Technology Assessment: The Case of the Direct Use of Solar Energy

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I

The crucial role played by natural resources is plainly written on the face of the history of our species. The banners hardly let the true motifs be known, but all important wars and military expeditions have aimed at the control, if not the direct possession, of natural resources. The point is more obvious nowadays than ever. But for a more instructive case one should think of The Great Migration, which lasted one full millenium and transformed Europe from top to bottom. It was triggered by the exhaustion of the soil of Central Asia caused by the sheep grazing and overgrazing since times immemorial. Later, toward the end of the sixteenth century, the industrial activity of the period that may be properly called the Wood Age was also fighting for its life because of another fateful scarcity. In Western Europe, but especially in England, forests in increasing number had fallen victims to man's hatchet. Wood was then the only source of clean *fire power* whether for smelting metals, melting glass, baking ceramics and bricks, or firing limestone. During the reign of Elizabeth I restrictive measures against cutting were introduced in England as well as in some parts of the Continent. The "wood crisis" was avoided and the door for a new and more powerful technology was also opened only because of a "miraculous" historical event: the invention of the steam engine.

The old, legendary Prometheus taught man to make fire. It was the first momentous technological event in mankind's exosomatic evolution. For fire is a process that enables us *to obtain fire power from matter.* Moreover—a point that must be well marked—fire is a *chain process.* Starting with just a little flame we can burn an entire forest, nay, all the existing forests. Fire would stop *only* after all available combustible matter is burned out.

To the modern Prometheus—Thomas Savery or, rather, Thomas Newcomen—we owe the second momentous technological innovation. This innovation enabled us to *transform fire power into motor power.* And like fire, the steam engine also leads to a chain process. With just the quantity of coal necessary to operate one steam engine we can mine a far greater quantity of coal. That is not all. With the excess we can operate many other steam engines with the help of which we can mine not only still more coal but also ores of all kinds. We can thus do many other things with the fire power of the fossil fuels, the most important fact being that we can in the end produce many more steam engines than we had at the beginning. The chain would end *only* when all the accessible fossil fuels have been used up. Toward such a situation we are now heading. Our present predicament is analogous in all respects to the "wood crisis" of the sixteenth century.

It was, however, only after the 1973-1974 oil embargo that almost everybody began speaking of the "energy crisis" and being concerned in various degrees over its possibly fateful consequences. Only economists as a whole continue to ignore the crucial economic role of natural resources, as well as the entropic problem confronting mankind's present economy—in some

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nations because they are "overdeveloped," in others because they are underdeveloped and in great need. Officials of the most influential economic associations miss no occasion to ward off any impression that "official" economics might be interested in problems related to the scarcity of natural resources. Because the Program Committee was "very selective"—one official communication explains—no invited paper for the 1977 Tokyo World Congress of the International Economic Association dealt with the problems raised by the limitations of natural resources, although the general topic of that Congress was "Economic Growth and Resources." Nothing need be added to Mogens Boserup's final verdict of the Congress's *modus operandi* [1977]:

> "There was a remarkable degree of consensus in turning down, or rather ignoring, all the 'doomsday' attitudes and opinions on natural resources. And even apart from that particular issue, there was an almost complete absence of sharp confrontation of opinions.
> As we know, a gathering of economists which fails to produce disagreement on essential issues is a rare occurrence—and even a scandal, some would say .... A question [thus] immediately comes to my mind: Why do economists agree so largely on the issue of natural resources, not only at an I.E.A. meeting in Tokyo, but in the profession as a whole?"

A still more recent communication from another official source explicably denies that even technology assessment could constitute an accepted preoccupation for a member of the established profession.

I beg to utterly differ. First, scarcity is the very element about which the economic process turns and spins.[1] Second, the economic choice at any level looks for what is "better" in some sort of way that promotes individual or social welfare. I owe, therefore, no apology whatsoever for my endeavors over the years to bring home the point that natural resources matter in the economic process and matter substantially [Georgescu-Roegen, 1960, 1966, 1971, 1976b], or for dealing in this paper with the economically crucial issue of technology assessment.

