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I. Introduction

Ever since the oil embargo of 1973–74 everyone speaks of the *energy* crisis. And whether we are "optimists" or "pessimists", by now most of us recognize that what will happen in the end to this crisis is not an idle question. Only economists still refuse to see the indissoluble relationship between the scarcity of natural resources and the economic process as a whole. As an excuse we hear, for example, that the limitations of natural resources cannot lead to any interesting conclusions [72, 43], as if scarcity were not the very element around which the economic system turns and spins. But the "official" position is systematically defended by the decision-makers of the most influential economic associations. No invited paper at the Tokyo World Congress of the International Economic Organization dealt with the limitations of natural resources. As explained by an official communication, the Program Committee was "very selective." Most curiously, the general theme of the Congress was "Economic Growth and Resources" and the year was 1977! All the more we should admire Mogens Boserup's candid verdict at the closing session.

> 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.
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> 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? [7].

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A contrasting situation prevails in other circles, where new energy experts in ever increasing numbers now expatiate to their hearts' delight on the issue of accessible sources of energy, more often than not contributing to the confusion of both students and policy makers.

Some writers, however, did not have to wait for the warning spelled out by the oil embargo. Long before it, they re-examined with new insights the old problem of the relation between the supply of accessible natural resources, the size of population, and the well-being of the people. But what is highly significant is that, with practically no exception, these writers also argued that energy is the only necessary support of the economic process. This position is not, therefore, a product of the oil embargo; it represents the result of a genuine intellectual endeavor.

It is natural to refer to the belief that energy alone counts as the "energetic" dogma, even though this meaning is slightly different from those used by physics in the past. At first, "energetics"—a term coined by William Macquorn Rankine—denoted the science we now call "thermodynamics". Subsequently, "energetics" was used to denote a school of thought defended by a few illustrious scientists (such as Wilhelm Ostwald and George Helm in Germany and Pierre Duhem in France) influenced in part by the scientific epistemology of Ernst Mach [45]. Against the idea set forth by Ludwig Boltzmann that the laws of energy are the direct consequences of the laws of Newtonian mechanics applied to the motion of *material* particles, the energetic school maintained that, on the contrary, matter must in the ultimate analysis reduce to the only "substance", energy. The current view that only energy matters for mankind's specific mode of existence is not completely identical with that school's position, but at bottom the two are sufficiently similar to justify using the term "energetics" for its label.

The fierce controversy surrounding the old energetic school represented a purely academic issue at the time. The same is not true for the present energetic dogma. Being the currently dominating dogma, it determines the principles that guide policy makers concerned with the energy shortage and technology assessment. Some of us may think that the validity of these principles also constitute only a purely academic issue. For mankind as a whole, however, it is a truly vital matter.

In this paper, I propose, first, to explain in broad terms the technical reasons why the energetic dogma is wrong, why matter matters, too.[1] Second, I shall use the analytical representation of a multi-process for discussing the general problem of energy analysis. On this basis, I shall show where the

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[1] I may explain that from my first analysis of the entropic nature of the economic process I have maintained that both energy *and* matter irrevocably degrade from available into unavailable forms [29, 75, 93–6; 30, 142, 277–80]. At the time, believing that my thesis was common knowledge at least among natural scientists, I did not go into technical details. But the accentuation of the energetic position after the oil embargo convinced me that my belief was wrong; I then began offering specific arguments in support of my thesis [31–38].

recent claims that energy analysis is the rational basis for economic valuation go wrong. Third, on the basis of the impossibility of reducing matter to energy, I shall show that economic choice is a purely economic matter, not a physico-chemical one. Finally, I shall apply some of these results to the problem of what constitutes a *viable* technology, as distinct from *feasible* recipes. As an application, I shall investigate the viability of a technology based on direct use of solar radiation through the recipes known *at present*.[2] Surprising though it might seem to the current energetic temper, the conclusion of this last probing is that such a technology is not *viable*, that any direct use of solar radiation by any present recipe is a "parasite" of the current technology based on other sources. This result calls for a thorough reorientation of our present approach to technology assessment.

II. The Energetic Dogma

Different writers justify the modern dogma of energetics in different, sometimes in substantially different, ways. For example, one of the earliest propounders, Fred Cottrell [22] argued that all that mankind needs is to obtain *net energy*. The definition of this concept presents no apparent difficulties. If we use, for example, the energy equivalent of one ton of crude oil to extract ten tons of shale oil, a simple arithmetical substraction tells us that the resulting net energy is the equivalent of nine tons of oil. Twenty years later, one of the ablest American ecologists, H. T. Odum [53], revived Cottrell's idea and raised it to the rank of the only criterion of efficiency: the greater the net energy obtained by a process, the more efficient is that process.[3] Because of its simplicity, the principle has since been widely accepted and also defended with even greater force. Indeed, what could be more senseless than to use one ton of oil to obtain less than one ton of oil and nothing else?

However, this very idea prompts one to ask "why not relate efficiency to *net matter*?" Indeed, we use copper in the process of producing copper; hence, we thereby gain some net matter. Whatever we may do, we are faced with new snags. Copper mining also implies a *negative* net energy, whereas any power plant implies numerous *negative* net matters.

Even though Odum is not as explicit on this point as one would wish, we must grant him that net energy must be computed by subtracting from the gross output not only the energy directly used in the process but also the amount of energy necessary to produce or repair all *material* parts worn out by the process (Sec. VI). With this explanation, however, the slip of the energetic bias is showing badly. For without this bias, one may very well propose, by

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[2] Even though another official communication affirms that technology assessment is not an accepted preoccupation for the established profession, I owe no apology whatsoever for dealing with that problem in this paper.

[3] A different approach focuses instead on gross energy (Sec. VI).

symmetry, to reduce everything to net matter, defined as the excess of matter output over the matter necessary to produce the matter and the energy used up. Such a proposal could point out that matter is used in a power plant to produce energy just as in another process energy is used to produce matter. The truth, as we shall see in time, is that neither net energy by itself nor net matter by itself can constitute a general principle of technology assessment (Sec. VIII).

Another mode of justifying energetics in recent times may be traced back to the now classic volume *The Next Hundred Years*, where we read that "All we need do is to add sufficient energy to the system and we can obtain whatever materials we desire" [11, 90, 95, 114]. The energetic gospel in this plain form has been spread by numberless other authors. But Harrison Brown and his associates have also justified it by the axiom that recycling of matter can, in principle, be complete [11, 90–92]. Interesting also is that they immediately added that "fundamentally there is no lower limit to the grade of an ore which can be processed," which obviously is a necessary implication of that axiom.[4]

The few physicists and chemists who have touched this issue also seem to support energetics. For example, Alvin Weinberg, quoted in [32], described energy as "an ultimate raw material" because "energy is convertible into most of the other requirements of life"—which can only consist of matter. Take also Glenn Seaborg, who argued that science will ultimately eliminate all technical inefficiencies so that with an abundant amount of energy we shall be able "to recycle almost any waste, . . . to extract, transport and return to nature when necessary all materials in an acceptable form, in an acceptable amount, and in an acceptable place so that the natural environment will remain natural and will support the continued growth and evolution of all forms of life" [65].

Taken at its face value, this is quite strong energetic position; it comes near to claiming that the whole planet could be maintained intact forever. But an even more stringent expression of the modern energetic dogma is due to Kenneth Boulding [4]: "There is, fortunately, no law of increasing material entropy."[5] This declaration exposes without any shadows the root of that dogma; matter does not count, only energy counts for mankind's economic struggle.

The foregoing variants seem to cover the entire spectrum of the energetic arguments. However, they all lead to one and the same analytical picture of the economic process in its relation to the environment. It is the picture

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[4] Energetics also permeates Brown's position in his earlier volume [10]. But, curiously, both volumes cite facts that go directly against the energetic dogma (see below, Sec. V).

[5] Years after taking this position and yet arguing that a close relation exists between the Entropy Law and the economic process, Boulding [5], turned to arguing that entropy is a "negative potential" and hence is not a concept fit for explaining evolutionary development. But still more recently he came to realize that materials also are vital environmental elements [6].

represented by the multi-process matrix of flows and funds shown in Table I [30].[6] To avoid irrelevant issues, let us divide the economic process only into those consolidated processes and aggregated categories that are relevant for the present argument:

P_1: produces "controlled" energy, *CE*, from energy in situ, *ES*;
P_2: produces "capital" goods, *K*;
P_3: produces "consumer" goods, *C*;
P_4: recycles completely the material wastes, *W*, of all processes into recycled matter, *RM*;
P_5: maintains the population, *H*.

The special features of the foregoing picture must be well marked. First, neither a growing nor a declining economy can provide an acid test for the energetic dogma. Material growth cannot feed on an environmental flow of energy alone,[7] whereas a declining economy may very well need no flow of environmental matter. The test case must therefore be a stationary process, or, with Marx's more felicitous terminology, a reproducible one.

But regardless of the actual system, one point is beyond any doubt ever since Lord Kelvin observed more than one hundred years ago that energy is not lost but only becomes unavailable to us [74, 189; 78, 236–39]. All processes, therefore, necessarily produce dissipated (unavailable) energy, *DE*, which returns to the environment. In the energetic model, however, no matter leaves the economic process; all matter is completely recycled within that process. Thus, no matter has to be brought into the economic process from the environment. The only flows between the economic process and the environment are energy flows, namely, the input flow e_1 and the output flow $d = \Sigma d_i$.

Second, the representation of Table I reflects one elementary aspect of reality that needs unparsimonious emphasis in view of the "flow complex" that seems to dominate modern economic thought [29, 88; 30, 219]. Like all actual processes, the economic process has a material scaffold represented by its fund elements: capital equipment, K_i; people, H_i and H; and Ricardian land, L_i. We can never handle energy without a material lever, a material receptor, or a material transmitter. We ourselves are material structures without which no biological life can exist. In including the material funds (actually, the agents) in the analytical picture, I have assumed—a perfectly fair assump-

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[6] This analytical representation is both simple and safe. It does away with the bewildering flow diagrams used by ecologists and energy analysts (in which funds are ignored), and it avoids the analytical pitfall of "internal flow" that awaits the users of the input-output table [30, 253–62]. Also, the flow-fund model should not be confused with the flow-stock model introduced by Sir John Hicks in the theory of market disequilibriums. The function of the stocks is to accumulate flows and to decumulate themselves into flows. Funds participate in a process but without changing.

