesabi Range in [14, 11f].

[19] The widespread notion that the oceans may be turned into an immense source of food also is a great delusion [13, 59f].

[20] Data on recycling are scarce and inadequate; a few are found in [12, 205; 16, 14]. For steel, see [14].

[21] All this proves that, even though the Entropy Law may sound extremely simple, its correct interpretation requires special care.