Energy and Economic Myths

Nicholas Georgescu-Roegen, 1975

Used with permission of Dieoff.com.
Reprinted from *Southern Economic Journal,* 41, no. 3, January 1975.
See original at < http://dieoff.com/page148.htm >.

Hardly anyone would nowadays openly profess a belief in the immortality of mankind. Yet many of us prefer not to exclude this possibility; to this end, we endeavor to impugn any factor that could limit mankind's life. The most natural rallying idea is that mankind's entropic dowry is virtually inexhaustible, primarily because of man's inherent power to defeat the Entropy Law in some way or another.

To begin with, there is the simple argument that, just as has happened with many natural laws, the laws on which the finiteness of accessible resources rests will be refuted in turn. The difficulty of this historical argument is that history proves with even greater force, first, that in a finite space there can be only a finite amount of low entropy and, second, that low entropy continuously and irrevocably dwindles away. The impossibility of perpetual motion (of both kinds) is as firmly anchored in history as the law of gravitation.

More sophisticated weapons have been forged by the statistical interpretation of thermodynamic phenomena, an endeavor to reestablish the supremacy of mechanics propped up this time by a *sui generis* notion of probability. According to this interpretation, the reversibility of high into low entropy is only a highly improbable, not a totally impossible event. And since the event *is possible,* we should be able by an ingenious device to cause the event to happen as often as we please, just as an adroit sharper may throw a "six" almost at will. The argument only brings to the surface the irreducible contradictions and fallacies packed into the foundations of the statistical interpretation by the worshipers of mechanics [32, ch. 6]. The hopes raised by this interpretation were so sanguine at one time that P. W. Bridgman, an authority 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" [11].

Occasionally and *sotto voce* some express the hope, once fostered by a scientific authority such as John von Neumann, that man will eventually discover how to make energy a free good, "just like the unmetered air" [3, p. 32]. Some envision a "catalyst" by which to decompose, for example, the sea water into oxygen and hydrogen, the combustion of which will yield as much available energy as we would want. But the analogy with the small ember which sets a whole log on fire is unavailing. The entropy of the log and the oxygen used in the combustion is lower than that of the resulting ashes and smoke, whereas the entropy of water is higher than that of the oxygen and hydrogen after decomposition. Therefore, the miraculous catalyst also implies entropy bootlegging. 1

With the notion, now propagated from one syndicated column to another, that the breeder reactor produces more energy than it consumes, the fallacy of entropy bootlegging seems to have reached its greatest currency even among the large circles of literati, including economists. Unfortunately, the illusion feeds on misconceived sales talk by some nuclear experts who extol the reactors which transform fertile but nonfissionable material into fissionable fuel as the breeders that "produce more fuel than they consume" [81, p. 82]. The stark truth is that the breeder is in no way different from a plant which produces hammers with the aid of some hammers. According to the deficit principle of the Entropy Law .... even in breeding chickens a greater amount of low entropy is consumed than is contained in the product[2].

Apparently in defense of the standard vision of the economic process, economists have set forth themes of their own. We may mention first the argument that "the notion of an absolute limit to natural resource availability is untenable when the definition of resources changes drastically and unpredictably over time .... A limit may exist, but it can be neither defined nor specified in economic terms" [3, pp. 7, 11]. We also read that there is no upper limit even for arable land because "arable is infinitely indefinable" [55, p. 22]. The sophistry of these arguments is flagrant. No one would deny that we cannot say *exactly* how much coal, for example, is accessible. Estimates of natural resources have constantly been shown to be too low. Also, the point that metals contained in the top mile of the earth's crust may be a million times as much as the present known reserves [4, p. 338; 58, p. 331] does not prove the inexhaustibility of resources, but, characteristically, it ignores both the issues of accessibility and disposability.3 Whatever resources or arable land we may need at one time or another, they will consist of accessible low entropy and accessible land. *And since all kinds together are in finite amount, no taxonomic switch can do away with that finiteness.*

The favorite thesis of standard and Marxist economists alike, however, is that the power of technology is without limits [3; 4; 10; 49; 51; 69; 74]. We will always be able not only to find a substitute for a resource which has become scarce, but also to increase the productivity of any kind of energy and material. Should we run out of some resources, we will always think up something, just as we have continuously done since the time of Pericles [4, pp. 332-334]. Nothing, therefore, could ever stand in the way of an increasingly happier existence of the human species. One can hardly think of a more blunt form of linear thinking. By the same logic, no healthy young human should ever become afflicted with rheumatism or any other old-age ailments; nor should he ever die. Dinosaurs, just before they disappeared from this very same planet, had behind them not less than one hundred and fifty million years of truly prosperous existence. (And they did not pollute environment with industrial waste!) But the logic to be truly savored is Solo's [73, p. 516]. If entropic degradation is to bring mankind to its knees sometime in the future, it should have done so sometime after A.D. 1000. The old truth of Seigneur de La Palice has never been turned around, and in such a delightful form[4].

In support of the same thesis, there also are arguments directly pertaining to its substance. First, there is the assertion that only a few kinds of resources are "so resistant to technological advance as to be incapable of eventually yielding extractive products at constant or declining cost" [3, p. 10] [5]. More recently, some have come out with a specific law which, in a way, is the contrary of Malthus's law concerning resources. The idea is that technology improves exponentially [4, p. 236; 51, p. 664; 74, p. 45]. The superficial justification is that one technological advance induces another. This is true, only it does not work cumulatively as in population growth. And it is terribly wrong to argue, as Maddox does [59, p. 21], that to insist on the existence of a limit to technology means to deny man's power to influence progress. Even if technology continues to progress, it will not necessary exceed any limit; an increasing sequence may have an upper limit. In the case of technology this limit is set by the theoretical coefficient of efficiency .... If progress were indeed exponential, then the input i per unit of output would follow in time the law $i = i_0^{-t(1+r)}$ and would constantly approach zero. Production would ultimately become incorporeal and the earth a new Garden of Eden.

Finally, there is the thesis which may be called the fallacy of endless substitution: "Few components of the earth's crust, including farm land, are so specific as to defy economic replacement; . . . nature imposes particular scarcities, not an inescapable general scarcity" [3, pp. 10f][6]. Bray's protest notwithstanding [10, p. 8], this is "an economist's conjuring trick." True, there are only a few "vitamin" elements which play a totally specific role such as phosphorus plays in living organisms. Aluminum, on the other hand, has replaced iron and copper in many, although not in all uses[7]. However, substitution within a finite stock of accessible low entropy whose irrevocable degradation is speeded up through use cannot possibly go on forever.

