ECO-THERMODYNAMICS: ECONOMICS AND THE SECOND LAW

by

R.U. AYRES*

96/51/EPS

This working paper was published in the context of INSEAD's Centre for the Management of Environmental Resources, an R&D partnership sponsored by Ciba-Geigy, Danfoss, Otto Group and Royal Dutch/Shell and Sandoz AG.

* Sandoz Professor of Management and the Environment at INSEAD, Boulevard de Constance, 77305 Fontainebleau Cedex, France.

ECO-THERMODYNAMICS: ECONOMICS AND THE SECOND LAW

Robert U. Ayres
CMER, INSEAD
Fontainebleau, France

August 1996

Abstract

The laws of physics, especially the first and second laws of thermodynamics, have significant implications for economic theory. The major implications of the First Law (conservation of mass/energy) are straightforward and have been discussed at length elsewhere. In brief, raw material inputs to economic processes are not "consumed". Having been extracted from the environment in the first place, they eventually return to the environment as wastes.

The economic implications of the Second Law (entropy law) are far subtler. There is a considerable literature, initiated by the work of Georgescu-Roegen, on the supposed constraints on economic growth imposed by the fact that economic processes utilize "low-entropy" raw materials (fossil fuels and high grade metal ores) and discard "high entropy" wastes. Since low-entropy natural resource stocks are indeed finite, the "weak" form of G-R's thesis is essentially a generalization of Malthus' basic argument. However, insofar as the G-R thesis goes further, it is not in accord with physical reality and is easily refuted. In particular, the flux of available low-entropy energy (*exergy*) from the sun is extremely large and certainly adequate to sustain economic activity in the solar system indefinitely, even though fossil fuel and metal ore stocks may eventually be exhausted.

It is argued in this paper that the real economic significance of the Second Law lies in the fact that exergy is (i) not conserved and (ii) is a useful common measure of resource quality, as well as quantity, applicable to both materials and energy. Thus exergy can be used to measure and compare resource inputs and outputs, including wastes and losses. This is potentially important in itself. Moreover, since exergy is not conserved it is truly consumed (i.e. used up) in economic processes. Hence, exergy is not produced by economic activity but is no less a "factor of production" than labor or capital. This fact has strong implications for economic growth theory, especially in regard to assessing the role of technical progress.

Background

Two major laws of physics — the first and second laws of thermodynamics — are, respectively, the law of conservation of mass/energy and the so-called "entropy law". The law of mass/energy conservation reduces in practice to two conditions that must be satisfied by any physical change or transformation whatever and, by extension, to any economic activity involving physical materials. Except for nuclear reactions, mass and energy are not interconvertible in practice. Hence, the conservation of mass/energy implies separate conservation rules for energy and mass. The law of conservation of energy implies that energy inputs must equal energy outputs for any transformation process, but this rule is surprisingly lacking in practical significance for reasons that will be seen later.

The law of mass conservation, on the other hand, is far from trivial. The so-called "mass-balance principle" states that mass inputs must equal mass outputs for every process (or process step), *and that this must be true separately for each chemical element.* In the first place, this condition implies that all resources extracted from the environment must eventually become unwanted wastes and pollutants. This means, among other things, that "externalities" (market failures) associated with production and consumption are actually pervasive and that they tend to grow in importance as the economy grows [Ayres & Kneese, 1969; Kneese *et al* 1970].

Furthermore, the mass-balance condition provides powerful tools for estimating process wastes and losses for industrial processes, or even whole industries, where these cannot be determined directly. Even where other data are available, the mass balance condition offers a means of verification and interpolation, to fill in gaps. I have discussed some of the economic implications of this principle in several other publications over a period of more than two decades [e.g. Ayres & Cummings-Saxton 1975; Ayres 1978; Ayres & Kneese 1989; Ayres & Simonis 1994, Ayres 1995]. Nothing new need be added here.

The second law of thermodynamics also has economic and environmental significance. However, unlike the first law, the significance of the second law for economics has been largely misunderstood. This paper is an attempt to clear up the confusion.

Entropy and the Second Law of Thermodynamics

The term *entropy* is too much used and too little understood. This is unfortunate. Technically, entropy is an extensive state variable that is definable for any material substance or any system.[1] The term "extensive" means that it is proportional to the "size" of the system (like volume or mass) in contrast to an "intensive" variable (like temperature, pressure or density). The term, along with the underlying concept, was introduced by Rudolph Clausius, in the 19th century, to help explain the tendency of temperature, pressure, density and chemical gradients (in fact, all sorts of gradients) to flatten out and gradually disappear over time. But, while this tendency is observable everywhere, the general measure of it is not. There are no "entropy meters" for sale in the local scientific supply shops.

The physical law behind the concept is deceptively simple to state: If the system is isolated and closed, so that it does not exchange matter or energy with any other system, its entropy increases with every physical action or transformation that occurs inside the system. Entropy can never decrease in an isolated system or in the universe as a whole. When the isolated system reaches a state of internal equilibrium its entropy is maximized. When two systems interact with each other, their total combined entropy also tends to increase over time.

This non-decreasing property, roughly speaking, is known as the Second Law of Thermodynamics, or just the "entropy law".

The entropy law, since its formulation 150 years ago, has been endowed with enormous, but somewhat mysterious significance. It has an almost mystical aura, at least in some circles. Extrapolating to the limit, Clausius himself spoke of the "heat death" of the universe, a daunting metaphor of inevitable decay. Sir Arthur Eddington, a well-known astronomer and scientific generalist, called it "the supreme law of nature". He also dubbed it "time's arrow", indicating that the forward direction of time can be defined as the direction in which entropy increases, and conversely. C. P. Snow, the physicist-turned-novelist, characterized this law as the *sine qua non* of an educated person. Nicolas Georgescu-Roegen, tried to make it the cornerstone of a whole new approach to economics, if not a new world-view. (I return to this later).

Many scientists have tried to explain increasing entropy in terms of increasing "disorder", implying that disorder arises inevitably from "order". While this explanation has some intuitive appeal, it is potentially misleading, since the term "order" is itself difficult to define consistently and unambiguously [e.g. Landsberg 1984a]. One of the problems with interpreting entropy as disorder has been the apparent inconsistency between increasing entropy, on the one hand, and the apparent directionality of biological evolution on the other.

One source of confusion is that the entropy law — at least in the sense of increasing disorder — seems, to the uninitiated, to be in conflict with the notion of evolutionary "progress". The idea of "progress" is actually a leftover from 19th century bio-theology. It is currently much debated, and strongly challenged by evolutionary biologists. The famous paleoanthropologist, Stephen Jay Gould, has been particularly averse to the notion that evolution is leading in any preordained or predictable direction. He is equally skeptical that the direction which evolution has actually taken should be equated with progress.

However, there is much less dispute that biological evolution has "tended" toward increasing complexity. The paleological record clearly indicates a trend toward organisms with bigger brains and more elaborate nervous systems [e.g. Dollo 1893; Fisher 1930; Blum 1968; Maynard-Smith 1970]. Arguing from the conclusion, it has been suggested that the rate of entropy production by a living organism can be regarded as a measure of its complexity [Artigliani 1991].

The complexity of an object such as a machine, or an organism, is essentially equivalent to its *information content*. This can be understood as the stored information required to completely describe the object. The parallel between computer codes and the genetic code, which contains all the instructions needed for the organism to reproduce itself, is obvious. Thus, the evolutionary increase in complexity of organisms corresponds to a parallel trend toward more and more chromosomes and genes, indicating increasing information storage and transmission [e.g. Britten & Davidson 1969; Eigen 1971; Layzer 1977; Sagan 1977].

The link between complexity and information has been greatly clarified by the development of computer science. Since physical objects can be represented by pictures or designs, the complexity of the object can now be measured precisely (in principle, at least) in terms of the minimum number of instructions required to generate its design in the computer. The parallel with evolving artificial intelligence has been emphasized by Moravec [Moravec 1991]. There is also an obvious parallel with economic and technological evolution [e.g. Ayres 1994].

In summary, biological evolution seems to be tending towards increasing "order", in some increasingly defined sense. This tendency appears contrary to a naive interpretation of the entropy law. This has led a number of scientists, especially non-physicists, astray in the past.

The most seductive temptation is "vitalism": the idea that somehow living substance — life itself — is exempt from the laws of physics and chemistry, especially the entropy law. This idea was particularly attractive in the 19th century to people looking for physical evidence of the existence of a supreme being. But there are hints of vitalism even in the more recent works of Georgescu-Roegen.

As it happens, the mechanism that drives biological evolution in the direction of increasing complexity, or stored information is not yet well understood. Darwinian models are unsatisfactory in some ways. Indeed, it has been suggested that biological evolution is actually being driven, indirectly of course, by the entropy law. There is an ambitious program of theoretical research under way to explain detailed evolutionary mechanisms in terms of explicit thermodynamic models [Brooks & Wiley 1988]. It is too early to know how successful their approach will be. On the other hand, there is absolutely no contradiction between the second law of thermodynamics and this evolutionary tendency toward increasing complexity. Physicists have been pointing this out for a long time, but to little avail.

In fact, living organisms have the ability to accumulate low entropy matter (physical information) in their bodies, as they grow. Plants do this by capturing low entropy energy from the sun, using some to drive the process and storing the surplus as biomass. Animals, in turn, ingest low entropy biomass — food — and excrete high entropy materials as metabolic wastes, thus increasing the entropy of their environment. The earth itself receives low entropy (high temperature) solar energy and re-radiates high entropy (low temperature) heat. The second law of thermodynamics is satisfied at every moment.