II

An additional and necessary clarification. While I have argued that the economic process is entropic in every one of its *material* fibers, that it endures on speeding up the entropic degradation of the environment, and that man's exosomatic evolution is responsible for the most important facts of socio-political life, I have also insisted that it is senseless to think of representing that process by a system (however vast) of thermodynamic equations. Nor does it make any sense to reduce economic value to the net or to the gross *energy* necessary to produce an object. The contrary opinion of some prominent thermodynamicists notwithstanding [Odum, 1973 and Slesser, 1975], economics cannot be reduced to thermodynamics.

Two are the reasons for this. The first is that in the economic process not only the flow elements count. They represent only those elements that undergo transformation—say, the flour that is transformed into bread. The economic process also involves fund elements, i.e., agents that perform the transformation of the flow elements. And the point we must bear in mind is that no material part of these agents goes into the output elements. The agents only provide services. True, they wear out, which is the reason why the flow elements are necessary. In a broad yet instructive stroke, the *raison d'être* of the economic process is to maintain in good functioning order not only our bodies—our endosomatic organs—but also our material instruments—our detachable limbs, i.e., our exosomatic organs [Georgescu-Roegen, 1971, Chapter ix; 1976c, 1977b]. Unless the agents can produce the flows that would keep them in good functioning order, the material scaffold of the economic process will either collapse or resort to another technology (a point to be retained for further

[1] The point is worth making in view of the fact that Solow [1973] argued that no interesting conclusions can be derived from the finitude of mankind's entropic dowry and, hence, one need not be preoccupied with such a problem. Economics should then not study how an individual deals with his finite budget either.

reference).

The second reason involves an omission of physical sciences, specifically, of thermodynamics. Although thermodynamics is the only branch of theoretical physics that has ever gone beyond the mechanistic interpretation of actuality, it stopped short of taking into account all macro-elements of the entropic transformation. We may recall that "thermodynamics" is a term coined by Lord Kelvin. But the first label of that science was "energetics" suggested by William Macquorn Rankine. In retrospect, Rankine's proposal seems the more fitting by far. Indeed, thermodynamics, although no longer a science of heat dynamics, pays attention only to what happens to energy. For example, thermodynamics considers only what happens to the heat that causes a piston to move inside a cylinder, but it completely ignores what happens to the piston, to the cylinder, or to any other material part of that apparatus.

This omission may explain, I believe, the fact that not only the uninitiated but also the literati speak only of the energy crisis. In fact, the literati from all fields swear by what one may call the energetic dogma [Georgescu-Roegen 1979a, 1978]. This dogma is most clearly expressed by Kenneth Boulding's [1966] assertion that "There is, fortunately, no law of increasing material entropy." Or, as we read in one of the keenest essays on mankind's ecological predicament [Brown, 1957], "All we need to do is to add sufficient energy to the system and we can obtain whatever material we desire."

But the simplest of the everyday facts—the wearing out of tires, motors, shoe soles, etc., as well as the washing away of the topsoil by rain, show that matter also becomes dissipated and ultimately can no longer be available for our particular purposes. So, from my earliest attemps of describing the entropic nature of the economic problem, I spoke of the inevitable entropic degradation of both energy *and* matter [Georgescu-Roegen, 1966, p. 94; 1971, p. 278]. But the general adherence to the energetic dogma prompted me to supply my own position with a more solid foundation. Step-by-step, I came to formulate two new thermodynamic laws that pertain to *matter in bulk*[2] [Georgescu-Roegen, 1976a, 1976c, 1977a, 1977b]. They are:

A. No mechanical work can be performed without the use of matter in bulk.

B. No closed system—i.e., no system that can exchange only energy with the outside—can perform mechanical work at a constant rate indefinitely.