[7] Obvious though this point may seem, it calls for some technical justifications, which will be provided later (Sec. III).

tion, I think—that the energetic position does not go so far as to claim that actual processes require no material structures of the kind we recognize side by side with energy at the macro-level.

Third, the output flow of capital, x_{22}, is destined to maintain the capital funds K_i in a reproducible condition; their wear-and-tear is thus compensated for by the maintenance flows x_{2i}. Similarly, the flows x_{i5} maintain the population H "intact". These are the elementary conditions for the (P_i)'s to be reproducible. And since in the case under consideration all flows must be expressed in physical units (calories or moles, for instance), the following equalities must always prevail as an aggregated translation of the conservation laws at the macro-level:

$$\begin{array}{lll} d_1 = e_1 - x_{11}, & d_i = x_{1i} & (i = 2, 3, 4, 5), \\ w_1 = x_{21}, & w_2 = x_{42} - x_{22}, & w_3 = x_{23} + x_{43} - x_{33}, \\ w_4 = x_{44} - x_{24}, & w_5 = x_{25} + x_{35}. & \end{array} \tag{1}$$

Fourth, every recipe (P_i) is assumed to be *feasible*; that is, it can produce its product provided it is supported by the specified funds and is fed the specified inputs. But the feasibility of every recipe (P_i) does not necessarily

Table I. The Economic Process in Relation to the Environment According to the Energetic Dogma

Product	(P_1)	(P_2)	(P_3)	(P_4)	(P_5)
			Flow Coordinates		
CE	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$	$-x_{15}$
K	$-x_{21}$	x_{22}	$-x_{23}$	$-x_{24}$	$-x_{25}$
C	*	*	x_{33}	*	$-x_{35}$
RM	*	$-x_{42}$	$-x_{43}$	x_{44}	*
ES	$-e_1$	*	*	*	*
W	w_1	w_2	w_3	$-w_4$	w_5
DE	d_1	d_2	d_3	d_4	d_5
			Fund Coordinates		
Capital equipment	K_1	K_2	K_3	K_4	K_5
People	H_1	H_2	H_3	H_4	H_5
Ricardian land	L_1	L_2	L_3	L_4	L_5

imply the *viability* of the *technology* represented by all the processes together (an important point to be retained for further reference). The necessary and sufficient conditions for the viability of the technology of our reproducible economic system is given by the inequalities $x_{i5} \geqslant x^0_{i5}$, x^0_{i5} being a minimum determined by the standard of living, and the well-known relations

$$\sum{}' x_{1i} = x_{11}, \qquad \sum{}' x_{2i} = x_{22}, \qquad x_{35} = x_{33}, \qquad \sum{}' x_{4i} = x_{44}, \qquad \sum{}' w_i = w_4, \tag{2}$$

where the prime accent shows that the variable subscript cannot be equal to the fixed one.[8]

III. Perpetual Motion of the Third Kind

Let us now recall that in the thermodynamic terminology established by Ilya Prigogine a system that can exchange only energy with its surroundings is *closed*. The economic process represented by Table I is therefore a closed system. In addition, this closed system is reproducible—i.e., it is a steady state, to use the thermodynamic terminology. According to the energetic dogma, it can provide internal *mechanical* work at a constant rate as long as a constant flow e_1 of environmental energy is forthcoming. Because of the theoretical importance of such a system for the energetic thesis and for other issues as well, I have proposed to refer to it as *perpetual motion of the third kind*.[9] And since my position is that this perpetual motion is impossible, by analogy with the negation of the other two perpetual motions by the first and second thermodynamic laws we may regard this impossibility as a fourth law of thermodynamics [31; 34–38].[10]

A technical point that must be dealt with before anything else in connection with this proposition concerns the famous Einsteinian equivalence between mass and energy, $E = mc^2$. For as even a Nobel laureate, Hannes Alfvén propounds, "matter, then, can be seen as a form of energy" [1]. The assertion only bespeaks the familiar bias in favor of energy. It is not because matter is not just mass, but some positive amount of mass and some positive

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[8] The case in which all w_i's are null, which does away with any need for recycling, corresponds to Boulding's tenet.

[9] To my knowledge, only Zemansky [78, 193] uses the same term for a closely related system—namely, for a system in which work is not dissipated against friction, viscosity, etc. My definition, I believe, is more relevant analytically.

[10] This law should not be regarded (as has proved possible quite often) as a corollary of the Entropy Law. According to this law, an *isolated* system—i.e., a system that can exchange neither matter nor energy with its surroundings—tends toward the Heat Death—or toward Chaos if one includes matter under the rule of that law [29, 75; 30, 142; 32, 8]. The confusion may stem from the loose practice of using "closed" instead of "isolated", e.g., [46].

Here it may be well to recall that a system which can exchange both matter and energy is *open*. The fourth logical category, a system that may exchange only matter, is factually impossible since any transport of matter involves energy as well.

amount of energy structured in the definite patterns of the chemical elements and their compounds, that Einstein's equivalence does not bear out that view. I wish to submit that there is an intrinsic asymmetry between matter and energy, which is due to the asymmetry between mass and energy. Indeed, as long as we do not recognize the irreducible asymmetry between the two terms of the Einstein formula—which with properly chosen units may be written in the perfectly symmetrical form $E = m$—we are just as justified to speak of a "crisis of matter" as of a "crisis of energy".

Energy is converted into mass (and vice versa) in numerous nuclear reactions which begin and end with some mass. In the familiar relations

Proton + Antineutrino ⇄ *Neutron* + *Positron*

Neutron + Neutrino ⇄ *Proton* + *Electron*

where the underlined terms have a positive mass. Pairs of anti-particles with positive mass may be entirely converted into pure energy, as it happens when an electron and a positron by colliding turned into a photon. To be sure, the reverse reaction also is *possible*. Photons may be converted into pairs of electrons and positrons, as it happened on a large scale immediately after the Big Bang while the temperature of the universe was still greater than 6×10^9 degrees Kelvin, which is the threshold of that reaction. But since such pairs are extremely unstable (like all pairs of matter and antimatter), they almost instantaneously disintegrate into pure energy. This is why positrons exist only in some intense astronomical phenomena or in high-energy laboratories. For photons to split into neutrons and antineutrons the temperature must be higher than 10^{13} degrees Kelvin, which is one hundred times higher than that believed to prevail at one hundredth of a second after the Big Bang. This last temperature—about 10^{11} degrees Kelvin—is greater than the hottest stars [75]. Nothing can be surmized about what happened before that particular moment, but what we know is that *material* particles—protons and neutrons were not produced then and cannot be produced now from pure energy.[11] And since without nucleons there can be no atoms, hence no matter, the present explanations of the origin of the chemical elements cannot do without assuming that the combined number of the protons and neutrons has always been the same as in the initial hot soup [73; 75]. To express the fact that nowhere in the universe matter can be created out of pure energy, the Einstein relation should be written $E + mc^2 = E_0 + m_0c^2$, $m_0 > 0$ whenever m includes some nucleon mass, that is, some matter. (The subscript identifies initial amounts.)

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[11] Only what is proven to work at the time has a legitimate place in the arguments of the sort developed here. Speculations have no proof value and may even be dangerous. For example, were the servants of science to persistently preach that we will certainly learn how to block out gravitation by some cavorite—the material discovered by Mr. Cavor in one of H. G. Wells's fantasies—people would be misled in building houses without stairs and without elevators.

Heavier elements are currently fused from lighter ones but only in stars, where the temperature reaches astronomical levels, between 10^7 and 10^{10} degrees Kelvin.[12] But at these temperatures matter exists only in a desaggregated state as plasma. Should a closed system become so hot, it could no longer produce any mechanical work (let alone harbor life).

Nuclear reactions are certainly going on at all times on our planet, too. Radioactive elements continuously decay. However, these phenomena as well as all nuclear reactions set up by us usually convert mass into energy, *not vice versa*. Mass is converted into energy even when we light up a match. This loss of mass is fantastically small because of the large value of c. But the difference between the weight of spent nuclear cores and their initial weight can be shown on ordinary scales. And at the Sun's dimension, 4,200,000 tons of mass are "lost" every second. Certainly, we can also convert energy into additional mass, but only in very special cases (usually, in laboratory installations) and in relatively small amounts and not into *nucleon* mass.

At the temperatures at which mechanical work can be performed, the overwhelming chemical elements are stable. In a closed system the amount of each element remains constant. "Materials are not destroyed",—Slesser, an energy specialist, tells us, "the iron molecule in iron ore is still an iron molecule when it is turned into steel or when it ultimately ends up as rust" [70]. Seaborg also argues that "we have here on earth the same amount of matter we have had since the dawn of history"—in truth, since the earth became a stable planet [65]. Only, both Slesser and Seaborg intended their observations as a support of energetics, in the same way in which Brooks and Andrews claimed that "the literal notion of running out of mineral supplies is ridiculous. The entire planet is composed of minerals" [9].

The simplest way to expose the fallacy of the Brooks-Andrews argument is to note that, by the same token, we could maintain that we cannot possibly run out of energy because the entire planet is full of energy. Indeed, the thermal energy contained in the ocean waters would alone suffice to maintain an undreamed-of industrial activity for billions of years to come. The rub is that all (or practically all) this fantastic amount of energy is unavailable for conversion into mechanical work by an engine of *finite* dimensions, which must by necessity operate in *cycles*. Indeed, as Planck suggested [57; 58], the thermal energy of a bath of constant temperature could be converted into mechanical work by an infinitesimally slow moving piston-and-cylinder of an *infinite* length (on the same familiar principles that govern the isothermal expansion of the gas in a Carnot cycle).[13]

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[12] Despite the immensity of these ovens the material universe still consists mainly of hydrogen, according to some estimations, 92.06 percent, with helium representing 7.82 percent [2].