In Solow's hands, substitution becomes the key factor that supports technological progress even as resources become increasingly scarce. There will be, first, a substitution within the spectrum of consumer goods. With prices reacting to increasing scarcity, consumers will buy "fewer resource-intensive goods and more of other things" [74, p. 47] [8]. More recently, he extended the same idea to production, too. We may, he argues, substitute "other factors for natural resources" [75, p. 11]. One must have a very erroneous view of the economic process as a whole not to see that there are no material factors other than natural resources. To maintain further that "the world can, in effect, get along without natural resources" is to ignore the difference between the actual world and the Garden of Eden.

More impressive are the statistical data invoked in support of some of the foregoing theses. The data adduced by Solow [74, pp. 44f] show that in the United States between 1950 and 1970 the consumption of a series of mineral elements per unit of GNP decreased substantially. The exceptions were attributed to substitution but were expected to get in line sooner or later. In strict logic, the data do not prove that during the same period technology necessarily progressed to a greater economy of resources. The GNP may increase more than any input of minerals even if technology remains the same, or even if it deteriorates. But we also know that during practically the same period, 1947-1967, the consumption per capita of basic materials increased in the United States. And in the world, during only one decade, 1957-1967, the consumption of steel per capita grew by 44 percent [12, pp. 198-200]. What matters in the end is not only the impact of technological progress on the consumption of resources per unit of

GNP, but especially the increase in the rate of resource depletion, which is a side effect of that progress.

Still more impressive, as they have actually proved to be, are the data used by Barnett and Morse to show that, from 1870 to 1957, the ratios of labor and capital costs to net output decreased appreciably in agriculture and mining, both critical sectors as concerns depletion of resources [3, 8f, 167-178]. In spite of some arithmetical incongruities[9], the picture emerging from these data cannot be repudiated. Only its interpretation must be corrected.

For the environmental problem it is essential to understand the typical forms in which technological progress may occur. A first group includes the *economy innovations,* which achieve a net economy of low entropy, be it by a more complete combustion, by decreasing friction, by deriving a more intensive light from gas or electricity, by substituting materials costing less in energy for others costing more, and so on. Under this heading we should also include the discovery of how to use new kinds of accessible low entropy. A second group consists of *substitution innovations,* which simply substitute physicochemical energy for human energy. A good illustration is the innovation of gunpowder, which did away with the catapult. Such innovations generally enable us not only to do things better but also (and especially) to do things which could not be done before, to fly in airplanes, for example. Finally, there are the *spectrum innovations,* which bring into existence new consumer goods, such as the hat, nylon stockings, etc. Most of the innovations of this group are at the same time substitution innovations. In fact, most innovations belong to more than one category. But the classification serves analytical purposes.

Now, economic history confirms a rather elementary fact -- the fact that the great strides in technological progress have generally been touched off by a discovery of how to use a new kind of accessible energy. On the other hand, a great stride in technological progress cannot materialize unless the corresponding innovation is followed by a great mineralogical expansion. Even a substantial increase in the efficiency of the use of gasoline as fuel would pale in comparison with a manifold increase of the known, rich oil fields.

This sort of expansion is what has happened during the last one hundred years. We have struck oil and discovered new coal and gas deposits in a far greater proportion than we could use during the same period. Still more important, all mineralogical discoveries have included a substantial proportion of *easily* accessible resources. This exceptional bonanza by itself has sufficed to lower the real cost of bringing mineral resources *in situ* to the surface. Energy of mineral source thus becoming cheaper, substitution innovations have caused the ratio of labor to net output to decline. Capital also must have evolved toward forms which cost less but use more energy to achieve the same result. What has happened during this period is a modification of the cost structure, the flow factors being increased and the fund factors decreased[10]. By examining, therefore, only the relative variations of the fund factors during a period of exceptional mineral bonanza, we cannot prove either that the unitary total cost will always follow a declining trend or that the continuous progress of technology renders accessible resources almost inexhaustible, as Barnett and Morse claim [3, p. 239].

Little doubt is thus left about the fact that the theses examined in this section are anchored in a deep-lying belief in mankind's immortality. Some of their defenders have even urged us to have faith in the human species: such faith will triumph over all limitations[11]. But neither faith nor assurance from some famous academic chair [4] could alter the fact that, according to the basic law of thermodynamics, mankind's dowry is finite. Even if one were inclined to believe in the possible refutation of these principles in the future, one still must not act on that faith now. We must take into account that evolution does not consist of a linear repetition, even though over short intervals it may fool us into the contrary belief.

A great deal of confusion about the environmental problem prevails not only among economists generally (as evidenced by the numerous cases already cited), but also among the highest intellectual circles simply because the sheer entropic nature of all happenings is ignored or misunderstood. Sir Macfarlane Burnet, a Nobelite, in a special lecture considered it imperative "to prevent the progressive destruction of the earth's irreplaceable resources" [quoted, 15, p. 1].

And a prestigious institution such as the United Nations, in its Declaration on the Human Environment (Stockholm, 1972), repeatedly urged everyone "to improve the environment." Both urgings reflect the fallacy that man can reverse the march of entropy. The truth, however unpleasant, is that the most we can do is to prevent any unnecessary depletion of resources and any unnecessary deterioration of the environment, but without claiming that we know the precise meaning of "unnecessary" in this context.

The Steady State: A Topical Mirage

Malthus, as we know, was criticized primarily because he assumed that population and resources grow according to some simple mathematical laws. But this criticism did not touch the real error of Malthus (which has apparently remained unnoticed). This error is the implicit assumption that population may grow beyond any limit both in number and time *provided that it does not grow too rapidly.* 12 An essentially similar error has been committed by the authors of *The Limits,* by the authors of the nonmathematical yet more articulate "Blueprint for Survival," as well as by several earlier writers. Because, like Malthus, they were set exclusively on proving the impossibility of growth, they were easily deluded by a simple, now widespread, but false syllogism: since exponential growth in a finite world leads to disasters of all kinds, ecological salvation lies in the stationary state [42; 47; 62, pp. 156-184; 6, pp. 3f, 8, 20]. 13 H. Daly even claims that "the stationary state economy is, therefore, a necessity" [21, p. 5].