The important point is that biological organisms are not closed systems; neither is the earth. The fact that they can exist for a long time (billions of years) in a more or less steady state far from thermal or chemical equilibrium is entirely due to the continuing flow of low entropy energy from the sun. A living organism, by virtue of its metabolism, can be regarded as an entropy generator. During the most active stages of cellular reproduction and differentiation, entropy production is maximal. The work of Prigogine *et al*, and of Landsberg, has given us a more detailed understanding of the nature of thermodynamic processes far from equilibrium, including the thermodynamics of evolution [Prigogine *et al* 1972; Nicolis & Prigogine 1977; Landsberg 1984a,b].

The accumulation of low entropy substances within the organism, or in the biosphere as a whole, (or in the *technosphere*) can be defined in terms of *potential entropy*, meaning the entropy that will eventually be generated when the organism dies and its component materials dissipate and are re-absorbed into the environment. This can also be defined as *physical information*, which has units of entropy. Obviously the biosphere, the technosphere, and the earth's crust, atmosphere and oceans are also repositories of accumulations of physical information, or potential entropy.

Although the term entropy is commonly used in such discussions as the above, the notion of low/high entropy as applied to materials and energy stocks and flows is confusing, given the way the concept is usually introduced to students in terms of reversible/irreversible thermodynamic processes of change. Also, it's association with inherently vague concepts like "disorder" make it difficult to understand intuitively.

However, to avoid confusion it is easier to think in terms of another variable that carries less mystical baggage. This is called *exergy*, which is formally defined as the maximum amount of *work* that a subsystem can do on its surroundings as it approaches thermodynamic equilibrium reversibly. Exergy is proportional to potential future entropy production but has the units of energy. This variable, which is commonly used in both mechanical and chemical engineering, has also been called *available work*, *availability* and *essergy* (for *essence of* *energy*) at various times. It is, incidentally, proportional to *potential entropy*, or *physical information*, as defined above. Exergy is the most general measure of "distance" from thermodynamic equilibrium. Thus, it can also be thought of as the degree of "distinguishability" of a subsystem from its surroundings.

Exergy and Exergy Balance

Exergy is not a conserved variable, like energy. It can be gained or lost in physical processes. However, exergy can be accumulated. It can also be stored in mineral ores or fossil fuels, for instance. Finally, exergy inflows and outflows to and from any subsystem are definable and measurable. However, before going further I must make a brief excursion into technicalities.

Exergy is defined as the potential work that can be extracted from a system by reversible processes as the system equilibrates with its surroundings. It is, in fact, the "useful" part of energy and is what most people mean when they use the term "energy" carelessly (as in economics). There are four components of exergy. They are (i) *kinetic* energy associated with relative motion, (ii) *potential field* exergy associated with gravitational or electro-magnetic field differentials, (iii) *physical* exergy (from pressure or temperature differentials) and (iv) *chemical* exergy (arising from differences in chemical composition).

Exergy is only non-zero when the system under consideration is distinguishable from its surroundings — the environment — in one or more of these four dimensions. However, for our purposes a considerable simplification is possible. In considering mass flows into and out of economic (i.e. industrial) processes the first three components of exergy can be safely neglected. Only the last of the four categories, namely chemical composition, is important. Thus, to calculate the chemical exergy of a mass flow stream it is only necessary to have data on the chemical composition of that stream *vis a vis* the environment into which it flows. Obviously, to calculate chemical exergy the appropriate environmental reference state must also be characterized precisely.

To compile generic exergy tables, therefore, it is necessary to adopt a general convention on reference states. This could be a daunting task if a very local definition were adopted for each case. However, noting that there are three major environmental media — or "sinks" —a reasonably general definition has been proposed [Szargut *et al* 1988]. The reference state for most elements is taken to be either its most oxidized or chlorinated form, depending on volatility and solubility. In the case of chemical elements found in the atmosphere as such (oxygen, nitrogen, inert gases) and carbon — because carbon reacts with atmospheric oxygen to yield a gaseous but relatively insoluble oxide (CO_2) — the composition of the atmosphere is taken to be the reference state. In the case of chemical elements whose oxides or chlorides are soluble in water, the composition of the ocean is taken to be the reference state. For all other elements, mainly metals whose oxides are insoluble solids, the average composition of the earth's crust down to some specified depth[2] is taken to be the reference state. The latter definition is somewhat arbitrary, to be sure, but it turns out that calculated values in most cases are not extremely sensitive to the crustal depth assumption.

In the case of hydrocarbon fuels and carbohydrates such as cellulose and sugars the exergy content of a fuel is very closely related to the usual measure ("heat of combustion"). However, the term exergy is much more widely applicable. Given the above conventions, it is definable for any material substance whatsoever, whether combustible or not. For instance, the exergy content of a metal ore reflects its quality and the amount of natural "low entropy" that is stored in the ore and that would be lost if the ore were dissipated (mixed) uniformly into the earth's crust. The better the quality of the ore, the greater its exergy content.

Without presenting the derivation in full, it is sufficient for our purposes to present the main result [Szargut *et al* 1988]. It is that the standard chemical exergy, per mole, of any pure *compound* involving these elements can now be computed by means of a simple formula, viz.

$$B = G + \sum_j n_j B_j \qquad (1)$$

where G is the standard Gibbs free energy of formation of the compound, the η_j are molar fractions of the jth chemical element and the index j runs over the elements in the compound. The G values are tabulated in standard reference works, such as the *Handbook of Physics and Chemistry*. The B_j values have been calculated for all the important elements [Szargut *et al* 1988]. To calculate the chemical exergies of mixtures and composite materials, such as ores and alloys, it is only necessary to have detailed composition data and do the sums.

Exergy, as defined above, is not only a natural measure of the resource *inputs* to an economic system. It is also a measure of the material *outputs*. Exergy is not conserved. It is lost in all processes, mostly — but not entirely — as low temperature heat. But some exergy is lost in the form of chemically or physically reactive materials. These production and/or consumption wastes are dissipated into the environment.

It is not only unutilized exergy (i.e. waste heat or unburned fuel) that can drive undesired environmental processes in a non-equilibrium situation. Low temperature heat is rarely damaging to the environment. On the contrary, it is far more likely to be the insertion of unfamiliar chemical species (i.e. chemical potentials) in delicately balanced bio-geochemical cycles that can cause trouble. At the micro-scale, even very small trace amounts of some chemicals are enough to disrupt life processes. In fact, there is a general label for such disruptive chemicals: *toxins*. The first point to emphasize is that unexpended potential entropy increase has the potential for disruption of delicately balanced dissipative structures, far from equilibrium. For this reason, unexpended exergy — potential entropy increase — can be regarded as a potential for causing environmental harm [Ayres & Martinàs 1995].

Recall that exergy is not a conserved quantity like mass or energy. Thus, all mass extracted from the earth's crust must either be added to anthropogenic stocks (e.g. durable goods and structures) or eventually discarded as wastes. On the other hand, since mass is conserved, the goal of "zero emissions" that is often proposed by environmentalists is physically impossible, at least if wastes and emissions are to be measured in terms of mass. One can only attempt to reduce the overall consumption of materials (mass), and make sure that the waste stream is as harmless as possible when discarded. This implies that its exergy content should be minimized, insofar as possible.

Note that, since exergy is not conserved, the exergy content of a physical waste stream is typically much less than the exergy content of the inputs. The more efficient the process (in the second law, or exergetic sense), the less exergy is embodied in the materials that must be discarded. There is no reason *in principle* why the exergy content of material wastes could not be reduced very nearly to zero. But before considering ways and means of reducing the waste exergy embodied in materials, we need ways to measure and/or estimate it.

To calculate the exergy content of waste materials, in practice, there are two approaches. Ideally they should be used together for mutual verification. The first approach requires a detailed knowledge of the chemical composition of the waste stream and the Gibbs free energies of formation of the components. Once these are known, the calculation of exergy proceeds component by component. The difficulty is obvious: for many chemical and metallurgical processes it is difficult to obtain reliable data on the chemical composition of the wastes. Nevertheless, the composition of the waste stream can be estimated approximately, in many cases, if the basic chemical reactions, temperatures, pressures and yields are known. Indeed, commercially available software suitable for use in a desktop computer is capable of making such calculations at minimal cost [Ayres 1995; Wolfgang & Ayres 1995].

The second, alternative approach involves using the exergy "balance" equation:

$$B_{in} = B_{product} + \Delta B_{process} + B_{waste} \qquad (2)$$

which can be rewritten

$$B_{waste} = B_{in} - \Delta B_{process} - B_{product} \qquad (3)$$

Here $\Delta B_{process}$ is essentially a balancing term. It represents internal exergy lost in the process.

Evidently, if $\Delta B_{process}$ is known, the exergy content of wastes can be determined directly from the composition of the process inputs (including utilities) and that of the main products. The exergies of process inputs and product outputs are computed, as before, using *Equation 1*, when Gibbs free energies of formation are known. However, as a practical matter, the exergy loss (or gain) in the process is typically much larger than the exergy content of the waste. Thus, to use *Equation 3* it is necessary to calculate process losses very precisely. This is sometimes feasible, but rarely easy.

I discuss applications of these relationships later.