Law A is symmetrical to the First Law of Thermodynamics, which denies the possibility of motion without an expenditure of energy. Law B is symmetrical to the Entropy Law, which denies the possibility of obtaining mechanical work indefinitely from a given initial amount of energy.[3]

III

The fact that matter matters in the way just described bears upon several important economic issues. First, a corollary of Law B is that complete recycling is impossible, for otherwise a closed system could perform mechanical work at a steady rate indefinitely by continuously recycling its initial endowment of matter. The second conclusion is that economic choice goes far beyond physico-chemical calculations, since there is no general law of conversion of energy into matter in bulk or even conversely. Third, no criterion involving energy alone—be it net or gross energy—is suitable for a corect technology assessment.[4] In assessing a technology (in the sense this term will be defined presently), we must take into account the wearing out of its material scaffold. To this last problem I now

[2] To refer to a law pertaining to matter in bulk as a thermodynamic law seems improper. But a precedent already exists because of the very use of "thermodynamics" to denote the science of energy in any macroform.

[3] In my previous writings, I propose to refer to Law B as the Fourth Law of Thermodynamics.

[4] The net energy criterion is in fact the official criterion for ERDA [1975].

turn and shall use the topical case of the direct use of solar energy as an illustration of my argument.

First, by a *feasible recipe* let us denote any known procedure for manipulating the material environment for some given purpose. For an instructive clarification, one should note that quarrying the moon is now a feasible recipe. Any such recipe is described by its specific flow and fund coordinates [Georgescu-Roegen, 1971, Chapter ix; 1976c, 1977a]. Provided these elements are forthcoming, the corresponding recipe can be carried out regardless of any other considerations.

Next, by "technology" let us denote a package of feasible recipes containing at least one such recipe for every commodity necessary for the maintenance of the funds involved. That is, a technology consists of a general system by which environmental matter-energy is used for various purposes. To be sure, no technology can produce its own environmental source of support. The technology of the Wood Age, for example, was limited by the available forests.

However, a technology may not be viable even if its particular source of support exists in ample supply. Coal deposits were in ample supply before the invention of the steam engine; yet the recipes of that time for mining coal, *although feasible*, were not capable of making coal the basis of a viable technology. A *viable* technology is one that, just like a viable biological species, is capable of reproducing itself. Undoubtedly, every viable technology, just like any viable species, is the off-spring of some previous technology. The first bronze hammer, for an unadorned example, was produced by some stone hammers. However, from that moment on, all bronze hammers were hammered only by bronze hammers. And to focus the argument on a solar technology based on the presently known recipes, *such a technology if it is to be viable must be capable of reproducing itself after being set up by the technology now in use.* The feasibility of known recipes is not sufficient for the viability of a technology.

IV

On these thoughts, I may now turn to examine the viability of a technology based on any of the presently known feasible recipes for the direct use of solar energy. We may safely include under the term "collectors" any of the devises used by these recipes.

The matrix of Table 1 represents in some broad aggregative lines the flows of a technology based *only* on the direct use of solar energy.[5] Process P_1 collects solar energy, SE,, with the aid of some collectors, C, and some other capital equipment, K. Process P_2 produces collectors with the aid of some solar energy and some capital equipment. Finally, process P_3 produces capital equipment with the aid of some solar energy.[6]

For that technology to be viable, we must have:[7]

$$x_{11} - x_{12} - x_{13} > 0, - x_{31} - x_{32} + x_{33} > 0, \quad (1)$$

with the obvious equality,

$$x_{21} = x_{22}. \quad (2)$$

TABLE 1

THE FLOW MATRIX OF A TECHNOLOGY BASED ON THE DIRECT USE OF SOLAR ENERGY

	(P_1)	(P_2)	(P_3)
SE	x_{11}	$-x_{12}$	$-x_{13}$
C	$-x_{21}$	x_{22}	*
K	$-x_{31}$	$-x_{32}$	x_{33}

[5] To save space, the fund elements—the labor power, the capital equipment, and the Ricardian land—are omitted. But we should not lose sight of their existence.

