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ANALYSIS

When, where, and by how much do biophysical limits constrain the economic process? A survey of Nicholas Georgescu-Roegen's contribution to ecological economics[1]

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1. Introduction

In the 1960s the neoclassical paradigm came under increasing attack for its lack of attention to the environmental basis of human well-being. Like water beading off the feathers of a duck, most of the attacks were repelled or ignored by the discipline without serious regard. Many of the criticisms were levied by natural scientists who easily could be dismissed as not really 'understanding economics'. High-profile attacks such as the *Population Bomb* (Ehrlich, 1968) and the *Limits to Growth* (Meadows et al., 1972) had to be dealt with, at least superficially, not because they challenged the core assumptions of the neoclassical paradigm, but principally because they received lots of attention in the popular press and culture as well as in academic circles. 'Circling the wagons' to defend the paradigm against the cataclysmic vision of the *Limits to Growth* was easy. Economists eagerly pointed out that these models failed because they did not appreciate the power of innovations to overcome resource scarcity and environmental degradation (Porter and van der Linde, 1995).

Frontal assaults from card-carrying members of the traditional economic paradigm have been greeted with more pervasive silence because they

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could not be dismissed as outsiders unfamiliar with core assumptions, theories, and analytical methods. It is in this category that the work of Nicholas Georgescu-Roegen falls. His demolition and reconstruction of standard economics was not the passing swipe of a naive opportunist. Rather, he had a deep and thorough understanding of economic theory, economic history, and mathematics, as well as considerable knowledge of physics and the history and philosophy of science. His genius was rooted in his instincts about the relevance of biophysical principles for human economic aspirations. Georgescu-Roegen had a vision of economics rooted in the physics, chemistry, and biology of human existence, and the analytical and intellectual capabilities to weave those pieces together with the humanistic tradition of economics.

It is not surprising that Georgescu-Roegen is virtually ignored by mainstream economics. By definition, adherents to a paradigm believe that all relevant phenomena are best understood through the conceptual lens of that paradigm, and that all problems can be solved with the analytical tools used in that paradigm. The more strident and accurate the attacks, the more they are ignored or explained away by the existing paradigm. Thus, one measure of Georgescu-Roegen's insight is the degree to which he is ignored by mainstream economics while being championed in other areas. But the real testament to his vision is the degree to which his 'pre-analytic' vision of the economic process helped define a basis for natural and social scientists to work together, and his identification of key, unresolved questions about sustainability. In this way, Georgescu-Roegen made an enormous contribution to ecological economics.

This paper presents our judgment of the contribution that Georgescu-Roegen made to ecological economics. It is organized around some of the major topics he addressed or contributed to. Section 2 discusses Georgescu-Roegen's contribution to the 'pre-analytic vision' that shaped to a significant extent the field of ecological economics. Section 3 discusses the critical issue of substitution between human and natural capital, and how Georgescu-Roegen was among the first to recognize and formalize this issue. Section 4 addresses Georgescu-Roegen's infamous fourth law of thermodynamics about the importance of matter. Section 5 presents examples of when, where, and by how much thermodynamics and/or biophysical limits constrain the economic process. We end with a discussion of the unfinished research agenda suggested by Georgescu-Roegen's work that awaits the attention of ecological economics.

2. The 'pre-analytic vision' of ecological economics

Traditional economic analysis concentrates on the exchange of commodities among the members of an economy, focusing on the role of consumer preferences, technologies, and capital endowments for the existence and stability of market equilibria. Georgescu-Roegen sought to ground economic analysis in the biophysical realities of the economic process. His efforts occurred independently of, and at the same time as Boulding (1966) was being celebrated for demonstration of the environmental implications of the mass-balance principle, Odum (1971) was working on energy flow analysis, Ayres and Kneese (1969) were using the materials balance approach, and the application of input-output techniques to the analysis of energy use in ecological and economic systems by Hannon (Hannon, 1973a, 1975) and Bullard and Herendeen (1975). Together, these studies influenced to a significant extent the field of ecological economics—the questions it asks and the methodologies it applies. But what distinguishes Georgescu-Roegen's contribution from the other pioneers was his ability to incorporate biophysical principles into the everyday language and models of standard economics. In doing so his work pointed towards the economic importance of the laws of conservation of mass and energy, and the entropy law.

Economists and ecological economists discuss and debate important details of Georgescu-Roegen's work (Tang et al., 1976; Kahlil, 1990, 1991; Bianciardi et al., 1993; Gowdy, 1993; Daly, 1995), and they debate conventional economists about the usefulness of thermodynamics in economic analysis (e.g. Young, 1991; Daly, 1992). Such debates have developed in part due to the vagueness of some of Georgescu-Roegen's arguments, and to instances where he over-extended his interpretations of thermodynamics and its role in economic systems. We discuss some of his main arguments—including their vagueness and limitations—in greater detail below. However, before we do so, we wish to recognize Georgescu-Roegen's fundamental contribution to the conceptual framework of the field of ecological economics.

Among pioneers of ecological economics, Georgescu-Roegen (1971) went the farthest in exposing the shortcomings of specific conventional economic theories and specific economic tools such as production functions. His fame and notoriety on the subject stem from the sweeping claims he made about the constraints imposed by the entropy law, and the degree to which he is cited by many influential scholars in the field (Daly, 1973).

The testament to his fundamental insight is the degree to which thermodynamics—and more generally the analysis of energy and material flows—forms a cornerstone of the 'pre-analytic vision' of ecological economics, as well as the empirical work of many of its practitioners. Georgescu-Roegen's claim that the entropy law formed the 'taproot' of economic scarcity stemmed from a simple series of observations. The economic process is a work process and as such it is sustained by a flow of low entropy energy and matter from the environment (Fig. 1). As materials and energy are transformed in production and consumption processes higher entropy waste heat and matter ultimately are released to the environment. The circular flow of exchange value, which grabs the spotlight in conventional economic analysis, is an intermediate step in the process powered by the unidirectional flow of energy and materials.

The conceptual model represented in Fig. 1 (and variations of it) is a starting point for the work of many ecological economists. Numerous studies of material and energy flows across the economy-environment boundary applied mass and energy balances to account for those flows and their contribution to economic production (Ayres and Kneese, 1969; Odum, 1971; Daly, 1973; Slesser, 1978; Ayres, 1978). Others have expanded on the use of mass and energy balances to account for changes in the quality of the material and energy flows as production and consumption occur (Costanza, 1980; Cleveland et al., 1984; Hall et al., 1986; Gever et al., 1986; Faber et al., 1987; Peet, 1992; Perrings, 1987; Ruth, 1993; Ruth and Bullard, 1993; O'Connor, 1991; Binswanger, 1993). The importance of the entropic perspective advanced by Georgescu-Roegen and the other pioneers is evidenced further by the prominent attention devoted to it in histories of thought (Martinez-Alier, 1987; Cleveland, 1987), surveys of ecological economics (Krishnan et al., 1995; Costanza et al., 1997), and this special issue of 'Ecological Economics' in his honor.