This vision of a blissful world in which both population and capital stock remain constant, once expounded with his usual skill by John Stuart Mill [64, bk. 4, ch. 6], was until recently in oblivion. 14 Because of the spectacular revival of this myth of ecological salvation, it is well to point out its various logical and factual snags. The crucial error consists in not seeing that not only growth, but also a zerogrowth state, nay, even a declining state which does not converge toward annihilation, cannot exist forever in a finite environment. The error perhaps stems from some confusion between finite stock and finite flow rate, as the incongruous dimensionalities of several graphs suggest [62, pp. 62, 64f, 124ff; 6, p. 6]. And contrary to what some advocates of the stationary state claim [21, p. 15], this state does not occupy a privileged position *vis-à-vis* physical laws.

To get to the core of the problem, let *S* denote the actual amount of accessible resources in the crust of the earth. Let *Pi* and *si* be the population and the amount of depleted resources per person in the year *i*. Let the "amount of total life," measured in years of life, be defined by [formula omitted] , from *i* = 0 to *i* = 0o. S sets an upper limit for *L* through the obvious constraint [formula omitted]. For although *si* is a historical variable, it cannot be zero or even negligible (unless mankind reverts sometime to a berry-picking economy). Therefore, *P* = 0 for *i* greater than some finite n, and *Pi* > 0 otherwise. That value of *n* is the maximum duration of the human species [31, pp. 12f; 32, p. 304].

The earth also has a so-called carrying capacity, which depends on a complex of factors, including the size of *si.* 15 This capacity sets a limit on any single *Pi.* But this limit does not render the other limits, of *L* and *n,* superfluous. It is therefore inexact to argue —as the Meadows group seems to do [62, pp. 91f]— that the stationary state can go on forever as long as *Pi* does not exceed that capacity. The proponents of salvation through the stationary state must admit that such a state can have only a finite duration —unless they are willing to join the "No Limit" Club by maintaining that *S* is inexhaustible or almost so— as the Meadows group does in fact [62, p. 172]. Alternatively, they must explain the puzzle of how a whole economy, stationary for a long era, all of a sudden comes to an end.

Apparently, the advocates of the stationary state equate it with an open *thermodynamic* steady state. This state consists of an *open* macrosystem which maintains its entropic structure constant through material exchanges with its "environment." As one would immediately guess, the concept constitutes a highly useful tool for the study of biological organisms. We must, however, observe that the concept rests on some special conditions introduced by L. Onsager [50, pp. 89-97]. These conditions are so delicate (they are called the principle of *detailed* balance) that in actuality they can hold only "within a deviation of a few percent" [50, p. 140]. For this reason, a steady state may exist in fact only in an approximated manner and over a finite duration. This impossibility of a macrosystem not in a state of chaos to be perpetually durable may one day be explicitly recognized by a new thermodynamic law just as the impossibility of perpetual motion once was. Specialists recognize that the present thermodynamic laws do not suffice to explain all nonreversible phenomena, including especially life processes.

Independently of these snags there are simple reasons against believing that mankind can live in a perpetual stationary state. The structure of such a state remains the same throughout; it does not contain in itself the seed of the inexorable death of all open macrosystems. On the other hand, a world with a stationary population would, on the contrary, be continually forced to change its technology as well as its mode of life in response to the inevitable decrease of resource accessibility. Even if we beg the issue of how capital may change qualitatively and still remain constant, we could have to assume that the unpredictable decrease in accessibility will be miraculously compensated by the right innovations at the right time. A stationary world may for a while be interlocked with the changing environment through a system of balancing feedbacks analogous to those of a living organism during one phase of its life. But as Bormann reminded us [7, p. 707], the miracle cannot last forever; sooner or later the balancing system will collapse. At that time, the stationary state will enter a crisis, which will defeat its alleged purpose and nature.

One must be cautioned against another logical pitfall, that of invoking the Prigogine principle in support of the stationary state. This principle states that the minimum of the entropy produced by an Onsager type of open thermodynamic system is reached when the system becomes steady [50, ch. 16]. It says nothing about how this last entropy compares with that produced by other open systems. 16

The usual arguments adduced in favor of the stationary state are, however, of a different, more direct nature. It is, for example, argued that in such a state there is more time for pollution to be reduced by natural processes and for technology to adapt itself to the decrease of resource accessibility [62, p. 166]. It is plainly true that we could use much more efficiently today the coal we have burned in the past. The rub is that we might not have mastered the present efficient techniques if we had not burned all that coal "inefficiently." The point that in a stationary state people will not have to work additionally to accumulate capital (which in view of what I have said in the last paragraphs is not quite accurate) is related to Mill's claim that people could devote more time to intellectual activities. "The trampling, crushing, elbowing, and treading on each other's heel" will cease [64, p. 754].

History, however, offers multiple examples —the Middle Ages, for one— of quasi stationary societies where arts and sciences were practically stagnant. In a stationary state, too, people may be busy in the fields and shops all day long. Whatever the state, free time for intellectual progress depends on the intensity of the pressure of population on resources. Therein lies the main weakness of Mill's vision. Witness the fact that — as Daly explicitly admits [21, pp. 6-8]— its writ offers no basis for determining even in principle the optimum levels of population and capital. This brings to light the important, yet unnoticed point, that the *necessary conclusion of the arguments in favor of that vision is that the most desirable state is not a stationary, but a declining one.*

Undoubtedly, the current growth must cease, nay, be reversed. But anyone who believes that he can draw a blueprint for the ecological salvation of the human species does not understand the nature of evolution, or even of history —which is that of permanent struggle in continuously novel forms, not that of a predictable, controllable physico-chemical process, such as boiling an egg or launching a rocket to the moon.

Some Basic Bioeconomics [17]

Apart from a few insignificant exceptions, all species other than man use only *endosomatic* instruments, as Alfred Lotka proposed to call those instruments (legs, claws, wings, etc.) which belong to the individual organism *by birth.* Man alone came, in time, to use a club, which does not belong to him by birth, but which extended his endosomatic arm and increased its power. At that point in time, man's evolution transcended the biological limits to include also (and primarily) the evolution of exosomatic instruments, i.e., of instruments produced by man but not belonging to his body. 18 That is why man can now fly in the sky or swim under water even though his body has no wings, no fins, and no gills.