Entropy and Economics

It must also be said that the interface between entropy (or exergy) and economics is particularly conducive to grand and (often) faulty generalizations. The first economist to consider the subject in depth, Nicolas Georgescu-Roegen, focussed on the entropy law as a metaphor of inevitable decline, with some further embellishments that will be considered later [Georgescu-Roegen 1971, 1979]. Well-known technophobe Jeremy Rifkin has written a popular book, with Georgescu-Roegen's approval and active participation (he wrote an "Afterword"), that includes the following paragraph:

> "The Entropy Law says that evolution dissipates the overall available energy for life on this planet. Our concept of evolution is the exact opposite. We believe that evolution somehow magically creates greater overall value and order on earth. Now that the environment we live in is becoming so dissipated and disordered that it is apparent to the naked eye, we are for the first time beginning to have second thoughts about our views on evolution, progress, and the creation of things of material value....Explanations and rationalizations aside, there is no way to get around it. Evolution means the creation of larger and larger islands of order at the

expense of ever greater seas of disorder *in the world.* There is not a single biologist or physicist who can deny this central truth...." [Rifkin 1980, p. 55].

Regrettably, what Rifkin claims to be a "central truth" is not true at all, because the world is not isolated from the solar system. However, his statement concisely reflects what has come to be known as the "thermodynamic" view of environmental economics, primarily associated with Georgescu-Roegen and, more recently, with Herman Daly. Daly has discussed the entropy law in a number of places, but the following is representative:

> "Service comes from two sources, the stock of artifacts and the natural ecosystem. The stock of artifacts requires throughput for its maintenance, which requires depletion and pollution of the ecosystem. In other words the structure (low entropy) of the economy is maintained by imposing a cost of disorder on the ecosystem. From the entropy law we know that the entropy increase of the ecosystem is greater than the entropy decrease of the economy. As the stock and its maintenance throughput grow, the increasing disorder exported to the ecosystem will at some point interfere with its ability to provide natural services." [Daly 1991, p. 34].

However, the "central truth" as formulated above is simply untrue if "the earth" (Rifkin) or "the ecosystem" (Daly) are interpreted — as normal usage of the language would suggest — as the planet Earth, as distinguished from the solar system (including the sun). To put it another way, the above quotations are only true *if* we regard the "energy available for life on this planet" as the energy generated by thermonuclear fusion in the sun. This is certainly finite, but it is expected to be sufficient for another seven to ten billion years. As applied to the earth or "the ecosystem" (i.e. the biosphere) considered in isolation, the above quotations misconstrue the entropy law.

In another place, Daly quotes a Danish economist, Mogens Boserup, as follows:

> "I am told that [the sun] is huge enough to last for a few billion years, which is far beyond the conceivable duration of the species *homo sapiens*. Therefore the entropy story, entertaining or thrilling as it may be, is irrelevant, in the precise sense that nothing follows from it for human action and policy, today or in any future for which we can conceivably talk and plan." [Daly 1991, p. 226]

In rebuttal, Daly says

> "There are three time frames worth distinguishing: first the extremely long-run concept of entropy as the ultimate equilibrium state, the "heat death" or chaos; second the immediate moment-to-moment concept of entropy as a directional process or "time's arrow" and a gradient down which all physical processes ride; third, the medium-run period of one generation or one average lifetime, say twenty-five to seventy-five years, over which solar low-entropy remains essentially constant, while terrestrial sources of low entropy, upon which industrial civilization is based, may become significantly depleted" [ibid p. 227]

So far no physicist would disagree. Daly continues, however,

> "Let us agree with Boserup that the first meaning is irrelevant. ...Recognition of the

third time frame would have kept Boserup from missing the point that industrial growth is *limited by the stock of terrestrial low entropy, rather than by the stock of solar low-entropy* which is superabundant but is itself irrelevant because solar energy is flow-limited..." (Italics added).

Here Daly stumbles on a point of fact. Solar radiation is unquestionably the driver of evolution on earth, as already noted. It is also flow-limited, in the sense that thermonuclear fusion occurs at a fixed rate that humans cannot (yet) influence. But the flow of solar energy from the sun to the earth is enormous and the biosphere actually utilizes relatively little of it. To be more explicit, plant metabolism uses only 3% to 5% of the solar exergy impinging upon the earth's surface.[3] Plants, in turn, provides the energy source for the metabolism of the biosphere. Direct consumption of biomass by humans for food and materials requires only a tiny fraction of this amount.[4] More subtle interactions between human activities and the natural exergy balance should be considered, of course. See Appendix.

Moreover, although humans consume very little solar exergy at present *except* in the form of biomass (because fossil fuels are so cheap), this is not a permanent limitation. In fact, solar energy incident on earth exceeds direct exergy consumption by humans by a factor of 10,000. Technologies are available to convert this exergy into electricity with an efficiency of 15% or so, potentially rising to 30% or more as technology improves. Costs are considerably higher than fossil fuels, at present (because fossil fuels are currently so cheap), but costs will drop considerably as the technology is developed further and production experience is accumulated. In short, even if we allow for a significant increase in future energy consumption, solar power is not a scarce resource.

Some authors — mainly those associated with the conventional energy establishment — have dismissed the potential for solar power on the grounds that it is too dilute (i.e. the intensity is too low) to be utilized effectively. It is also asserted that the capital costs of solar systems are likely to be unreasonably high. Moreover, whereas solar electricity might very well become economically attractive within a few decades, this is not necessarily the case for liquid fuels derived from solar hydrogen. However, whatever the validity of these claims, these are technical and engineering problems, not fundamental limits. They only imply that more concentrated sources of exergy, such as fossil fuels, are likely to be preferred as long as they are available and cheap. However, in the long run, solar exergy is certainly available for human use in almost unlimited quantities.

Even if the solar radiation impinging on the earth itself were totally utilized for human and biospheric purposes, there is no practical limitation to the ultimate availability of solar power. Satellites can capture solar exergy in space, that would otherwise miss the earth entirely. Similarly, the surface of the moon could, in principle, be used as an exergy collector.

Thus solar exergy is not particularly scarce, nor is it likely to be. Its availability is *not* a near-term limiting factor for life on earth, except in special and local circumstances. It follows that, in the long run, the economic system is not dependent exclusively on the stock of low entropy fuels and mineral ores accumulated in the past.

Contrary to the argument of Georgescu-Roegen and Daly, it is important to emphasize that "order" is continuously created *in the biosphere* including humans, by self-organized systems including, but not limited to, living organisms utilizing the low entropy solar flux. To be sure, an equal and opposite energy flux is re-radiated away from the earth at a much lower temperature (high entropy). The entropy of the universe increases as the sun shines on the earth (and into space). But this fact, as such, has virtually no significance for human life, or human civilization. The entropy law does not imply that order in the form of artifacts and infrastructure is *necessarily* being produced at the expense of increasing the entropy (disorder) of the biosphere itself.

Of course it is true that human civilization is still addicted to fossil fuels and virgin ores. Our economic system is not currently making direct use of solar energy, except through agriculture, forestry and hydro-electricity. Most exergy consumed in the industrial countries is obtained from stocks of fossil fuels ("embodied" solar exergy accumulated over tens or hundreds of millions of years. From this perspective, it is true that humans are using up the stockpile thousands of times faster than it was built up. It is also true that this trend is unsustainable. Again, however, this is not a major near-term constraint. In fact, the environmental consequences of excessive fossil fuel use will constrain future use much sooner than the stock itself will be exhausted. In any case, there are a number of technologically feasible alternatives. Fossil fuels are being used up before other sources because they are cheap, not because there are no alternatives. It is economically rational to use the cheapest resources first.

Georgescu-Roegen has tried to strengthen his case for entropic limits by postulating a "Fourth Law" of thermodynamics. G-R's "fourth law" states that matter becomes progressively unavailable, just as energy does , and that this process is irreversible *even if available energy (i.e. exergy) is plentiful.* Moreover, he asserts that the process of mixing, dispersion and dissipation will continue to the point where *all matter is unavailable.*[5] In other words, he says that the elements become increasingly mixed together and thus more and more difficult to separate from each other, *without limit.*

G-R's "fourth law", however, is not consistent with physics.[6] Given enough exergy any element can be recovered from any source where it exists, no matter how dilute or diffuse. For instance, gold and uranium can be recovered from seawater, in principle. Of course, exergy alone is not sufficient. Some capital equipment (congealed exergy) is also necessary for processing. However the only way G-R's "fourth law" could be true would be if the recovered and purified materials were insufficient *in principle* to maintain the capital equipment required for the materials recovery operation. This is unlikely to be true even in interstellar space (where there is plenty of dust that could be captured by a fast-moving spacecraft, for instance). It is certainly not true if we are talking about the materials trapped in the gravitational field of the Earth.

It is also a fact that, in any finite closed system (where the entropy law is applicable, by definition), there is a physical limit to dissipation. In other words, the highest entropy state of matter on earth is the state in which all chemical elements in the system — say, the earth's crust — are equally dispersed and the matter is homogenized. In such an homogenous mass, all elements must be present with finite concentrations. This concentration is the minimum.

In fact, if any material species is *not* equally dispersed, it must be found in some locations at concentrations lower than average and in other locations at concentrations higher than the average. Thus, the average is actually the most unfavorable case in terms of recycling. Matter cannot be less available than it would be in a completely homogenized earth — or a completely homogenized universe, for that matter. (The real earth is quite inhomogeneous, thanks to differential densities, volatilities, solubilities and reactivities of the atmosphere, oceans and land surface). Even if materials had to be separated from a completely homogeneous degraded "soup", the second law of thermodynamics does not imply that this cannot continue as long as the exergy supply continues. In short, it is clear that in a closed system with a continuing exergy supply, *enough* degraded (i.e. average) matter can be recycled and upgraded to maintain an effective materials extraction and supply system indefinitely. This contradicts G-R's "fourth law".

Other economists have been more circumspect in characterizing the economic implications of the second law e.g. [Berry *et al* 1978; Faber *et al* 1987; Ruth 1993, 1995]. However, except for Ruth's work on the eco-thermodynamics of natural resource depletion, their results have been more theoretical than practical. For instance, a scientifically defensible statement of the "thermodynamic" perspective might be the following:

> "Energy and mass conservation, together with the second law of thermodynamics (entropic irreversibility), implies the inevitability of unwanted by-products or waste energy in the course of economic production and consumption" [Faucheux 1994, p.8].