3. Are natural capital and human-made capital substitutes or complements? Both, of course!

Ecological economists frequently use Solow's (Solow, 1974) statement that "the world can, in effect, get along without natural resources" as evidence for the flawed treatment of the economy-

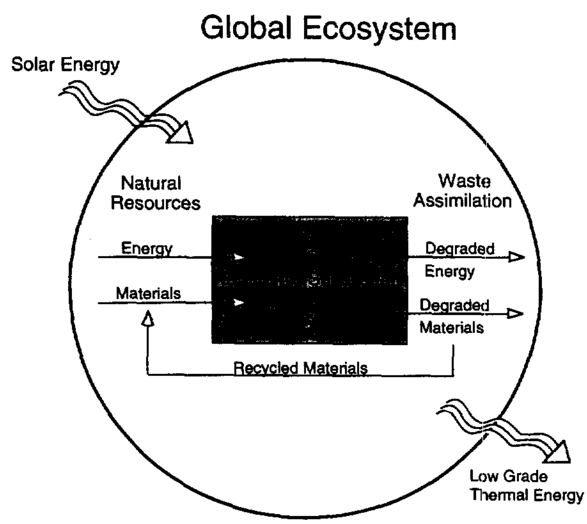

Fig. 1. The economy is an open subsystem of the larger closed environmental system. The economic process is sustained by the irreversible, unidirectional flow of low entropy energy and materials from the environment, through the economic system, and back to the environment in the form of high entropy, unavailable energy and materials (modified from Hall et al., 1986 and Goodland et al., 1991).

environment relation in the neoclassical discipline (Daly, 1996). Solow's statement is a red flag because it seems to be a definitive answer to a paramount question in ecological economics: what is the minimum amount of natural capital required to sustain a given standard of living, and to what degree can human-made capital substitute for depleted resources and a degraded environment? The different prescriptions for 'sustainable development' embody different assumptions about the potential for such substitutions. The criterion of weak sustainability assumes a large degree of substitutability between human-made and natural capital (Pearce and Atkinson, 1993), while strong sustainability assumes that they are largely complements (Costanza and Daly, 1992).

To assess the roles of natural and human capital, we must first define what kind of substitution we are talking about. There are some categories where substitution is feasible and common. Clearly, one form of natural capital can substitute for another. The greatest potential lies with energy and minerals. We can transform aluminum instead of copper into electrical wire, and we can combust biomass instead of oil to provide energy. But substitution possibilities diminish across the broader categories of ecosystem services. For example, energy and minerals cannot substitute for the protection against harmful cosmic radiation provided by ozone, the regulation of global climate, or the information embodied in biodiversity.

Another common category is the substitution within different types of manufactured capital and human capital, as when one type of machine replaces another or when new ideas supplant old ones. There also is substitution between human capital, as when power saws replace carpenters and when computerized robots replace auto workers.

The main issue, however, is the relation between natural capital, which yields a flow of natural resources and environmental services that enter the production process, and the manufactured capital which transforms the resources into goods and services. Is the flow of natural resources and environmental services—and the stock of natural capital that yields the flow—substitutable by manufactured capital?

Many ecological economists argue that this class of substitution is quite limited (Hall et al., 1986; Ayres and Nair, 1984; Common and Perrings, 1992; Costanza and Daly, 1992; Victor, 1994). There are several reasons for this. There are some services that only natural capital can provide. Examples are the creation and maintenance of fertile soil, the regulation of global climate, the storage and recycling of nutrients, photosynthesis, and the maintenance of biodiversity. These forms of natural capital provide essential, irreplaceable services in the functioning of the overall environmental life support system, and cannot be substituted for by any form of human capital.

Another limitation is that natural capital and manufactured capital overwhelmingly are complements. The case for complementarity is based on the following arguments.

1. Historically, manufactured capital and natural capital have been developed as complements, not substitutes (Daly, 1991). The stock of manufactured capital such as tractors, oil rigs, and fishing vessels has been increased with the express intent of increasing the use of natural capital such as fertile soil, oil deposits and fish populations. It is ridiculous to talk of one without the other. As Costanza and Daly (1992) observe, if manufactured and natural capital were perfect substitutes, there would be no need to develop and accumulate manufactured capital since an equivalent form already exists!

2. From a biophysical perspective, production is a work process that uses energy to transform materials into goods and services (Cleveland et al., 1984). The fund-flow model proposed by Georgescu-Roegen (1971, 1975) describes production as a transformation process in which a flow of materials, energy, and information is transformed by two agents of transformation, human labor and manufactured capital. Natural capital is what is being transformed (the material cause), while manufactured capital effects the transformation (the efficient cause). For example, all machines require energy for their operation and they function by acting on a flow of materials from natural capital (Victor, 1994). Thus, adding to the stock of pulp mills does not produce an increase

in pulp unless there is also the wood fiber to feed them. The two are clearly complements.

3. There is a biophysical interdependence between manufactured and natural capital. Tools, machines, and factories are made of natural capital, and the humans who direct them also consume natural resources. Thus, producing more of the 'substitute', i.e. manufactured capital, requires more of the thing that it is supposed to substitute for.

Georgescu-Roegen had a great deal of insight into the substitute/complement issue, particularly points 2 and 3. For Georgescu-Roegen, a great sin of conventional economic analysis is the confusion of funds and flows, leading to a fundamental misrepresentation of the relation between manufactured and natural capital. A glaring example of this is the standard representation of funds and flows in models such as the Cobb-Douglas production function, namely:

$$Q = K^{\alpha_1} L^{\alpha_2} R^{\alpha_3} \tag{1}$$

where Q is output per time period; K is the stock of capital; R is the flow of natural resources; L is labor supply per time period; and α_1, α_2, α_3 are fixed parameters. As Georgescu-Roegen (1979a, b,c) observes, this implies that with a constant labor force L_0, one could obtain any given Q_0 if the flow of natural resources satisfies the condition

$$R^{\alpha_3} = \frac{Q_0}{K^{\alpha_1} L_0^{\alpha_2}} \tag{2}$$

Consequently, we could maintain a constant output indefinitely with an ever-diminishing amount of R if the quantity of K can be increased sufficiently. But Georgescu-Roegen (1979a) exposes this 'conjuring trick', charging that excessive preoccupation with "paper and pencil exercises has led to accepting these exercises without any concern for their relation to facts" (p. 97). Of course, on an economy-wide level the increase in K implies an increase in the use of R, so that if $K \rightarrow \infty$, R will be rapidly exhausted by the production of capital (Christensen, 1989). Other analysts have echoed Georgescu-Roegen's point that in certain applications or interpretations, widely used models such as the Cobb-Douglas or constant elasticity of substitution (CES) production functions embody the physically impossible assumption that a given output can be maintained as energy or material inputs vanish if manufactured capital can be increased sufficiently (Dasgupta and Heal, 1979; Meshkov and Berry, 1979; Ayres and Nair, 1984; Perrings, 1987; Ruth, 1995a). The laws of conservation of mass and energy clearly dictate that no agent can create the stuff on which it operates, i.e. manufactured capital cannot create the resources it transforms and the materials it is made from.