[13] Peculiar thermodynamic ideas such as this bring to mind Dirk ter Haar's statement that the concept of entropy "is not easily understood even by physicists," [30] may seem a severe judgment typical of an authority in a field. However, nowadays most physicists have only a

Certainly, the whole planet is made of matter. But the argument based on this point ignores the fact that, just like the thermal energy of the Earth, not all terrestrial matter is in available form. Matter also continuously degrades into an unavailable form.

Two factors may explain why this last fact is widely ignored. The first is the peculiar attraction our minds feel for all strains of mechanical models. The most probable reason is that we act on the material surroundings mainly by pushing and pulling. The mechanistic dogma had already lost its Laplacean grip on physics, when, in his Baltimore lectures (1894), Lord Kelvin confessed that he could not understand a phenomenon unless he was able to represent it by a mechanical model. It is the attraction of the mechanistic *Weltbild* that induces us to believe that matter cannot be definitively irrecoverable. Indeed, in mechanics, matter can only change its place, not its quality; hence any system may move back and forth without suffering any change.[14]

The second factor is that, curious though it may seem, the foundation of thermodynamics is energetic—as Rankine perceived it—for thermodynamics is concerned only with what happens to energy. To be sure, matter enters into the picture, but only as a support of chemical reactions (because they always involve energy transformations) and in problems of pure (nonchemical) mixtures (because unmixing necessitates work). Both these aspects have been introduced into thermodynamical theory by J. Willard Gibbs, who is thus regarded as the founder of "chemical energetics" [66].

Take the ultra familiar apparatus consisting of a piston-and-cylinder filled with some gas that is generally used to describe and justify the basic laws of thermodynamics and to prove Carnot's fundamental proposition that maximum efficiency is obtained only by a perfectly *reversible* engine. To circumvent the undeniable fact that because of friction no motion can be reversible, thermodynamic theory assumes that any motion is reversible if its speed is infinitesimally slow.[15] Such a speed does eliminate friction from the

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superficial knowledge of thermodynamics (if any), so that some may go wrong even on the notion of heat (see *Journal of Economic Literature*, December 1972, p. 1268, and note 14, below).

[14] A celebrated symptom of our mechanistic propensity was Ludwig Boltzmann's famous endeavor to explain irreversible phenomena by blending the perfect determinism of the reversible laws of Newtonian mechanics with probability . For the economist this hybrid construction presents a crucial interest. By maintaining that the regeneration of unavailable energy is only highly *improbable*, not *impossible*, the propounders of the probabilistic theory foster the belief in the possibility of cheating at the entropy game (just as we may cheat at any game of chance) or, as P. W. Bridgman ridiculed the thought some 50 years ago, of "bootlegging entropy" [29; 30; 32]. It is regrettable therefore that not all physicists know that Boltzmann's construction met with irrefutable criticism from some of the greatest physicists, for which see [25; 30]. Far sadder it is they do not know that through his pathbreaking contributions Ilya Prigogine showed that Boltzmann's "'mechanical theory' of the evolution of matter [is based on] intuitive arguments [and] the program was never realized, despite frequent affirmations to the contrary" [60–62]. If one has not gone beyond Boltzmann, one is apt to proclaim (as Auer does) that the Entropy Law sets no obstacle to endless economic growth [3].

[15] It may be well to explain that in thermodynamics a motion is reversible only if the motion and *everything else in its surroundings* can be returned to the original situations [57; 78].

picture, but it introduces an even more essential obstacle. With an infinitesimally slow speed a piston would take an infinite time to move over any finite distance. Time and again, infinity steps in to set things out of bounds for us mortals.[16] Because a reversible engine thus exists on paper only, no actual engine can operate at maximum efficiency.

In the end, thermodynamics had to recognize the existence of friction as well as of a few other germane factors, which account not only for irreversibility in nature, but also for the fact that available energy cannot be completely converted into *useful* work. Part of this energy is always converted into irrecuperable heat.

Friction thus appears as a ghost, so to speak, in the backstage of the thermodynamic setup, a ghost that robs us of available energy. Indeed, thermodynamics did not move further to recognize and analyze the elementary fact that friction robs us of *available matter* as well. It did not tackle even the specific laws of the energy degraded by friction. This task was left to the engineers, but even they have established only tables for the forces of friction of the most frequently used materials. With the help of these tables, we can determine the work against friction W_f, to be used in the (still incomplete) transformation formula:

$$Q_a = W_u + W_f, \tag{3}$$

where Q_a is available energy and W_u is useful work (the internal energy of the system being assumed to remain constant).[17]

About the dissipation of matter by friction we still know practically nothing. One possible explanation of this conspicuous lacuna is the difficulty of explaining the phenomenon of friction. Mechanical laws applied to material particles cannot explain it. Its laws have a purely empirical basis and on closer and closer examination are usually found to be "'falser' and 'falser'" [27]. And a consummate student of the problem concludes that the subject of friction "remains a highly controversial one, and there are very few statements that can be made in this field which will find no opposition" [63].

But friction is not the "imperfection" only of matter in bulk that robs us of both energy *and* matter. There are neither perfectly rigid nor perfectly elastic materials; there are no perfect insulators and no perfect conductors; nor are there materials for which the force of friction is infinite (the opposite case of frictionless materials). And it is because of these numerous imperfec-

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[16] Recall Planck's infinite piston mentioned earlier.

[17] The traditional formula is $Q = W$ because in thermodynamics work is defined only in the absence of friction [24]. Formula (3) was recently proposed by Silver [67]. But he, too, stopped short of mentioning the material effect of friction. Moreover, to cover all energy wastes, the formula should read $Q_a = W_u + W_f + Q_l$, where Q_l is the leakage of thermal energy—i.e., the amount of thermal energy that always descends a temperature gradient *without performing any work*.

tions (the list is not exhaustive) that the robber, the only robber, of energy and matter is matter itself.

All over the material world there is rubbing by friction, cracking and splitting by changes in temperature or evaporation, there is clogging of pipes and membranes, there is metal fatigue and spontaneous combustion. Matter is thus continuously displaced, altered, and scattered to the four corners of the world. It thus becomes less and less available for our own purposes.

The energetic dogma claims that this dissipation can be completely reversed provided there is enough available energy. But the operation must necessarily involve some material instruments. Because there are no perdurable material structures these instruments will necessarily wear out. They will have to be replaced by others produced by some other instruments, which will also wear out and will have to be replaced, and so on, in an unending regress. This regress is a sufficient ground for denying the possibility of complete recycling, just as the same kind of regress is the reason often invoked in thermodynamics against the possibility of completely erasing the changes caused in the *energy* structure by a natural process [24, 24].

Finally, another possible (and important) thought in support of complete recycling must be entertained. It relates to John von Neumann's proof that a universal Turing machine may be so designed that if left in a floating medium together with a large number of each one of its elementary parts it will reproduce itself [52]. Could not then the fund elements of the process represented by Table I constitute such a "machine"? This machine does "float" in a medium that, although closed, contains all the necessary elements for its reproduction, namely, the waste outputs of processes (P_i)'s. Yet the idea that the economic process could be a universal Turing machine must be rejected. Neumann's proof is a very ingenious paper-and-pencil exercise based on a requirement that makes the project impossible in practice. The troublesome requirement for a universal Turing machine is that its capacity for instruction must be limitless [30, 86–93]. And even if we softened this condition to "practically infinite," the machine would still require a practically infinite sequence of time intervals to reproduce itself, since each "move" of the machine requires a duration. Therefore, this last justification of complete recycling runs against the same familiar obstacle as all other ideal schemes: the unreachable infinity.

But the energetic thesis can be examined from still other analytical viewpoints.

IV. The Dissipation of Matter and Planck's Law

I have spoken of some asymmetry between energy and mass and between energy and matter. There is still another asymetry. Both mass and energy are homogeneous "substances". Energy is the same whether it is associated with a photon or with the force of the wind. This is certainly why the idea of reducing everything to energy has such a strong appeal. But there also is no qualitative difference whatever between the mass, say, of a proton and that of any other elementary particle. However, this last fact is of no value for the relationship between the economic process and the environment. In the economic process it is not mass as such that counts. What counts is matter in bulk (and, of course, energy). And the rub is that unlike mass and energy, matter is a highly heterogeneous category. Every chemical element has at least one property that characterizes it completely and hence renders it indispensable for some technical recipes.

We must therefore expect that, in contrast with the general theory of energy (thermodynamics), the study of the transformations of matter in bulk should be hard going, as we have just seen for the case of friction alone. It is a rather simple problem to understand how energy degrades as heat dissipates from the hotter to the colder bodies of a system, because in this way it becomes less and less available to be converted into mechanical work. Remember the famous Carnot principle: we must have a difference of temperature between the boiler and the condenser in order to obtain mechanical work by a cyclical engine. Without entering into the technical maze, one may see why the increase in the dissipation of energy is measured by the thermodynamic formula for entropy:

$$\Delta S = (\Delta Q/T)_{reversible} \tag{4}$$

where ΔQ is the heat transferred by conduction at the absolute temperature T.[18]

For the entropy of the simple mixture of two *distinct* ideal gases of the same pressure P and temperature T, we have Gibbs's famous formula:

$$\begin{aligned} S = {} & -R\left[m_1 \ln(m_1/m) + m_2 \ln(m_2/m)\right] + (c_1 m_1 + c_2 m_2)\ln T \\ & + (a_1 m_1 + a_2 m_2) - Rm \ln P, \end{aligned} \tag{5}$$

where $m_1 + m_2 = m$ are the corresponding moles, R is the gas constant, and a_i, c_i are physical characteristics of the gases. Mixing two gases of the same pressure and temperature thus increases the entropy by[19]

$$\Delta S = -R\left[m_1 \ln(m_1/m) + m_2 \ln(m_2/m)\right], \tag{6}$$

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[18] Even though "hotness" is one of the most common sensations, the flow of heat (as strictly conceived in thermodynamics) has no direct physical significance and there are no *direct* operations for measuring it [8; 24].