This statement of the economic implications of the two laws of thermodynamics is unexceptionable but lacking in headline potential. Certainly, human activity generates waste products capable of disturbing the natural environment. It is also true that humans are currently utilizing fossil fuels representing hundreds of millions of years of bioaccumulation, without replacing this store of "natural capital". Similarly, humans are extracting and degrading geological accumulations of high grade metal and other ores, while discarding "garbo-junk". This provides some superficial justification for the "thermodynamic perspective".

But, as many analysts have argued, the supply of natural resources — while finite — is almost certainly not the limiting factor for human survival and prosperity. On the contrary, it is technologically feasible to shift from non-renewable to renewable resources. Most economists believe that this would happen automatically as soon as the cost of extracting and refining virgin resources rises to the point where it exceeds the cost of recovery, reuse and recycling. Resource prices would undoubtedly rise, but this need not reduce consumer welfare in the long run. (The transitional economic dislocations might be severe, but this is a different order of problem).

The long-run dangers arising from human activity probably come from another direction entirely. It is not the finiteness of resource stocks, but the fragility of self-organized natural cycles that we have to fear. Unfortunately, the services provided by these cycles are part of the global commons. They are priceless, yet "free". Markets play no role in the allocation of these resources. There is no built-in mechanism to ensure that supply will grow to meet demand. Indeed, there is every chance that the supply of environmental services will dwindle in coming decades as the demand, generated by population growth and economic growth, grows exponentially. In fact, a slightly disguised version of the dilemma posed by Malthus is upon us.

Exergy as a Measure of Resource/Waste Stocks & Flows

I noted earlier that the first law has two implications. One is the mass balance principle, about which I have nothing to add here to what has been said elsewhere. The other is the fact that energy is conserved in all processes. I said that the latter point is virtually empty of practical significance. The reason is that most discussions of "energy" are really about available energy, i.e. "exergy", which is not conserved.

If the entropy law does not imply that the economic system has a short and finite lifetime determined by the fixed stock of "low entropy" on the earth, then what does it imply? Does the second law of thermodynamics have any significant economic implications after all? I believe that it does, both for micro- and macro- perspectives. For the micro perspective, it is helpful to recognize that physical laws (first and second laws together) impose certain constraints on the economic system because they impose constraints on materials transformation processes that are essential to the economy.

Obviously virtually all industrial processes are driven by "free" exergy, usually provided by fossil fuels or electric power imported from outside. Exergy balance conditions constitute an effective constraint on possible industrial process outcomes. If these conditions are violated — as in the case of the "perpetual motion machine" — the postulated process cannot occur. As a practical matter, *existing* materials transformation processes obviously must satisfy the second-law conditions (since they do occur). Modelling actual industrial systems can be done without explicit attention to second law constraints. However, in constructing hypothetical future industrial systems (based, for instance, on solar hydrogen), or modelling processes in the natural world under altered conditions (such as the carbon cycle or the nitrogen cycle), it is unquestionably important to take second-law constraints into account.

One of the objectives of process designers is to minimize input cost and, by extension, exergy consumption. Of course, in principle one cannot simultaneously minimize two objective functions. Nevertheless, in practice it often turns out that the cost of operating a system is closely related to its exergy efficiency. This means that it is important to ascertain the capital cost of a process technology as a function of its exergy efficiency. "Thermo-economics" as applied to process optimization has become a subject of systematic research and study in some of the world's top engineering schools. The technicalities of process design need not concern us further at this stage.

The second law of thermodynamics has immediate importance for energy analysis on the next level of aggregation, too. Since energy is conserved in all transformation processes (the first law), there is no meaningful way to compare two energy conversion processes without utilizing second-law considerations. In comparing two possible energy conversion systems — for instance, a system involving large-scale co-generation and "district heating" *vis a vis* a system involving solar powered heat pumps — it is essential to use exergy as the unit of comparison, rather than energy.

Since exergy balance conditions apply to every process, the exergy-content of all process inputs (including utilities) must be equal to the exergy lost in a process plus the exergy content of process outputs. Exergy lost in the process is converted into entropy. Entropy *per se* does no harm. It merely reflects the homogenization and elimination of differences and gradients. But entropy can be generated by unnatural processes initiated by waste emissions from industry and consumption. It can be argued that the "potential entropy" (or exergy content) of products and waste residuals is actually the most general measure of potential environmental disturbance resulting from human economic activities [Ayres & Martinàs 1995]. The above statement is too abstract to be meaningful for most economists. In any case, computational details need not concern us here. Suffice it to say that *the exergy content of wastes is computable*. This permits us to make meaningful comparisons between systems, and over time.

To summarize: the importance of the second law of thermodynamics for engineering economics is that it specifies precise conditions that must be satisfied by *all* physical processes. In particular, all material transformation processes must satisfy both first law (material balance) and second law (exergy balance) conditions. Hence economic models with physical implications — especially models intended to analyze future situations where new processes and technologies can be expected — should explicitly reflect these constraints.

All this is fairly straightforward, so far. But, there is more. Efficient markets allocate resources optimally if, and only if, all actors in the market possess full information. Prices and price changes constitute information. If a resource is becoming scarce its price will increase. This information induces consumers to seek substitutes to the resource, and it induces producers to invest in added capacity, or R&D to find and develop new resources.

Needless to say, in real markets information is also a scarce commodity with market value. It is not free, nor even cheap. Decision-makers with better information can make better decisions. This applies at all levels of decision-making, or course. But I am particularly concerned with decision-making at the highest level, as it concerns national policy with respect to resources, transportation, environment, economics and so on. Because information has value, national governments collect statistics and maintain large data bases.

If all services of importance to human society were provided through efficient markets, optimal resource allocation would correspond exactly to the least cost solution. To find this it would be sufficient to collect and publish price and monetary input/output information alone. But, because markets are imperfect and many social and environmental services are "priceless" (as I commented earlier), it is necessary to use other supplementary measures and indicators in order to make rational decisions. This means it is necessary to collect and maintain other kinds of data. In particular, it is important to collect data on material resources, material transformation and production, waste generation and pollutant emissions. For instance, it is necessary to conduct evaluations of benefits vs. costs, in many situations where price or "value" data is lacking. There is much discussion of the pros and cons of available methodologies for valuation of non-market services in monetary terms, using hedonic analysis, or surveys to determine "willingness to pay" (WTP) or "willingness to accept" (WTA). However, this is not the place to comment on this area of economics research.

But for rational decision-making it is also important to develop measures for assessing and comparing the stocks and flows of physical resources and wastes. How is one to compare "reserves" of different metals or minerals, *vis a vis* fuels? How is one to assess the relative performance of different industries in terms of physical resource utilization? Or in terms of waste generation and emissions? How can we assess the comparative performance of firms within an industry, or of industries with each other, or of nations with each other? How can we even assess the performance of a firm, or an industry, or a nation, from one year — or decade — to the next?

For these purposes a single common measure would be of great value. It would provide a potential tool for comparing technologies and identifying potential areas of improvement. It is also a potentially valuable tool for life-cycle analysis at the product or process level. Being *the* measure of potential work embodied in a material — whether it be a fuel, a food or a material used for other purposes — makes exergy a more natural choice for a common measure of resource quantity than either mass or energy. Unfortunately, it has not yet been applied in this role. In the case of fuels, another thermodynamic variable, the heat of combustion, has been used for this purpose, under the incorrect and misleading title "energy". (In most of the resource literature, the term *energy* is used incorrectly where *exergy* should be used instead.)

The importance of availability for resource accounting was, and still is, completely ignored in the standard energy accounting methodology [e.g. Nakićenović *et al* 1996]. It has scarcely even been suggested in connection with accounting for other resources. Geologists and resource economists had certainly noticed the fact that ore grades have been declining, on the average, over time [Herfindahl 1967; COMRATE 1975; Skinner 1976]. The depletion phenomenon is particularly evident in the case of copper, lead, zinc, tin, silver and gold ores. Declining fossil energy resource quality is also significant for national economic growth accounting [Hall *et al* 1986].

However, up to now, concerns about ore grade/quality have not seemed to justify the incorporation of resource quality measures in the resource accounting system. I think it is now appropriate to measure resource quality as well as quantity. A certain shale deposit may contain as much energy as a deposit of natural gas, but if much of the energy (actually exergy) in the shale is needed to separate the kerogen from the ash, remove the unwanted sulfur compounds, and gasify the remainder, its exergy content is much lower. Two copper mines may contain equal amounts of copper, but if the ore grade is different, the amount of exergy embodied in the copper (which is inversely related to the amount of exergy required to process the ore) can be very different [e.g. Ruth 1995].

The first systematic attempt to use exergy as a general quality measure of all resources, including renewables (food and forest products) and mineral ores, was conducted in Sweden by G. Wall [Wall 1977, 1986]. Later Wall applied this approach to Japan [Wall 1990] and Italy [Wall *et al* 1994; Sciubba 1995]. Several other national studies to estimate energy and/or exergy efficiency for a wide range of countries have been published recently, e.g. Canada [Rosen 1992], Brazil [Schaeffer & Wirtshafter 1992]; OECD countries [Nakićenović 1993], and Turkey [Ozdogan & Arikol 1995].