3.1. The dimensions of substitution between manufactured and natural capital

The complementary relation between manufactured capital and natural capital does not preclude all substitution between the two. The potential for substitution depends on the following: the type of substitution (direct versus indirect and marginal versus non marginal); where the system boundaries are drawn (micro- versus macro-economy); the time scale (long versus short run) and the spatial scale (local versus global).

Manufactured capital, usually in conjunction with human capital, can substitute for natural capital in two ways (Victor, 1994). Direct substitution occurs when manufactured capital provides a service equivalent to that of natural capital. For example, chemical pesticides can substitute for natural predators and photovoltaic cells can convert solar energy into useful forms just as photosynthesis, although the quality of the energy is quite different.

Manufactured capital indirectly substitutes for natural capital through what is commonly called efficiency-increasing technical progress (Costanza and Daly, 1992). This occurs when more efficient machines increase the productivity of natural capital. Examples are cars that get more miles per gallon and light bulbs that give more lumens per watts. Georgescu-Roegen (1979b) emphasized the clear limits to the type of substitution because technical change does not occur in a vacuum. It requires an investment of human and natural capital in edueation, research and development, and ultimately new processes, machines, equipment, factories, etc. Thus, efficiency-increasing technical progress has a definite limit, "unless we believe that the ultimate fate of the economic process is an earthly Garden of Eden" (Georgescu-Roegen, 1979b).

The potential to substitute manufactured capital for natural capital is greater for marginal decreases in natural capital than for non-marginal ones (Victor, 1994). There may be many possibilities to substitute manufactured capital for small losses of natural capital. For example, hats and sunscreen could protect against a decline in stratospheric ozone, and dikes could protect against a rise in sea level caused by global warming. But these measures would be ineffective against a complete loss of stratospheric ozone and a dramatic rise in sea level.

The potential for substitution varies with the boundaries of analysis. For example, home insulation directly substitutes for heating fuel, a clear substitution of manufactured capital for natural capital *within the household sector*. From this perspective, substitution possibilities increase as you scale-up from individual processes to firms and entire industries because the possibilities for changes in technology and input and output mix increase the possibility to substitute one form of capital for another. This apparent increase in substitution possibilities underlie the 'technological optimist' position that technology has been and will continue to be a powerful antidote to resource depletion and environmental degradation (Barnett and Morse, 1963).

Elasticities of substitution between human-made and natural capital calculated for individual processes, firms, or industries may accurately reflect substitution possibilities *at those scales*. However, they may not accurately reflect possibilities for the economy as a whole because they do not account for the indirect natural capital costs of producing and maintaining manufactured capital. Put another way, the aggregate of potential savings at the macroeconomy is less than the sum of the savings one would calculate by adding the savings from sectoral-level analyses that do not account for the indirect costs. Returning to our example, insulation requires fuel and other types of natural capital to manufacture, meaning that for the economy as a whole, the net substitution of insulation for fuel is less than that indicated by an analysis of the household sector in isolation from the rest of the economy. The debate about substitutability has been characterized by careless extrapolation of theory or empirical analysis from smaller scales to sweeping conclusions about how 'essential' natural capital is for all of humanity.

Time and space scales are critical dimensions of substitution. Over time spans of seconds, minutes, days, and even months, many technologies are relatively fixed, so substitution possibilities are small or zero. Generally speaking, longer time frames provide more potential for technological change and substitution. But this is not always the case. Shale oil could replace depleted conventional oil deposits with refinements of existing technologies. Over the very long run, however, the depletion of all types of fossil fuel will require major breakthroughs in both basic science and technology development to develop equivalent technologies. This could limit substitution over the long run.

Space has a similar effect on substitution possibilities. A society can increase its potential for substitution if it has access to regional or global supplies of natural capital. Indeed, much of the debate about the merits of free trade are based on the simple fact that trade expands an economy's access to natural resources, waste assimilation services, and ecosystem services from other regions (Ekins et al., 1994). Societies can significantly offset domestic depletion with imports, as the United States does by importing one-half of its oil. But there are clear limits to the degree to which all societies can increase their potential for substitution by expanding the spatial scale of natural capital appropriation. These limits are set by the rate at which solar energy reaches the Earth, the rate of global photosynthesis, the rate that water evaporates, and other components of global biogeochemical cycles that form the basis of the planet's natural capital.

Despite the importance of the substitution issue, there is scant empirical work that accounts for the interdependencies between the two types of capital. Most of the work has focused on measuring substitution between energy, labor and manufactured capital at the single industry level using traditional production function approaches (see Berndt and Field, 1981 for a review). In contrast, Kaufmann and Azary-Lee (1991) explicitly account for the indirect energy used elsewhere in the economy to produce the capital substituted for fuel in the US forest products sector. They found that from 1958 to 1984 the indirect energy costs of capital offset a significant fraction of the direct fuel savings. In some years, the indirect energy costs of capital are greater than the direct fuel savings. The results of Kaufmann and Azary-Lee's analysis are consistent with the arguments made above that scale is critical in assessing substitution possibilities. In this case, the assessment of substitution at one scale (the individual sector) overestimates the energy savings at a larger scale (the entire economy).

4. A fourth law of thermodynamics?

One of Georgescu-Roegen's (1979b; 1982) most renowned arguments is that "matter matters too." Georgescu-Roegen reacted strongly against energy theories of value (Costanza, 1980; Hannon, 1973b; Odum, 1971). He argued that the principle of entropy applied to materials as well as energy. Energy and materials always are used together; we can never handle energy without a material receptor, material lever, or material transmitter (Georgescu-Roegen, 1979c). Thus, Georgescu-Roegen argued that there is a 'dual' of the first law of thermodynamics, namely that no mechanical work can be performed without the use of some matter. He further asserted that the second law of thermodynamics, which precludes the possibility of a machine converting energy to work with 100% efficiency, is due to 'imperfections in matter'. That is, there are no frictionless materials, no perfect insulators, no perfect conductors, no perfectly elastic materials, etc. (Georgescu-Roegen, 1979c). These imperfections preclude the perfect conversion of energy into mechanical work. Consequently, a full understanding of material and energy transformations requires explicit attention to matter.

The hand-in-glove relation between energy and material use produces a continuous conversion of matter from high quality to low quality state, in a manner directly analogous to the dissipation of energy. Georgescu-Roegen (1979b) states:

> All over the material world there is rubbing by friction, cracking and splitting by changes in temperature or evaporation, there is clogging of pipes and membranes, there is metal fatigue and spontaneous combustion. Matter is thus, continuously displaced, altered, and scattered to the four corners of the world. It thus, becomes less and less available for our purposes (p. 1034).