The exosomatic evolution brought down upon the human species two fundamental and irrevocable changes. The first is the irreducible social conflict which characterizes the human species [29, pp. 98-101; 32, pp. 306-315, 348f]. Indeed, there are other species which also live in society, but which are free from such conflict. The reason is that their "social classes" correspond to some clear-cut biological divisions. The periodic killing of a great part of the drones by the bees is a natural, biological action, not a civil war.

The second change is man's addiction to exosomatic instruments —a phenomenon analogous to that of the flying fish which became addicted to the atmosphere and mutated into birds forever. It is because of this addiction that mankind's survival presents a problem entirely different from that of all other species [31; 32, pp. 302-305]. It is neither only biological nor only economic. It is bioeconomic. Its broad contours depend on the multiple asymmetries existing among the three sources of low entropy which together constitute mankind's dowry —the free energy received from the sun, on the one hand, and the free energy and the ordered material structures stored in the bowels of the earth, on the other.

The *first* asymmetry concerns the fact that the terrestrial component is a *stock,* whereas the solar one is a flow. The difference needs to be well understood [32, pp. 226f]. Coal *in situ* is a stock because we are free to use it all today (conceivably) or over centuries. But at no time can we use any part of a future flow of solar radiation. Moreover, the flow rate of this radiation is wholly beyond our control; it is completely determined by cosmological conditions, including the size of our globe. 19 One generation, whatever it may do, cannot alter the share of solar radiation of any future generation. Because of the priority of the present over the future and the irrevocability of entropic degradation, the opposite is true for the terrestrial shares. These shares are affected by how much of the terrestrial dowry the past generations have consumed.

Second, since no practical procedure is available at human scale for transforming energy into matter .... accessible material low entropy is by far the most critical element from the bioeconomic viewpoint. True, a piece of coal burned by our forefathers is gone forever, just as is part of the silver or iron, for instance, mined by them. Yet future generations will still have their inalienable share of solar energy (which, as we shall see next, is enormous). Hence, they will be able, at least, to use each year an amount of wood equivalent to the annual vegetable growth. For the silver and iron dissipated by the earlier generations there is no similar compensation. This is why in bioeconomics we must emphasize that every Cadillac or every Zim —let alone any instrument of war— means fewer plowshares for some future generations, and implicitly, fewer future human beings, too [31, p. 13; 32, p. 304].

Third, there is an astronomical difference between the amount of the flow of solar energy and the size of the stock of terrestrial free energy. At the cost of a decrease in mass of 131×10^{12} tons, the sun radiates annually 10^{13} Q -- one single Q being equal to 10^{18} BTU! Of this fantastic flow, only some 5,300 Q are intercepted at the limits of the earth's atmosphere, with roughly one half of that amount being reflected back into outer space. At our own scale, however, even this amount is fantastic; for the total world consumption of energy currently amounts to no more than 0.2 Q annually. From the solar energy that reaches the ground level, photosynthesis absorbs only 1.2 Q. From waterfalls we could obtain at most 0.08 Q, but we are now using only one tenth of that potential. Think also of the additional fact that the sun will continue to shine with practically the same intensity for another five billion years (before becoming a red giant which will raise the earth's temperature to 1,000°F). Undoubtedly, the human species will not survive to benefit from all this abundance.

Passing to the terrestrial dowry, we find that, according to the best estimates, the initial dowry of fossil fuel amounted to only 215 Q. The outstanding recoverable reserves (known and probable) amount to about 200 Q. These reserves, therefore, could produce only two weeks of sunlight on the globe. 20 If their depletion continues to increase at the current pace, these reserves may support man's industrial activity for just a few more decades. Even the reserves of uranium 235 will not last for a longer period if used in the ordinary reactors. Hopes are now set on the breeder reactor, which, with the aid of uranium 235, may "extract" the energy of the fertile but not fissionable elements, uranium 238 and thorium 232.

Some experts claim that this source of energy is "essentially inexhaustible" [83, p. 412]. In the United States alone, it is believed, there are large areas covered with black shale and granite which contain 60 grams of natural uranium or thorium per metric ton [46, pp. 226f]. On this basis, Weinberg and Hammond [83, pp. 415f] have come out with a grand plan. By stripmining and crushing all these rocks, we could obtain enough nuclear fuel for some 32,000 breeder reactors distributed in 4,000 offshore parks and capable of supplying a population of twenty billion for millions of years with twice as much energy per capita as the current consumption rate in the USA. The grand plan is a typical example of linear thinking, according to which all that is needed for the existence of a population, even "considerably larger than twenty billion," is to increase all supplies proportionally. 21 Not that the authors deny that there also are nontechnical issues; only, they play them down with noticeable zeal [83, pp. 417f]. The most important issue, of whether a social organization compatible with the density of population and the nuclear manipulation at the grand level can be achieved, is brushed aside by Weinberg as "transscientific" [82]. 22 Technicians are prone to forget that due to their own successes, nowadays it may be easier to move the mountain to Mohammed than to induce Mohammed to go to the mountain. For the time being, the snag is far more palpable. As responsible forums openly admit, even one breeder still presents substantial risks of nuclear catastrophes, and the problem of safe transportation of nuclear fuels and especially that of safe storage of the radioactive garbage still await a solution even for a moderate scale of operations [35; 36; especially 39 and 67].

There remains the physicist's greatest dream, controlled thermonuclear reaction. To constitute a real breakthrough, it must be the deuterium-deuterium reaction, the only one that could open up a formidable source of terrestrial energy for a long era. 23

However, because of the difficulties alluded to earlier .... even the experts working at it do not find reasons for being too hopeful.

For completion, we should also mention the tidal and geothermal energies, which, although not negligible (in all, 0.1 Q per year), can be harnessed only in very limited situations.

The general picture is now clear. The terrestrial energies on which we can rely effectively exist in very small amounts, whereas the use of those which exist in ampler amounts is surrounded by great risks and formidable technical obstacles. On the other hand, there is the immense energy from the sun which reaches us without fail. Its direct use is not yet practiced on a significant scale, the main reason being that the alternative industries are now much more efficient economically. But promising results are coming from various directions [37; 41]. What counts from the bioeconomic viewpoint is that the feasibility of using the sun's energy directly is not surrounded by risks or big question marks; it is a proven fact.