[19] Because the same technical detail will come up later in Sec. VI, it may be well to add here that the enthalpy, H, does not change [48; 57; 58]. Enthalpy, which corresponds to the intuitive notion of heat content, is the amount of thermal energy necessary to bring the substance from absolute zero to its temperature state while pressure is kept constant. In practice, enthalpy is the calorific value of a fuel—i.e., the maximum amount of thermal energy that can be obtained by burning it.

a very familiar formula that nowadays is used on both solid and flimsy grounds.

Ordinarily, this formula is mentioned in connection with a paradox pointed out by Gibbs himself [66]. If the two gases are identical, (6) is still positive, although the mixture then causes no entropy change whatsoever. But another aspect of (6), stemming from an observation by Max Planck [58, 104], bears on the present argument. Planck suggested that in the case of (6) "it would be more to the point to speak of a dissipation of matter than of a dissipation of energy".[20]

According to either (6) or (5) the greatest dissipation for a given m occurs when $m_1 = m_2$. But let us consider the case in which $m_1 = 1$ and $m_2 = 10^{100}$. Then, ΔS is completely negligible. Yet, on the basis of the intuitive conception of dissipation, it stands to reason that, *if gas 1 is the valuable one*, from the particular human viewpoint the dissipation is far greater in the latter than in the former case. It is in the latter case that we can properly say that one mole of gas 1 has become unavailable to us. Indeed, to reassemble those molecules would be a task as formidable as reassembling the molecules of a small amount of ink spread over the Atlantic Ocean!

Undoubtedly, we can reassemble the scattered pearls of a necklace that broke in a room, in a theater, even somewhere in Manhattan provided we are prepared to expend enough time, enough energy, and wear out numberless objects in the process. The extrapolation of this macroscopic recipe to the microscopic level of molecules or even of small bits of matter is clearly unwarrented. From all we know, can one believe in the possibility of reassembling not all, but practically all the rubber molecules of our worn-out tires, all the lead dissipated through the exhaust pipes, or all the copper dissipated from our pennies through use? In a reasonably finite time as well? The object lesson is that at the microscopic level the same recipe that succeeds for reassembling the pearls of a broken necklace would require, among other hard-to-conceive facilities, an *infinite* time. The operation belongs therefore to the same category as the irreversible engine and Planck's scheme for using the heat of the oceans. Planck even concludes that, because $\Delta S > 0$, "diffusion like friction and heat conduction is an irreversible process" [57, 113; 58; 78].

The preceding analysis shows, however, that (6) measures in reverse the intensity of diffusion conceived so as to make sense in our actual manipulation of matter. According to that formula, mixing one carload of needles with one carload of hay creates a greater diffusion than losing one important needle in a carload of hay that corresponds to the task of complete recycling or of mining any rock. Although we can easily extract a metal from a rich ore, the

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[20] Understandingly, Planck did not say "dissipation of mass."

task is harder and harder as the metal content decreases, and for a content of, say, 10^{-100} it becomes impossible.

There remains however the issue of the thermodynamic interpretation of (6). For this, we may recall that in thermodynamic theory $T\Delta S$ represents the work necessary to restore the corresponding system to its original position. In the present case, this means to separate again the two gases completely. A theoretical blueprint for performing this separation was imagined by Jakobus Henrikus van't Hoff (the first Nobel Prize winner in chemistry). The device—the van't Hoff box—consists of a perfectly isolated cylinder with two pistons working in opposite directions; each piston consists of a semi-permeable membrane, one permeable only to gas 1, the other only to gas 2. The mixture is placed between the two pistons, which at first are far apart. As the pistons are pushed infinitesimally slowly against each other, the gases are separated since each gas gets behind its own semi-permeable membrane. It is easily shown that the work necessary for this pushing is indeed equal to the product of (6) by T [58; 78]. This result seems to provide a strong support to the purest energetic dogma. If we have enough energy (equal at least to $T\Delta S$), we can extract the entire amount of any gas from any mixture. Several snags, however, beset the actual implementations of this idea.

First, just as in actuality there are no completely frictionless, no perfectly elastic, and no other perfect materials, there are no perfect semi-permeable membranes. The separation therefore cannot be complete.[21] Second, with use all membranes become clogged [57; 58]. They wear out, just as does any other part of a mechanism; in the end they must be replaced, thus starting the endless regress mentioned earlier.[22]

Van't Hoff box constitutes at least an ideal procedure for unmixing gases, but no similar device exists for other mixtures. In practice, each mixture separation is achieved by some particular procedure, by chemical reactions, centrifugal or magnetic forces, etc. To be sure, the absence of a general blueprint does not prove that some ideal blueprint may not exist for each particular mixture. But several arguments plead against this thought.

Let us remember Maxwell's demon, the demon presupposed to separate the fast-moving from the slow-moving molecules of a gas. It is now generally believed that this miraculous demon has been "exorcised," so that, like any other living creature, it must consume a greater amount of available energy than it creates by the separation of "hot" from "cold" molecules. Now, to separate a mixture of, say, nitrogen and oxygen, we need a demon far more miraculous than Maxwell's. Indeed, Maxwell's demon does not have to bring back absolutely every molecule to its initial container. Moreover, it may safely

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[21] Another imperfection is responsible for the fact that in actuality some mixed gases always remain between the membranes no matter how much the pistons are pressed against each other.

[22] Highly pertinent to the topic of this paper is the recent discovery (by R. K. Knoll and S. M. Johnson of NASA, Cleveland) that solar collectors also become progressively clogged.

leave some "hot" or "cold" molecules in the wrong container; it is only the average speed that counts. Our new demon, on the contrary, *must not leave even one single molecule mixed with those of the other kind*. To exorcise it, we must not only supply it with enough energy but also endow it with a material existence. And since matter keeps dissipating, the problem now boils down to whether our demon can recycle itself completely while recycling the gas mixture, also completely. The system of Table I depicts, in fact, such a demon. No wonder that the miraculous features of our demon are tacitly implied in many ideas concerning the unlimited renewability of material resources.

To Brown [10], it seems, belongs the idea of mining the whole crust by utilizing the energy of the radioactive elements thus obtained. Such a miraculous technology would come to an end only after all rocks had been crushed. The sad truth is that no blueprint has been put forward to describe how this technology may work. Instead, the idea is regarded as a real flight of fancy by practically all geologists, who generally support Peter Flawn's dictum that even "the average rock will never be mined" [28; 18; 68]. As Preston Cloud, who is known to have opposed with all his authority all minerological flights of fancy, tried to enlighten the layman, "it is the uncommon features of a rock that make it a candidate for mining!" This is why almost certainly your backyard is not a potential mine.

Brooks and Andrews denounced Flawn's dictum by invoking the fact that titanium is also mined (as a by-product) from presumably sub-average grades. A few other writers also proclaimed that "the world will not run out of geologic resources," assuring us that only the energy limit may prevent the mining of any ordinary rocks [21]. But most have a hard time remaining consistent when faced with such facts, for example, as the existence of a geochemical barrier cutting off the mining of copper at 16 times the average abundance]20, 129].

Let us also observe with necessity that even if the average rock could be mined, this would not entail that the entire mineral content of the crust is accessible. The distribution of grades has a peculiar bimodal shape and is thus very skew [69]. Hence, the overwhelming majority of rocks are much poorer than the average grade. Whether or not a mineral may be mined from a given rock depends on the specific theoretical cutoff for that mineral and for that type of rock, not on its average crustal abundance. Matter, to recall, is heterogeneous, so that for each substance and rock there is some specific mining procedure(s). This is why it seems well nigh impossible to establish a general formula for deciding whether or not a substance is available from a given mixture. In this lies the theoretical difficulty (hinted at earlier) of defining the unavailable form of matter by a general analytical formula.

Curves describing how the amount of rock crushed and the amount of energy used vary with respect to the rock's metal content are readily available in the literature. They all are asymptotic to the vertical axis [56]. Those for energy should actually be asymptotic to a line parallel to that axis, so as to reveal the existence of a theoretical cutoff, however small this may be.

As a last argument we may mention a statement by Planck, which although very important, seems to have passed unnoticed. At the end of an elaborate discussion of all types of mixtures, Planck arrived at a formula which entitled him to conclude that "neither a gas nor a liquid nor a solid body can ever be completely freed from the last traces of foreign contaminating substances" [57, 125; 58, 238]. Exceptions occur, but only at absolute zero [58, 239; 48, 46].

Now, according to the third law of thermodynamics, enunciated by W. Nernst, absolute zero cannot be attained in actuality. Therefore, Nernst's and Planck's negations are mutually bound. They also form a twin package. The former says that matter *in bulk* cannot be "purified" of thermal energy, the latter that it cannot be purified of any contaminant.

And what deserves strong emphasis is that, in contrast with the Entropy Law, the truth of these laws is not subject to any instrumental constraints. They are true in an absolute sense. To explain, *in theory* we can restore a partial system to exactly its original position, if we have a certain amount of energy and some specific apparatus at our disposal. There is no way, however, to circumvent the impossibilities affirmed by either Nernst's law or Planck's.

It is Planck's law for matter than provides us with a very important analytical argument against the energetic dogma, which necessarily implies that *recycling may be complete* and that *any rock can be mined*.

V. Matter Matters, Too

Complete recycling being impossible, even in a steady state the "transactions" between the economic process and the environment must necessarily consist of some available matter as well in order to compensate for the matter dissipated continuously and irrevocably. As Harrison Brown observed, if all the iron produced in the United States between 1870 and 1950 (about 2 billion tons) had still been in use in 1950, there would have been then 13.5 tons per capita, almost double the actual figure [10]. The same difference would be even more impressive were it established on the entire past production. We all know where the difference went. "Oxidation by the air, corrosion by liquids, and other general wear [certainly because of friction and metal fatigue] take heavy tolls" [10]. As is always the case, some iron is also "lost" during production processes. Although it is not possible to estimate the amount of iron "that has been lost never to be recovered", Brown [11] estimates that about 10 percent of the iron used for steel production is lost irrecoverably and that over 100 years the remaining iron becomes unavailable matter. Just to maintain the iron equipment existing in 1954 (without providing for any economic growth), a flow of ore convertible into about 0.3 tons of iron per person had to be mined each year.