Georgescu-Roegen emphasized that "the Entropy Law in its present form states that *matter, too, is subject to an irrevocable dissipation*" (Georgescu-Roegen, 1976, p. 8, original emphasis). This statement is, without doubt, correct for isolated systems. All changes in the thermodynamic state of materials must be accompanied by a degradation of the quality of energy. If the system is isolated, i.e. no mass or energy flows cross its boundaries, the system will ultimately reach a state at which no gradients in temperature, pressure or material composition exist that enable the system to change its state. Such a state of the system is referred to as heat death.

In subsequent arguments Georgescu-Roegen (1977) asserted that "isolated systems present only a small interest to us. If we set aside the case of the whole universe, isolated systems are set up (with some degree of tolerance) only in laboratories" (p. 267). In much of his work on the role of matter in economic processes he then focused on closed, rather than isolated systems, i.e. systems that *do* have energy flows crossing their boundaries but *do not* have material flows across their boundaries:

> Having in mind the statistical interpretation of thermodynamics, one may argue that we can certainly reassemble the pearls of a broken necklace scattered over the floor. Is not recycling such a type of operation? To see the error in extrapolating from the molar to the molecular level, let us suppose that the same pearls are first dissolved in some acid and the solution is

> spread over the oceans—an experiment which depicts what actually happens to one material substance after the other. Even if we had as much energy as we pleased, it will take us a fantastically long, practically infinite time, to reassemble the pearls (Georgescu-Roegen, 1977).

Inspired by this and similar examples, Georgescu-Roegen went on to elevate his observations to a Fourth Law of Thermodynamics, or Law of Matter Entropy, describing the degradation of the organizational state of matter:

> [...]a system that can exchange only energy with its outside and performs work indefinitely at a constant rate [...] is another thermodynamic impossibility. [... S]ooner or later, some elements will become totally dissipated. (Georgescu-Roegen, 1981, pp. 53–54).

The bottom line for Georgescu-Roegen is that due to material dissipation and the generally declining quality of resource utilization, materials in the end may become more crucial than energy. This leads him to criticize Boulding's (1966) claim of no law of increasing material entropy. He rejects Daly's (Daly, 1973) version of a steady-state economy on the grounds that materials dissipate in a closed system such as the Earth just as energy does. Georgescu-Roegen states:

> Complete recycling being impossible, even in the steady state, the 'transactions' between the economic process and the environment must necessarily consist of some available matter as well in order to compensate for the matter dissipated continuously and irrevocably (Georgescu-Roegen, 1979b, p. 1039).

4.1. *The fallacy of infinite resources*

Georgescu-Roegen also rejects the 'infinite resources' arguments made by Brown et al. (1957), Brooks and Andrews (1974) and Goeller and Weinberg (1976), because they ignore the importance of changes in the quality of matter. For example, Brooks and Andrews (1974) state that the literal notion of running out of materials is ridiculous because the entire planet is composed of minerals. Georgescu-Roegen exposed the fallacy of this argument by observing that, by the same token, we could argue that we will never run out of energy because the entire planet is full of energy. Indeed, the ocean contains enough energy to support undreamed of economic activity for millennia to come. However, the temperature gradient in the ocean is so small that for all practical purposes the enormous store of energy is unavailable. Similarly, Georgescu-Roegen (1979b) argues that many of the materials are in low quality deposits that for all practical purposes render them unavailable.

Georgescu-Roegen's emphasis of material quality shares a common theme with the biophysical perspective of resource scarcity held by some ecological economists (Slesser, 1978; Hall et al., 1986; Gever et al., 1986; Cleveland, 1991, 1993; Peet, 1992; Ruth, 1993) and a number of physical scientists (Cook, 1976; Chapman and Roberts, 1983). The biophysical manifestation of scarcity is the use of, and often times the depletion of, increasing amounts of natural and human-made capital to deliver a unit of resource to society. A decline in the quality of the natural resource base due to cumulative depletion, an increase in the instantaneous rate of exploitation, or an increase in the scale of extraction, increases the amount of natural capital used to extract a unit of natural resource. The biophysical perspective of scarcity measures the cost of obtaining natural resources in physical terms, and thereby emphasizes the throughput of energy and materials required to extract resources, and the resultant impact of that throughput on a broad array of ecosystem services in different quantities and spatial scales.

Natural resources in a highly organized state are more economically useful because they have lower energy costs. The inverse relation between resource quality and the energy cost has been demonstrated for a wide range of minerals and fossil fuels (Page and Creasey, 1975; Chapman and Roberts, 1983; Cleveland, 1993; Ruth, 1995c). The increased effort required to develop lower grade resources also increases their environmental cost. In metal mining, for example, deterioration of ore quality in underground mines spurs the expansion of surface mining where the volume of waste material produced per ton of ore is twelve times greater (Gelb, 1984). The stripping ratio (tons of waste per ton of ore extracted) in metal, nonmetal, and coal surface mines in the US has increased sharply in the last half century (Dale, 1984; Gelb, 1984). That decline in resource quality increases the land required to produce a ton of coal which, in turn, increases the amount of degraded land that must be reclaimed and the quantity of water used in reclamation. Cleveland (1993) found that the increase in the energy cost of petroleum extraction in the US also is associated with an increase in the quantities of water used and CO_2 released in the extraction process.

4.2. The critique of the net energy school

Georgescu-Roegen (1979b, 1986) criticized the energy analysis school as represented by Cottrell (1955), Odum (1971), Slesser (1978), and Costanza (1980) for the same reasons he criticized the infinite resources school. According to Georgescu-Roegen, they too implicitly or explicitly assume that perfect recycling of materials is possible if sufficient energy is available. He charges that this 'energetic dogma' leads to the erroneous conclusion that available energy is the only ultimate limiting resource.

Georgescu-Roegen's criticisms of the energy analysis school have an ironic twist. By lumping them in with all other alleged disciples of the 'energetic dogma', he missed the important similarities and goals he shared with them. The work by Odum, Costanza, Slesser and other energy analysts emphasized the need to ground economic theory and methods in physics and ecology, much in the same way Georgescu-Roegen did. The biophysical model of resource scarcity is rooted in the importance of resource quality—including energy and materials—that Georgescu-Roegen emphasized so vigorously. Georgescu-Roegen's excessive preoccupation with the 'matter matters' argument, and his reaction against energy theories of value, prevented him from seeing that many of these individuals and ideas were allied closely with his own.

4.3. Critiques of the 'Fourth Law'

Georgescu-Roegen's Fourth Law has been criticized by a number of analysts in economics and the physical sciences. Ayres and Miller (1980) argue that Georgescu-Roegen's assertion that intrinsically scarce materials cannot be recovered (regardless of energy expenditure) from average rocks and the ocean is just plain wrong. They observe that physical dissipation of materials can never result in a distribution worse (from the standpoint of recovery) than a hypothetical homogenous regolith in which every element is present exactly in its average crustal abundance. They argue that all elements can be extracted from such a regolith provided there is enough available energy. Ayres and Miller conclude that, in theory, energy is the only resource that could ultimately limit economic growth.