The conclusion is that mankind's entropic dowry presents another important differential scarcity. From the viewpoint of the extreme long run, the terrestrial free energy is far scarcer than that received from the sun. The point exposes the foolishness of the victory cry that we can finally obtain protein from fossil fuels! Sane reason tells us to move in the opposite direction, to convert vegetable stuff into hydrocarbon fuel —an obviously natural line already pursued by several researchers [22, pp. 311-313]. 24

Fourth, from the viewpoint of industrial utilization, solar energy has an immense drawback in comparison with energy of terrestrial origin. The latter is available in a concentrated form; in some cases, in a too concentrated form. As a result, it enables us to obtain almost instantaneously enormous amounts of work, most of which could not even be obtained otherwise. By great contrast, the flow of solar energy comes to us with an extremely low intensity, like a very fine rain, almost a microscopic mist. The important difference from true rain is that this radiation rain is not collected naturally into streamlets, then into creeks and rivers, and finally into lakes from where we could use it in a concentrated form, as is the case with waterfalls. Imagine the difficulty one would face if one tried to use *directly* the kinetic energy of some microscopic rain drops as they fall. The same difficulty presents itself in using solar energy directly (i.e., not through the chemical energy of green plants, or the kinetic energy of the wind and waterfalls). But as was emphasized a while ago, the difficulty does not amount to impossibility. 25

Fifth, solar energy, on the other hand, has a unique and incommensurable advantage. The use of any terrestrial energy produces some noxious pollution, which, moreover, is irreducible and hence cumulative, be it in the form of thermal pollution alone. By contrast, any use of solar energy is *pollution-free.* For, whether this energy is used or not, its ultimate fate is the same, namely, to become the dissipated heat that maintains the thermodynamic equilibrium between the globe and outer space at a propitious temperature. 26

The *sixth* asymmetry involves the elementary fact that the survival of every species on earth depends, directly or indirectly, on solar radiation (in addition to some elements of a superficial environmental layer). Man alone, because of his exosomatic addiction, depends on mineral resources as well. For the use of these resources man competes with no other species; yet his use of them usually endangers many forms of life, including his own. Some species have in fact been brought to the brink of extinction merely because of man's exosomatic needs or his craving for the extravagant. But nothing in nature compares in fierceness with man's competition for solar energy (in its primary or its by-product forms). Man has not deviated one bit from the law of the jungle; if anything, he has made it even more merciless by his sophisticated exosomatic instruments. Man has openly sought to exterminate any species that robs him of his food or feeds on him —wolves, rabbits, weeds, insects, microbes, etc.

But this struggle of man with other species for food (in ultimate analysis, for solar energy) has some unobtrusive aspects as well. And, curiously, it is one of these aspects that has some far-reaching consequences in addition to supplying a most instructive refutation of the common belief that every technological innovation constitutes a move in the right direction as concerns the economy of resources. The case pertains to the economy of modern agricultural techniques ....

Justus von Liebig observed that "civilization is the economy of power" [32, p. 304]. At the present hour, the economy of power in all its aspects calls for a turning point. Instead of continuing to be opportunistic in the highest degree and concentrating our research toward finding more economically efficient ways of tapping mineral energies —all in finite supply and all heavy pollutants— we should direct all our efforts toward improving the direct uses of solar energy -- the only clean and essentially unlimited source. Already-known techniques should without delay be diffused among all people so that we all may learn from practice and develop the corresponding trade.

An economy based primarily on the flow of solar energy will also do away, though not completely, with the monopoly of the present over future generations, for even such an economy will still need to tap the terrestrial dowry, especially for materials. Technological innovations will certainly have a role in this direction. But it is high time for us to stop emphasizing exclusively —as all platforms have apparently done so far— the increase of supply. Demand can also play a role, an even greater and more efficient one in the ultimate analysis.

It would be foolish to propose a complete renunciation of the industrial comfort of the exosomatic evolution. Mankind will not return to the cave or, rather, to the tree. But there are a few points that may be *included in a minimal bioeconomic* program.

First, the production of all instruments of war, *not only of war itself,* should be prohibited completely. It is utterly absurd (and also hypocritical) to continue growing tobacco if, avowedly, no one intends to smoke. The nations which are so developed as to be the main producers of armaments should be able to reach a consensus over this prohibition without any difficulty if, as they claim, they also possess the wisdom to lead mankind. Discontinuing the production of all instruments of war will not only do away at least with the mass killings by ingenious weapons but will also release some tremendous productive forces for international aid without lowering the standard of living in the corresponding countries.

Second, through the use of these productive forces as well as by additional well-planned and sincerely intended measures, the underdeveloped nations must be aided to arrive as quickly as possible at a good (not luxurious) life. Both ends of the spectrum must effectively participate in the efforts required by this transformation and accept the necessity of a radical change in their polarized outlooks on life. 27

Third, mankind should gradually lower its population to a level that could be adequately fed only by organic agriculture. 28 Naturally, the nations now experiencing a very high demographic growth will have to strive hard for the most rapid possible results in that direction.

Fourth, until either the direct use of solar energy becomes a general convenience or controlled fusion is achieved, all waste of energy —by overheating, overcooling, overspeeding, overlighting, etc.— should be carefully avoided, and if necessary, strictly regulated.

Fifth, we must cure ourselves of the morbid craving for extravagant gadgetry, splendidly illustrated by such a contradictory item as the golf cart, and for such mammoth splendors as *two-garage* cars. Once we do so, manufacturers will have to stop manufacturing such "commodities."

Sixth, we must also get rid of fashion, of "that disease of the human mind," as Abbot Fernando Galliani characterized it in his celebrated *Della moneta* (1750). It is indeed a disease of the mind to throw away a coat or a piece of furniture while it can still perform its specific service. To get a "new" car every year and to refashion the house every other is a bioeconomic crime. Other writers have already proposed that goods be manufactured in such a way as to be more durable [e.g., 43, p. 146]. But it is even more important that consumers should reeducate themselves to despise fashion. Manufacturers will then have to focus on durability.

Seventh, and closely related to the preceding point, is the necessity that durable goods be made still more durable by being designed so as to be repairable. (To put it in a plastic analogy, in many cases nowadays, we have to throw away a pair of shoes merely because one lace has broken.)