[6] This process is supposed to be completely integrated so that it starts with mining the necessary ores.

[7] Conditions (1) and (2) may be easily transformed into the well-known conditions for the feasibility of a linear input-output system [Georgescu-Roegen, 1966, Chapter 9]. But without the assumption of linearity these conditions are necessary but not sufficient. The present analysis may thus proceed best in the direct manner.

The fact that, in spite of the present din about solar energy, not even experimental pilot plants of the sort described by P_2 and P_3 have been set up by one of the various R & D agencies working in this direction is sufficient proof that a technology based on collectors is not viable.[8] For, although one might argue that it is only because of the prevailing prices that such processes are not commercially used, the absence of experimental pilot plants proves that inequalities (1) cannot be true.

The truth is that any present recipe for the direct use of solar energy is a "parasite," as it were, of the current technology, based mainly on fossil fuels. All the necessary equipment (including the collectors) are produced by recipes based on sources of energy other than the sun's [Georgescu-Roegen, 1979a, 1978]. And it goes without saying that, like all parasites, any solar technology based on the present feasible recipes would subsist only as long as its "host" survives.

That is not all. As I propose to argue now, from all we can say, any presently feasible recipe for the direct use of solar energy causes a deficit in the general balance of energy; that is, any such recipe indirectly consumes more of some other form(s) of energy than it produces directly.

In passing now to examine the three possible analytical cases, let us weaken the second condition (1) to:

$$x_{33} = x_{31} + x_{32}, \tag{1a}$$

a change that actually strengthens the argument to be outlined now. The non-viability of the technology under consideration then boils down to the inequality:

$$x_{11} < x_{12} + x_{13}. \tag{3}$$

[8] Let us not ignore the point that (in case one has in view the aluminum collectors, for example) P_3 must include the mining of bauxite, its transportation, as well as the reproduction of the entire plant for extraction and reduction of alumina.

The least favorable case to my contention is that in which:

$$x_{11} > x_{12}, x_{11} - x_{12} < x_{13}. \tag{4}$$

This means that the energy made available by collectors more than suffices for their reproduction. However, the capital equipment has to be reproduced by a process, P_3^*, that uses some other kind of energy, say, fossil fuel energy, *FE*. We must then add to our system still another process, P_4, that produces *FE* with the aid of some capital equipment produced by P_3^*. The corresponding flow matrix is shown in Table 2.

TABLE 2

THE CASE OF COLLECTORS PRODUCED BY SOLAR ENERGY

	(P_1)	(P_2)	(P_3^*)	(P_4)	Net
SE	x_{11}	$-x_{12}$	*	*	$x_{11}-x_{12}$
C	$-x_{22}$	x_{22}	*	*	*
K	$-x_{31}$	$-x_{32}$	y_{33}	$-y_{34}$	*
FE	*	*	$-y_{43}$	y_{44}	*

The net product is:

$$NP = x_{11} - x_{12}, \tag{5}$$

with

$$y_{33} = x_{33} + y_{34}, y_{43} = y_{44}. \tag{6}$$

Since $y_{33} > x_{33}$, we should expect that $y_{43} > x_{13}$.[9] This means that $y_{44} > x_{13}$, which in view

[9] The energy y_{43} need not be in the same ratio to y_{33} as x_{13} is to x_{33}. Because of its higher intensity, the energy obtained from fossil fuels may be more efficient than the collected solar energy. In principle, the possibility of $y_{43} < x_{13}$ cannot be excluded, but it is highly unlikely. However, only actual data could decide the issue. I take it that the fact that the case of Table 2 does not work in practice is an indirect but sufficient indication that $y_{43} > x_{13}$.