It recently has been pointed out that on a fundamental physical level there is no such *law* as the Fourth Law of Thermodynamics stated by Georgescu-Roegen (Bianciardi et al., 1993; Ruth, 1995a). Whether at the molar or molecular level, in principle it is always possible to use the incoming high-quality energy to trace, collect and reassemble the dissipated elements. Well-documented counter examples to Georgescu-Roegen's Fourth Law include the biogeochemical cycles—driven by the influx of solar radiation—that constantly funnel dissipated materials through a closed, global ecosystem and temporarily generate high material concentrations. It is those processes that lead to the formation of pearls from ocean water in the first place, the agglomeration of metals in ores and the formation of fossil fuels.

The theoretical flaws of Georgescu-Roegen's Fourth Law have led some to dismiss Georgescu-Roegen's ideas or deny their significance (Månsson, 1994). What should be at issue, however, is not a 'categorical impossibility' of perfect recycling asserted by Georgescu-Roegen (1981, 1986). More important are the relationships among the processes that lead to a dissipation of high-quality energy and degradation of material resources on the one hand and the processes that capture high quality energy and change materials from less desired to more desired thermodynamic states on the other hand. With thermodynamics, central for an assessment of these relationships are the concepts of information and time.

To be able to trace and collect dispersed materials requires not only the availability of energy but also information and time. The fundamental physical relationships among those three inputs into processes that upgrade the state of materials have been described by Szilard (1929) and applied to industrial systems by Spreng (1993), Chen (1992, 1994), Ruth and Bullard (1993) and Ruth (1993, 1995b). The role of information relative to the other inputs into production processes prompted Boulding (1982) to claim that energy itself is unimportant. What is important is the knowledge to make use of material endowments that are present in less desired forms and change their state to more desired ones. In the case of biological systems, that knowledge is embodied in their genetic make-up. In the case of economies, it is present in the capital goods, human capital, institutions and other repositories of knowledge such as computers and libraries (Ruth, 1996a).

Biological systems, however, differ markedly from economic systems with regard to the time available to trace, collect and upgrade materials. Ore deposits and fossil fuels have been formed over time periods that are far too long to be of relevance for economic decision making. The formation of ore deposits and fossil fuels is powered by the inflow of solar radiation, utilized at low efficiencies, and heat from the Earth's core. In contrast, economic systems use significant amounts of nonrenewable resources to speed up the production of goods and services. Thus, from an economic perspective, an increasing dispersal of materials is constraining as long as tracing, collecting and upgrading those materials requires expenditures of finite, costly sources of low-entropy energy.

These perspectives highlight human participation in biogeochemical cycles and the importance of thermodynamics for understanding the environmental significance of that role. For example, the price of a material produced from virgin sources or from waste is a direct function of its degree of concentration in the parent source material or its dilution in the waste stream, respectively (Allen and Behmanesh, 1994). Hence, the recycling potential for materials in hazardous waste streams is determined by their dilution, because highly dilute materials require more work, and hence higher cost, to upgrade to a desired raw material state.

The increase in entropy from energy use can be compared to the decrease in entropy that results from upgrading the state of materials either from virgin ores or waste residuals to arrive at a physical measure of the efficiency of economic processes. Comparisons of this measure over time provide insight into the ability of technical change—that itself requires materials and energy to take place—to counteract depletion and pollution (Ruth, 1996b; Ayres et al., 1996). An advantage of these measures over traditional economic measures of efficiency is their ability to make judgments that are irrespective of changes in consumer preferences, market forms or other institutional settings that mask the physical reality of production and consumption processes.

Despite the flaws in Georgescu-Roegen's definition of a Fourth Law, his insistence on the importance of materials for production and consumption processes highlighted the differences between economic processes and 'natural' processes. His focus on the dispersal of materials and limits on recycling foreshadowed the development of the fields of industrial metabolism (Ayres and Simonis, 1994) and industrial ecology (Graedel and Allenby, 1995) in which the analysis of material cycles is used to understand how production and consumption impact the environment, and how to design new technologies that reduce such impacts. Georgescu-Roegen's emphasis on physical limits to recycling, however, emphasizes more the need for efficiency improvements in production and for curtailing consumption than the current literature on industrial metabolism and industrial ecology—with their focus on material cycles—suggest.

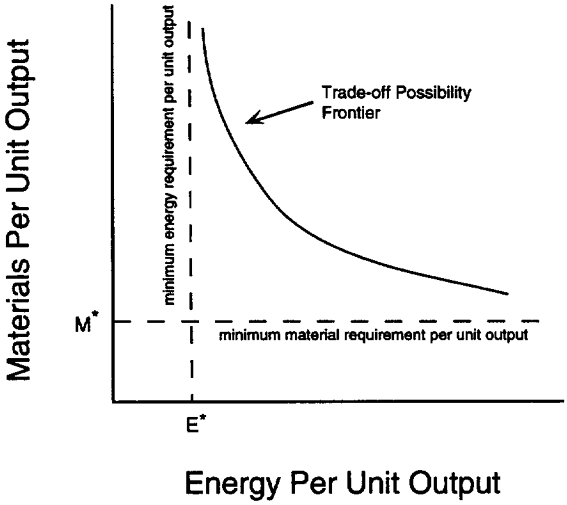

Fig. 2. Trade-off possibility frontier for energy and material inputs per unit of output (modified from Ruth, 1995a,b,c).

5. Constraints at the process and industry level

Georgescu-Roegen believed that the entropy law placed broad but immutable constraints on human economic aspirations. These constraints were not of the trivial sort envisioned by some economists, such as the ultimate death of the sun. Rather, they defined the limits within which human ingenuity and human interests were free to operate. In most cases, Georgescu-Roegen did not define these limits explicitly, nor did he engage in any empirical research that measured them. But a host of researchers have further developed these ideas in theoretical and empirical terms.

Thermodynamic limits to the ability to generate a desired output from economic processes have been most extensively investigated at the level of individual processes. The limits to substitution are easily identified for individual processes by an energy-materials analysis that defines the fundamental limitations of transforming materials into different thermodynamic states and on the use of energy to achieve that transformation. The production function represented in Fig. 2 illustrates these constraints. The minimum material and energy inputs required to produce a desired output are defined by M^* and E^*, respectively. The function which describes the substitution possibilities between M and E is bounded by these lower limits. This approach has been used in empirical analyses of material and energy use in individual processes such as copper extraction (Ruth, 1995a), and copper and aluminum processing (Ruth, 1995b).

Thermodynamic analyses have shown where technological improvements exhibit strong diminishing returns due to thermodynamic limits, and where there is substantial room for improvements in the efficiency of energy and material use. For example, the thermal efficiency of power plants has been relatively constant for many years, reflecting the fact that it is approaching the thermodynamic limit. Chapman and Roberts (1983) describe other material processing industries that are approaching thermodynamic thresholds. In the area of energy technologies, thermodynamic analyses suggest good reasons for not pursuing research on thermal methods for generating hydrogen from water (Warner and Berry, 1986). On the other hand, thermodynamic analyses provide strong motivation to carry out research on heat-driven separation processes (Orlov and Berry, 1991).