Eighth, in a compelling harmony with all the above thoughts we should cure ourselves of what I have been calling "the circumdrome of the shaving machine," which is to shave oneself faster so as to have more time to work on a machine that shaves faster so as to have more time to work on a machine that shaves still faster, and so on *ad infinitum.* This change will call for a great deal of recanting on the part of all those professions which have lured man into this empty infinite regress. We must come to realize that an important prerequisite for a good life is a substantial amount of leisure spent in an intelligent manner.

Considered on paper, in the abstract, the foregoing recommendations would on the whole seem reasonable to anyone willing to examine the logic on which they rest. But one thought has persisted in my mind ever since I became interested in the entropic nature of the economic process. Will mankind listen to any program that implies a constriction of its addiction to exosomatic comfort? Perhaps the destiny of man is to have a short but fiery, exciting, and extravagant life rather than a long, uneventful, and vegetative existence. Let other species –the amoebas, for example– which have no spiritual ambitions inherit an earth still bathed in plenty of sunshine.

Notes

1. A specific suggestion implying entropy bootlegging is Harry Johnson's: it envisages the possibility of reconstituting the stores of coal and oil "with enough ingenuity" [49, p. 8]. And if he means with enough energy as well, why should one wish to lose a great part of that energy through the transformation?
2. How incredibly resilient is the myth of energy breeding is evidenced by the very recent statement of Roger Revelle [70, p. 169] that "farming can be thought of as a kind of breeder reactor in which much more energy is produced than consumed." Ignorance of the main laws governing energy is widespread indeed.
3. Marxist economists also are part of this chorus. A Romanian review of [32], for example, objected that we have barely scratched the surface of the earth.
4. To recall the famous old French quatrain: "Seigneur de La Palice / fell in the battle for Pavia. / A quarter of an hour before his death / he was still alive." (My translation.) See Grand *Dictionnaire Universel du XIX~ Siecle,* vol. 10, p. 179.
5. Even some natural scientists, e.g., [1], have taken this position. Curiously, the historical fact that some civilizations were unable "to think up something" is brushed aside with the remark that they were "relatively isolated" [13, p. 6]. But is not mankind, too, a community completely isolated from any external cultural diffusion and one, also, which is unable to migrate?
6. Similar arguments can be found in [4, pp. 338f; 59, p. 102; 74, p. 45]. Interestingly, Kaysen [51, p. 661] and Solow [74, p. 43], while recognizing the finitude of mankind's entropic dowry, pooh-pooh the fact because it does not "lead to any very interesting conclusions." Economists, of all students, should know that the finite, not the infinite, poses extremely interesting questions. The present paper hopes to offer proof of this.
7. Even in this most cited case, substitution has not been as successful in every direction as we have generally believed. Recently, it has been discovered that aluminum electrical cables constitute fire hazards.
8. The pearl on this issue, however, is supplied by Maddox [59, p. 104]: "Just as prosperity in countries now advanced has been accompanied by an actual decrease in the consumption of bread, so it is to be expected that affluence will make societies less dependent on metals such as steel."
9. The point refers to the addition of capital (measured in *money terms*) and labor (measured in *workers employed*) as well as the computation of net output (by subtraction) from physical gross output [3, pp. 167f].
10. For these distinctions, see [27, pp. 512-519; 30, p. 4; 32, pp. 223-225].
11. See the dialogue between Preston Cloud and Roger Revelle quoted in [66, p. 416]. The same refrain runs through Maddox's complaint against those who point out mankind's limitations [59, pp. vi, 138, 280]. In relation to Maddox's chapter, "Manmade Men," see [32, pp. 348-359].
12. Joseph J. Spengler, a recognized authority in this broad domain, tells me that indeed he knows of no one who may have made the observation. For some very penetrating discussions of Malthus and of the present population pressure, see [76; 77]
13. The substance of the argument of The Limits beyond that of Mill's is borrowed from Boulding and Daly [8; 9; 20; 21].
14. In International Encyclopedia of the Social Sciences, for example, the point is mentioned only in passing.
15. Obviously, any increase in *si* will generally result in a decrease of *L* and of *n.* Also, the carrying capacity in any year may be increased by a greater use of terrestrial resources. These elementary points should be retained for further use ....
16. The point recalls Boulding's idea that the inflow from nature into the economic process, which he calls "throughput," is "something to be minimized rather than maximized" and that we should pass from an economy of flow to one of stock [8, pp. 9f; 9, pp. 359f]. The idea is more striking than enlightening. True, economists suffer from a flow complex [29; 55; 88]; also, they have little realized that the proper analytical description of a process must include *both flows and funds* [30; 32, pp. 219f, 228-234]. Entrepreneurs, as far as Boulding's idea is concerned, have at all times aimed at minimizing the flow necessary to maintain their capital funds. If the present inflow from nature is incommensurate with the safety of our species, it is only because the population is too large and part of it enjoys excessive comfort. Economic decisions will always forcibly involve both flows and stocks. Is it not true that mankind's problem is to economize *S* (a stock) for as large an amount of life as possible, which implies to minimize *sj* (a flow) for some "good life"?
17. I saw this term used for the first time in a letter from Jiri Zeman.
18. The practice of slavery, in the past, and the possible procurement, in the future, of organs for transplant are phenomena akin to the exosomatic evolution.
19. A fact greatly misunderstood: Ricardian land has economic value for the same reason as a fisherman's