Incidentally, thermodynamic theory can be of no help here, for another omission of thermodynamics is the intensity dimension. If we were to rely only on thermodynamic theory, we ought to be able to send a rocket to the moon by striking a sufficinet number of matches *one after another*.

of the second inequality (4) proves that P_1 and P_2 consume more energy, y_{44}, than they produce together, $x_{11} - x_{12}$.

A somewhat symmetrical case is that in which

$$x_{11} > y_{13}, x_{11} - y_{13} < x_{12}, \tag{7}$$

where y_{13} is the necessary solar energy to produce an amount of capital y_{33} that now must also suffice to support P_4 (Table 3).[10] Obviously, P_4 is needed to supply P_2 with the necessary energy. But since

$$y_{44} = x_{12} + y_{43} > x_{12} > x_{11} - y_{13}, \tag{8}$$

no additional consideration is needed to prove that the system entails a deficit of energy.

TABLE 3

THE CASE OF CAPITAL EQUIPMENT PRODUCED BY SOLAR ENERGY

	(P_1)	(P_2)	(P_3^*)	(P_4)	Net
SE	x_{11}	*	$-y_{13}$	*	$x_{11}-y_{13}$
C	$-x_{22}$	x_{22}	*	*	*
K	$-x_{31}$	$-x_{32}$	y_{33}	$-y_{34}$	*
FE	*	$-x_{12}$	$-y_{43}$	y_{44}	*

The remaining case is the only one that truly reflects the actual situation. The energy collected by P_1 does not suffice to operate any of the other necessary supporting process. This means that

$$x_{11} < x_{12}, \; x_{11} < x_{13}. \tag{9}$$

The case corresponds to Table 4, from which it follows that

$$y_{44} = x_{12} + y_{43} > x_{12} > x_{11}. \tag{10}$$

This means that in this case, too, obtaining energy directly from solar radiation implies a greater expenditure, y_{44}, of other forms of energy. Denis Hayes, one of the most devoted students of solar energy, recently claimed that [1978] "we can use solar energy now [because] the technology is here." Several feasible recipes for harnessing solar energy are indeed here; but a viable solar technology not yet. The reason is simple. The intensity of solar radiation reaching the ground level being extremely weak, a large material scaffold is needed for its collection. It is highly plausible that the difficulty may not be superable at all, given that the intensity of solar radiation is a cosmological constant beyond our control. Only recipes for capturing solar radiation in outer space, where its intensity is greater by several orders of magnitude, may hold some hope. But they have not yet been tried out.

TABLE 4

THE ACTUAL CASE OF SOLAR RECIPES

	(P_1)	(P_2)	(P_3^*)	(P_4)	Net
SE	x_{11}	*	*	*	x_{11}
C	$-x_{22}$	x_{22}	*	*	*
K	$-x_{31}$	$-x_{32}$	y_{33}	y_{34}	*
FE	*	$-x_{12}$	$-y_{43}$	y_{44}	*

In closing this paper, in which I have endeavored to examine some consequence of the fact that matter matters, too, one general point is in order. It is not only the harnessing of solar energy that needs a substantial amount of matter. The same is true for fission reactors. And, who can say at this time how big a fusion reactor might be? If the control of that reaction is ever achieved, we may discover that the size of a fusion reactor is comparable to that of Manhattan. After all, fusion is a reaction analogous to that which goes on in the sun itself. By contrast, the fossil fuels are the most advantageous by far to use. Coal, gas, and crude oil can be in fact made to burn with the aid of a simple match. The mineralogical bonanza enjoyed by the advanced economies during the past two hundred years or so had two unique advantages: fossil fuels

[10] Let us note that although both (4) and (7) may be true at the same time, it does not mean that (1) is true.

have not only been easily accessible, but they are easily used as well. The intensity of their energy is neither too weak, nor too strong.[11]

[11] Elton Hinshaw, who read an earlier version, made many useful suggestions.

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