Comparisons of first law efficiencies with second law efficiencies also highlight the role of the quality of energy in industrial processes and guide the choice among alternatives (Gyftopoulos et al., 1974). Detailed energy analyses identify ways to reduce losses in the ability to do useful work when changing the thermodynamic states of materials. Among the most comprehensive studies calculating the deviation of actual technologies or operations from their thermodynamic ideal is Szargut et al. (1988). Their study quantified a 'cumulative degree of perfection', a measure of the deviation from thermodynamic ideals of series of production processes spanning from recovery of raw materials to the refining of the desired products. A selection of estimates is presented in Table 1. The values range widely, indicating significant opportunities for many material processing industries to increase their material and energy use efficiencies. It is also striking, however, that fossil fuel processing and paper and plastic production show less room for efficiency improvements—products to which modern industrial societies became increasingly accustomed.

Following the arguments of Lotka (1922) and Odum (1955), Georgescu-Roegen emphasized that the thermodynamic constraints on economic processes imply a relationship between the time it takes to perform a process and the energy required to carry out that process. This relationship is illustrated by the fact that even in the presence of infinite energy supplies it would take infinitely long to assemble the beads of a necklace that had been dissolved in the oceans. Although a recurring theme in his arguments, the relationship between energy and material use and time is not explicit in the thermodynamic laws he invokes.

This line of research has produced a number of studies that stress that production processes are carried out in a finite span of time (Weinberg, 1977, 1978; Andresen, 1983; Andresen et al., 1984). These studies indicate that reversible (quasi-equilibrium) thermodynamics is inadequate for the evaluation of real processes and that 'finite-time thermodynamics' may be more meaningful (Ruth, 1993). In finite time thermodynamics, constraints are imposed on the rate at which processes are performed. Applications of finite-time thermodynamics can be found, for example, in Månsson (1985) who analyzed the efficiency of the ammonia synthesis process, and Berry and Anderson (1982) who evaluated the performance of an idealized auto engine.

The constraints on the rate of a process are frequently difficult to quantify even in the case of a single production technology. A reasonable quantification at the level at which biogeochemical cycles operate probably is impossible. Yet, finite-time thermodynamics provides the means to identify trade-offs between energy and material use and time, and thus, may help substantiate many of Georgescu-Roegen's intuitive arguments.

Table 1
Cumulative degree of perfection for the production of materials (Szargut et al., 1988)

Material	Cumulative degree of perfection (%)
Glass (from raw materials in the ground)	0.8
Nickel (from ore concentrate)	1.6
Copper (electrolytic; from Cu_2S ore)	3.1
Lead (from ore in the ground)	3.5
Cement (wet method; medium rotary kiln)	6.2
Tin (from ore concentrate with 20% tin in concentrate)	15.4
Paper (from standing timber)	18.7
Iron ore sinter (from ore)	27.0
Cellulose (from wood; waste products used as fuels)	27.4
Open hearth steel (liquid; 70% scrap)	34.4
Electric steel (liquid, 100% scrap)	35.4
Pig iron (from magnetic taconite at 32.5% Fe content)	40.0
Pig iron (from ore in the ground; mining and blast furnace from high grade haematite ore)	44.0
Polyethylene (low density; from crude oil)	52.5
Benzene (from crude oil)	68.1
Benzene (liquid; from bituminous coal)	71.6
Paper (from waste paper)	74.3
Diesel oil (typical value)	83.5
Natural gas (typical value)	87.5

6. Constraints at the macroeconomic level

Constraints at the macroeconomic level cannot be defined as explicitly as they can for individual processes or industries. The thermodynamic constraints that are imposed on individual production processes may be of little meaning for an industry as a whole because industry is able to choose among various processes. Processes that are close to their thermodynamic ideal can be replaced altogether by those that produce comparable outputs with more direct methods, thus eliminating waste in intermediate production stages (Berg, 1980). Moreover, as we argued above, opportunities to respond to depletion or degradation multiply at the macroeconomic level.

Despite the adaptability and flexibility of society in responding to environmental change, there is sound theoretical work that demonstrates the relevancy of biophysical principles for entire economic systems, and empirical evidence that such constraints already are evident in a few key areas.

6.1. Theoretical foundations

Daly (1991) points out that conventional macroeconomics completely ignores the biophysical principles, elucidated by Georgescu-Roegen and described above, that bind human economic existence to the environment. Daly argues that the physical exchanges crossing the boundary between the total ecological system and the economic subsystem constitute the subject matter of environmental macroeconomics. These flows should be considered in terms of their total volume or scale relative to the environment. The absolute scale of the flows is indicated by Daly's now famous example of the environmental Plimsoll line. Daly argues that the major task of environmental macroeconomics is to design an economic institution that will keep the scale of the economy from sinking our 'biospheric ark'.

Daly's recommendations for an environmental macroeconomics are borne out by theoretical work that incorporates the conservation of matter/energy and other biophysical principles in conventional models of economic growth. Ayres and Miller (1980) criticized the insupportable assumption in long-range optimal path models that goods and services (including capital goods) are 'intangible', requiring no physical embodiment of resources and available energy, and permitting unlimited substitution of fixed capital for resource input flows. They also question the assumption that technical progress is automatic, exogenous, and subject to no limits. Ayres and Miller develop an optimal growth model which assumes that technology requires finite natural capital inputs and reaches finite limits. They also developed a production function that is consistent with the conservation of mass/energy and subject to the assumption that both capital and consumption goods embody energy. Their most important theoretical result is that the optimal path leads to a stationary state with finite capital and finite technical knowledge. Ayres and Miller reject Georgescu-Roegen's criticism of a steady-state economy on the basis that energy is the ultimate limiting resource, meaning that dissipated or low grade materials can be processed given sufficient available energy.

The classical economic model fares no better under the light of physical realities. Perrings (1986) develops a variant of the von Neumann-Leontief-Sraffa neoRicardian general equilibrium model in the context of a jointly determined economy-environment system subject to a conservation of mass constraint. The model demonstrates that the conservation of mass contradicts the free disposal, free gifts, and non-innovation assumptions of such models. Accounting for the conservation of mass destroys the determinacy of the closed, time variant system in the classical model. An expanding economy causes continuous disequilibrating change in the environment. Since market prices in an interdependent economy-environment system often do not accurately reflect environmental change, such transformations of the environment often will go unanticipated.

Ruth (1993) develops a stylized intertemporal, multi-sector optimization model that traces material cycles and energy flows in the ecosystem. The economic component of the model consists of agriculture, mineral extraction, processing and manufacturing, and of a consumption sector. All economic processes are governed by thermodynamic laws, and endogenous technical change moves each process asymptotically closer to its thermodynamic limit. Mass and energy balances trace flows of waste heat and waste materials across the economy-environment boundary. The results indicate upper limits for savings in exergy in light of endogenous technical change and time lags in the availability of improved technologies. Changes in waste absorption capacity of the environment are not explicitly considered in the model. Their presence would limit savings potentials further if emissions required additional material and energy expenditures to trace and collect pollutants.