Wall's work, and its successors, focussed mainly on the conversion of "primary" exergy into "useful" exergy (e.g. space heating, hot water, mechanical energy). These analyses are incomplete insofar as they implicitly assume that "useful" exergy is equivalent to final services. In fact, this is not so. Indeed, "useful energy" tends to be used quite inefficiently (e.g. due to poor insulation, wasteful use of transport vehicles, etc.) Data is sketchy but, taking into account the missing last step in the conversion chain, namely the efficiency of generating final services from useful exergy, it is clear that the overall second-law efficiency of modern economies is only a few percent, consistent with the earlier estimates by Ayres & Narkus-Kramer [Ayres & Narkus-Kramer 1976; also Ayres 1989].[7]

All of the above-mentioned studies were carried out at a very aggregated level. Among them, only Wall considered non-fuel resources such as forest products and iron ore, and he did not attempt to incorporate sophisticated calculations of the exergy content of non-fuel materials and materials losses at various stages of processing. (Nor did he deal with the problem of end-uses, mentioned above.) Nevertheless, Wall's work was path-breaking, in that it suggested for the first time a common way of measuring stocks and flows of all natural resources. Its weakness was that it failed to recognize, still less address, the serious computational problems involved in such a system.

Using the computational tools and data base developed by engineers and chemists it is now a fairly straightforward exercise to implement a more complete exergy accounting system [Ayres *et al* 1996]. This system would serve as a resource accounting framework, covering both stocks and flows of fuels, agricultural and forest products, and other industrial materials. It would provide a natural basis for assessing the efficacy of resource use and identifying policy tradeoffs and cost effective opportunities for conservation. As discussed below, it would also provide a natural means of including waste flows and pollution in the same comprehensive framework.

Exergy analysis can also be used in life cycle analysis (LCA). The use of exergy analysis offers three advantages for LCA over the standard approaches using energy and mass, separately. First, by using exergy as a common measure of inputs and outputs, we can immediately estimate *exergetic efficiency*, namely the ratio of exergy outputs to total exergy inputs (including utilities). This provides an indication of the theoretical potential for future improvement for a process. In other words, if the exergetic efficiency of the process is low

— say 20% or less — it is very likely that process improvements could be introduced in the future that would sharply cut both the raw material and/or fuel inputs (which are costly) but also the waste effluents associated with the process. On the other hand, if a process is already very efficient, the scope for future improvements is correspondingly reduced.

The second potential advantage of using exergy analysis for LCA is that it facilitates the comparison of "apples" with "oranges". Up to now, the problem of comparing impacts in different environmental domains remains unresolved. There is probably no ideal solution. I believe, however, that the use of exergy as a common measure will offer some advantages in this area. There are many reasons for desiring a single composite measure, however imperfect, if only for screening purposes. The use of GNP as a general measure in economics can be cited as an illustration of the value of such a measure.

This sort of argument has been used in support of the use of energy (or "net energy") as a general measure for both ecological and economic systems [IFIAS 1975]; [Odum & Odum 1981]; [Spreng 1988]; [Slesser 1993]. A similar argument is used to support the choice of materials (i.e. mass) input intensity as a common measure for comparing diverse activities and processes, from steel production to yogurt manufacturing [e.g. Schmidt-Bleek 1992, 1994]. Both these measures have serious deficiencies, however, insofar as general application is concerned. No single measure can serve every purpose, and exergy is no exception. However, exergy is clearly superior to either net energy or mass in that it incorporates their useful features while surmounting some of their limitations.

While exergy embodied in wastes is *not* a reliable measure of human or eco-toxicity, it is certainly a more realistic indicator of potential environmental impact than either mass or waste heat (which is the only measure available from "net energy" analysis). The major drawback up to now has been unfamiliarity and the difficulty of obtaining data and performing calculations. These difficulties have now been, or can be, substantially overcome.

The third advantage of using exergy in the context of LCA really follows from the second. However, there is a specific application of LCA that cannot be implemented without a unitary measure, and which would not be convincing if either net energy analysis or materials intensity analysis were used. This use would be for year-to-year environmental performance comparisons for large firms, industries or nations.

To be sure, a stand-alone report of composite exergy losses and emissions and nothing else would not convey much information to most readers. But, in all fairness, the current approach to environmental reporting generally falls into one of two traps. Either it presents a long list of non-comparable emissions, from airborne particulates to biological oxygen demand, which most readers cannot evaluate. Or, it presents a list of percentage reductions in "emissions" or "wastes" over prior years without any background information to enable the reader to assess the real benefit of the reductions. The use of a common measure like exergy in combination with a balanced set of mass flows in an LCA format exhibiting both inputs and outputs, would constitute a major step forward over current practices.

A time-series of exergy-based assessments of the aggregate efficiency and waste generation of a multi-product firm, or an industry such as pulp and paper or petroleum refining (or a single firm in one of these industries) would be a valuable supplement to the sort of data-poor advertising-style environmental report that is typically issued today. The same holds true for year-to-year and national-level statistical comparisons, such as those compiled by the *World Bank Development Report* (annual), UNIDO's *Industrial Development Report* (annual), World Resources Institute's *World Resources*(bi-annual) and Worldwatch Institute's *State of the World*, and *Vital Signs* (both annual).

Exergy as a Factor of Production

The criterion for a true factor of production is that it be produced *outside* the economic system, everything else being an intermediate. In the 18th century labor and land were considered to be the two factors of production. Capital, in turn, is an intermediate that is produced from labor (and pre-existing capital). Capital, to a Marxist, is nothing more than an accumulation of labor surplus. To Marxists, there is only one factor of production, namely labor. Land has gradually been relegated to the historical footnotes. Nevertheless, most economists today consider labor and capital to be the factors of production. Indeed, they are so used to this formulation that they seldom stop to question the underlying assumptions.

However, a more sophisticated neo-classical response would be that energy (exergy) is an intermediate good rather than a true factor of production because it is not really *scarce*. The idea is that exergy, or thermodynamic work, is "produced" by some combination of labor and capital. Indeed, the difference between labor and thermodynamic work was anything but obvious in the days when human labor was primarily an exercise of the muscles. The distinction has become progressively clearer since animals, and later, machines, took over most of the activities involving physical strength or power and the role of human workers in most situations came to be understood more clearly as sensing, eye-hand coordination, design, planning, supervision, inspection and monitoring. In other words, human workers (except in rare cases) are not valued for jobs that horses or steam engines could do just as well, but rather for sensory acuity, physical dexterity, information processing and problem-solving skills [Ayres 1987, 1994].

The resource scarcity argument was thrashed out to some extent by neo-classical economists in the 1970's, largely in response to the worldwide publicity associated with the publication of the famous Report to the Club of Rome [Meadows *et al* 1972]. It is not necessary to recapitulate the discussion in detail. Suffice it to say that a number of leading theoreticians explored variations of economic growth models in which "resources" (meaning exergy) were given some explicit role. The general conclusion was that resource scarcity would not limit economic growth in the long run, given continued capital investment and technological progress. In most of these models, it was assumed that human capital and natural capital (i.e. "resources") are inherently substitutable and interchangeable, *without limit* [e.g. Solow 1974; Stiglitz 1974, 1979]. Only a few theoreticians even acknowledged that natural resource inputs might be essential to production, although the quantities needed might be virtually infinitesimal [e.g. Dasgupta & Heal 1974, 1979].

Evidently any conventional production function of the homogeneous type (Cobb-Douglas being only the simplest example) assumes unlimited substitutability between factors. This implies that resource inputs can be reduced to arbitrarily small levels, but only by correspondingly increasing capital inputs. Georgescu-Roegen in his 1971 book and many subsequent papers, especially his 1979 critique of Solow and Stiglitz [Georgescu-Roegen 1979] argues that this is a "conjuring trick". He says:

> "Solow and Stiglitz could not have come out with their conjuring trick had they borne in mind, first, that any material process consists in the transformation of some materials into others (the flow elements) by some agents (the fund elements), and second, that natural resources are the very sap of the economic process. They are *not* just like any other production factor. A change in capital or labor can only diminish the amount of waste in the production of a commodity: no agent can create the material on which it works." [8]

Daly comments that the neo-classical production function (of labor and capital) is equivalent to an assertion that it is possible to make a cake with only a cook and a kitchen, but that no flour, sugar or eggs are needed. This clearly contradicts both the first and second laws of thermodynamics. It is evident that G-R (and Daly) envision the economic system as a materials-processing system in which final products — commodities — are necessarily material in nature. (Indeed, this is a perfectly accurate description of the real economic system as it functions today. This vision lies at the core of the emerging field of industrial ecology, for instance). If the above description were timeless, the G-R/Daly critique would be devastating.

But, a perfectly acceptable neo-classical answer to their critique (I imagine) would be that in the distant future the economic system *need not* produce significant amounts of material goods at all. In principle, it could produce final services from very long-lived capital goods, with very high information content, and non-scarce renewable sources of energy, such as sunlight. At the end of its useful life, a capital good in this hypothetical economy would be repaired, upgraded and remanufactured, but rarely discarded entirely.

In short, it can be argued, as I have in the past, that there is no limit *in principle* to the economic output that can be obtained from a given resource input [e.g. Ayres 1978; Ayres & Kneese 1989]. Another way of say the same thing is that there is no limit *in principle* to the degree of dematerialization that can be achieved in the very long run. One must hasten to add that this does not mean that no materials need be processed at all. Nor does it imply that recovery, remanufacturing and recycling can be 100% efficient. No such claim need be made. My claim is, simply, that nobody can define a finite absolute minimum material input requirement for (with the obvious exception of food and drink) to produce a unit of economic welfare.