Of course, this maintenance flow varies from substance to substance according not only to the changing technology but also to the size of the stock existing in the process. In the case of gold this flow is naturally small for several reasons—its chemical resilience, its particular use, and the relatively small amount of it in existence. Yet it is hardly exact to assert that "most gold ever mined is still available" [68]. The millions and millions of past bracelets, necklaces, coins, etc. have not all been kept at a Fort Knox.

The fact that the flow of dissipated matter increases with the size of the material stock must be recognized as a very important link in the argument of this paper. For it explains, on the one hand, why, even if some cutoffs may be so low that it may be almost impossible to ascertain them by a laboratory experiment, their effect at the scale of the entire planet and in the long run cannot be ignored. On the other hand, it explains why we are apt to believe in the perpetuity of the so-called natural cycles of oxygen, carbon, nitrogen, etc., that adorn all ecological manuals.[23]

As far as the economic process itself is concerned, we must not ignore the substantial dissipation of matter caused not by purely natural phenomena but by some activities of living creatures, of mankind's, above all. It is the dissipation of some vital elements by man's consumption of food and timber in places far away from the farm and the forest that produced those items. The practice—a consequence of the high and growing level of urbanization everywhere in the world—also wastes available energy. Most curiously, we are aware of this waste, but not of the waste of available matter. The difference is responsible for the fallacy that forests can provide "an endless supply of wood" because the flow of sunshine is practically endless [51]. Yet forests cannot be everlasting anymore than topsoil can retain its quality forever without outside intervention [30, 302].[24]

The conclusion of the foregoing analysis is that for the environmental transactions we must keep two separate books—one for matter, one for energy—for at the macro-level no practical procedure exists for converting energy into matter or matter of whatever form into energy. The relation of matter and energy is not like that between, say, dollars and yen, nor even between land and working implements in agricultural production (Sec. VII).

A new multi-process matrix must therefore replace that of Table I. In this

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[23] It is because of the immensity of every one of these stocks that the amount continuously leaving the cycle is not conspicuous over short periods. One of the telling facts is that practically all the carbon deposited as calcium carbonate on the bottom of the oceans will not re-enter the so-called carbon cycle. And this is only a minor troublesome factor of the global circulation of environmental carbon [76].

[24] Very likely, it will be the more palpable waste—of the energy consumed by transportation—that, in case of a serious difficulty in obtaining environmental low entropy, will bring about a substantial amount of deurbanization [31].

new matrix (Table II), an additional process, (P_0), transforms matter *in situ*, *MS*, into controlled matter, *CM*. All other processes have the same roles as before and are identified by the same notations. But there are several important changes.

First, new flows, s_i, represent the dissipated matter, *DM*, produced by every process and passed into the environment. Second, the recycling process, (P_4), no longer recycles all material waste, as assumed in the energetic model. Since dissipated matter is irrecoverably lost, (P_4) can recycle only matter that is still available but has no longer a shape useful to us: broken bottles, broken pipes, run-down batteries, worn-out motors, etc. Because recyclable materials belong in garbage cans or in junk yards, for brevity, we may refer to them as "garbojunk", *GJ*.[25] Third, another inherent aspect of the economic process is represented by a flow of items that also are returned to the environment and are labeled here "refuse", *R*. This flow consists in large part of available matter and available energy, but in a form that is not potentially useful to us at present. The crushed rock of an open-pit copper mine, most urban waste, and nuclear garbage, for example, belong to this category.[26]

As in the case of Table I, the relations:

$$\begin{aligned} &\Sigma' x_{0i} = x_{00}, \quad \Sigma' x_{1i} = x_{11}, \quad \Sigma' x_{2i} = x_{22}, \quad x_{35} = x_{33}, \\ &\Sigma' x_{4i} = x_{44}, \quad \Sigma' w_i = w_4 \end{aligned} \tag{7}$$

represent the viability of the steady state. However, because *R* may include both energy and matter, we can no longer write the relations for the conservation of these items separately, as in (1).

VI. Energy Analysis and Economics

My position has been (and still is) that the Entropy Law is the taproot of economic scarcity. In a world in which that law did not operate, the same energy could be used over and over again at any velocity of circulation one pleased and material objects would never wear out. But life could certainly not exist either.[27] In our world, everything that has some usefulness (desirability) for us consists of low entropy. It is for these reasons that the economic process is entropic in all its material fibers [29; 30; 32]. But I have also

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[25] The possibility of recycling garbojunk marks a second asymmetry between energy and matter. Recycling of matter is possible because some material objects are "durable" in the sense that, in contrast with energy, they are not *instantaneously* degraded through their participation in producing mechanical or other types of work. The point bears on the old economic controversy over repeated use versus instantaneous consumption.

[26] In order to save space, the fund coordinates are not represented explicitly in Table II.

[27] We often connect the Entropy Law with disorder, yet without it there would be no order in actual phenomena. The truth is that the Entropy Law is the law of orderly succession. For—a piquant observation—without the Entropy Law you would not dare take a bath, one half of the water might become *by itself* so hot as to scald your neck and the other so cold as to frostbite your toes.

Table II. The Actual Relationship Between the Economic Process and the Environment

Product	(P_0)	(P_1)	(P_2)	(P_3)	(P_4)	(P_5)
			Flow Coordinates			
CM	x_{00}	*	$-x_{02}$	$-x_{03}$	$-x_{04}$	*
CE	$-x_{10}$	x_{11}	$-x_{12}$	$-x_{13}$	$-x_{14}$	$-x_{15}$
K	$-x_{20}$	$-x_{21}$	x_{22}	$-x_{23}$	$-x_{24}$	$-x_{25}$
C	*	*	*	x_{33}	*	$-x_{35}$
RM	*	*	$-x_{42}$	$-x_{43}$	x_{44}	*
ES	*	$-e_1$	*	*	*	*
MS	$-M_0$	*	*	*	*	*
GJ	w_0	w_1	w_2	w_3	$-w_4$	w_5
DE	d_0	d_1	d_2	d_3	d_4	d_5
DM	s_0	s_1	s_2	s_3	s_4	s_5
R	r_0	r_1	r_2	r_3	r_4	r_5

maintained (without always being read correctly) that although low entropy is a necessary condition for usefulness, it is not also a sufficient one (just as usefulness is a necessary but not sufficient condition for economic value.) Poisonous mushrooms, for example, consist of low entropy [29, 94; 30, 282].

The entropic nature of the economic process notwithstanding, it would be a great mistake to think that it may be represented by a vast system of thermodynamic equations—as has been proposed, for example, by Lichnerowicz [50]. The entropic process moves through an intricate web of anthropomorphic categories, of utility and labor, above all. Its true product is not a physical flow of dissipated matter and energy, but the enjoyment of life—account being also taken of the drudgery of labor [30, ch. x]. And, in spite of some voices to the contrary, pleasure is not related by a definite quantitative law to the low entropy consumed. Nor is labor's "disutility" related by such a law to the expended low entropy. William Petty was right in teaching that nature is the mother and labor the father of wealth—only he ought to have said "of our existence." Therefore, even if we accepted the energetic view, in which the whole economic process is maintained only by the flow of environmental energy e_1, economic value could still not be reduced to energy.[28]

Nevertheless, the possibility of reducing prices to energy units, Btu's instead of dollars, has been in the focus of attention ever since the oil embargo prompted people to think of energy and to attempt an analysis of its circulation in man's activities. Gilliland [42] even argued that energy analysis is the natural way for doing away with the difficulty of adding apples and oranges, which is what economists have to do. Slesser [70] and R. S. Berry (quoted by Slesser) propound the strongest form of this dogma: to measure the cost of things in money "which is after all nothing more than a highly sophisticated value judgment" does not offer a firm basis for economic valuation. Actually, if economists were to look at scarcity in a more complete way, their "estimates would come closer and closer to the estimates [of] the thermodynamicists". This simply means to do away with economics and replace it by thermodynamics.[29] This position is so generally embraced that net energy analysis now constitutes the official criterion for technology assessment and energy policy in the United States [26].

All this is highly surprising in view of the fact that a great confusion still prevails even among the experienced practitioners of energy analysis. There is, first, the controversy concerning the difference between Odum's net energy analysis and the gross energy analysis based on some principles set up by a 1974 meeting of IFIAS, the International Federation of Institutes of Advanced Study (note 2, *supra*). Slesser, a representative of the latter school, claims that one has "yet to see a rigorous definition of net energy" [71]. It is true that even in his latest writings Odum is not sufficiently clear on many important points, such as whether the energy of labor should be taken into account. Moreover, he often confuses the reader by such requirements as that even money must be included in the general flow [54]. However, the situation is not much more enviable in the other camp, as is evidenced by a series of highly critical letters to the editor and small notes which failed to clear the

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[28] I have myself insisted that prices are parochial elements of the economic system and also that the market mechanism by itself it incapable of preventing environmental catastrophes. But I did not deny the necessity of the market mechanism for the allocation of resources and the distribution of income among the members of the *same generation* [32; 34].

[29] Hayek [43, 51], as Keith Wilde recently reminded me, protested long time ago against "the various forms of social 'energetics' [as those propounded by] Ernest Solvay, Wilhelm Ostwald and Frederick Soddy." However, none of these authors held the same position as the modern energetists. What they claimed is that regardless of how economic value is established, the economic process cannot violate any of the natural laws, including the laws of thermodynamics. In fact, Ostwald was the first author to observe that from the dawn of mankind's existence technological progress has always consisted in increasing the power of our biological organs. And contrary to Hayek's accusation, Ostwald [55, 164] explicitly argued that "we would err if we measured value only in proportion to the amount of free energy." Only Soddy plunged into economic matters proper and devoted several works to a solution of the instabilities caused by credit creation. An interesting recent paper by Daly [23] aims at rehabilitating Soddy.

air.[30] One critic charged that because "the energy analysts disagree in their basic ground rules" energy analysis can be used "to prove whatever case you choose" [47]. Even one of the prominent energy analysts, P. F. Chapman, recognized that "there are almost as many methods [of analysis] as there are workers in the field" and energy analysis may follow four different aims and adopt three different methods [13]. Results, as he showed, may even be contradictory. There has been some controversy even over how to measure energy (as we shall presently see).