6.2. Empirical evidence

The theoretical work by ecological economists suggest a much different long-run path for the economy, one in which the vision of unlimited economic growth is replaced with distinct limits to the ability of technology to push back biophysical constraints. But is there any evidence that such constraints already have impinged on economic welfare in a particular economy? We cite a number of important examples, limited to our experience and familiarity with the US.

One obvious area to examine is the scarcity of natural resources. The economic effect of rising scarcity is measured by a resource's opportunity cost: how much society must give up to obtain a unit of the resource. It is widely assumed that there is little or no evidence for increasing scarcity of most resources. This position is based on an interpretation of the historical record which finds no sign of upward trends for cost and price (Simon, 1981). Many of these assessments are based on the 'biocular excitement test', pioneered by Barnett and Morse (1963): plotting resource prices as a function of time, drawing a conclusion about the trend in scarcity, and positing the mechanisms that generate the deduced trend.

But empirical tests of scarcity should be based on sound theory that produces a testable hypothesis, and they should utilize the most powerful methods available for testing those hypotheses. Slade (1982) made a significant contribution by modifying the standard Hotelling (1931) model of optimal depletion, in which she incorporates explicit diminishing returns to technical innovation and the cost-increasing effects of resource depletion. The revised model predicts a long-run U-shaped path for resource prices. She then used regression analysis to test the U-shaped hypotheses, and found evidence that most metal prices in the US show such a pattern. Some metals had passed the trough in the long-run path, indicating rising opportunity costs. Hall and Hall (1984) also used regression analysis to test the hypotheses that the long-run downward trend in cost and price described by Barnett and Morse (1963) reversed in the 1960s and 1970s. Their results indicate that a number of fuels and metals showed signs of rising scarcity. It is interesting to note that the work of Slade and Hall and Hall receive little attention in the literature, particularly from economists, while the mantra of Barnett and Morse lives on.

Detailed analyses of particular resources in the US indicate rising opportunity costs. Cleveland and Stern (1993) develop functions more flexible than those used by Slade (1982) and Hall and Hall (1984), and use them to test for rising scarcity of forest products in the US. The results of their econometric analysis indicate that the real price of forest products increased dramatically from 1800 to 1990, although the price trend had leveled off in the post-war period. Nevertheless, the opportunity cost of forest products is much higher today than in the past despite substantial innovation in the industry and substitution of plastics and metals for many uses of wood.

The depletion of oil in the US also has had significant negative economic consequences. Efforts to increase supply from a depleted resource base has diverted productive resources from alternative uses and has accelerated environmental damage. New capital formation in the oil and gas industry increased from a total investment of 3–7% from 1973 to 1982, but the industry's contribution to GDP declined from 4 to 2% (Kaufmann and Cleveland, 1991). Resource depletion also has increased the energy required to extract oil, leading to a doubling of the amount of CO_2 released per barrel extracted (Cleveland, 1992).

Energy and other natural resources could be a limiting factor if they were in some sense 'essential' in the production of output. Neoclassical models tend to exclude energy and materials as factors of production, or assume a large degree of substitutability between them and human capital (Solow, 1978). On the other hand, some biophysical analysts emphasize energy inputs at the expense of human-made capital (Cleveland et al., 1984). Stern (1993) develops a multivariate autoregression model that tests for the importance of energy, capital, and labor in producing GDP in the US from 1947 to 1990. He finds Granger causality from quality-corrected energy use to GDP, suggesting that a decline in energy use results in a reduction in economic growth. This could have significant economic repercussions if energy became more scarce, or if the quality of fuel use diminished (we return to the importance of fuel quality below).

An increasing number of studies attempt to measure the economic costs of depletion and degradation and use them to 'correct' standard measures of economic welfare such as GDP.

Repetto et al. (1989) finds that deforestation and soil degradation in Costa Rica significantly diminish that country's economic growth in the last several decades when they are accounted for. Per capita GDP in the US and other nations grew much more slowly, or not at all, when the effects of depletion and degradation are accounted for (Daly and Cobb, 1989). These results indicate that technology and substitution have not been sufficiently strong to offset the effects of depletion at the macroeconomic scale in some nations.

7. Constraints at the global level

Necessary biophysical conditions for global sustainability require that society does not use natural resources faster than they are regenerated by the environment, produce wastes faster than the environment can absorb, detoxify, or dilute them, and does not diminish the ability of the ecosystems to generate life support services. Simple in principle, there is significant uncertainty in the minds of some about how close we are to achieving these conditions. For some, the vast stores of many minerals and fuels at low grades, the untapped flows of renewable resources, and the multiplicity of ways that human societies respond to depletion and degradation push global limits far from the current level of demand for environmental services. (Simon, 1981; Bailey, 1993). There is substantial uncertainty associated with global stocks and flows of resources and global waste assimilation capacity, and disagreement on what constitutes a just distribution of wealth between and among generations. These uncertainties and differences are used to argue that biophysical limits at small temporal and spatial scales evaporate at the global, long-run scale.

The global carrying capacity debate has emphasized food production and population growth, consistent with a long-standing tradition of using per capita food production or per capita land availability as a barometer of carrying capacity (Brown, 1994). Concern about long-run food production is justified given the trends in per capita land availability in some regions, the supply of water for irrigation (Postel, 1992), the intensive use of fossil fuels in industrial agriculture (Pimentel, 1991), degradation of existing land, and the economic, technological, and institutional obstacles that face developing nations trying to fully implement the Green Revolution.

As important as the food issue is, we believe there are two forces more likely to constrain our economic choices: the disruption of key environmental services caused by increasing human participation in global biogeochemical cycles and the depletion of conventional fossil fuels, especially crude oil. The former describes the effects of the increase in scale of the growing economic subsystem relative to the size of the finite stocks and flows of life support generated by ecosystems. The second relates to the depletion of the nonrenewable energy resource that has powered the transformation of the global economy and environment in the last 200 years, and for which a renewable substitute of equivalent potential has yet to be identified. On both points there is mounting empirical evidence that suggests we are approaching—or may have already breached—the Plimsoll line for some key environmental services.

7.1. Human participation in global biogeochemical cycles

The effects of the increase in the scale of human existence is evidenced by the increasing degree to which we participate in many global material cycles. Three prominent examples are the carbon, hydrologic, and nitrogen cycles. The most troubling sign is our appropriation of the products of global photosynthesis. Humanity currently directly and indirectly uses about 40% of global terrestrial net primary production each year (Vitousek, 1994). Humanity now uses 26% of total terrestrial evapotranspiration and 54% of runoff that is geographically and temporally accessible (Postel et al., 1996). Increased use of evapotranspiration and new dam construction will confer minimal benefits globally because most land suitable for rain-fed agriculture is already in production and because most of the major rivers in the world already are dammed. Humans now fix more nitrogen annually than natural processes through the production of fertilizers and the combustion of fossil fuels (Vitousek, 1994). Our participation in other material cycles now rivals or surpasses natural flows (Nriagu, 1979). Even for a freshman student in ecology, this massive diversion of materials and energy from or into other organisms and systems at a variety of spatial-temporal scales would raise concern about the long-run ability of the environment to support a human population that will double in the next century or so. Can anyone seriously suggest, for example, that humans could appropriate 80% of global NPP?