Nevertheless, the neoclassical tendency to omit resources as factors of production has one critical weakness. It is that the simple physical fact that exergy is *used up* in the economic production process, but cannot itself be created or "produced" by human activity. This will be equally true in my hypothetical dematerialized economic system of the distant future as of the real system as it operates today. Nor is exergy available in unlimited amounts at zero cost. Exergy as a factor of production is no less scarce than reproducible capital. If one can be substituted for, so can the other. Substitution works in both directions.

To be sure, an oil well requires capital investment and labor to "produce" oil, but the oil itself (and its exergy content) is a gift of nature. The same capital and labor are required to dig the well, whether or not it turns out to be a gusher or a dry hole. But the oil and gas were produced by natural processes, not by human actions. The same holds for minerals, forest products and agricultural products. In any case, it makes no sense to regard physical capital, which is unquestionably a product of human activity, as scarce while treating the exergy supply as unlimited. Capital may be scarce at a given moment in time because of time delays in the system, but exactly the same argument also applies in the case of exergy flows.

A heterodox view has been put forward by the so-called "biophysical school". This group has argued that the *only* factor of production is low-entropy "stuff" from the environment (i.e. *exergy*), and that even labor is an intermediate. In terms of explanatory power, this formulation is as good, if not better, than the neo-classical approach. The proponents of this view have called themselves ecological economists. For a coherent summary of this perspective and some of its implications, see [Cleveland *et al* 1984; Cleveland 1991; Costanza 1991].

However, it seems to me that, while exergy is indeed a factor of production, it is not the *only* exogenous input, as the biophysicists argue. I think labor is clearly exogenous to the economic system, just as virtually all economists have always insisted. Human labor could not exist without human beings, which require food and shelter. These, in turn, are "produced" by the economic system, to be sure. But humans pre-existed the economic system. It is true that humans require exergy (i.e. food) to survive. But so do all plants and animals. I cannot accept the argument that exergy is exogenous but labor is not. They both are exogenous, insofar as this term has meaning.

On the other hand, capital is certainly endogenous. It embodies both labor and exergy. Capital can be regarded as a factor of production, however, in the very precise sense that capital (in combination with labor and exergy inputs) is productive *by definition*. Capital consists of either money or tangible products (of labor and exergy and capital) that can be used (in combination with labor and exergy) to help produce other products. The argument for treating physical capital as an *independent* factor of production is the pragmatic one that, once produced, it endures for a significant time. The case of financial capital, especially liquid capital (cash), is less clear since liquid capital can — in principle — be consumed rather than invested. Conceptually, however, one can treat capital as a given. In a static model, capital pre-exists. It is there, or it isn't. It's origin does not matter. In a dynamic model, of course, capital must be produced in order to accumulate. But there is no conceptual difficulty in producing capital from capital, labor and exergy.

To summarize the last several paragraphs, I think there are three factors of production. They can be labelled K for capital stock, L for labor supply and E for exergy supply (including both food, feed, fuels and raw materials). One consequence of the academic discussion of resource economics in the 1970s was that "energy" was recognized for the first time in some growth models as a distinct factor of production (i.e. distinct from, but analogous to, labor and capital) [e.g. Allen *et al* 1976; Allen 1979]. Later, some economists added "materials" to the production function, distinguishing four factors of production, adding materials (M) to the other three. These production functions are generally called KLEM functions, reflecting the equal status of the four factors. I suggest that the two traditional factors E, M can and should be combined into a single factor, namely exergy.[9]

Capital is normally measured in monetary terms ($) because there is no common physical unit. Labor is normally measured in man-hours, notwithstanding the fact that skill levels (and remuneration) vary enormously. Exergy is measured in energy units, such as ergs, calories, kilojoules, BTUs or kilowatt-hours. Economic output (GDP= Q) is measured in monetary units. Since the labor supply is closely related and generally proportional to the population, it is convenient and not unreasonable to simplify the analysis by dividing all the variables by L. Then the problem is to explain GDP per capita ($q = Q/L$), in terms capital invested per capita ($k = K/L$) and exergy flux per capita ($e = E/L$).

The reason I have discussed "factors of production" at such — doubtless tedious — length can now be explained. Economists in the late 1950s were surprised to find that they could not adequately explain economic growth per capita in terms of changes in the two factors, capital and labor. Most of the growth in GDP had to be attributed to a residual, namely a time dependent multiplier $A(t)$ of the production function as a whole, or of one or more of its factors.[10] That multiplier was labelled "technical progress" [Solow 1957]. But no independent definition of technical progress has ever been offered. In fact, for economists, technical progress has essentially been identified with increasing *factor productivity* or (more usually) just labor productivity. Nobody has worried much about the circularity of this definition.

But, it is clear from many sorts of evidence that a large part — probably by far the largest part — of the historical increase of "labor productivity" that apparently drives economic growth is, in fact, attributable to the vast increase in the exergy flux, per unit of human labor, supplied from outside the system. In effect, exergy (in combination with machines, i.e. capital) has been a substitute for human labor in many sectors. (Machines, alone, cannot replace human labor.) If one adds exergy to the production function, then economic output — and growth — must be reallocated among three factors, labor, capital and exergy. This allocation would surely explain a much larger fraction of total historical growth, leaving correspondingly less to be explained by exogenous multipliers.

But to reformulate the growth problem in this manner introduces practical difficulties. One of them is the so-called Kuznets ("inverted U") curve, which shows that increasing output for industrializing economies tends to be closely correlated with exergy inputs, whereas after some point exergy requirements per unit output begin to decline as services begin to outweigh material production. This is an empirical observation that has been repeated a number of times. It is obviously incompatible with a traditional multiplicative production function of the Cobb-Douglas or CES type. It would require something more like a Leontief-type of production function.

This is not the place to discuss additive or hierarchical production functions or their implications. However, it is quite important for growth theorists to confront this problem. For reasons that have been adequately discussed elsewhere, long-term sustainability requires that future economic growth must rely much more on services and be less dependent on exergy inputs than in the past. This means it must be correspondingly more dependent on labor and capital. This is rather good news, in one sense, since labor is now in surplus supply almost everywhere whereas natural resources will inevitably become scarcer. On the other hand, the productivity of labor and physical capital must be increased *without* increasing exergy inputs. This brings out into the open a very fundamental issue: to explain how the economy can continue to generate an increasing flow of final services from a decreasing flow of physical inputs. This conundrum needs to be addressed seriously by economists and environmentalists.

Endnotes

1. For that matter it is also defined for non-material systems, such as radiation fields. Actually, material substances do have well-defined entropy measures (at well-defined temperatures and pressures). For many chemical elements and compounds entropy values per unit mass (mole) can be looked up in reference books such as the *Handbook of Physics and Chemistry.*

2. The technical problem here is that the earth's crust is not in chemical equilibrium with either the atmosphere or the oceans. In particular, the earth's crust contains significant quantities of hydrocarbons and sulfides, of biological origin, that are potentially reactive with oxygen but which are not exposed to the atmosphere. Obviously in the very long run, in the absence of biological activity, these materials would be oxidized and all of the free oxygen in the atmosphere would ultimately be combined with nitrogen, carbon or sulfur. Thus, the essence of the convention is to assume that the three media (air, oceans and crust) are in chemical equilibrium in the short run, i.e. in terms of the time scales of interest.

3. Most incident solar radiation is either re-radiated by clouds, absorbed and re-radiated by the earth's surface or absorbed by evaporation of water, from plant respiration or directly from the ocean surface. Solar warming of surface waters in the tropics drives the ocean currents. Evaporation also drives the hydrological cycle. Interactions between the two affect phenomena like the "El Nino" events.

   In short, 97% of global insolation is effectively wasted. A great deal of this is theoretically available to humans, either through solar heating devices or (better) for direct conversion to electricity via photovoltaic cells. These technologies are already on the shelf, or would be, given modest additional engineering development. Note that the global heat balance of the earth would not be affected by converting a significant fraction of incoming solar radiation to electrical energy, since the latter is ultimately dissipated as heat in any case. While it would be unwise to interfere extensively with the hydrological cycle, it would make a good deal of sense to capture solar power from the extensive deserts of the world, which currently reradiate the energy directly back to space. Cooling the surface of the land would actually permit the recolonization of vegetation into some regions that are now completely bare and arid.

4. However, it has been estimated that when indirect uses are taken into account, as much as 50% of the earth's biospheric production is beneficially used by humans [Vitousek 1986].

5. A more precise statement is the following: (i). Unavailable matter cannot be recycled and (ii) a closed system (i.e. a system that cannot exchange matter with the environment) cannot perform work indefinitely at a constant rate.

6. In fact, physicists have suggested other "fourth laws" [e.g. Landsberg 1984b].

7. In sharp contrast to most estimates in the 1970's, Gilli, Nakićenović and Kurz now argue forcefully that the theoretical potential for improvement might be as great as 20-fold [Nakićenović *et al* 1996]. On the global scale, Nakićenović *et al* now estimate that primary to useful energy efficiency is around 30% while exergy efficiency is about 10% (*ibid*).

8. I am indebted to Herman Daly for calling my attention to this quotation in his commentary "Georgescu-Roegen vs. Solow/Stiglitz" presented at the ISEE Conference, Boston, Aug. 1996.

9. In earlier work I tried to treat all resources, together with technology, as different but equivalent "kinds" of physical information [Ayres & Miller 1980; Ayres 1988]. I have since realized that this was going too far; they are not equivalent. However, the equivalence between energy and material resources is much more justifiable.

10. When the multiplier applies to the production function as a whole, it is called "neutral" technological progress. When it applies to L or K, it is "labor enhancing" or "capital enhancing".

References

[Allen 1979] Allen, Edward L., *Energy & Economic Growth in the United States* [Series: Perspectives in Energy] , The MIT Press, Cambridge MA, 1979.