The issue of whether energy analysis provides an equivalent basis to the price system was recently entertained by David Huettner [46]. But, here again, the letters to the editor that his article provoked suggest that he, too, failed to make his case.[31] In deriving his price equations Huettner followed the fallacious practice in standard economics of ignoring the essential difference between flows—the material elements that are changed by a production process—and funds—the agents that perform the change [31; 32]. As a result, his price equations had exactly the same form as his equations for the presumed energy equivalents. Because of this identity the real difference between economic valuation and energy calculations could not be brought to light so as to settle the question raised by Price, "why energy analysis gives a different answer than the economic analysis" [59]. The flow-fund model used in my tables will settle this issue without much ado.

Let us consider first the simplest case, that of Table I, and begin with the net energy analysis. We must first decide what net energy is in that structure. I think that in the spirit of the Cottrell-Odum conception we may safely assume that net energy aims at determining how much controlled energy, *CM*, is accessible in all forms to the ultimate consumers. However, few additional observations now appear necessary. First, for the concept of net energy we do not have to distinguish between the various kinds of environmental energy, *ES*. In other words, it does not matter whether the net energy is derived from fossil fuels or from the wind, for example. Second, the dissipated heat must not be counted at all in computing net energy. That is, we must not add d_1 to the net output of energy x_{11}, or deduct d_i from the gross input x_{1i}. Finally, we must also not count in any way the energy spent by people in performing work or in consuming goods. To do so would be to mix economics with energy analysis. The analysis would then be falsified by a double counting resulting in an extensive cancellation, for in a steady state—which is still our testing ground—the total input flow of any environmental element is exactly equal to the corresponding total output flow.

Four possible definitions of net energy seem to deserve attention: a) x_{11}; b) the difference between x_{11} and the energy equivalent of x_{21}; c) x_{15}; and d) x_{15} plus the energy equivalent of x_{25} and x_{35}. The first suggestion can be easily dis-

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[30] *New Scientist*, 9, 16, and 23 January 1975.

[31] *Science*, 15 April 1977, 259–62, especially M. Slesser. See also *Science*, 2 April 1976, 8–12.

carded. If x_{11} is, say, electricity produced from fossil fuels *in situ*, that electricity is not net energy even with respect to the process (P_1). For part of that electricity has been used in a roundabout process to produce, among other things, the material flow x_{21} necessary for compensating the wear and tear of K_1 during the mining of e_1 and its use in a thermoplant.

Suggestion (b) leads to

$$\textit{Net energy} = x_{11} - (x_{21})_e, \tag{8}$$

where $(x)_e$ denotes the energy equivalent of x. But this definition raises the troublesome question: what is the energy equivalent of a steel beam?

Here, again, various ideas have been at work. One simple method consists of taking into account only the energy *directly* used by a process because such data are readily available from official statistics. This method leads to

$$(x_{21})_e = x_{21}(x_{12}/x_{22}), \tag{9}$$

and

$$\textit{Net energy} = (x_{11}x_{22} - x_{12}x_{21})/x_{22}. \tag{10}$$

Obviously, this represents a substantial underestimation, for the production of x_{22} needs x_{42} units of *RM* as well. We must, therefore, find out $(x_{42})_e$ as well. We are thus involved in an algorithm that will not end until an energy equivalent is established for every type of product.[32] The result is a system of equations which recalls the Leontief system [16; 77].[33] Let us then denote by a_i the energy equivalent per unit of flow product of (P_i). From Table I we obtain:

$$\begin{aligned} \textit{Net energy} &= x_{11} - a_2x_{21}, \\ &-x_{12} + a_2x_{22} - a_4x_{42} = 0, \\ &-x_{13} - a_2x_{23} - a_4x_{43} + a_3x_{33} = 0, \\ &-x_{14} - a_2x_{24} + a_4x_{44} = 0, \end{aligned} \tag{11}$$

which by (2) yields

$$\textit{Net energy} = x_{15} + a_2x_{25} + a_3x_{35}. \tag{12}$$

This relation shows that suggestion (b) is equivalent to suggestion (d) and also that (c) would not do. It also shows that, for example, the average cost of K in units of controlled energy (net energy) is a_2.

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[32] It may be well to emphasize that the term "energy equivalent" does not imply a physical equivalence in the sense that a pound of copper, for example, may be converted into its energy equivalent or vice versa.

[33] This is an almost insuperable task for the analyst even if a detailed input-output table in real terms is available. But this difficulty is wholly irrelevant to the issue under consideration now. Chapman, however, insists that in this method one should in *principle* consider a *subsystem*, not the whole national economy [13]. Moreover, in the illustrative application of this method to the energy sector, it is not clear how the energy equivalence of non-energy items was computed [16]. From repeated remarks on the matter, we may infer that for these items the energy equivalent of the dollar was used, a procedure that is totally incompatible with energy analysis.

Net energy defined by (11) can also be expressed as a function of the flow coordinates alone:

$$\textit{Net energy} = \begin{vmatrix} x_1 & -x_{21} & 0 \\ -x_{12} & x_{22} & -x_{42} \\ -x_{14} & -x_{24} & x_{44} \end{vmatrix} \div \begin{vmatrix} x_{22} & -x_{42} \\ -x_{24} & x_{44} \end{vmatrix} \tag{13}$$

This formula proves the extremely curious result that in the case of an energetic system, the net energy does not depend on the flows of the consumer goods industry.

Energy analysts are far from agreeing on whether or not we should attribute an energy equivalent to W. The difficulty is identical to that of attributing a cost to joint products in economics. But if we introduce the w_i's in (11) and denote by a prime the new energy equivalents and by z_w' the energy equivalent of w, by (2) we obtain immediately

$$a_i' - a_w' = a_i, \tag{14}$$

which means that the new equivalents are not completely determined. This result, which in some arguments may be quite troublesome, should have been expected.

We may turn now to the gross energy analysis. The stated aim of this analysis is to determine the amount of energy *in situ* "needed directly and indirectly to deliver a good or a service to the final customer" [49; 71]. However, "a quagmire of confusion" seems to prevail about the precise rules of how to achieve it [49]. Gross energy analysis has in view mainly the fossil fuels. For this reason, the recommended unit of energy is the calorific value, which represents the energy potentially available by burning a given amount of such fuels [16; 59].[34] A difficulty arises because there is no accepted calorific value for nuclear fuels. Nor can one speak of such a value for the energy input of a hydroelectric plant. The principles also provide that solar energy should not be counted as an input since it is "a free good" [19], a position which has its snags (and which does not affect the net energy approach). One author argues that labor and even profits "are also energy inputs" [77]. However, most of the gross energy analysts stick to the rules (also adopted above) according to which neither labor nor waste enter into the calculation [71]. There also are issues that concern both methods and about which no practitioner is explicit. One such issue is what precisely should be included in the capital cost x_{2i}.

Let now X denote the transposed matrix of the first four rows and four col-

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[34] In a more sophisticated form it is explained that we should consider only free energy, which determines the maximum mechanical work obtainable under normal pressure and temperature. Specifically, it is the Gibbs free energy, $G = H - TS$, that is meant [59; 70]. However, the enthalpy, H, is used instead (note 19, above), because in burning fuel under normal conditions ΔG does not differ substantially from ΔH [24, 73].

umns of Table I; let e denote the column vector $(e_1, 0, 0, 0)$; and let $b = (b_1, b_2, b_3, b_4)$ be the column vector of the energy equivalents in units of ES. We have

$$Xb = e\,. \tag{15}$$

From this and (1) we obtain

$$e_1 = b_1 x_{15} + b_2 x_{25} + b_3 x_{35}\,, \tag{16}$$

which shows how much energy *in situ*, b_i, is needed for a unit of every good consumed by the households.[35]

The comparison of (12) and (15) yields

$$\textit{Net energy} = e_1 / b_1\,, \tag{17}$$

or, equivalently,

$$b_i = b_1 a_i\,, \qquad (i = 2, 3, 4)\,. \tag{18}$$

These results show, first, why the main issue in gross energy analysis turned around the proper unit for energy. If e_1 consists of fossil fuels, then Champan [13] is vindicated for insisting that one kWh of electricity should be counted as about four kWh's of calorific power, which simply means that $b_1 = 4$.

But the same relations prompt one to wonder why all the fight about which approach is the correct one since the two sets of energy equivalents are related by the simple relations (18). The truth is that, whereas a can be deduced from b, the converse is not true. This does not mean, however, that gross energy analysis is the better approach. According to the rule mentioned earlier, in the case of solar energy $e_1 = 0$, hence $b = 0$[36] and *Net Energy* $= \infty$. Briefly, within its own scope gross energy cannot discriminate between two technologies based on solar energy alone (also Sec. VIII). On the other hand, net energy analysis completely ignores the efficiency of the technologies by which resources *in situ* are transformed into controlled energy. As far as net energy analysis is concerned, it does not matter whether two tons or one million of tons of oil *in situ* are depleted for abtaining one ton of oil net.

Still reasoning on the basis of Table I, let us turn now to economic valuation, briefly, to what the normal prices would be in such an economic world. The point that can hardly be overemphasized in this connection is that in any economic system both the quantities represented by the flow elements *and* the services provided by the agents have value. Let $p = (p_1, p_2, p_3, p_4)$ be the column vector of the prices of the flow elements, and let P_K, P_H, P_L be the prices of services during their specific periods. The economic equations are

$$Xp = B\,, \tag{19}$$

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[35] It is easily seen that only b_3 is affected by the flow coordinates of (P_3). Also, the introduction of an energy equivalent b_w for W will lead to a system identical to (15) in which b is replaced by b', with $b' = b_1, b_i' = b_i - b_w, i \neq 1$.