net. Ricardian land catches the most valuable energy, roughly in proportion to its total size [27, p. 508; 32, p. 232].
20. The figures used in this section have been calculated from the data of Daniels [22] and Hubbert [46]. Such data, especially those about reserves, vary from author to author but not to the extent that really matters. However, the assertion that "the vast oil shales which are to be found all over the world [would last] for no less than 40,000 years" [59, p. 99] is sheer fantasy.
21. In an answer to critics (*American Scientist* 58, no. 6, p. 610), the same authors prove, again linearly, that the agro-industrial complexes of the grand plan could easily feed such a population.
22. For a recent discussion of the social impact of industrial growth, in general, and of the social problems growing out of a large-scale use of nuclear energy, in particular, see [78], a monograph by Harold and Margaret Sprout, pioneers in this field.
23. One percent only of the deuterium in the oceans would provide 10^8 Q through that reaction, an amount amply sufficient for some hundred millions of years of very high industrial comfort. The reaction deuterium-tritium stands a better chance of success because it requires a lower temperature. But since it involves lithium 6, which exists in small supply, it would yield only about 200 Q in all.
24. It should be of interest to know that during World War II in Sweden, for one, automobiles were driven with the poor gas obtained by heating charcoal with kindlings in a container serving as a tank!
25. [Editors' note: Georgescu-Roegen's more recent writings are less sanguine about the prospects for direct use of solar energy. See his "Energy Analysis and Economic Valuation," Southern Economic Journal, April 1979.]
26. One necessary qualification: even the use of solar energy may disturb the climate ff the energy is released in another place than where collected. The same is true for a difference in time, but this case is unlikely to have any practical importance.
27. At the Dai Dong Conference (Stockholm, 1972), I suggested the adoption of a measure which seems to me to be applicable with much less difficulty than dealing with installations of all sorts. My suggestion, instead, was to allow people to move freely from any country to any other country whatsover. Its reception was less than lukewarm. See [2, p. 72].
28. To avoid any misinterpretation, I should add that the present fad for organic foods has nothing to do with this proposal ....

References

[1] Abelson, Philip H. "Limits to Growth." *Science,* 17 March 1972, p. 1197.
[2] Artin, Tom. *Earth Talk: Independent Voices on the Environment.* New York: Grossman, 1973.
[3] Barnett, Harold J., and Chandler Morse. *Scarcity and Growth.* Baltimore: Johns Hopkins University Press, 1963.
[4] Beckerman, Wilfred. "Economists, Scientists, and Environmental Catastrophe." *Oxford Economic Papers* (November 1972), 327-344.
[5] Blin-Stoyle, R. J. "The End of Mechanistic Philosophy and the Rise of Field Physics." In *Turning Points in Physics,* edited by R. J. Blin-Stoyle et al. Amsterdam: North-Holland, 1959, pp. 5-29.
[6] "A Blueprint for Survival." *The Ecologist* (January 1972), 1-43.
[7] Bormann, F. H. "Unlimited Growth: Growing, Growing, Gone?" *BioScience* (December 1972), 706-709.
[8] Boulding, Kenneth. "The Economics of the Coming Spaceship Earth." In *Environmental Quality in a Growing Economy,* edited by Henry Jarrett. Baltimore: Johns Hopkins University Press, 1966, pp. 3-14.
[9] Boulding, Kenneth. "Environment and Economics.' In [66], pp. 359-367.
[10] Bray, Jeremy. *The Politics of the Environment,* Fabian Tract 412. London: Fabian Society, 1972.
[11] Bridgman, P. W. "Statistical Mechanics and the Second Law of Thermodynamics." In *Reflections of a Physicist,* 2d ed. New York: Philosophical Library, 1955, pp. 236-268.
[12] Brown, Harrison. "Human Materials Production as a Process in the Biosphere." *Scientific American* (September 1970), 195-208.
[13] Brown, Lester R., and Gail Finsterbusch. "Man, Food and Environment." In [66], pp. 53-69.
[14] Cannon, James. "Steel: The Recydable Material." *Environment* (November 1973), 11-20.
[15] Cloud, Preston, ed. *Resources and Man.* San Francisco: W. H. Freeman, 1969.
[16] Cloud, Preston. "Resources, Population, and Quality of Life.' In *Is There an Optimum Level of Population?,* edited by S. F. Singer. New York: McGrawHill, 1971, pp. 8-31.
[17] Cloud, Preston. "Mineral Resources in Fact and Fancy." In [66], pp. 7188.
[18] Commoner, Barry. *The Closing Circle.* New York: Knopf, 1971.
[19] Culbertson, John M. *Economic Development: An Ecological Approach.* New York: Knopf, 1971.
[20] Daly, Herman E. "Toward a Stationary-State Economy. " In *Patient Earth,* edited by J. Harte and R. Socolow. New York: Holt, Rinehart and Winston, 1971, pp. 226-244.
[21] Daly, Herman E. *The Stationary-State Economy.* Distinguished Lecture Series no. 2, Department of Economics, University of Alabama, 1971.
[22] Daniels, Fartington. *Direct Use of the Sun's Energy.* New Haven: Yale University Press, 1964.
[23] Einstein, Albert, and Leopold Infeld. *The Evolution of Physics.* New York: Simon and Schuster, 1938.