7.2. The depletion of fossil fuels

Among the countless technologies humans have developed, only two have increased our power over the environment in an *essential* way. Georgescu-Roegen (1982) called these Promethean technologies. Promethean I was fire, unique because it was a qualitative conversion of energy (chemical to thermal) and because it generates a chain reaction that sustains so long as sufficient fuel is forthcoming. As Georgescu-Roegen (1982) described:

> The mastery of fire enabled man not only to keep warm and cook the food, but, above all to smelt and forge metals, and to bake bricks, ceramics, and lime. No wonder that the ancient Greeks attributed to Prometheus (a demigod, not a mortal) the bringing of fire to us (p. 30).

Promethean II was the heat engine. Like fire, heat engines achieve a qualitative conversion of energy (heat into mechanical work) and they sustain a chain reaction process by supplying surplus energy. Surplus energy or (net energy) is the gross energy extracted less the energy used in the extraction process itself. The Promethean nature of fossil fuels is due to the much larger surplus they deliver compared to animate energy converters such as draft animals and human labor. The energy surplus delivered by fossil fuel technologies is the energetic basis of the Industrial Revolution (Cottrell, 1955; Odum, 1971; Cleveland et al., 1984; Cleveland, 1993). Georgescu-Roegen (1982) himself described the economic and environmental significance of the large energy surplus delivered by fossil fuel technologies.

The unparalleled ability of fossil fuels, and especially oil, to produce economic wealth is due to another attribute: energy quality. This refers to the fact that a heat unit of different fuels have different abilities to do work. The ability of a heat unit to do work varies among energy types because heat is the lowest common denominator among fuels. But humans use energy for tasks other than supplying heat, so the standard practice of aggregating fuel types by heat equivalents misses important differences in energy quality. For example, 1 kcal of electricity used to power an electric locomotive can move a train about three times farther than 1 kcal of diesel fuel used to power a diesel locomotive. Open hearth and electric arc furnaces require different quantities of coal and electricity, respectively, to produce a ton of steel.

Kaufmann (1994) demonstrates the profound economic importance of the physical and engineering aspects of energy quality. It is not possible to measure in physical units the economic work associated with many services provided by fuels, such as heating homes, driving cars, and dispelling darkness. Furthermore, people want a particular service delivered in a particular way, such as motive power with safety, style, comfort, etc. Thus, the economic significance of a fuel is its marginal product: the amount of economic value generated by a heat unit. The results of Kaufmann's (1994) econometric model indicates that the marginal product of fuels in the US economy varies over time, but that there is a consistent ranking of fuel quality: primary electricity is the highest quality, followed by oil, gas, and coal.

Energy quality plays a dominant role in determining the quantity of energy a society requires to produce wealth. The decrease in the energy/real GDP ratio in most industrial nations often is attributed to energy-saving technical change and substitutions caused by the energy price shocks. But detailed empirical analyses indicate that much of the variation of the energy real/GDP ratio is due to shift changes in the composition of fuel use, and hence changes in the quality of fuel use.

Kaufmann (1992) and Cleveland et al. (1984) show that much of the variation in the energy/real GDP ratio for the five largest industrial nations in the post-war period is due to changes in energy quality. Kaufmann (1992) finds no statistical evidence for autonomous energy saving technical change in this period. As he states:

> [This] should not be interpreted as an argument that substitution or technical change cannot reduce the amount of energy used to produce a unit of output ... Technical change has reduced the amount of energy (as measured in heat units) used to produce a unit of output. But characterizing that technical change as 'energy saving' is misleading. Over the last forty years, technical change has reduced the amount of heat energy used to produce a unit of output by developing new techniques for using oil, natural gas, and primary electricity in place of coal. These technical innovations ... take advantage of the physical characteristics of these energies that allow oil, natural gas, and primary electricity to do more useful work per heat unit than coal. This interpretation implies that technical change is not something shaped solely by the mind of man ... but rather technical change is shaped in part by the physical attributes of energies available from the environment (p. 53).

7.3. *The search for Prometheus III*

Georgescu-Roegen (1982) realized a fundamental challenge faced by humanity: the need to replace fossil fuels with solar technologies that have Promethean qualities. He also recognized an unalterable limitation of solar energy: it inherently is a lower quality fuel than fossil fuels. The diffuse nature of incoming solar radiation requires a significant investment of energy and materials to capture, collect, and concentrate sunlight. This means that many solar technologies deliver a lower energy surplus than fossil fuels (Cleveland et al., 1984; Hall et al., 1986; Gever et al., 1986). Equally important, the substantial 'material scaffold' required to collect solar energy is made from fossil fuels. Solar energy, therefore, currently is a 'parasite' on fossil fuel systems because they cannot 'reproduce' themselves (Georgescu-Roegen, 1979c). Many biomass-based fuels such as ethanol are what Georgescu-Roegen called 'feasible recipes' but fail the test of 'viable technologies' because of low net energy yields and high environmental costs (Pimentel, 1991). On the other hand, some technologies such as solar parabolic collectors have become viable through innovations that improve their net energy yields (Cleveland and Herendeen, 1989). The issue is whether a sufficient number of solar technologies can move from 'feasible' to 'viable' status in terms of their net energy return, and whether they can be scaled-up in time to offset the effects of fossil fuel depletion.

8. Discussion

Our review and interpretation of Georgescu-Roegen's contributions to Ecological Economics generates a number of unanswered questions about the importance of thermodynamics, and more generally biophysical constraints, in the economic process. Some of the more important issues are:

What are the possibilities for substituting human-made capital (including technology) for natural capital? A substantial amount of empirical work needs to be done to appropriately measure and represent human and natural capital in quantitative models of economic production, and to measure the potential for substitution between them. There is a conspicuous gap in our knowledge of the role played by ecosystem services in production.

Which renewable energy technologies have the greatest potential to be the next Promethean technology? Some renewable technologies have been hailed as a panacea for the depletion of fossil fuels, but many of those fail rudimentary net energy and environmental requirements.

Develop models of material and energy use and emissions that represent substitution, technical change, and resource depletion in a way that does not violate biophysical constraints, and which capture the ways that economic forces ameliorate or offset depletion and degradation.

Develop databases such as those in Szargut et al. (1988) (see Table 1) and Ayres et al. (1996) that list for the non-physicist what the physical constraints on technology are, i.e. make the quantitative biophysical information available to economists in a form they can understand and use in their models.

Train a new generation of scientists who in addition to expertise in a narrow field of inquiry have familiarity with the basic concepts and analytical tools used in economics and biophysical models.

These and other issues raised by Georgescu-Roegen's work undoubtedly will provide fertile ground for research by ecological economists and others interested in the issue of sustainability.

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