[36] This is so because if $|X| = 0$, then (15) has no solution.

where B is the column vector (B_1, B_2, B_3, B_4) and

$$B_i = P_K K_i + P_H H_i + P_L L_i. \tag{20}$$

We have further

$$p_1 x_{15} + p_2 x_{25} + p_3 x_{35} = \Sigma B_i. \tag{21}$$

which is the equation of the national budget.

Only in the highly unrealistic case, in which only the services of labor are included in the budgets B_i, can (19) determine all relative prices.[37] In actuality, the indeterminateness is removed by additional factors of a purely economic nature, such as tastes and income distribution.[38]

It is now perfectly clear that in *absolutely* no situation is it possible for the energy equivalents to represent economic valuations. Although the matrix of the price system (19) is the same as that of the systems of energy equivalents, (11) and (15), the former system cannot be equivalent to either of the latter. Actually, reducing economic value to energy is a more extreme position than the purest theory of labor value. To put in a homely way, according to the energetic portion one ounce of black caviar (which is mostly protein) should have the same price as one ounce of spaghetti (mostly carbohydrates) if it would take the same amount of either gross or net energy to produce them. Such an equivalence will never work.

VII. Global Analysis and Economic Choice

The analysis of the realistic case, in which not only energy but also matter counts, proceeds in the same way as for a generalized Leontief system in which there are several but distinct prime factors of production (say, uniform labor and uniform land). This means that the relations pertaining to one factor can be established by assuming that the other factors are in infinite supply [29, ch. 10].

Let us then abstract first from the MS. Let Y denote the transposed matrix of the first five rows and five columns of Table II; let f denote the column vector of the new gross energy equivalents $(f_0, f_1, f_2, f_3, f_4)$ and e the column vector $(0, e_1, 0, 0, 0)$. As before, we have

$$Yf = e, \tag{22}$$

which yields

$$e_1 = f_1 x_{15} + f_2 x_{25} + f_3 x_{35}, \tag{23}$$

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[37] In no actual economy is $P_K = 0$. Moreover, where institutionally $P_L = 0$, differential rent still gives rise to income transfers (illicit, naturally).

[38] Should W be attributed a market price, p_w, the new prices, p', will satisfy analogous relations to those of note 35, above.

with

$$f_i = e_1 \Delta_{i1} / \Delta \,, \tag{24}$$

where Δ is the determinant of Y and Δ_{i1} the minor of the element of subscripts $(i, 1)$.

For gross matter equivalents we shall abstract from the *ES*. If g denotes the column vector of these equivalents and m the column vector $(M_0, 0, 0, 0, 0)$, then

$$Yg = m \tag{25}$$

from which we obtain

$$M_0 = g_1 x_{15} + g_2 x_{25} + g_3 x_{35} \,, \tag{26}$$

with

$$g_i = M_0 \Delta_{i0} / \Delta \,. \tag{27}$$

The corresponding formulae for the net energy follow straightforwardly:

$$\textit{Net energy} = e_1 / f_1 \,, \qquad \textit{Net matter} = M_0 / g_0 \,. \tag{28}$$

The conclusion is that to deliver a marginal unit of, say, C to the ultimate consumer we must consume f_2 units of energy *in situ* as well as g_2 units of matter *in situ*.

The upshot of the foregoing considerations is that, whatever the source of the energy used (solar or terrestrial), we must not ignore the depletion of the terrestrial deposits of available matter caused by any productive process. For all practical purposes, the Earth is a closed thermodynamic system, notwithstanding the meteorite fall and the material particles that occasionally escape the gravitation pull. In the very long run, therefore, some material elements will become more critical than energy for an industrial system of the prevailing sort [30; 32]. An increasing number of natural scientists have recently become convinced of this point and now even insist that a number of important elements are already approaching the pressing limit of scarcity [17; 69]. But sad to say, instead of following the old commandment and "beat our swords into plowshares," we keep on forging the plowshares of future generations into our present dreadful "swords".

Let us remember that energy and matter in bulk are not convertible into each other (Sec. VI), i.e., there is no relation $F(M, e) = \text{const}$. We do not have, therefore, a grid of isoquants which could enable us to reduce the economic choice pertaining to natural resources to physico-chemical calculations. Take the case of two technologies, $T_1(M_0^1, e_1^1)$ and $T_2(M_0^2, e_1^2)$, producing the same result and such that $M_0^1 > M_0^2$, $e_1^1 < e_1^2$. If they use terrestial resources, no proposition of physics or chemistry can tell us which technology is *economically* preferable. The nature of the issue is purely economic for it involves a multitude of factors of varying historical uncertainties and imponderabilities.

Since matter also matters, it would be misleading to reduce economic choice to energy alone. Actually, in some cases it is only matter that counts. Assume that the above technologies use "free" solar energy. The choice must now take into account net energy, *NE*, instead of gross energy. And how to choose between $T_1(M_0^1, NE_1)$ and $T_2(M_0^2, NE^2)$ when $M_0^1 > M_0^2$ and $NE^1 < NE^2$ is again an economic, not a purely technical problem. However, if $NE^1 = NE^2$, matter is decisive, T_2 is preferable, regardless of how much gross energy it uses.

One factor (besides those mentioned earlier) that may explain why matter has been ignored by the modern analysis of entropic transformations is the bonanza of fossil fuels that began about two hundred years ago and is still going on. This bonanza has an immense double advantage. It takes relatively little matter to extract fossil fuels from where they lie in the bowels of the earth *and* even less to convert them into industrial thermal energy. The same is not true for nuclear energy, which requires large installations for refining, enriching and conversion. The difficulties that now stand in the way of the direct use of solar energy by the *presently known* recipes also stem from the immense requirements of matter. From all we can judge now, the necessary amount of matter for a technology varies according to the intensity of the energy used. It is high for weak-intensity energy (as is the solar radiation at ground level) because such energy must be concentrated into a much higher intensity if it is to support the intensive industrial processes as those now supported by fossil fuels. And it is high for high-intensity energy because such energy must be contained (besides being "sifted" first).

VIII. Global Analysis and Technology Assessment

Nowadays we hear over and over again that nothing should stop us from using a technology based on solar energy because solar energy "is free, after all" [19]. However, absolutely every environmental energy *is* free, in the sense that nature does not have a check-out counter at which we should pay for resources *in situ*. Money royalties are instituted by man, not by nature. Perhaps by saying that solar energy is free we simply mean that it is "extremely abundant". And it is indeed abundant: its annual flow reaching the upper atmosphere is some twelve thousand times greater than the world's current consumption of energy from all sources! Unfortunately, abundance of energy *in situ* alone is not necessarily an advantage. This is the case of solar energy, which also has the great shortcoming of being extremely weak when it reaches us.

The direct use of solar energy constitutes now such a highly hopeful topic,[39] that it should be instructive to assess such a technology on the basis

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[39] E.g., *Congressional Record: Senate*, 31 July 1975 and 10 December 1975; Sylvia Potter, "We

of the ideas developed in this paper. Let us begin by recalling the necessary distinction between "recipe" and "technology" as well as the fact that *feasible* recipes do not necessarily constitute a *viable* technology (Sec. II). Legions of successful experiments represent feasible recipes that *at present* cannot be part of a viable technology. A striking example is the feasible recipe for quarring the Moon, which could not possibly replace now the mining of the Earth. Further, let us confine our argument to a technology based on those recipes for harnessing solar energy directly *that are known to work at present*.[40] We may safely include under the term "collectors" any devices used by these recipes.

For simplicity, we may divide the whole system into only three individual processes: (P_1) produces collected solar energy, SE, with the aid of collectors, CL, and some capital equipment, K; (P_2) produces collectors with the aid of SE and K; (P_3) produces K from mineral deposits by using SE (Table III).[41] Obviously,

$$x_{21} = x_{22}, \tag{29}$$

since collectors have no use outside (P_1).

It is legitimate to assume that all recipes (P_i) are feasible (P_1) is certainly feasible. Collectors also are currently produced, although by other sources of energy—mainly, by fossil fuels energy, FE. The same is true of K. But since energy is a homogeneous "stuff," fossil fuel energy could very well be replaced by collected solar radiation. The only possible snag may concern intensity. Unfortunately, the intensity of energy (expressed by dQ/dt) is another aspect—besides matter—ignored by thermodynamics, which cannot therefore cast any light on the issue.[42] However, we should not overlook the fact that proven recipes can raise the temperature of collected solar radiation to quite impressive levels. The solar oven Odeillo (in the Pyrenees) produces a temperature near to 4,000° centigrade, and has a power of about 65 kW. If we wanted a greater power, we may, conceivably, build as many Odeillos as needed. A solar power plant, however, requires an immense and elaborate installation. The plant projected by ERDA at Barston (California) involves not less than 1,700 polished mirrors, each of 400 square feet—a total of some 18 acres—moved by a very complicated mechanism that turns them so as to follow the sun while focusing on the boiler exactly and continuously. Yet its power is a modest 10 MW.

Stand on Threshold of Solar Energy Era," *News and Observer* (Raleigh, N.C.), 16 September 1975; "European Common Market Heats Up on Solar Energy," *International Herald Tribune*, 25 July 1977.

[40] Accordingly, we do not consider the suggestion for collecting solar radiation in outerspace and transmitting the collected energy to the ground level. The recipe is still unproven.

[41] Let us note that (P_1) must include a fund of CL besides the fund of K.

[42] According to the standard formula $Q = W$, one should be able to send a rocket to the moon by spreading the necessary Q over time so thinly that it would amount to lighting up one match after another. The omission explains why many writers are puzzled by the paradox that solar energy, immensely abundant though it is, seems so very hard to be used directly for our *present industrial* needs.