[24] "The Fragile Climate of Spaceship Earth." *Intellectual Digest* (March 1972), 78-80.
[25] Georgescu-Roegen, Nicholas. "The Theory of Choice and the Constancy of Economic Laws." *Quarterly Journal of Economics* (February 1950), 125-138. Reprinted in [29], pp. 171-183.
[26] Georgescu-Roegen, Nicholas. "Toward a Partial Redirection of Econometrics," Part III. *Review of Economics and Statistics* 34 (August 1952), 206211.
[27] Georgescu-Roegen, Nicholas. "Process in Farming versus Process in Manufacturing: A Problem of Balanced Development." In *Economic Problems of Agriculture in Industrial Societies,* edited by Ugo Papi and Charles Nunn. London: Macmillan; New York: St. Martin's Press, 1969, pp. 497-528.
[28] Georgescu-Roegen, Nicholas. "Further Thoughts on Corrado Gini's *Dellusioni dell' econometria.*" *Metron* 25, no. 104 (1966), 265--279.
[29] Georgescu-Roegen, Nicholas. *Analytical Economics: Issues and Problems.* Cambridge: Harvard University Press, 1966.
[30] Georgescu-Roegen, Nicholas. "The Economics of Production." *American Economic Review* 40 (May 1970), 1-9.
[31] Georgescu-Roegen, Nicholas. "The Entropy Law and the Economic Problem." Distinguished Lecture Series no. 1, Department of Economics, University of Alabama, 1971. Reprinted in this volume.
[32] Georgescu-Roegen, Nicholas. *The Entropy Law and the Economic Process.* Cambridge: Harvard University Press, 1971.
[33] Georgescu-Roegen, Nicholas. "Process Analysis and the Neoclassical Theory of Production." *American Journal of Agricultural Economics* 54 (May 1972), 279-294.
[34] Gillette, Robert. "The Limits to Growth: Hard Sell for a Computer View of Doomsday." *Science,* 10 March 1972, pp. 1088-1092.
[35] Gillette, Robert. "Nuclear Safety: Damaged Fuel Ignites a New Debate in AEC. " *Science,* 28 July 1972, pp. 330-331.
[36] Gillette, Robert. "Reactor Safety: AEC Concedes Some Points to Its Critics." *Science,* 3 November 1972, pp. 482-484.
[37] Glaser, Peter E. "Power from the Sun: Its Future." *Science,* 22 November 1968, pp. 857-861.
[38] Goeller, H. E. "The Ultimate Mineral Resource Situation." *Proceedings of the National Academy of Science,* USA (October 1972), 2991-2992.
[39] Gofman, John W. "Time for a Moratorium." *Environmental Action* (November 1972), 11-15.
[40] Haar, D. ter. "The Quantum Nature of Matter and Radiation." In *Turning Points in Physics,* edited by R. J. Blin-Stoyle et al. (Amsterdam: North-Holland, 1959), pp. 30--44.
[41] Hammond, Allen L. "Solar Energy: A Feasible Source of Power?" *Science,* 14 May 1971, p. 660.
[42] Hardin, Garrett. "The Tragedy of the Commons." *Science,* 13 December 1968, pp. 1234-1248.
[43] Hibbard, Walter R., Jr. "Mineral Resources: Challenge or Threat?" *Science,* 12 April 1968, pp. 143-145.
[44] Holdren, John, and Philip Herera. *Energy.* San Francisco: Sierra Club, 1971.
[45] Hotelling, Harold. "The Economics of Exhaustible Resources." *Journal of Political Economy* (March-April 1931), 137-175.
[46] Hubbert, M. King. "Energy Resources." In [15], pp. 157-242.
[47] Istock, Conrad A. "Modem Environmental Deterioration as a Natural Process." *International Journal of Environmental Studies* (1971), 151-155.
[48] Jevons, W. Stanley. *The Theory of Political Economy,* 2d ed. London: Macmillan, 1879.
[49] Johnson, Harry G. *Man and His Environment.* London: The British-North American Committee, 1973.
[50] Katchalsky, A., and Peter F. Curran. *Nonequilibrium Thermodynamics in Biophysics.* Cambridge, Mass.: Harvard University Press, 1965.
[51] Kaysen, Carl. "The Computer That Printed Out W*O*L*F*." *Foreign Affairs* (July 1972), 660-668.
[52] Kneese, Allen, and Ronald Ridker. "Predicament of Mankind." *Washington Post,* 2 March 1972.
[53] Laplace, Pierre Simon de. *A Philosophical Essay on Probability.* New York: Wiley, 1902.
[54] Leontief, Wassily. "Theoretical Assumptions and Nonobservable Facts." *American Economic Review* (March 1971), 1-7.
[55] "Limits to Misconception." *The Economist,* 11 March 1972, pp. 20-22.
[56] Lovering, Thomas S. "Mineral Resources from the Land." In [15], pp. 109-134.
[57] MacDonald, Gordon J. F. "Pollution, Weather and Climate." In [66], pp. 326-336.
[58] Maddox, John. "Raw Materials and the Price Mechanism." *Nature,* 14 April 1972, pp. 331-334.
[59] Maddox, John. *The Doomsday Syndrome.* New York: McGraw-Hill, 1972.
[60] Marshall, Alfred. *Principles of Economics,* 8th ed. London: Macmillan, 1920.
[61] Marx, Karl. *Capital.* 3 vols. Chicago: Charles H. Kerr, 1906-1933.
[62] Meadows, Donella H., et al. *The Limits to Growth.* New York: Universe Books, 1972.
[63] Metz, William D. "Fusion: Princeton Tokamak Proves a Principle." *Science,* 22 December 1972, p. 1274B.
[64] Mill, John Stuart. *Principles of Political Economy.* In Collected Works, edited by J. M. Robson, vols. 2-3. Toronto: University of Toronto Press, 1965.

[65] Mishan, E. J. *Technology and Growth: The Price We Pay.* New York: Praeger, 1970.
[66] Murdoch, William W., ed. *Environment: Resources, Pollution and Society.* Stamford, Conn.: Sinauer, 1971.
[67] Novick, Sheldon. "Nuclear Breeders." *Environment* (July-August 1974), 6-15.
[68] Pigou, A. C. *The Economics of Stationary States.* London: Macmillan, 1935.
[69] *Report on Limits to Growth.* Mimeographed. A Study of the Staff of the International Bank for Reconstruction and Development, Washington, D.C., 1972.
[70] Revelle, Roger. "Food and Population." *Scientific American* (September 1974), 161-170.
[71] Schrodinger, Erwin. *What Is Life?* Cambridge, England: The University Press, 1944.
[72] Silk, Leonard. "On the Imminence of Disaster" *New York Times,* 14 March 1972.
[73] Solo, Robert A. "Arithmomorphism and Entropy." *Economic Development and Cultural Change* (April 1974), 510-517.
[74] Solow, Robert M. "Is the End of the World at Hand?" *Challenge* (MarchApril 1973), 39-50.
[75] Solow, Robert M. "The Economics of Resources or the Resources of Economics." Richard T. Ely Lecture, *American Economic Review* (May 1974), 1-14.
[76] Spengler, Joseph J. "Was Malthus Right?" *Southern Economic Journal* (July 1966), 17--34.
[77] Spengler, Joseph J. "Homosphere, Seen and Unseen: Retreat from Atomism. " *Proceedings of the Nineteenth Southern Water Resources and Pollution Control Conference,* 1970, pp. 7-16.
[78] Sprout, Harold, and Margaret Sprout. *Multiple Vulnerabilities.* Mimeographed. Research Monograph No. 40, Center of International Studies, Princeton University, 1974.
[79] Summers, Claude M. "The Conversion of Energy." *Scientific American* (September 1971), 149-160.
[80] Wallich, Henry C. "How to Live with Economic Growth." *Fortune* (October 1972), 115-122.
[81] Weinberg, Alvin M. "Breeder Reactors." *Scientific American* (January 1960), 82-94.
[82] Weinberg, Alvin M. "Social Institutions and Nuclear Energy." *Science,* 7 July 1972, pp. 27-34.
[83] Weinberg, Alvin M., and R. Philip Hammond. "Limits to the Use of Energy." *American Scientist* (July-August 1970), 412--418.