[Allen *et al* 1976] Allen, Edward L. *et al*, *U.S. Energy & Economic Growth, 1975-2010*, Publication (ORAU/IEA-76-7), Oak Ridge Associated Universities Institute for Energy Analysis, Oak Ridge TN, 1976.

[Artigliani 1991] Artigliani, Robert. ``Social Evolution: A Non-Equilibrium Systems Model", in: Laszlo, E.(ed), *The New Evolutionary Paradigm* (Series: World Futures General Evolution Studies) 2(ISBN 2-88124-375-4), Gordon & Breach Scientific Publishers, New York, 1991.

[Ayres 1978] Ayres, Robert U., *Resources, Environment & Economics: Applications of the Materials/Energy Balance Principle*, John Wiley & Sons, New York, 1978.

[Ayres 1987] Ayres, Robert U., *Manufacturing & Human Labor as Information Processes*, Research Report (RR-87-19), International Institute for Applied Systems Analysis, Laxenburg, Austria, July 1987.

[Ayres 1988] Ayres, Robert U. "Optimal growth paths with exhaustible resources: An information based model" *Journal of Environmental Economics and Management* 1988

[Ayres 1989] Ayres, Robert U., *Energy Inefficiency in US Economy*, Research Report (WP-RR-12), International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria, 1989.

[Ayres 1994] Ayres, Robert U., *Information, Entropy & Progress*, American Institute of Physics, New York, 1994.

[Ayres 1995] Ayres, Robert U., ``Economics, Thermodynamics & Process Analysis", *Journal of Environmental & Resource Economics*, 1995.

[Ayres 1995a] Ayres, Robert U. "Life Cycle Analysis: A Critique" *Resources, Conservation and Recycling Vol 14*. 1995 pp. 199-223.

[Ayres *et al* 1996] Ayres, Robert U., Leslie W. Ayres and Katalin Martinàs "Ecothermodynamics: Exergy and Life Cycle Analysis" CMER Working Paper 96/EPS, INSEAD, Fontainebleau, France Jan. 1996

[Ayres & Cummings-Saxton 1975] Ayres, Robert U. & James Cummings-Saxton. ``The Materials-Process-Product Model: Theory & Applications", in: Vogeley (ed), *Mineral Materials Modeling —A State-of-the-Art Review* :178-244, Johns Hopkins University Press, Baltimore, 1975.

[Ayres & Kneese 1969] Ayres, Robert U. & Allan V. Kneese, ``Production, Consumption & Externalities", *American Economic Review*, June 1969. Reprinted in *Benchmark Papers in Electrical Engineering & Computer Science*, P. Daltz & H. Perloff (eds), Dowden, Hutchison & Ross Inc., Stroudsburg PA, 1974 and in Bobbs-Merrill Reprint Series, New York, 1974.

[Ayres & Kneese 1989] Ayres, Robert U. & Allen V. Kneese. ``Externalities: Economics & Thermodynamics", in: Archibugi & Nijkamp (eds), *Economy & Ecology: Towards Sustainable Development*, Kluwer Academic Publishers, Netherlands, 1989.

[Ayres & Martinàs 1995] Ayres, Robert U. & Katalin Martinàs, ``Waste Potential Entropy: The Ultimate Ecotoxic", *Économique Appliquée, XLVIII*, 1995 pp. 95-120.

[Ayres & Miller 1980] Ayres Robert U. and Stephen M. Miller "The role of technological change and resource constraints on an optimal growth path" *Journal of Environmental Economics and Management 7* 1980 pp. 353-371.

[Ayres & Narkus-Kramer 1976] Ayres, Robert U. & Mark Narkus-Kramer, *An Assessment of Methodologies for Estimating National Energy Efficiency*, Winter Meeting, American Society of Mechanical Engineers, November 1976.

[Ayres & Simonis 1994] Ayres, Robert U. & Udo E. Simonis (eds), *Industrial Metabolism; Restructuring for Sustainable Development* (UNUP-841), United Nations University Press, Tokyo, 1994. (ISBN 92-808-0841-9)

[Berry *et al* 1978] Berry, R. S., Geoffrey Heal & Peter Salamon, ``On a Relation Between Economic & Thermodynamic Optima", *Resources & Energy* **1**, October 1978 :125-127.

[Blum 1968] Blum, H. F., *Time's Arrow & Evolution*, Princeton University Press, Princeton NJ, 1968. 3rd edition.

[Britten & Davidson 1969] Britten R, J. & E. H. Davidson "Gene Regulation for Higher Cells: A Theory" *Science* Vol. 165, 1969 pp. 349-357

[Brooks & Wiley 1986] Brooks, Daniel R. & E. O. Wiley, *Evolution as Entropy: Towards a Unified Theory* *of Biology*, University of Chicago Press, Chicago, 1986.

[Cleveland *et al* 1984] Cleveland, Cutler J., Robert Costanza, Charles A. S. Hall, and Robert Kaufmann "Energy and the U.S. Economy: A Biophysical Perspective" *Science 225*, 1984 pp. 890-897

[Cleveland 1991] Cleveland, Cutler J. "Natural Resource Scarcity and Economic Growth Revisited: Economic and Biophysical Perspectives" in R. Costanza (ed) *Ecological Economics: The Science and Management of Sustainability* New York, Columbia University Press, 1991 pp. 289-317

[COMRATE 1975] *Mineral Resources and the Environment* Report of the Committee on Mineral Resources and the Environment, National Academy of Sciences - National Research Council, Washington DC, National Academy Press, 1975

[Costanza 1991] R. Costanza (ed) *Ecological Economics: The Science and Management of Sustainability* New York, Columbia University Press, 1991

[Daly 1991] Daly, Herman E., *Steady-State Economics*, Island Press, Washington DC, 1991.

[Daly 1996] Daly, Herman E. "Georgescu-Roegen versus Solow/Stiglitz" presented at ISEE Conference, Boston, August 1996.

[Dasgupta & Heal 1974] Dasgupta, Partha & G. Heal. ``The Optimal Depletion of Exhaustible Resources", in: *Symposium on the Economics of Exhaustible Resources*, Review of Economic Studies, 1974.

[Dasgupta & Heal-a 1979] Dasgupta, Partha & G. Heal, *Economic Theory & Exhaustible Resources* (Series: Cambridge Economic Handbooks), Cambridge University Press, Cambridge, UK, 1979.

[Dollo 1893] Dollo, L. "Les Lois de l'Evolution" *Bull. Belg. Geol.* Vol. 7, 1893 pp. 164-167

[Eigen 1971] Eigen, Manfred, ``Self Organization of Matter & the Evolution of Biological Macro-molecules", *Naturwiss* **58**, October 1971.

[Faber *et al* 1987] Faber, Malte, H. Niemes and G. Stephan *Entropy, Environment and Resources* Berlin: Springer-Verlag 1987

[Faucheux 1994] Faucheux, Sylvie. ``Energy Analysis & Sustainable Development", in: Pethig, Rudiger(ed), *Valuing the Environment: Methodological & Measurement Issues*, Kluwer Academic Publishers, Dordrecht, Netherlands, 1994.

[Fisher 1930] Fisher R. A., *The Genetical Theory of Natural Selection* Oxford: Clarendon Press 1930.

[Georgescu-Roegen 1971] Georgescu-Roegen, Nicholas, *The Entropy Law & the Economic Process*, Harvard University Press, Cambridge MA, 1971.

[Georgescu-Roegen, 1979] Georgescu-Roegen, Nicholas, "Comments on the papers by Daly and Stiglitz" in V. Kerry Smith (ed) *Scarcity and Growth Reconsidered* RFF and Johns Hopkins University Press, Baltimore, 1979

[Georgescu-Roegen 1979a] Georgescu-Roegen, Nicholas, ``Myths About Energy & Matter", *Growth & Change* **10**(1), 1979.

[Hall *et al* 1986] Hall, Charles A. S., Cutler J. Cleveland and Robert Kaufmann, *Energy and Resource Quality: The Ecology of the Economic Process* N.Y. Wiley-Interscience, 1986.

[Herfindahl 1967] Herfindahl, Orris "Depletion and Economic Theory", in M. Gaffney (ed) *Extractive Resources and Taxation* Madison: U. of Wisconsin Press, 1967

[IFIAS 1975] IFIAS Workshop on Energy Analysis and Economics, Workshop Report #9, Stockholm, Aug. 1975

[Kneese, Ayres & d'Arge 1970] Ayres, Robert U., Ralph C. d'Arge & Allen V. Kneese, *Aspects of Environmental Economics: A Materials Balance - General Equilibrium Approach*, Johns Hopkins University Press, Baltimore, 1970.

[Landsberg 1984a] Landsberg, P. T. "Can Entropy and Order Increase Together?" *Physics Letters* 102A, 1984 pp. 171-173

[Landsberg 1984b] Landsberg, P. T. "Is Equilibrium Always an Entropy Maximum?" *J. Stat. Physics,* Vol 35. 1984 pp. 159-169

[Layzer 1977] Layzer, D. "Information in Cosmology, Physics and Biology", *Int. J. Quantum Chem.* Vol 12 (supp 1) 1977 pp. 185-195.

[Maynard-Smith 1970] "The Structure of Neo-Darwinism" in C. H. Waddington ed. *Towards a Theoretical Biology*, Vol 2, Chicago: Aldine Pub. Co. 1970, pp. 82-89

[Meadows *et al* 1972] Meadows, Donella H, Dennis L. Meadows, Jorgen Randers & William W. Behrens III, *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, Universe Books, New York, 1972.

[Moravec 1991] Moravec, Hans *Mind Children: The Future of Robot and Human Intelligence* Cambridge Mass: Harvard University Press, 1991.