For the technology depicted by Table III to be viable, we must have

$$y_1 = x_{11} - x_{12} - x_{12} > 0, \qquad y_3 = -x_{31} - x_{32} + x_{33} > 0, \tag{30}$$

where y_1 and y_2 represent the flows necessary for the *maintenance* of the corresponding fund factors (people and fixed capital).

The underlined term should be clearly understood. A viable technology is like a viable species, that is, once sprung from a previous technology all it needs to do is to maintain itself. To wit, the first bronze hammers were hammered by stone hammers, but during the succeeding age all bronze hammers were hammered by bronze hammers. Undoubtedly, to hammer a bronze hammer by stone hammers was a more demanding task than to hammer a stone hammer. But the threshold from an old to a new technology can be surmounted only by an additional cost *at the old prices*. If we ignore this point, we cannot see the weakness of the argument that solar technology is viable and the only thing necessary to bring it about is to find out how to produce collectors profitably. As the example of the Bronze Age shows, the viability of a technology requires only that its material scaffold be self-supporting, regardless.

Table III. Technology Based on Solar Energy

Product	(P_1)	(P_2)	(P_3)	Net flows
SE	x_{11}	$-x_{12}$	$-x_{13}$	y_1
C	$-x_{21}$	x_{22}	*	*
K	$-x_{31}$	$-x_{32}$	x_{33}	y_3

Let us now consider the problem of prices. If (30) is fulfilled, there exists a price system that makes the system work. That is, if X denotes now the transposed matrix of Table III and p is the column vector (p_1, p_2, p_3), the system

$$Xp = B \tag{31}$$

has a positive solution, B being defined as in (20). Therefore, if no such solution exists for $B > 0$, the technology is not viable. But, curiously, the converse is not true: (30) may have a positive solution without the technology being viable.[43] On the other hand, the brute fact that we are not already living in a technology based on solar radiation does not prove that such a

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[43] See *Mathematical Note* at the end.

technology is not viable. It may very well be less efficient than the fossil fuel technology in current monetary terms or in terms of human effort. The issue is quite involved. However, other absences prevail over this inconclusive standpoint.

The most accepted explanation of why solar energy has not yet replaced other sources of power is that the necessary collectors cost too much. Save for this remediable situation, a solar technology capable of sustaining the modern industrial activity is in fact viable. The difficulty is "a cost problem, not a material problem" [64, 17]. But if the only obstacle were the money deficits incurred by solar recipes, one question would cry for an answer. Over the past five years, at least, hundreds of millions of dollars have been spent for the development of more efficient recipes. ERDA, in particular, has interspersed this country with numberless model homes and experimental windmills. Yet no breakthrough has taken place to increase the confidence in a viable solar technology. None of the richly endowed research outfits have achieved even a workable pilot of a combined (P_1) and (P_2) working in mutual support, let alone a pilot of full-fledged solar technology to prove its viability *independent of prices*. For when it comes to prove that a technical idea is workable, cost does not matter much. Otherwise, we would not have succeeded in proving that we can put a man on the Moon.

The obvious upshot is that at present it is not possible to produce collectors only by the solar energy they collect. Any use of a presently feasible recipe based on solar collectors, therefore, is a parasite of the current technology. And, like any parasite, it could not survive its host [38; 39; 40; 41].

This means that instead of (30), we have[44]

$$x_{11} < x_{12}, \qquad x_{11} < x_{13}, \tag{31}$$

even if we weaken the other condition to

$$-x_{31} - x_{32} + x_{33} = 0. \tag{32}$$

For a global analysis of the way solar energy is now harnessed, we must consider the flow matrix of Table IV, in which (29) and (31) are assumed to hold. The energy necessary to produce collectors by (P_2) now comes from a non-solar (fossil fuels) power plant (P_4^0), which also provides the energy for the production of capital equipment by a new process, (P_3^0). The argument will be even more instructive if we assume that the only net flow is x_{11}.

From the fact that $y_{33} > x_{33} = x_{31} + x_{22}$, it reasonably follows that $y_{43} > x_{13}$. Hence, $y_{44} = x_{12} + y_{43} > x_{12} + x_{13}$, and by (31)

$$y_{44} > 2x_{11}. \tag{33}$$

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[44] The inequality $x_{11} < x_{13}$ is a foregone result of the other inequality, given just the enormous amounts of heat needed to produce metals from ores.

Table IV. The Present Mixed Technology

Product	(P_1)	(P_2)	(P_3^0)	(P_4^0)	Net flows
SE	x_{11}	*	*	*	x_{11}
CL	$-x_{21}$	x_{22}	*	*	*
K	$-x_{31}$	$-x_{32}$	y_{33}	$-y_{34}$	*
FE	*	$-x_{12}$	$-y_{43}$	y_{44}	*

This proves that not only is (P_1) a parasite of fossil fuels, but that *globally the recipe consumes twice as much of the other energy than its net output*.[45]

A further result will clarify the real meaning of non-profitable cost. Since the mixed technology represented by Table IV effectively produces a net output, a system of positive prices exists. If we consolidate the budget equations of (P_1) and (P_2), we obtain

$$B_1 + B_2 + p_3(x_{31} + x_{32}) = p_1 x_1 - p_4 x_2 . \tag{34}$$

Because of the first inequality (31), it follows that $p_1 > p_4$. In other words, in the mixed technology, the price of a BTU obtained from solar energy is higher than that obtained from fossil fuels.[46] It is thus seen that the fact that producing one BTU from solar energy is at present nonprofitable is not due to price; instead, it reflects a hidden waste of the solar recipe.

A successful pilot combination of (P_1) and (P_2) that needs only matter from the outside would constitute a significant achievement, but still not completely conclusive. This combination, which is represented by Table V, still requires process like $(P_3{}^0)$ and $(P_4{}^0)$. Instead of (31), we have

$$x_{11} > x_{12} , \qquad x_{11} < x_{13} . \tag{35}$$

Since even in this case, $y_{33} > x_{33}$, we obtain, as before,

$$y_{44} > x_{13} > x_{11} - x_{12} , \tag{36}$$

with the same result concerning the global energy deficit [41]. In this case, however, it does not seem necessary for this deficit to lead to $p_1 > p_4$.[47]

[45] Even if we believed that because of the superior intensity of FE, y_{43} may not be necessarily greater than x_{13}, (33) would be replaced by a weaker, but still relevant inequality.

[46] The fact that people neverhtheless buy home solar installations should not surprise us. People heat their homes with electricity even though this mode consumes more energy than using coal, for example. Also, people buy electric gadgets without necessarily deriving an amount of energy from them comparable with that which was used in the production of those gadgets.

[47] Perhaps this result may not stand further probing. For it appears highly curious indeed for a solar BTU depending indirectly on fossil fuels to cost less than an input BTU.

Table V. Collectors Produced by Solar Energy

Product	(P_1)	(P_2)	(P_3^0)	(P_4^0)	Net flows
SE	x_{11}	$-x_{12}$	*	*	$x_{11} - x_{12}$
CL	$-x_{21}$	x_{22}	*	*	*
K	$-x_{31}$	$-x_{32}$	y_{33}	$-y_{34}$	*
FE	*	*	$-y_{43}$	y_{44}	*

The statement by Denis Hayes, that "we can use solar energy now [because] the technology is here" [44], probably reflects the overenthusiasm of a keen student of the problems of energy scarcity. The truth is that only the feasible recipes are here, just as numberless other such recipes are. But a viable technology is not.

The discovery of far more efficient recipes may change the picture radically. However, harnessing solar radiation is not a problem that has just recently confronted us, as was the case of the peaceful use of nuclear energy some forty years ago. At that time, one could have easily gone wrong about the possibility of using the newly discovered energy; none other than Lord Rutherford did. But solar collectors have been used on a substantial scale for almost one hundred years now, and during all this time there has been practically no true breakthrough [12]. Undoubtedly, the Sun is the only steady and completely healthy source of energy whether for a new "Wood Age" or some other kind of solar age. At present, however, it seems very unlikely however that it will enable mankind to fly in jets, to live in skyscrapers, and to travel in automobiles at one hundred kilometers per hours, for example.

To try persistently to find more efficient recipes is not only legitimate, it is imperative. But to claim that solar technology is here before it actually is, or to preach that "come what may we shall find a way" will only conceal from the public awareness the seriousness of the acute problem of natural resources and thus render any move toward an adequate policy to deal with that problem far more difficult than it actually is.

Mathematical Note

Let X be the matrix of Table III and let the prime accent denote inversion. By (30), the system

$$Xs' = w \tag{37}$$

has a positive solution $s = (1, 1, 1)$ for $w = y \geqslant 0$.[48] By Theorem 5 [29, 324–25], it has a solution $s > 0$ for any $w > 0$. Hence $|X| = 0$,[49] and by Theorem 4 [29, 323], the system

$$X'p' = B', \tag{38}$$

where $B = (B_1, B_2, B_3) > 0$, has a solution $p > 0$. This proves that for any viable technology and for any fund prices, there exists a set of positive prices for the flow elements.

Let us now assume that (38) has a positive solution. From Theorem 4, again, it follows that

$$X\lambda' = z'$$

has a solution $\lambda > 0$ for any $z > 0$. Hence, $\Omega \in \Gamma$, where Ω is the non-negative quadrant and Γ is the convey cone determined by (P_1), (P_2), and (P_3). Unless $X = I$, there must be some w such that $w \in \Gamma$ but $w \in \Omega$. Nothing warrants that this is not the case for y. For a simple example:

$$X = \begin{bmatrix} 4 & -2 & -3 \\ -1 & +1 & 0 \\ -1 & -2 & 5 \end{bmatrix}$$

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[48] The vector notation $a \geqslant b$ excludes the of case $a = b$.

[49] Direct computation yields $|X| = x_{22}y_1(x_{31} + x_{32}) + x_{22}y_3(x_{11} - x_{12}) > 0$. Incidentally, the number of conditions of Theorem 7 [29, 326, 336] can be further reduced by one unit; if the minor of third order—in the precent case, $|X|$—is positive, so must the minor of second order be.

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