[Nakićenović 1993] Nakićenović, Nebojsa (ed), ``Long-Term Strategies for Mitigating Global Warming", *Energy* **18**(5), 1993 :401-609. [special issue]

[Nakićenović 1996] Nakićenović, Nebojsa, Paul V. Gilli & Rainer Kurz, ``Regional & Global Exergy & Energy Efficiencies", *Energy* **21**, 1996.

[Nicolis & Prigogine 1977] Nicolis, Gregoire & Ilya Prigogine, *Self-Organization in Non-Equilibrium Systems*, Wiley-Interscience, New York, 1977.

[Odum & Odum 1981] Odum, Howard T. & Eugene C. *Energy Basis for Man and Nature* N.Y. McGraw-Hill Book Co. 1975.

[Ozdogan & Arikol 1995] Ozdogan, S.. & M. Arikol, ``Energy & Exergy Analysis of Selected Turkish Industries", *Energy* **18**(1), 1995 :73-80.

[Prigogine *et al* 1972] Prigogine, Ilya, Gregoire Nicolis & A. Babloyantz, ``Thermodynamics of Evolution", *Physics Today* **23**(11/12), November/December 1972 :23-28(N) & 38-44(D).

[Rifkin 1980] Rifkin, Jeremy, *Entropy: A New World View*, Viking Press, New York, 1980. (ISBN 0-670-29717-8)

[Rosen 1992] Rosen, M.A., ``Evaluation of Energy Utilization Efficiency in Canada", *Energy* **17**, 1992 :339-350.

[Ruth 1993] Ruth, Matthias *Integrating Economics, Ecology and Thermodynamics* Dordrecht: Kluwer Academic Publishers, 1993

[Ruth 1995] Ruth, Matthias "Thermodynamic implications of natural resource extraction and technical change in US copper mining" *Environment and Resource Economics 6,* 1995 pp. 187-206

[Sagan 1977] Sagan, Carl, *Dragons of Eden - Speculations on the Evolution of Human Intelligence*, Random House, New York, 1977.

[Schaeffer & Wirtshafter 1992] Schaeffer, R. & R. M. Wirtshafter, ``An Exergy Analysis of the Brazilian Economy: From Energy Products to Final Use", *Energy* **17**, 1992 :841-855.

[Schmidt-Bleek 1992] Schmidt-Bleek, Friedrich "MIPS a Universal Ecological Measure" *Fresenius Environmental Bulletin* Vol. 1 1992 pp 306-311

[Schmidt-Bleek 1994] Schmidt-Bleek, Friedrich *Wieviel Umwelt Braucht der Mensch? MIPS das Maß für ökologisches Wirtschaften* Birkhaúser, Basel 1994.

[Sciubba 1995] Sciubba, Enrico, *An Application of a General Energetic Model to the Analysis of the Sustainability of Complex Systems*, IECEC Paper (EL-239), American Society of Mechanical Engineering, Washington DC, 1995.

[Skinner 1976] Skinner, Brian J. *Earth Resources* (2nd ed), Englewood Cliffs N. J. Prentice-Hall

[Slesser 1993] Slesser, Malcolm "Energy Resources as Natural Capital" *Int. J. of Global Energy Issues* Vol.5 1993 pp. 1-4

[Solow 1957] Solow, Robert "Technical Change and the Aggregate Production Function" *Rev. Econ. & Statistics* Aug. 1957 pp. 312-320

[Solow 1974] Solow, Robert M., ``The Economics of Resources or the Resources of Economics", *American Economic Review* **64**, 1974.

[Spreng 1988] Spreng, Daniel T. *Net Energy Requirements and the Energy Requirements of Energy Systems* N.Y. Praeger 1988.

[Stiglitz 1974] Stiglitz, Joseph, ``Growth with Exhaustible Natural Resources. Efficient & Optimal Growth Paths", *Review of Economic Studies*, 1974.

[Stiglitz 1979] Stiglitz, Joseph. ``A Neoclassical Analysis of the Economics of Natural Resources", in: Smith, V. Kerry(ed), *Scarcity & Growth Reconsidered*, Resources for the Future, Washington DC, 1979.

[Szargut *et al* 1988] Szargut, Jan, David R. Morris & Frank R. Steward, *Exergy Analysis of Thermal, Chemical, & Metallurgical Processes* (ISBN 0-89116-574-6), Hemisphere Publishing Corporation, New York, 1988.

[Vitousek 1986] Vitousek, Peter M., ``Human Appropriation of the Products of Photosynthesis", *Bioscience* **34**(6), 1986 :368-373.

[Wall 1977] Wall, Goran, *Exergy: A Useful Concept within Resource Accounting*, (77-42), Institute of Theoretical Physics, Chalmers University of Technology & University of Goteborg, Goteborg, Sweden, 1977.

[Wall 1986] Wall, Goran, ``Exergy Conversion in the Swedish Society", *Energy* **15**, 1986 :435-444.

[Wall 1990] Wall, Goran, ``Exergy Conversion in the Japanese Society", *Energy* **15**, 1990 :435-444.

[Wall *et al* 1994] Wall, Goran, Enrico Sciubba & Vincenzo Naso, ``Exergy Use in the Italian Society", *Energy* **19**(12), 1994 :1267-1274.

[Wolfgang & Ayres 1995] Wolfgang, Nichole & Leslie W. Ayres. *Simulation as a Useful Tool in Examining Waste Production*, INSEAD, Fontainebleau, France, April 1995.

APPENDIX: EXERGY BALANCE IN THE ATMOSPHERE

In particular, exergy inflows from the sun to the earth must be balanced by exergy outflows (i.e. IR heat radiation), exergy gains by or losses from terrestrial inventories and exergy losses from biospheric and economic processes. Stored exergy on the earth consists of biomass, fossil fuels and other potentially reactive minerals and compounds, including reduced forms of metals, reduced forms of sulfur and atmospheric oxygen and nitrogen. In a steady state condition, the difference between solar exergy inflows and IR exergy outflows is available to do work i.e. to drive terrestrial atmospheric, hydrospheric, geospheric and biospheric processes. Among these natural processes, only the biosphere extracts exergy from the solar influx and accumulates it in biomass, some of which is permanently sequestered in sediments and sedimentary. In short, whereas the physical processes merely "consume" exergy (being driven by it), the biological processes also accumulate and store some of it.

Some interesting implications follow from the exergy balance condition. For instance, consider the glacial periods, when the earth's temperature dropped 5 or 6 degrees Celsius, or about 2%, for reasons not yet fully understood. The outward efflux of exergy in the form of IR radiation — which depends on the fourth power of the earth's effective surface temperature — correspondingly decreased by around 7%. Part of this could have been due to the greenhouse effect operating in reverse. (It is known that CO_2 levels and temperature levels tracked each other rather closely). Snow cover over the glaciers must have significantly increased the earth's albedo, thus reducing the solar exergy flux absorbed in the atmosphere or at the earth's surface. If the solar exergy influx had not changed, it would follow that the exergy available for driving natural processes on the earth's surface must have *increased* quite significantly in consequence. Yet a lower surface temperature, with glaciers covering significant land areas, must have also reduced the ambient biomass and consequently the rate of photosynthesis. The only possible way of consuming excess exergy would have been to drive stronger atmospheric circulation, more violent storms and stronger ocean currents.

Now suppose industrial activities must be added to the equation. What happens when greenhouse warming increases the surface temperature? One immediate effect must be a higher exergy outflow from earth (as IR radiation). Another immediate effect is likely to be global warming, which should (other factors remaining equal) increase evapo-transpiration and the level of photosynthetic activity and the exergy consumed for plant metabolism. A third immediate effect of warming would seem to be to increase the evaporation of water from the oceans. The last two effects, taken together, would raise humidity, cloud cover and precipitation. The humidity effect would tend to increase greenhouse warming, whereas increased cloud cover would tend to increase the albedo and cause compensatory cooling. The other consequence of increased evaporation is a matching increase of precipitation. The important question is where will it occur?

There is normally a net transport of moisture from the oceans to the land, compensated by river flows back to the oceans. Net evaporation cools the oceans, while condensation warms the land. This influences the land-water temperature gradient, which drives the onshore/offshore winds. This part of the system is self-adjusting: if the land cools too much relative to the ocean, onshore winds bring in moisture, and conversely. Unless compensated for by some other phenomenon not yet taken into account — for instance decreased high level cloud cover, and reduced albedo — the consequences of surface warming (re-radiation and increased evaporation) *must* leave less solar exergy available to drive other atmospheric and ocean processes, notably the jet streams and the ocean currents. Presumably this explains why general circulation models (GCMs) predict that global warming will affect the polar regions most drastically, in the short run, while leaving the equatorial regions relatively unaffected.

One consequence would be accelerated melting of polar ice. This would suddenly increase the influx of fresh water into the Gulf Stream as it flows through the North Atlantic. Fresh water is less dense than salt water (made saltier due to evaporation from the surface of tropical oceans). Normally when the salty — and dense — Gulf stream water reaches a sufficiently northern latitude, and cools off sufficiently, it sinks into the depths where it returns back to the southern seas. An influx of fresh water at the surface would interfere with this sinking and accelerate the warming of the polar region.

Apart from atmospheric and oceanic implications, the advent of industrial activity has altered the pre-industrial balance. On the one hand, humans now dispose of a small but increasing direct share of available solar exergy "current income", mainly through agricultural use and hydrological engineering. In addition, humans are consuming exergy capital that was accumulated through past photosynthesis and sequestration. Indeed, it is the latter (mainly combustion of fossil fuels) that is the primary cause of climate warming and other environmental threats.